# A Precipitation-Runoff Model for the Analysis of the Effects of Water Withdrawals and Land-Use Change on Streamflow in the Usquepaug–Queen River Basin, Rhode Island

By Phillip J. Zarriello and Gardner C. Bent

Prepared in cooperation with the
Rhode Island Water Resources Board

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# Conversion Factors, Vertical Datum, and Acronyms

| Multiply | By | To obtain |
|---|---|---|
| acre | 0.004047 | square kilometer ($km^2$) |
| cubic foot per second ($ft^3/s$) | 0.02832 | cubic meter per second ($m^3/s$) |
| cubic foot per second per square mile ($ft^3/s/mi^2$) | 0.01093 | cubic meter per second per square kilometer ($m^3/s/km^2$) |
| foot (ft) | 0.3048 | meter (m) |
| foot per day (ft/d) | 0.3048 | meter per day (m/d) |
| foot squared per day ($ft^2/d$) | 0.09290 | meter squared per day ($m^2/d$) |
| foot squared per second ($ft^2/s$) | 0.09290 | meter squared per second ($m^2/s$) |
| gallon per day (gal/d) | 3.7854 | liter per day (L/d) |
| gallon per day per acre (gal/d/acre) | 935.4 | liter per day per square kilometer ($L/d/km^2$) |
| inch (in.) | 2.54 | centimeter (cm) |
| inch of mercury at 60°F (in. Hg) | 3.337 | kilopascal (kPa) |
| inches per acre (in/acre) | 0.006276 | millimeters per square meter ($mm/m^2$) |
| inches per hour (in/hr) | 25.4 | millimeter per hour (mm/hr) |
| inches per year (in/yr) | 25.4 | millimeter per year (mm/yr) |
| mile (mi) | 1.609 | kilometer (km) |
| mile per day (mi/d) | 1.609 | kilometer per day (km/d) |
| mile per hour (mi/hr) | 1.609 | kilometer per hour (km/hr) |
| million gallons (Mgal) | 3,785.4 | cubic meter ($m^3$) |
| million gallons per day (Mgal/d) | 0.04381 | cubic meter per second ($m^3/s$) |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD83), unless otherwise noted.

| | |
|---|---|
| AIC | Akaike Information Criterion |
| CGAP | Channel Geometry Analysis software Program |
| FBWR | Local climate station at the Fisherville Brook Wildlife Refuge |
| DSN | Data Set Number associated with the Watershed Data Management database |
| GENFTBL | GENerate FTaBLe software program |
| GENSCN | GENerate SCeNarios software program |
| HAP | Hunt-Annaquatucket-Pettaquamscutt |
| HRU | Hydrologic response unit |
| HSPF | Hydrologic Simulation Program–FORTRAN |
| HSPEXP | Expert system for the HSPF model |
| IDCONS | Constituent identification attribute associated with the Watershed Data Management database |
| IDLOCN | Location identification attribute associated with the Watershed Data Management database |
| IDSCEN | Scenario identification attribute associated with the Watershed Data Management database |
| IOWDM | Input and output data to the Watershed Data Management database program |
| IMPLND | HSPF impervious-area land element |
| LULC | Land Use Land Cover |
| METCMP | METerologic CoMPutation software |
| MFACT | Multiplier used to adjust time-series data read from the Watershed Data Management database |
| MOVE.1 | Maintenance of Variance Extension program |
| NOAA | National Oceanic and Atmospheric Administration |
| PERLND | HSPF pervious-area land element |
| PET | Potential Evapotranspiration |
| PEST | Parameter estimation |
| PROVID | National Oceanic and Atmospheric climate station near Providence, RI |
| QRPB | Streamflow-gaging station on the Queen River at Exeter, RI (01117355) |
| QRLY | Streamflow-gaging station on the Queen River at Liberty, RI (01117370) |
| QUFB | Queens Fort Brook subbasin |
| RCHRES | HSPF river or reservoir reach |
| RIDEM | Rhode Island Department of Environmental Management |
| RIEDC | Rhode Island Economic Development Corporation |
| RIWRB | Rhode Island Water Resources Board |
| RIGIS | Rhode Island Geographic Information System |
| STRMDEPL | Analytical program to compute streamflow depletion from a pumped well |
| SWSTAT | Surface water statistics program |
| *uci* | HSPF user control input file |
| USGS | U.S. Geological Survey |
| USQU | Streamflow-gaging station on the Usquepaug River at Usquepaug, RI (01117420) |
| URUS | Streamflow-gaging station on the Usquepaug River near Usquepaug, RI (01117410) |
| WDM | Watershed Data Management database |
| WDMUtil | Watershed Data Management Utility software |
| WUSG | Pawcatuck Watershed Water Use Stakeholders Group |

# Acronyms for HSPF Model Variables Referred to in Report

| | |
|---|---|
| AGWO | Active ground-water outflow from pervious areas |
| AGWRC | Active ground-water recession constant |
| AGWETP | Active ground-water evapotranspiration rate |
| DEEPFR | Fraction of ground water that enters a deep flow system |
| IFWO | Interflow outflow from pervious areas |
| INFILT | Infiltration rate |
| IVOL | Inflow volume to a reach |
| KVARY | Modifies the linearity of the active ground-water recession constant |
| LZSN | Lower zone nominal storage |
| MON-IRC | Monthly interflow recession constant |
| MON-INTERCEP | Monthly interception storage |
| MON-INTERFLW | Monthly interflow controls rate of flow from surface storage |
| MON-LZET | Monthly lower zone evapotranspiration rate |
| MON-UZSN | Monthly upper zone nominal storage |
| OUTDGT | Volume time series specified for a reach |
| OVOL | Outflow volume from a reach |
| SURI | Surface-water runoff from impervious areas |
| SURO | Surface-water runoff from pervious areas |

# A Precipitation-Runoff Model for the Analysis of the Effects of Water Withdrawals and Land-Use Change on Streamflow in the Usquepaug–Queen River Basin, Rhode Island

By Phillip J. Zarriello and Gardner C. Bent


## Abstract

The 36.1-square-mile Usquepaug–Queen River Basin in south-central Rhode Island is an important water resource. Streamflow records indicate that withdrawals may have diminished flows enough to affect aquatic habitat. Concern over the effect of withdrawals on streamflow and aquatic habitat prompted the development of a Hydrologic Simulation Program–FORTRAN (HSPF) model to evaluate the water-management alternatives and land-use change in the basin.

Climate, streamflow, and water-use data were collected to support the model development. A logistic-regression equation was developed for long-term simulations to predict the likelihood of irrigation, the primary water use in the basin, from antecedent potential evapotranspiration and precipitation for generating irrigation demands. The HSPF model represented the basin by 13 pervious-area and 2 impervious-area land-use segments and 20 stream reaches. The model was calibrated to the period January 1, 2000 to September 30, 2001, at three continuous streamflow-gaging stations that monitor flow from 10, 54, and 100 percent of the basin drainage area. Hydrographs and flow-duration curves of observed and simulated discharges, along with statistics compiled for various model-fit metrics, indicate a satisfactory model performance.

The calibrated HSPF model was modified to evaluate streamflow (1) under no withdrawals to streamflow under current (2000–01) withdrawal conditions under long-term (1960–2001) climatic conditions, (2) under withdrawals by the former Ladd School water-supply wells, and (3) under fully developed land use. The effects of converting from direct-stream withdrawals to ground-water withdrawals were evaluated outside of the HSPF model by use of the STRMDEPL program, which calculates the time delayed response of ground-water withdrawals on streamflow depletion.

Simulated effects of current withdrawals relative to no withdrawals indicate about a 20-percent decrease in the lowest mean daily streamflows at the basin outlet, but withdrawals have little effect on flows that are exceeded less than about 90 percent of the time. Tests of alternative model structures to evaluate model uncertainty indicate that the lowest mean daily flows ranged between 3 and 5 cubic feet per second ($ft^3/s$) without withdrawals and 2.2 to 4 $ft^3/s$ with withdrawals. Changes in the minimum daily streamflows are more pronounced, however; at the upstream streamflow-gaging station, a minimum daily flow of 0.2 $ft^3/s$ was sustained without withdrawals, but simulations with withdrawals indicate that the reach would stop flowing part of a day about 5 percent of the time.

The effect on streamflow of potential ground-water withdrawals of 0.20, 0.90, and 1.78 million gallons per day (Mgal/d) at the former Ladd School near the central part of the basin were evaluated. The lowest daily mean flows in model reach 3, the main stem of the Queen River closest to the pumped wells, decreased by about 50 percent for withdrawals of 0.20 Mgal/d (from about 0.4 to 0.2 $ft^3/s$) in comparison to current withdrawals. Reach 3 would occasionally stop flowing during part of the day at the 0.20-Mgal/d withdrawal rate because of diurnal fluctuation in streamflow. The higher withdrawal rates (0.90 and 1.78 Mgal/d) would cause reach 3 to stop flowing about 10 to 20 percent of the time, but the effects of pumping rapidly diminished downstream because of tributary inflows. Simulation results indicate little change in the annual 1-, 7-, and 30-day low flows at the 0.20 Mgal/d pumping rate, but at the 1.78 Mgal/d pumping rate, reach 3 stopped flowing for nearly a 7-day period every year and for a 30-day period about every other year. At the 0.90 Mgal/d pumping rate, reach 3 stopped flowing about every other year for a 7-day period and about once every 5 years for a 30-day period.

Land-use change was simulated by converting model hydrologic-response units (HRUs) representing undeveloped areas to HRUs representing developed areas on the basis of development suitability and town zoning. About 55 percent of the basin is suitable for development; this area would accommodate about 4,300 new low-density residential homes under current zoning. Increases in storm volume and peak flows, and decreases in base flow, typically associated with urbanization, were not evident in buildout simulations because the effective impervious area was assumed to increase by only 2 percent.

Under fully developed conditions, withdrawals from self-supply wells were estimated to reach 1.2 Mgal/d. Potential increases in water withdrawals for a fully developed basin have only a minor impact on the main stem streamflow, but the effects of urbanization could be more pronounced in localized areas where development is concentrated.

Streamflow-depletion rates were calculated for varying distances of a pumped irrigation well from a stream. For the irrigation rates and aquifer conditions tested, streamflow depletion, relative to the pumping rate, decreases rapidly as the pumped well was moved away from the stream. Streamflow depletion, relative to the peak withdrawal rate, decreased by about 60, 80, and 90 percent by locating the pumped well 500, 1,000, and 1,500 feet from the stream, respectively.

# Introduction

The Queen and Usquepaug River Basins, in south-central Rhode Island, are an important high-quality water resource that provides water for domestic and public supplies, irrigation, and a rich aquatic ecosystem. Streamflow records indicate that withdrawals could be adversely affecting aquatic habitat and diversity, water quality, and the value of the rivers as a scenic and recreational resource. Managing this resource to ensure sustainable supplies and adequate water for aquatic habitat is of concern to governmental agencies, environmental organizations, and private citizens. These concerns are intensified by the rapid development and population growth in the region and the likelihood of greater demands for clean water.

The Rhode Island Water Resources Board (RIWRB) is the principal State agency concerned with sustainable water supplies. The agency works closely with the Rhode Island Department of Administration's Statewide Planning Program to develop and refine policies affecting water supply, including emergency planning (Rhode Island Water Resources Board, 2002). In 1999, the Rhode Island General Assembly designated the RIWRB the sole authority to devise fair and equitable allocation of state water resources and to ensure that long-range considerations of water supply prevail over short-term considerations.

Towards this end, the RIWRB began a cooperative study with the U.S. Geological Survey (USGS) in 1999 to develop a physically based precipitation-runoff model for the Queen and upper Usquepaug River Basins (herein referred to as the Usquepaug–Queen Basin). Model simulations will assist the RIWRB, State, and local communities in understanding how the river is affected by present and possible future human activities, such as withdrawals for water supply and irrigation, and allow simulation of water-management alternatives to evaluate their effects on streamflow. In addition, data collected during this study will provide information to assist in water-management decisions at all levels and provide information necessary for stream-habitat assessments.

## Purpose and Scope

This report describes the development and calibration of the Hydrologic Simulation Program–FORTRAN (HSPF), a precipitation-runoff model for the Usquepaug–Queen Basin. The report also describes results of model simulations to evaluate (1) streamflows under no withdrawals to streamflow under current (2000–01) withdrawal conditions under long-term (1960–2001) climatic conditions, (2) effects on streamflow of withdrawals by the former Ladd School water-supply wells, and (3) the effects on streamflow under fully developed land-use conditions. The report includes information about the study area, climate, streamflow, and water-use data used in the model, methods used to obtain the data, and a logistic-regression equation developed to predict the likelihood of irrigation.

## Previous Investigations

The ground-water resources and water-quality conditions of the Usquepaug–Queen Basin were most recently investigated by Dickerman and others (1997). That study compiled and collected information on the hydrogeology of the basin, particularly the aquifer properties that were used to develop a ground-water-flow model (MODFLOW). The ground-water-flow model for the basin was developed to evaluate effects of pumping alternatives on water levels, base flow, and wetlands in the sand and gravel valley-fill deposits. Dickerman and others (1997) described the quality of water collected under base-flow conditions during August 1993 from 34 wells and 17 surface-water sites. The water-quality, hydrogeologic, and hydrologic data collected in that study is presented in a companion data report by Kliever (1995). Dickerman and others (1997) and Barlow and Dickerman (2001) indicate that ground water in the upper part of the Queens Fort Brook, a subbasin of the Usquepaug–Queen Basin, discharges to the Hunt-Annaquatucket-Pettaquamscutt (HAP) Basin.

Earlier hydrogeologic studies of the ground-water resources in the basin were completed as part of general statewide appraisals by Lang (1961) and Trench (1991) and as part of a quantitative study of the upper Pawcatuck River Basin by Allen and others (1963, 1966). Ground-water resources were investigated at the quadrangle scale by Hahn (1959) for the Slocum quadrangle, which covers about 90 percent of the basin and by Bierschenk (1956) for the Kingston quadrangle, which covers the basin area below Glen Rock Reservoir. Bedrock and surficial geology of the Slocum and Kingston quadrangles are described by Power (1957, 1959), Kaye (1961), and Moore (1964).

Armstrong and Parker (2003) characterized the aquatic habitat, stream temperature, and fish communities in the basin. In that study, minimum streamflow requirements for fish habitat were identified by standard flow-setting techniques at selected riffle sites. Some of the habitat-assessment sites are coincident with the streamflow-monitoring sites established for this study.

Water-use information was compiled for a 5-year period, 1995 through 1999, by Wild and Nimiroski (2004) as part of a quantitative water-use investigation of the Pawcatuck River Basin. This compilation includes domestic, public, commercial, and agricultural uses. Data from that study were used to supplement the water-use information collected during this study.

Regionalized equations for southern Rhode Island streams were developed for estimating the 7-day low flow that is expected to occur once every 10 years (commonly referred to as the 7Q10) by Cervione and others (1993). Streamflow at four partial-record stations was measured in the Usquepaug–Queen Basin as part of that study and the stations were reestablished to monitor streamflow in this study.

Water resources in the east-central part of the basin were investigated as part of an economic-development initiative of the former Ladd School facility (PARE Engineering Corporation, 2000; Paul B. Aldinger and Associates, Inc., 2000; and Horsley and Witten, Inc., 2001). Desbonnet (1999) provided a general overview of ground- and surface-water resources, water uses, and management issues in the Pawcatuck River Basin. One of the management issues discussed is the need to develop quantitative models for evaluating the effects of withdrawals on water resources.

# Description of the Basin

The Usquepaug–Queen Basin encompasses an area of 36.1 $mi^2$; the basin is mostly in Washington County with a small area in Kent County in south-central Rhode Island about 15 mi southeast of Providence (fig. 1). The Queen River ends at the outlet to Glen Rock Reservoir (fig. 2) at which point it becomes the Usquepaug River, a tributary to the Pawcatuck River. About 90 percent of the study area is in the Queen River Basin and the other 10 percent is in the Usquepaug River Basin, which terminates for the purposes of this study at the USGS streamflow-gaging station on the Usquepaug River near Usquepaug (01117420). Collectively, this area is referred to as the Usquepaug–Queen Basin in this report. This streamflow-gaging station is 1.2 mi upstream of the Chickasheen Brook and about 2.1 mi upstream of the confluence with the Pawcatuck River.

**Towns and Population:** The study area includes most of the town of Exeter and small parts of the towns of Richmond, North Kingstown, South Kingstown, East Greenwich, and West Greenwich (fig. 1). East and West Greenwich are in Kent County; the other towns are in Washington County.

Population in towns within the Usquepaug–Queen Basin increased by about 9 to 46 percent from 1990 to 2000 (Rhode Island Statewide Planning, 2003). The largest increases were in towns on the north side of the basin that are closest to the Providence metropolitan area. In Washington County, the population increased by 12.3 percent from 1990 to 2000 (from 110,006 to 123,546). Increases in population will likely continue and generate increased demands for water in this area.

**Climate:** Climate in the Usquepaug–Queen River Basin is classified as moist-continental (Food-Agriculture Organization, World climates, accessed December 10, 2003). Annual temperature for the 40-year period (1960–2000) at the National Oceanic and Atmospheric Administration (NOAA) station at T.F. Green Airport near Providence (PROVID in fig. 1) averaged about 51°F. Average temperatures vary from about 30°F in December and January to about mid 70°F in June and July. Freezing temperatures are common daily from December to the end of March (averaging 110 days a year) and temperatures above 90°F average about 10 days a year (National Oceanic and Atmospheric Administration, accessed December 10, 2003).

Precipitation averages about 45 in/yr (1960–2001), which is distributed throughout the year with a median monthly precipitation of about 3.5 in. Precipitation is slightly less during the summer months (median of 2.80 in. for June through August) and slightly more during other months of the year (median of 3.7 in.). The median minimum monthly precipitation was 0.55 in. and the median monthly maximum precipitation was 10.4 in. Measurable snowfall generally begins at the end of November, but may be as late as January. The greatest snowfall is usually in January through March and, on average, totals about 36 in. during the winter; however, the ground generally does not remain snow covered for any appreciable length of time (Zielinski and Kliem, 2003). Potential evapotranspiration (PET) averages about 30 in/yr and was greatest in June (averages about 6 in.) and least in December (averages about 0.2 in.).

**Hydrology:** A streamflow-gaging station at the basin outlet (fig. 2)—Usquepaug River near Usquepaug (01117420), referred to herein as USQU—was operated from 1958 to 1960, restarted in 1974, and has been in continuous operation since. Streamflow records from this station indicate that the mean annual flow at the basin outlet is 76 $ft^3/s$ (28.4 in/yr or about 63 percent of the mean annual precipitation). The highest peak discharge measured at this station is 1,060 $ft^3/s$ and the lowest daily mean discharge measured is 1.1 $ft^3/s$. Mean annual discharge during the 21-month period (January 2000 through September 2001) used for model calibration was 8 percent less in the 2000 calendar year (70 $ft^3/s$) and 12 percent larger in the 2001 water year[1] (85 $ft^3/s$) than the long-term mean annual discharge. Long-term mean monthly runoff (for water years 1975–2002) at the basin outlet ranged from 25 $ft^3/s$ in September to 138 $ft^3/s$ in March; during the 21-month model-calibration period, mean monthly runoff ranged from 20 to 230 $ft^3/s$. Peak discharge during the model-calibration period was 23 percent less (820 $ft^3/s$) than the peak of record and the minimum daily mean discharge was about 4.5 times larger (6.5 $ft^3/s$) than the minimum daily mean discharge of record.

[1]A water year is the 12-month period begining October 1 and ending September 30. It is designated by the calendar year in which it ends.

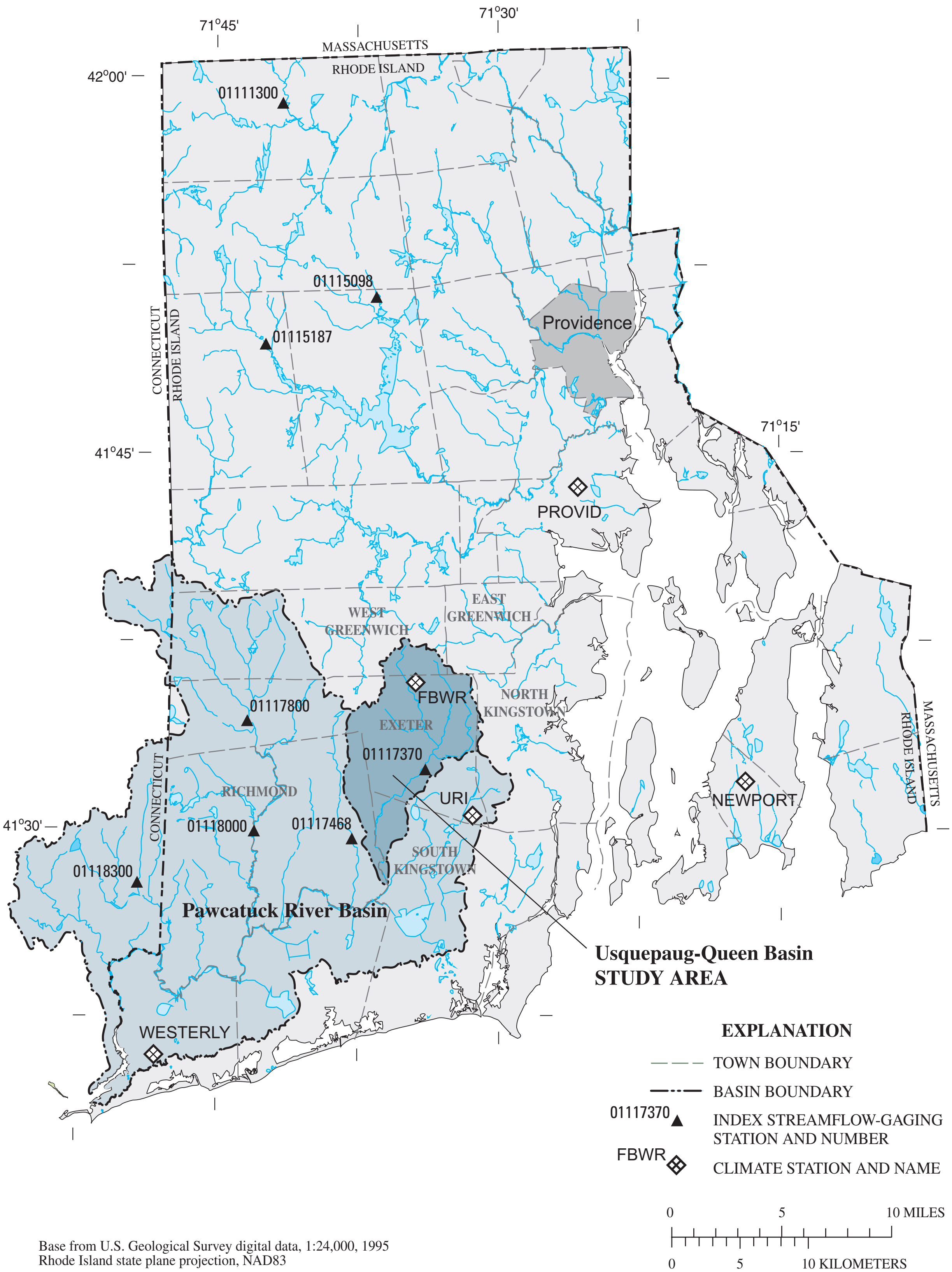



**Figure 1.** Location of Usquepaug–Queen River Basin, climate stations, and index streamflow-gaging stations used to develop continuous streamflow records at partial-record stations, Rhode Island.

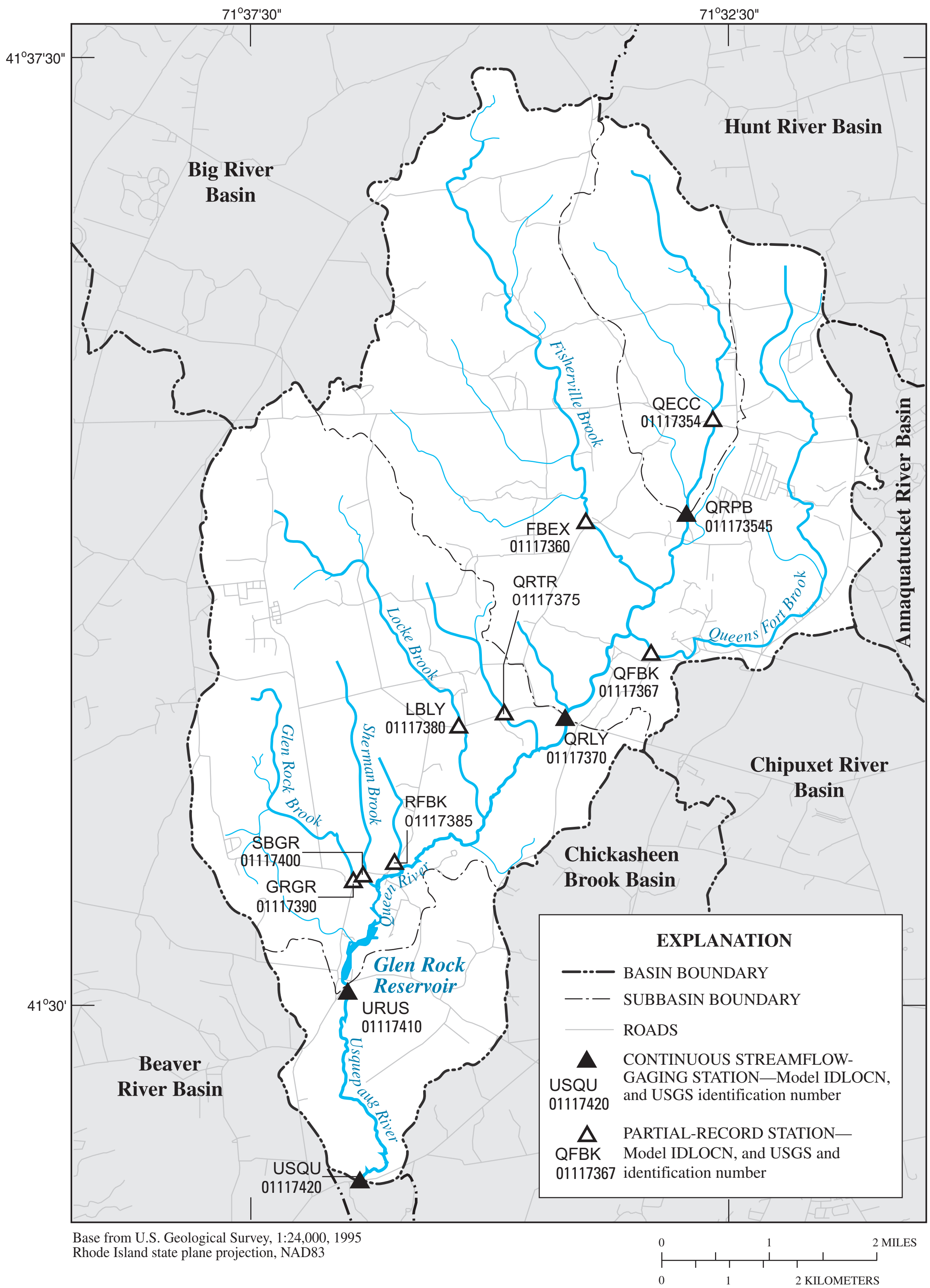



**Figure 2.** Continuous and partial-record streamflow-gaging stations in the Usquepaug–Queen River Basin, Rhode Island [basin location shown on fig. 2; IDLOCN, location identification attribute in the Watershed Data Management System (WDM); USGS, U.S. Geological Survey].

The drainage areas for streamflow-gaging stations on the Queen River at Exeter (011173545), and at Liberty (01117370), herein referred to as QRPB and QRLY, respectively, represent about 10 and 53 percent of the area of the Usquepaug–Queen Basin, respectively (fig. 2). Records from these stations indicate that the mean annual discharge per unit area for water years 2000–01 was about 2.27 and 2.04 $ft^3/s/mi^2$ at QRPB and QRLY, respectively. For the same period, mean annual discharge per unit area at USQU was 2.20 $ft^3/s/mi^2$. The discharge per unit area at QRPB and USQU for this period was about 11 and 8 percent greater, respectively, than the discharge per unit area at QRLY. Discharge at QRLY and USQU is affected by about 3.1 $mi^2$ of the Queens Fort Brook subbasin (16 and 8 percent of the drainage area to QRLY and USQU, respectively), which Dickerman and others (1997) and Barlow and Dickerman (2001) report discharges ground water to the Annaquatucket part of the HAP Basin (fig. 2). The percent difference in discharge per unit area at these stations reflects the basin area affected by ground-water loss to the HAP Basin.

**Water Use:** Total water use in the basin is estimated at 0.841 Mgal/d, and is mainly used for agricultural (56 percent) and domestic (40 percent) purposes according to average annual water-use statistics compiled for the 1995–99 period (Wild and Nimiroski, 2004). This compilation also indicates that a small amount of water was used for commercial (0.013 Mgal/d) and industrial (0.019 Mgal/d) purposes. Domestic uses include water supplies for two retirement homes and the Phoenix House (a drug and rehabilitation facility) and although considered public supplies, water is obtained from self-supply wells for these facilities. All other domestic and commercial supplies are obtained from private wells. Domestic water use is generally uniform from November through April, and generally increases during the summer months because of watering of lawns and gardens and other seasonal uses. Water for agricultural (irrigation) purposes is supplied mainly by withdrawals from streams, reservoirs, and ponds in the basin. One well for agricultural (irrigation) purposes in the basin began operation in 2000. Irrigation for agricultural (turf and vegetable farms and tree nurseries) and recreational (golf courses) activities is mainly limited to the months of May through October, when the evapotranspiration is highest.

**Topography:** Physiographically, most of the basin lies in the Coastal Lowlands region, except for the northwestern part of the basin, which is in the Central Highlands region (Denny, 1982). Topography can be characterized as gently rolling hills in the north and west parts of the basin and relatively flat in the south and east parts of the basin. Altitudes range from about 555 ft in the northwest corner of the basin to about 95 ft at the basin outlet (Dickerman and others, 1997).

**Surficial Geology:** Dickerman and others (1997) provide a detailed description of the basin's geology and surficial geological materials, which are composed mainly of glacial outwash and till. Outwash, which comprises coarse-grained sands and gravels, underlies about 32 percent of the basin along the valley of the main stem and the Fisherville Brook and Queens Fort Brook tributaries (fig. 3). These glacial meltwater deposits are reported to be up to 122 ft thick and "shingled" with fine-grain deposits. Small disconnected areas of outwash, which are shown in tributaries (for example, Locke Brook) by Dickerman and others (1997), are not shown on the generalized surficial-geology map (fig. 3) because they were not considered in the development of the precipitation-runoff model.

Most of the upland areas are underlain by generally thin tills of varying ages. Tills also underlie the valley-outwash deposits where they are reported to be as much as 60 ft thick (Dickerman and others, 1997). Tills generally have a compact sand-silt matrix, but can contain clay- to boulder-size deposits.

**Soils:** The U.S. Department of Agriculture, Natural Resources Conservation Service (formerly Soil Conservation Service) reports that soils are generally stony sand and silt loam in the uplands and fine sand and silt loam overlying the valley outwash deposits (Rector, 1981). Extensive muck soils are found mainly along the stream corridors in riparian wetlands. The upland soils are mainly in Hydrologic Soil Group "B" (infiltration rate of 0.15–0.30 in/hr) with small areas of Hydrologic Soil Group "C" (infiltration rate of 0.05–0.15 in/hr). Soils overlying outwash deposits are mainly Hydrologic Soil Group "A" (infiltration rate of 0.30–0.45 in/hr). Muck soils are in Hydrologic Soil Group "D" (infiltration rate of 0.00–0.05 in/hr).

**Wetlands:** Digital wetland data was obtained from RIGIS. Wetlands were interpreted from 1988 aerial photography and coded by the Cowardin 16 classification scheme to a 0.25-acre resolution (Rhode Island Geographic Information System, accessed December 10, 2002). This coverage was simplified into forested or nonforested wetlands. About 23 percent of the basin is classified as wetlands—21 percent forested and 2 percent nonforested. Most wetlands border the stream channels (fig. 4). Extensive wetland areas are in the headwaters of the Queen River and Locke Brook, along the Queen River between the confluences of Fisherville Brook and Queens Fort Brook, and in the southeastern part of the basin. The close proximity of the wetlands to the stream channels is an important hydrologic feature of the basin because of the potential loss of water through evapotranspiration.

**Land Use and Land Cover:** Digital land use and land cover (LULC) was obtained from RIGIS. This data represents 1995 land use coded by the Anderson modified level-3 classification scheme to polygons with a minimum resolution of one-half acre (Rhode Island Geographic Information System, accessed December 10, 2002). This cover was intersected with the wetlands cover to produce a composite land-use cover. The resulting 31 types of LULC represented in the basin (fig. 5) were simplified into 10 LULC types: moderate- to high density residential, low density residential, commercial/industrial/transportation, open, forest, nonforested wetlands, forested wetlands, golf course, turf farm, and irrigated crop.

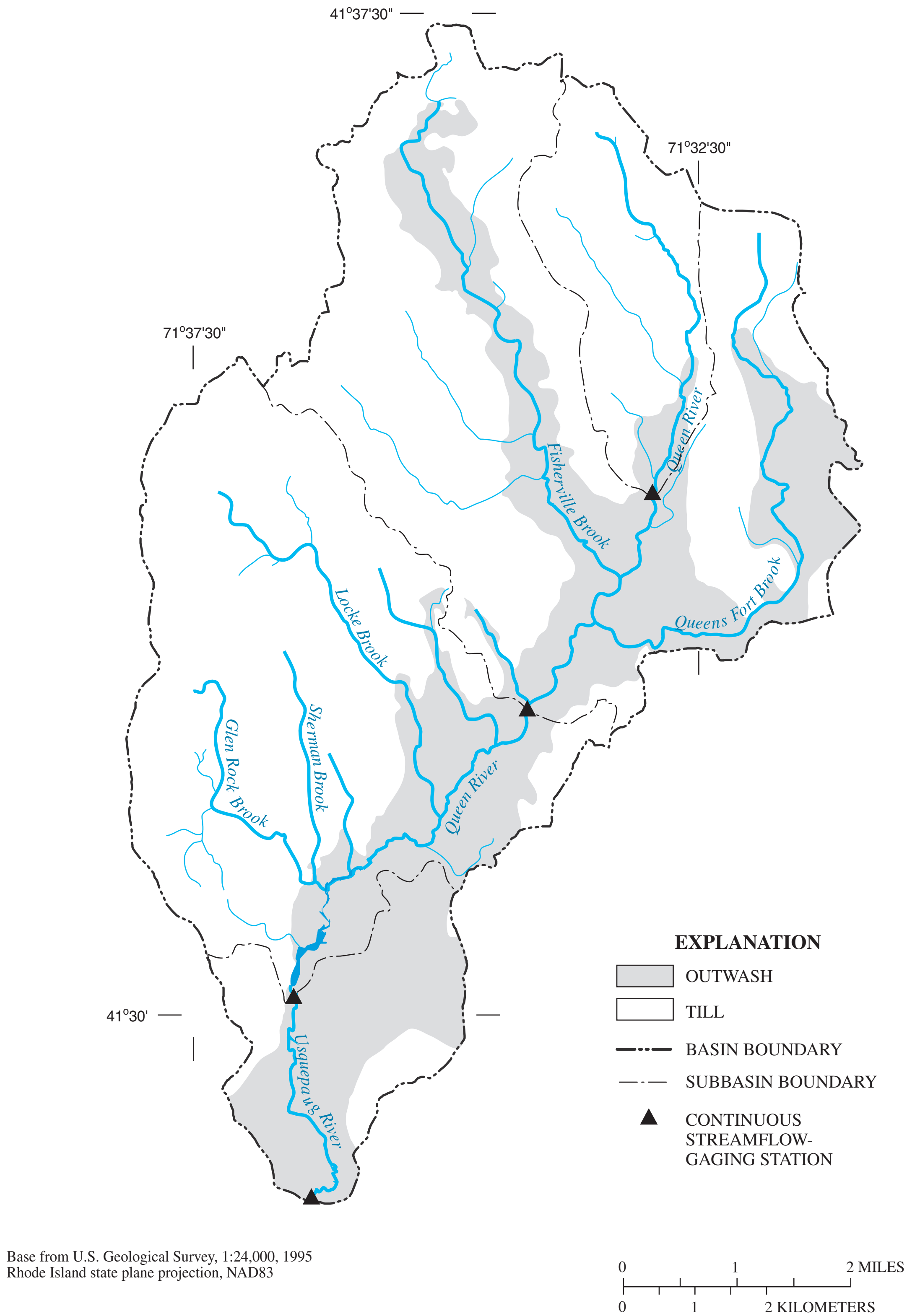



**Figure 3.** Generalized surficial geology of the Usquepaug–Queen River Basin, Rhode Island (basin location shown on fig. 1).

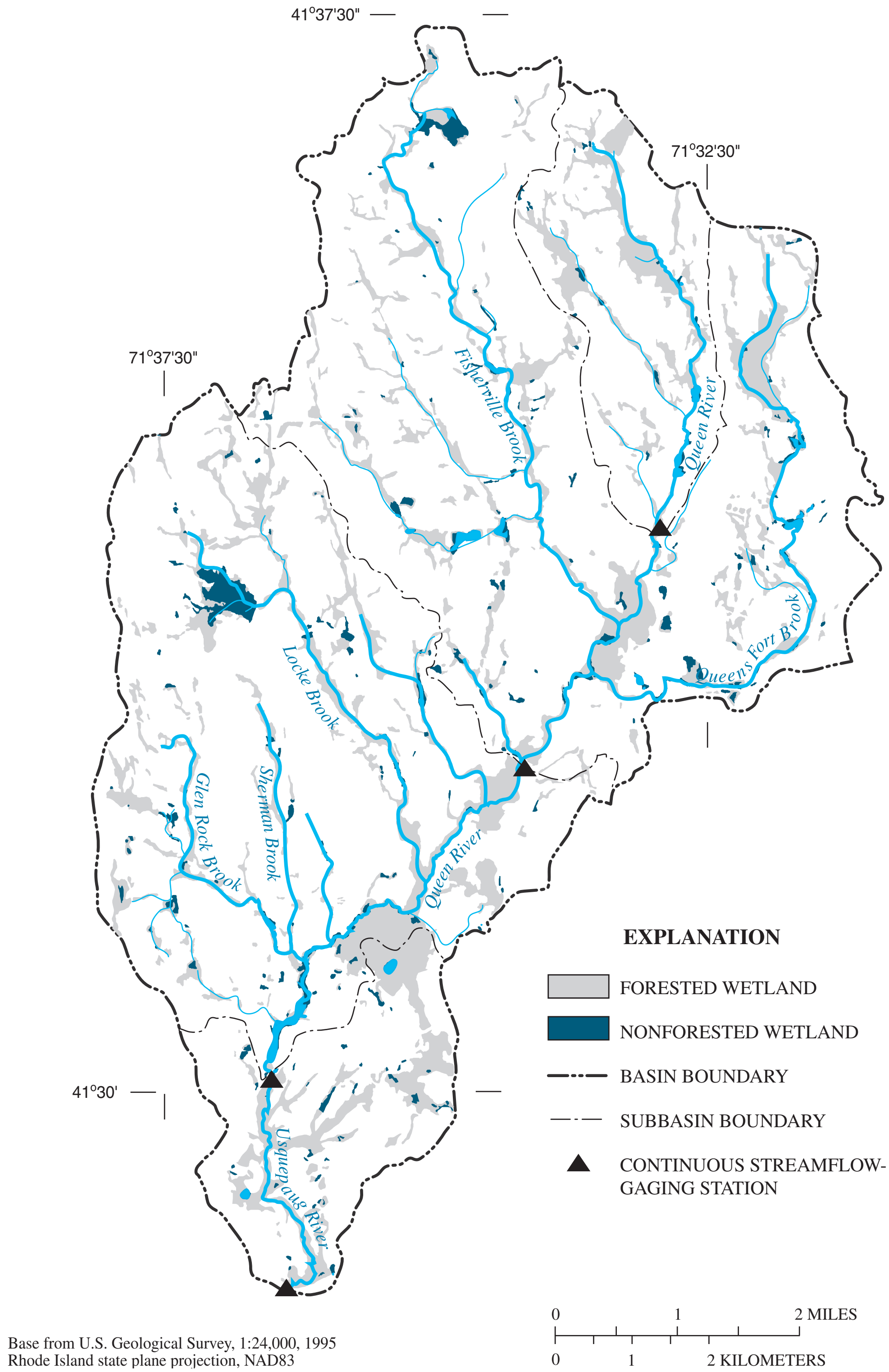



**Figure 4.** Generalized wetlands of the Usquepaug–Queen River Basin, Rhode Island (basin location shown on fig. 1).

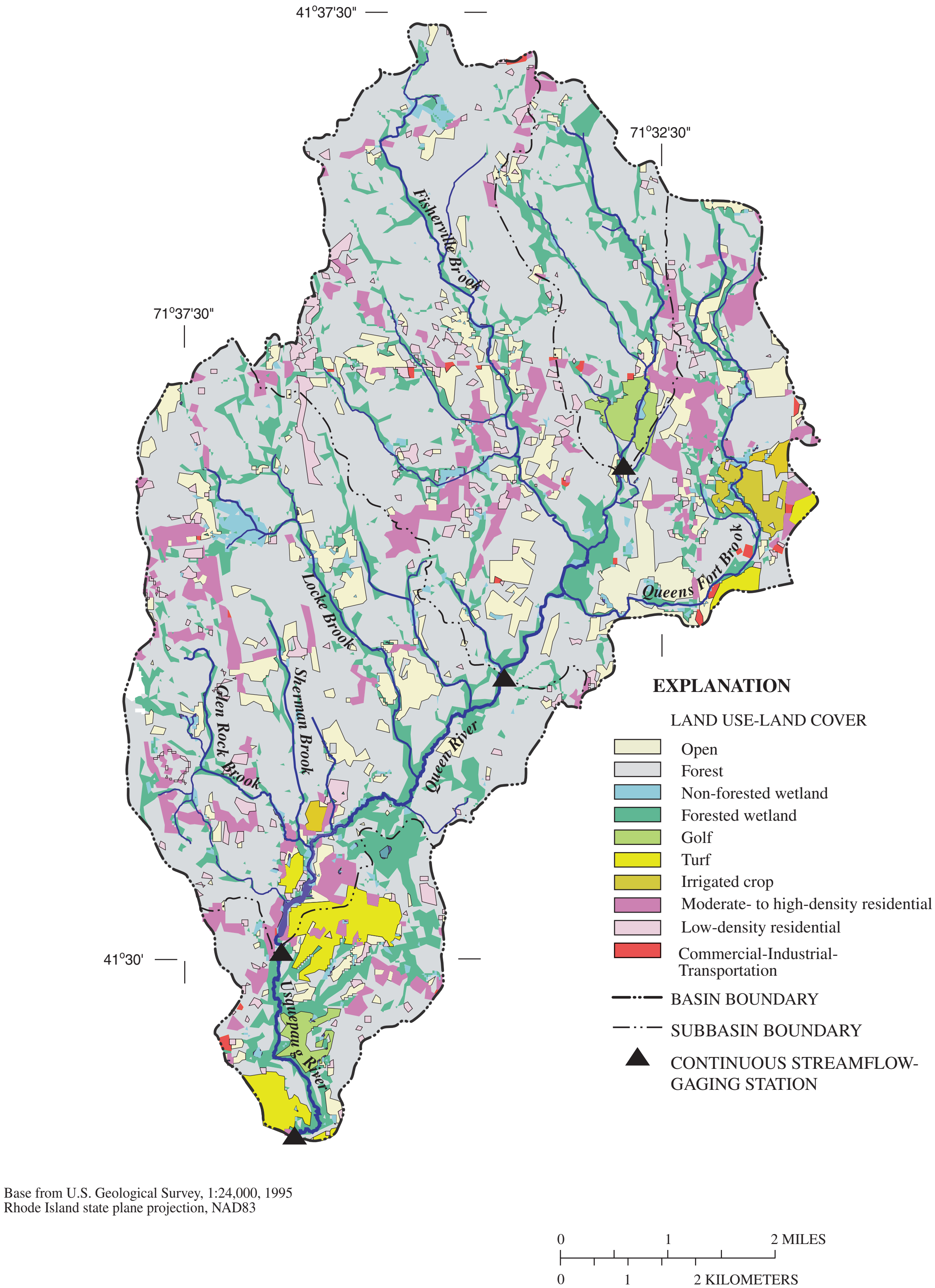



**Figure 5.** Generalized land use and land cover of the Usquepaug–Queen River Basin, Rhode Island (basin location shown on fig. 1).

The basin is predominantly classified as forest (75 percent), which includes forested wetlands (14 percent). Forests are composed of about 65 percent deciduous or mixed deciduous and about 35 percent evergreen or mixed evergreen. Open land composes about 9 percent of the basin area and includes areas classified as shrub, open space, or agricultural lands that are not irrigated, such as pastures. Many of the other types of LULC can be considered special forms of open lands. Golf courses, turf farms, and irrigated croplands are open lands, but were uniquely classified because these lands are highly managed, particularly with respect to water use. Collectively, these managed open-land categories compose about 4 percent of the basin area. Much of the area classified as urban also represents open land, particularly areas classified as low density residential, which are defined as residential lots larger than 1 acre. Much of the area between buildings or paved surfaces in these areas is pervious and includes areas of grass, trees, and shrubs.

Moderate to high density residential areas can also contain a large percentage of open space. Areas shown on figure 5 as moderate to high density residential were reclassified from medium-density residential (from 0.25- to 1-acre lots) and medium-high density residential (from 0.25- to 0.125-acre lots) in the Anderson classification. About 80 percent of the moderate to high density residential area is composed of residential areas with lot sizes between 0.25 and 1 acre in size. Intensive urban land use composes only about 1 percent of the basin area; this category includes areas classified as commercial, industrial, or transportation (0.3 percent) and medium-high density residential (0.7 percent).

# Time-Series Data

Climate, water-use, and streamflow data are required to run and calibrate the precipitation-runoff model. Climate data are required input to the model. Water-use data are needed to (1) account for water withdrawals to calibrate the model and (2) to simulate alternative water-management conditions. Streamflow data provide information necessary for model calibration.

## Climate

Climate data, including precipitation, air temperature, dew-point temperature, solar radiation, and wind speed for the basin were obtained from various sources. A climate station (FBWR) was established for this study in the north-central part of the basin (fig. 1) to provide local climate information for model calibration. Data from the FBWR station are available for the period November 22, 1999, through November 15, 2001. These data included precipitation, air temperature, dew-point temperature, solar radiation, wind speed, and vapor pressure.

Climate data from outside the basin was obtained from NOAA stations at T.F. Green Airport (PROVID), Newport Airport (NEWPORT), and Westerly Airport (WESTERLY). These stations are about 15 mi to the northeast, 16 mi to the east, and 20 mi to the southwest of the geographic center of the Usquepaug–Queen Basin, respectively (fig. 1). In addition to the NOAA stations, the University of Rhode Island (URI) operates a precipitation station at Kingston, R.I. about 5 mi southeast of the geographic center of the basin. The record length, time step, and type of climate data by site are summarized in table 1.

The PROVID station provided climate data for long-term (1960–2001) model simulations. Climate stations outside the basin were used to assess precipitation distribution during the model calibration. During a few periods, the local climate station recorded little or no precipitation while the other stations recorded appreciable and consistent amounts of precipitation. During these periods, a copy of the local precipitation data was modified to be consistent with the data from surrounding precipitation stations for model calibration.

Potential evapotranspiration (PET) was calculated by the Jensen-Haise method (Jensen and Haise, 1963) with daily temperature and average daily solar-radiation data collected at the FBWR and PROVID stations. The computer programs METCMP (Lumb and Kittle, 1995) or WDMUtil (U.S. Environmental Protection Agency, accessed December 10, 2003) were used to compute daily PET and disaggregate the daily values to an hourly value at each station.

**Table 1.** Climate data collected and compiled for the Usquepaug–Queen River Basin, Rhode Island.

[Location shown in figure 1. IDLOCN, attribute in Watershed Data Management (WDM) database that identifies location; NOAA, National Oceanic and Atmospheric Administration; •, data available; --, no data]

| Data | Source | | | | |
|---|---|---|---|---|---|
| | Local station | NOAA T.F.Green Airport | NOAA Newport Airport | NOAA Westerly Airport | University of Rhode Island |
| Name (IDLOCN) | FBWR | PROVID | NEWPORT | WESTERLY | URI |
| Time step | Hourly | Hourly | Hourly | Hourly | Daily |
| Begin date | 11/22/1999 | 1/1/1960 | 7/1/1996 | 7/28/1999 | 9/30/1998 |
| End date | 11/15/2001 | 3/31/2001 | 3/31/2001 | 3/31/2001 | 12/30/2001 |
| Precipitation | • | • | • | • | • |
| Air temperature | • | • | • | • | -- |
| Dew-point temperature | • | • | • | • | -- |
| Wind speed | • | • | • | • | -- |
| Solar radiation | • | • | -- | -- | -- |
| Computed potential evapotranspiration | • | • | -- | -- | -- |

## Water Withdrawals

Accounting of water withdrawals within the basin is required to calibrate the model and to simulate long-term effects of withdrawals on streamflow. Irrigation was the primary water use in the basin during the model-calibration period (January 2000 through December 2001). Withdrawals also included several minor public nonmunicipal self-supply wells (fig. 6). These withdrawals are from wells registered with the RIDEM as serving 25 or more people for 60 days or more and include a retirement home, a mobile-home park, and a drug rehabilitation home. Collectively, the self-supply public wells pumped an estimated 0.028 Mgal/d (Wild and Nimiroski, 2004), but most water is returned to the basin through on-site septic systems. Domestic self-supply wells pumped an estimated 0.31 Mgal/d that is also mostly returned to the basin through on-site septic systems.

An estimated 340 acres of turf farm, 110 acres of golf course, and 210 acres of vegetable, berry, and nursery farms withdraw water for irrigation. Unlike domestic water use, irrigation can vary widely from day to day and season to season. Estimating this climatically dependent water use is further complicated by a limited amount of measured data. Where available, measured withdrawals were incorporated into the precipitation-runoff model for calibration. Irrigation withdrawals were estimated for known unmeasured withdrawals during the model calibration and for all irrigation withdrawals for long-term simulations on the basis of the rates and patterns of irrigation withdrawals measured during this study.

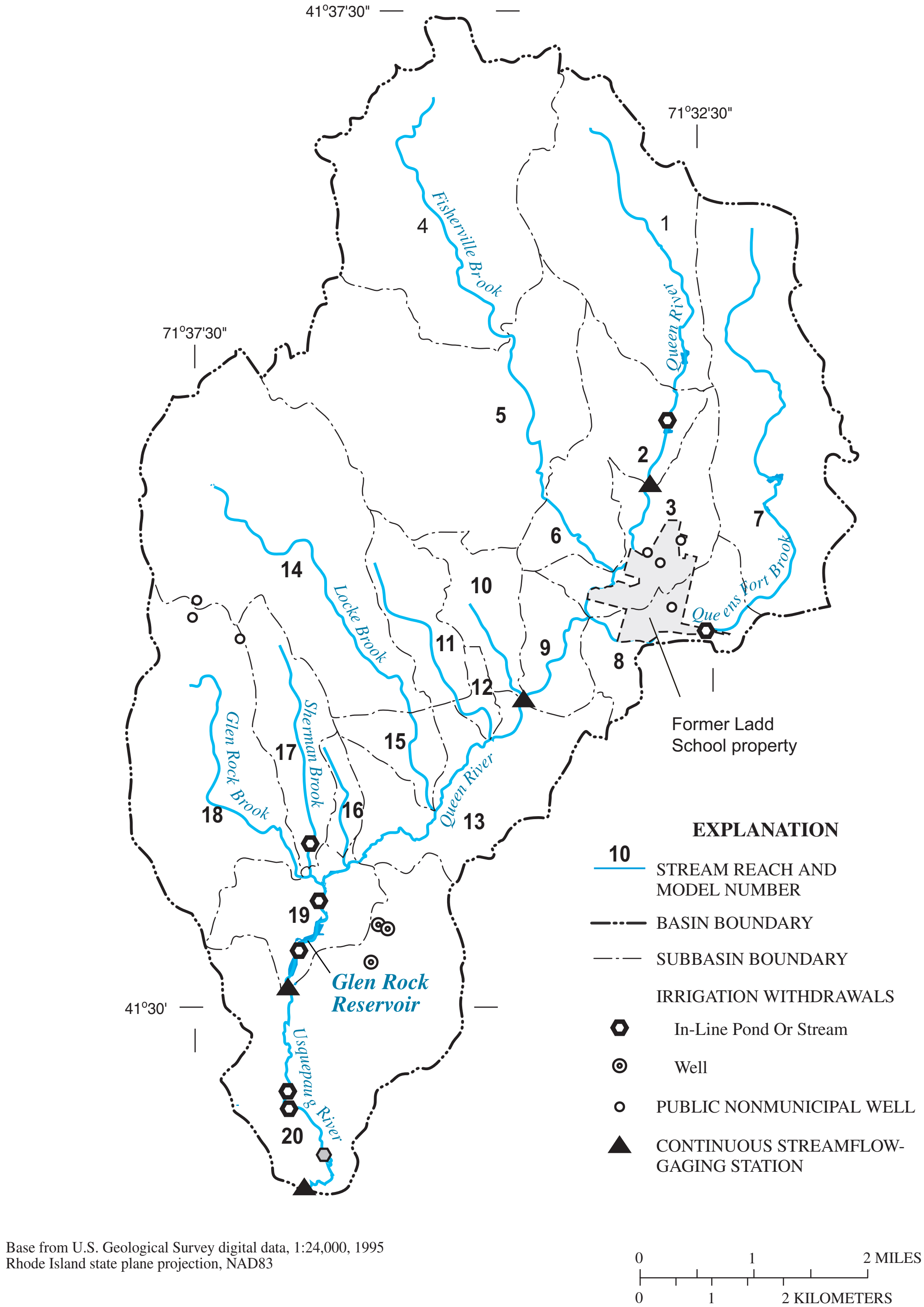



**Figure 6.** Principal withdrawal locations in the Usquepaug–Queen River Basin, Rhode Island (basin location shown on fig. 1).

## Data Collection

Irrigation withdrawals were collected by direct measurement at one golf course and at three turf farms in or near the basin during two irrigation seasons (April through November) in 2000 and 2001. These withdrawals were measured continuously with an impeller flowmeter installed between the pump and the irrigation nozzles. Volumes were added and recorded hourly at each site. At one location, withdrawals were estimated by linear interpolation between abrupt drops and rises in the observed streamflow hydrograph. The difference between the interpolated and observed hydrograph during these periods was assumed to represent withdrawals. The estimated average irrigation withdrawal at this site, 2,030 gal/d/acre, is consistent with the irrigation measured for a similar use (1,930 gal/d/acre) elsewhere in the basin during the irrigation days in 2000–01. Irrigation was observed on 83 days at the measured site and was estimated to occur on 72 days at the unmeasured site during 2000 and 2001. Estimated withdrawals at the unmeasured site may not include days when only greens were irrigated because the signature on the observed hydrograph is not pronounced.

Measured withdrawals at one turf farm were made in a nonideal location (flowmeter location did not meet the manufacturers specifications for minimal straight-pipe distance above and below the meter) and, therefore, withdrawals could be in error by up to 50 percent (Ronald Purdy, Data Industrial Corporation, oral commun., 2003). No corrections were made, however, because the measured volume compared well with the total volume measured by an independent meter and with other turf-farm withdrawals. The combined turf-farm withdrawals irrigate a total area of about 500 acres, which includes some area outside of the basin. When irrigating, turf farms apply an average of 1,820 gal/d/acre. Turf farms irrigated between 35 and 63 days per year during 2000 and 2001.

## Logistic-Regression Equation to Predict Irrigation Withdrawals

A logistic-regression equation was developed for long-term simulations to predict the probability of irrigation occurring on a specific day at golf courses and turf farms. The equation was developed from measured irrigation withdrawals during 2000 and 2001 and a suite of antecedent-precipitation and potential-evapotranspiration rates, which served as potential explanatory variables. The equation was developed with the stepwise-logistic procedure in SAS (SAS Institute, Inc, 1989; 1995). Explanatory climatic variables tested included total rainfall and potential evapotranspiration rates during the past 2, 5, 10, 15, and 20 days. Correlated explanatory variables were not used simultaneously during the stepwise regression analysis because colinearity between independent variables can result in undesirable consequences (Helsel and Hirsch, 1992). Explanatory variables spaced closely in time, for example, rainfall in the last 2 days and in the last 5 days, tended to be correlated and were not used concurrently.

The best predictive model indicated that total potential evapotranspiration in the past 2 days (PET2) and past 20 days (PET20) and total precipitation in the past 10 days (PREC10) were the most significant explanatory variables (in order of importance). Other climatic variables were dropped from the stepwise regression or only marginally added to the goodness-of-fit as indicated by the Chi-squared values and Akaike Information Criterion (AIC) values. The probability ($P$) of irrigation occurring on a specific day at golf courses and turf farms is given by

$$P = \frac{\mathrm{EXP}(-5.6791 + (\mathrm{PET2}*4.8271) + (\mathrm{PET20}*1.576) + (\mathrm{PREC10}*-1.207))}{1 + \mathrm{EXP}(-5.6791 + (\mathrm{PET2}*4.8271) + (\mathrm{PET20}*1.576) + (\mathrm{PREC10}*-1.207))}, \quad (1)$$

where

PET2 is total potential evaporation in the past 2 days, in inches;
PET20 is total potential evaporation in the past 20 days, in inches; and
PREC10 is total precipitation in the past 10 days, in inches.

Climate data for the logistic-regression equation were obtained from the local climate station (FBWR) established for the study. The logistic-regression equation was weighted by the number of irrigators that were pumping simultaneously. For example, if the four observed irrigators were all pumping or not pumping on a given day, that day was assigned a weight of 4; if three of four irrigators were pumping or not pumping on a given day, then that day was given a weight of 3, and so on. The logistic-regression equation was also refined by omitting observations on Saturdays and Sundays in the stepwise-regression procedure. Inspection of the data indicated that irrigation patterns on weekends tended to be inconsistent with the climate data. It was assumed that this inconsistency reflected altered weekend work schedules rather than the climatic conditions that necessitate irrigation.

Equation 1 yields the probability of irrigation during the irrigation season (April through November) as a value between 0 and 1.0; the closer the value is to 1.0, the greater the likelihood of irrigation. A probability of 0.35 provided the best cutoff value for predicting observed irrigation. At the 35-percent probability, the equation correctly predicted (for May through October 2001 and May through October 2002) turf-farm irrigation 81 percent of the time and balanced false positive predictions (9 percent of the time) with false negative predictions (10 percent of the time). A false positive means that the equation predicted irrigation when no irrigation was observed; a false negative means that the equation did not predict irrigation when irrigation was observed.

The evaluation of golf-course irrigation for the same period indicated a good model fit, but the results were slightly poorer than the model fit for the turf-farm irrigation. At the 35-percent probability, the equation correctly predicted irrigation 74 percent of the time, falsely predicted irrigation 9 percent of the time, and failed to predict irrigation 17 percent of the time. The equation produced nearly identical results when tested against independent golf-course irrigation data (not used to develop the equation).

To simulate long-term irrigation patterns, climatic data from the PROVID station (fig. 1) were used. However, the logistic-regression equation was developed from FBWR data and comparisons between FBWR and PROVID stations for the 22-month concurrent period of record (December 1999 through September 2001) indicated that precipitation was 14 percent greater and PET was 6 percent less at FBWR than at PROVID. Therefore, climatic data from 1960 through 2001 from the PROVID station (the period of record simulated with the PROVID data) were adjusted by these factors before applying the logistic-regression equation. The predicted irrigation with the adjusted PROVID climate data yielded nearly identical results as predicted irrigation with the FBWR climate data. Turf-farm irrigation was correctly predicted 82 percent of the time, failed to be predicted 11 percent of the time, and was incorrectly predicted 7 percent of the time. Golf-course irrigation was correctly predicted 74 percent of the time, failed to be predicted 11 percent of the time, and was incorrectly predicted 15 percent of the time.

The logistic-equation results provided a probability of irrigation for each user and each day during the irrigation season for the 1960–2001 period. If the probability of irrigation was 0.35 or greater, that day was assigned a value of 1 (irrigation); if the probability of irrigation was less than 0.35, the day was assigned a value of 0 (no irrigation). Days assigned a value of 1 were then assigned an hourly water-use distribution as described below.

### Distribution of Daily Irrigation Withdrawals

Daily irrigation patterns were obtained from available withdrawal records for three turf farms and one golf course. For each user, hourly withdrawal data were averaged for days with irrigation; the resulting average daily irrigation pattern was used to distribute water temporally on days with predicted irrigation. Withdrawals indicate different irrigation patterns according to use. Turf-farm irrigation varies widely (fig. 7*A*), but the combined average withdrawal peaks in the early afternoon. The average combined turf-farm irrigation was assumed to represent the daily distribution pattern for unmetered turf farms and other irrigation uses (vegetable and fruit farms and new-growth nurseries). Golf-course irrigation is bimodal (fig. 7*B*); irrigation typically begins about 2:00 a.m., peaks by 5:00 a.m., and ends by about 8:00 a.m. when golf activity begins, then resumes near the end of the day (6:00 p.m.) at a lower rate for about 4 hours.

## Streamflow

Continuous streamflow-gaging stations and partial-record stations were located throughout the basin (fig. 2) to provide data for calibration of the precipitation-runoff model and for evaluation of its performance. The continuous-record stations were the primary sites for these purposes; the partial-record stations provided supplemental information for evaluating the model performance over the entire basin.

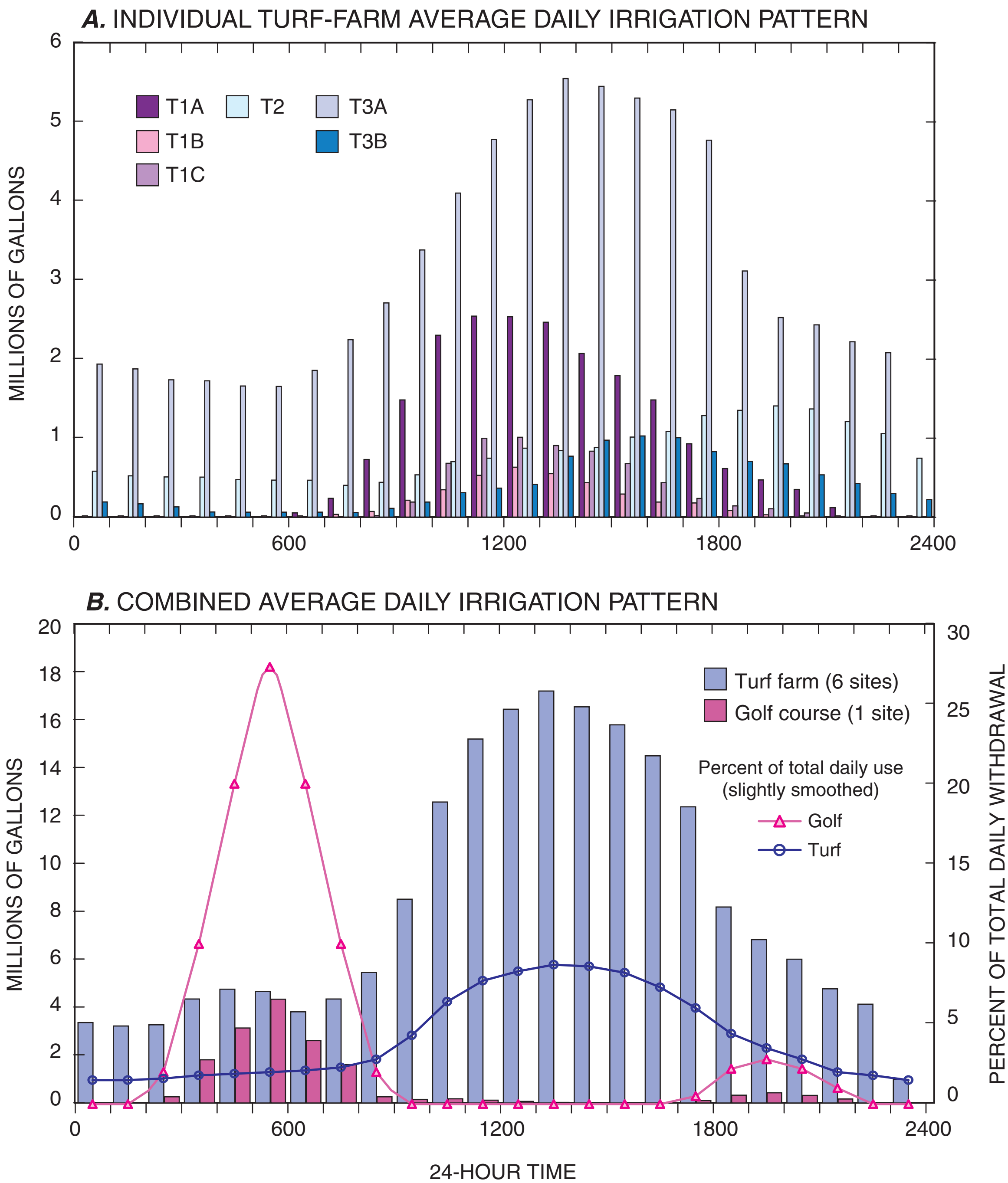



**Figure 7.** Observed average daily irrigation patterns for *A*, individual turf-farm withdrawals; and *B*, combined withdrawals, Usquepaug–Queen Basin, Rhode Island. (Three turf farms, T1–T3, were monitored for up to three seperate withdrawals.)

## Continuous-Record Stations

Four continuous streamflow-gaging stations are on the main stem of the Queen and Usquepaug Rivers (table 2, fig. 2). The downstream station (USQU) demarcates the extent of the study area and has been in continuous operation since December 1974, but hourly records are not readily available prior to October 1994. The upstream stations (QRPB, QRLY, and URUS) were installed for this study, and therefore have short periods of record. Drainage areas to QRPB, QRLY and USQU represent 10, 54, and 100 percent of the basin area, respectively. Streamflow data for these stations are published annually in the Massachusetts–Rhode Island Data Report (Socolow and others, 2001, 2002) and are available online (http://ma.water.usgs.gov/water/) through the National Water Information System (NWIS).

Streamflow records for the 2000 and 2001 water years were rated as good at QRPB and URUS and fair at QRLY and USQU, except for periods of missing record, which are rated poor at all stations. Records of discharge above 500 $ft^3/s$ at QRLY were rated poor (Socolow and others, 2001 and 2002). Streamflow records rated as good, fair, and poor mean that the measured discharge values are believed to be within 10 percent, 15 percent, and greater than 15 percent of the true discharge, respectively.

## Partial-Record Stations

To augment the continuous streamflow-gaging station data, partial-record stations were established at eight locations, mostly on tributary streams within the basin. Periodic streamflow measurements made at six of these stations were correlated with concurrent daily mean discharges at eight nearby unregulated continuous streamflow-gaging stations (index stations, fig. 1) to obtain a continuous record. Each partial-record station was collectively measured about 20 to 60 times during this study and in past studies. Streamflow measurements at partial-record stations are published in the Annual Water Resources Data Reports for Massachusetts and Rhode Island for the years in which the measurements were made. The number of correlated streamflow measurements depended on the availability of concurrent streamflow records at the index station (table 3). Correlations were generally made from a wide range of discharges at each partial-record station.

A mathematical procedure developed by Hirsch (1982) known as Maintenance of Variance Extension (MOVE.1) was applied to logarithms of the measured streamflow at the six partial-record stations and the same-day daily mean discharge at the index station. Scatter plots indicated that the relation between the log-transformed measured streamflow at each partial-record station and the same-day log-transformed daily mean discharges at each of the eight index stations was linear. Daily mean discharges for the 1999 through 2001 water years were computed for each partial-record station (table 3) from each of the eight index stations by the MOVE.1 procedure. The daily mean discharge at each partial-record station was then computed by a weighted average of the mean daily discharges calculated for each index station. The index-station discharge is weighted on the basis of the mean square error between the computed discharge and the measured discharge at the partial-record station.

The retransformation of the computed logs of discharges into arithmetic units for each equation can create a bias. This bias was evaluated by Duan's smearing method (Duan, 1983); however, a bias-correction factor was not applied to the retransformed log discharges because the overall bias among index stations was generally small (less than 1 percent). Continuous records were not computed for the unnamed tributary and Rake Factory Brook (QRTR and RFBK, respectively, fig. 2) because of their small drainage areas (less than 0.23 $mi^2$).

**Table 2.** Continuous streamflow-gaging stations and partial-record stations in the Usquepaug–Queen River Basin, Rhode Island.

[Location shown in figure 2. IDLOCN, identification attribute in the Watershed Data Management (WDM) system; $mi^2$, square mile]

| Site number | IDLOCN | Stream name | Drainage area ($mi^2$) | Continuous record |
|---|---|---|---|---|
| Continuous streamflow-gaging stations | | | | |
| 01117355 | QRPB | Queen River at Exeter | 3.67 | Yes |
| 01117370 | QRLY | Queen River at Liberty | 18.8 | Yes |
| 01117410 | URUS | Usquepaug River at the terminus of the Queen River | 20.8 | Yes |
| 01117420 | USQU | Usquepaug River near Usquepaug (basin outlet) | 36.1 | Yes |
| Partial-record stations | | | | |
| 01117354 | QECC | Queen River | 2.80 | Estimated |
| 01117360 | FBEX | Fisherville Brook | 8.14 | Estimated |
| 01117367 | QFBK | Queens Fort Brook | 4.09 | Estimated |
| 01117380 | LBLY | Locke Brook | 4.37 | Estimated |
| 01117390 | GRGR | Glen Rock Brook | 2.83 | Estimated |
| 01117400 | SBGR | Sherman Brook | 1.04 | Estimated |

**Table 3.** Summary of the relation between streamflow measurements at partial-record stations and mean daily discharge at nearby continuous streamflow-gaging stations (index stations) for computing a continuous record, Usquepaug–Queen River Basin, Rhode Island.

[Index-station locations shown in figure 1. Partial-record-station locations shown in figure 2. IDLOCN, identification attribute in the Watershed Data Management (WDM) system]

| Station number | IDLOCN | Station name | Index stations | Number of correlated streamflow measurements | Correlation coefficient |
|---|---|---|---|---|---|
| 01117354 | QECC | Queen River | 01111300 | 14 | 0.94 |
| | | | 01115098 | 14 | .96 |
| | | | 01115187 | 14 | .97 |
| | | | 01117370 | 15 | .98 |
| | | | 01117468 | 15 | .95 |
| | | | 01117800 | 15 | .96 |
| | | | 01118000 | 15 | .93 |
| | | | 01118300 | 15 | .86 |
| 01117360 | FBEX | Fisherville Brook | 01111300 | 47 | .91 |
| | | | 01115098 | 17 | .93 |
| | | | 01115187 | 17 | .94 |
| | | | 01117370 | 18 | .99 |
| | | | 01117468 | 52 | .97 |
| | | | 01117800 | 52 | .95 |
| | | | 01118000 | 52 | .95 |
| | | | 01118300 | 52 | .91 |
| 01117367 | QFBK | Queens Fort Brook | 01111300 | 17 | .84 |
| | | | 01115098 | 17 | .91 |
| | | | 01115187 | 17 | .93 |
| | | | 01117370 | 19 | .94 |
| | | | 01117468 | 19 | .96 |
| | | | 01117800 | 19 | .91 |
| | | | 01118000 | 19 | .91 |
| | | | 01118300 | 19 | .85 |
| 01117380 | LBLY | Locke Brook | 01111300 | 44 | .92 |
| | | | 01115098 | 17 | .95 |
| | | | 01115187 | 17 | .96 |
| | | | 01117370 | 18 | .98 |
| | | | 01117468 | 48 | .96 |
| | | | 01117800 | 48 | .96 |
| | | | 01118000 | 48 | .97 |
| | | | 01118300 | 48 | .93 |
| 01117390 | GRGR | Glen Rock Brook | 01111300 | 44 | .93 |
| | | | 01115098 | 17 | .92 |
| | | | 01115187 | 17 | .96 |
| | | | 01117370 | 18 | .97 |
| | | | 01117468 | 48 | .95 |
| | | | 01117800 | 48 | .93 |
| | | | 01118000 | 48 | .95 |
| | | | 01118300 | 48 | .95 |

**Table 3.** Summary of the relation between streamflow measurements at partial-record stations and mean daily discharge at nearby continuous streamflow-gaging stations (index stations) for computing a continuous record, Usquepaug–Queen River Basin, Rhode Island.—Continued

[Index-station locations shown in figure 1. Partial-record-station locations shown in figure 2. IDLOCN, identification attribute in the Watershed Data Management (WDM) system]

| Station number | IDLOCN | Station name | Index stations | Number of correlated streamflow measurements | Correlation coefficient |
|---|---|---|---|---|---|
| 01117400 | SBGR | Sherman Brook | 01111300 | 44 | 0.89 |
| | | | 01115098 | 17 | .79 |
| | | | 01115187 | 17 | .87 |
| | | | 01117370 | 18 | .89 |
| | | | 01117468 | 47 | .90 |
| | | | 01117800 | 47 | .90 |
| | | | 01118000 | 47 | .93 |
| | | | 01118300 | 47 | .95 |

The accuracy of this record-extrapolation technique is determined by: (1) the goodness-of-fit between the discharge measurements at the partial-record station and the same-day mean daily discharge records at continuous streamflow-gaging stations, (2) the accuracy of the discharge measurements, (3) the accuracy of the continuous-discharge record, and (4) the range of the measured flows at the partial-record station. Each of these factors can introduce error; therefore, the extrapolated record at the partial-record stations is considered an estimate. Because most measurements at the partial-record stations were made during low to moderate flows, the estimates of daily discharge at high flows could be poor.

# Precipitation-Runoff Model

The effects of water withdrawals on streamflow in the Usquepaug–Queen Basin were simulated with the Hydrological Simulation Program–FORTRAN (Bicknell and others, 2000), hereafter referred to as HSPF. The HSPF model was chosen because (1) its capabilities make it an appropriate management tool for the continuous simulation of hydrology and complex water-withdrawal patterns in the basin, and (2) the model has been a successful management tool for similar basins with similar water issues in New England (Zarriello and Ries, 2000). The computer code for HSPF and its companion programs are in the public domain and are freely available. In general terms, the model was developed by: (1) compiling, collecting and processing needed data, (2) creating a model structure that represents the basin, (3) calibrating the model, and (4) evaluating its performance. The calibrated model was then used to simulate selected withdrawal and land-use change in the basin.

## Functional Description of Hydrologic Simulation Program–FORTRAN (HSPF)

HSPF is a mathematical model designed to simulate the hydrology and movement of contaminants in a basin. Only the hydrologic simulation capability of HSPF was developed and used in this study, however. Runoff from a basin is quantified by the continuous simulation of hydrologic response to climatic and human stresses on the basis of the principle of conservation of water mass—that is, inflow equals outflow plus or minus any change in storage. In HSPF, a basin is represented by a collection of hydrologically similar areas that are referred to as hydrologic response units (HRUs) and that drain into a network of stream or lake segments (RCHRESs). For each HRU and RCHRES, the model computes a water budget (inflows, outflows, and changes in storage) for each time step. A complete description of the processes involved in computing water budgets and required input model variables is given in the "HSPF User's Manual" (Bicknell and others, 2000).

HRUs reflect areas of similar land use, soil, subsurface geology, and other factors deemed important in producing a similar hydrologic response to precipitation and potential evapotranspiration. HRUs are divided into pervious-area land elements (PERLNDs) and impervious-area land elements (IMPLNDs). HRUs are further divided into zones that define storages and processes between zones. PERLNDs and IMPLNDs have snow and surface zones that retain precipitation at the surface as interception storage or snowpack storage. All water that is not evaporated from the surface produces runoff from IMPLNDs, but PERLNDs allow excess precipitation to infiltrate into the subsurface, where storages and processes are represented by upper, lower, and ground-water zones.

Processes 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. Surface runoff from PERLNDs and IMPLNDs and subsurface discharge from PERLNDs are typically directed into reaches (RCHRES); however, water can be directed elsewhere if desired.

RCHRESs are model elements that represent a length of stream channel or reservoir. The downstream end of each RCHRES is referred to as a node. Nodes are typically placed to define channel segments with similar physical properties, such as reach segments with similar slope and width, junctions of tributary streams, lakes and reservoirs, and locations of data-collection sites. Nodes can be placed at other locations where estimates of streamflow are desired, such as upstream and downstream from municipal well fields, water diversions, or discharges of contaminants. The hydrologic characteristics used for kinematic wave routing of water in a RCHRES are defined by its storage-discharge properties specified in the FTABLE of the model input.

The *SCHEMATIC* or *NETWORK* blocks are used to represent the physical layout of the basin. The area of each IMPLND and PERLND that drains to a RCHRES is defined in this section of the model to formulate subbasins. The *SCHEMATIC* or *NETWORK* blocks are also used to define the linkage of one RCHRES to another. The *MASSLINK* associated with a *SCHEMATIC* block or *NETWORK* block alone controls the linkage of flow components between model elements. Typically, this linkage involves routing (1) surface runoff from PERLNDs and IMPLNDs, (2) interflow and base flow from PERLNDs to reaches, and (3) streamflow from reach to reach.

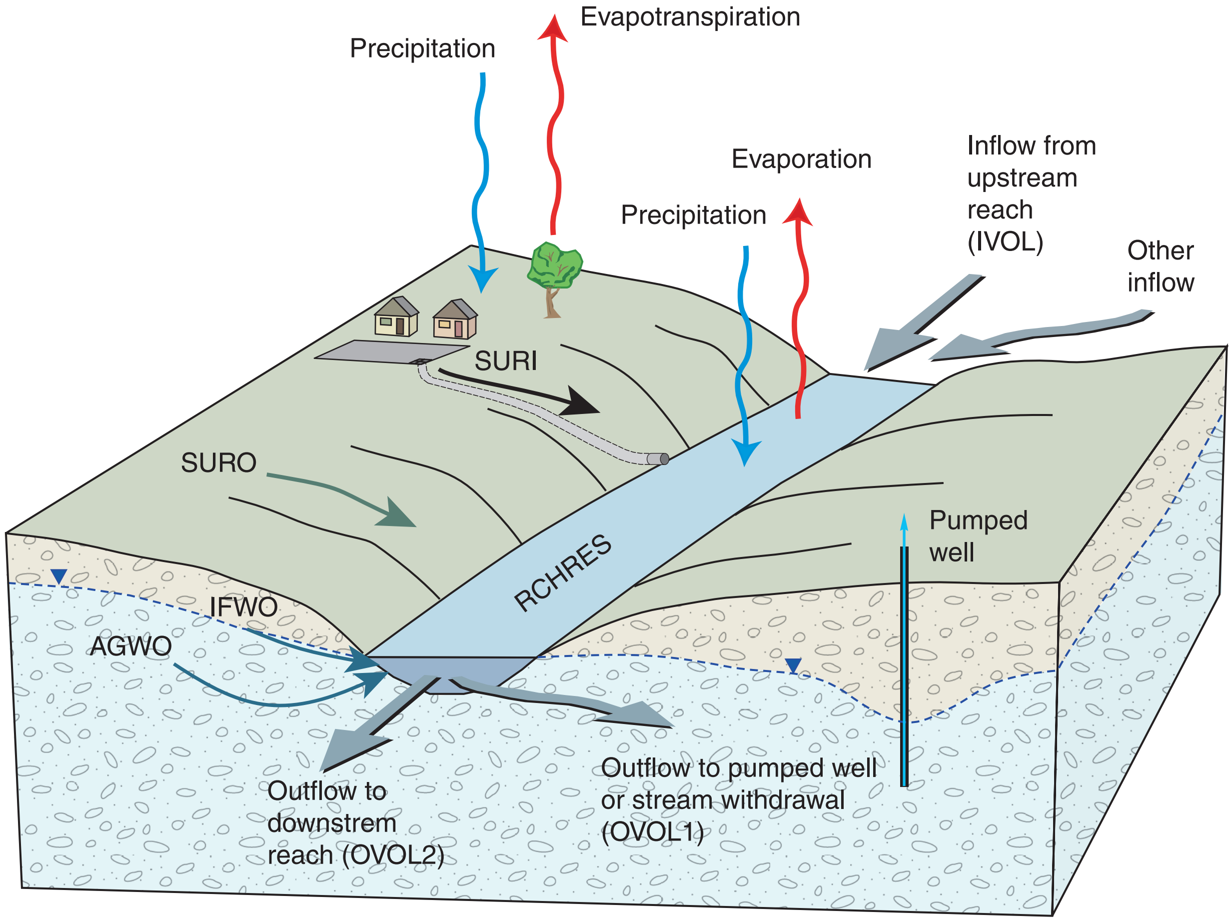
The inflows to and outflows from a stream reach are illustrated in figure 8. Surface runoff can discharge to a reach from impervious surfaces (SURI) and pervious surfaces (SURO). Infiltrated water can discharge to the reach through the subsurface as interflow (IFWO), a fast-responding shallow subsurface flow, or from active ground water (AGWO), a slow-responding base-flow component, or, optionally, exit from an HRU as deep ground-water flow that discharges outside of the basin. Inflow to a reach can also come from upstream reaches (IVOL), direct precipitation, and other user-specified sources such as treated wastewater. Two reach outflow exits (or gates) were designated for this study as illustrated in figure 8 (a reach can have up to five exits). The first outflow gate (OVOL 1) was the volume time series of water withdrawals (OUTDGT 1) for each reach read from the *EXT SOURCES* block (external sources). Specifying the first outflow gate for water withdrawals requires that these withdrawals be satisfied before water is routed through successive outflow gates. In the Usquepaug–Queen Basin model, water was routed downstream through the second outflow gate (OVOL 2) in reaches with withdrawals. In reaches with no withdrawals, a single outflow gate was specified.

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 model-process algorithms and sets user-specified input variables. The WDM file is a binary file that efficiently stores large amounts of data. The three primary model elements, PERLNDs, IMPLNDs, and RCHRESs, are organized by blocks in the *uci* file. Within each block are modules and submodules that define the movement of water and changes in storage between zones. Some modules are mandatory for simulations and others are optional. For example, the PERLND block requires PWATER modules to simulate hydrology, but the SNOW module is optional for simulating snowpack buildup and melt. A number of other blocks are required for administrative functions, such as controlling the operational sequence of the program and directing the model to external sources and the output of time-series data, and defining the linkage between model elements. Other blocks are available for data manipulation, displaying and reporting model results, and other optional model features.

## Database

The Watershed Data Management (WDM) file stores time-series data required for simulations or generated by the HSPF model. Precipitation and evapotranspiration are required time series; air temperature, dew-point temperature, solar radiation, and wind speed are required if snowpack buildup and melt are simulated. These data are typically entered into the WDM database by use of the software IOWDM (Lumb and others, 1990) or WDMUtil. The *EXT SOURCES* block of the *uci* file reads data from the WDM file and model-generated time series are passed to the WDM file through the *EXT TARGETS* block (external targets) of the *uci* file. Output time series can be generated for any component in the simulation process defined in the “Time Series Catalog” section of the user’s manual (for example, the active ground-water outflow from a PERLND—*AGWO* can be output directly), but streamflow time series are the primary output. Time-series data in WDM can be accessed, displayed, transformed, and plotted by use of ANNIE (Flynn and others, 1995), GenScn (Kittle and others, 1998), or WDMUtil software.

Dataset numbers (DSNs) and attribute information must exist in the WDM file to pass time-series data between the WDM file and the model. The WDM file is organized by DSNs and relational attribute information. The organization of the WDM file developed for the Usquepaug–Queen Basin is summarized in table 4. Attributes describe the data type, time step, location, and other important features of the data. The data type is defined by the constituent attribute *IDCONS*, which are defined for the Usquepaug–Queen Basin in table 5. The first 100 DSNs are used for measured meteorologic and streamflow time series. Data sets with numbers larger than 100 are generally organized by reach.




**EXPLANATION**

SURI–Surface runoff from impervious areas

SURO–Surface runoff from pervious areas

IFWO–Interflow (subsurface flow that responds rapidly to precipitation)

AGWO–Active ground-water flow (base flow)

RCHRES–Stream reach or reservoir segment

IVOL–Inflow volume

OVOLx–Outflow volume through individual exits (x = 1–5)

**Figure 8.** Simplified schematic representation of the Hydrologic Simulation Program–FORTRAN (HSPF) inflows and outflows to a stream.

**Table 4.** Organization and description of Data Set Numbers (DSNs) in the Watershed Data Management (WDM) database developed for the Usquepaug–Queen River Basin, Rhode Island.

| DSN | Purpose |
|---|---|
| 1–20 | Measured or computed streamflow data |
| 21–99 | Measured or computed climate data |
| 100–120 | Total withdrawals from a stream reach |
| 150 | Hourly turf-farm irrigation |
| 160 | Hourly golf-course irrigation |
| 167 | Irrigation flag predicted by logistic-regression equation (0=no irrigation, 1=irrigation) |
| 201–220 | Simulated streamflow by reach (base scenario) |
| 232–237 | Simulated irrigation withdrawals by reach |
| 1000 | Constant—used with a multiplier to compute domestic withdrawals |
| 1021–1203 | Individual surface-water withdrawal or stream depletion from ground-water withdrawal, where |
| 1xx1–1xx3 | xx, second and third digit, identifies the reach number, and |
| 102x–120x | x, last digit, identifies individual withdrawal points |
| 2191 | Combined ground-water withdrawals from pumped wells in reach 19 |
| 5001–5038 | Simulated flow components by hydrologic response unit (HRU) |
| 6x01–6x20 | Scenario simulation results, where x, second digit, identifies a unique scenario and the last two digits identify the reach number |

**Table 5.** Watershed Data Management (WDM) system constituent attribute (IDCONS) values for the Usquepaug–Queen Basin, Rhode Island.

[$ft^3/s$, cubic foot per second; mi/hr, mile per hour; mi/d, mile per day; °C, degrees Celsius; °F, degrees Fahrenheit]

| IDCONS | Purpose (units) |
|---|---|
| FLOW | Measured or simulated streamflow ($ft^3/s$) |
| | **Climate data** |
| AIRT | Measured air temperature (°C or °F) |
| DEWP | Measured dew-point temperature (°C or °F) |
| WIND | Measured wind speed (mi/hr) |
| TWND | Computed total wind movement (mi/hr or mi/d) |
| PREC | Measured precipitation (inches) |
| PET | Computed potential evapotranspiration (inches) |
| RHUH | Measured relative humidity (°C or °F) |
| VAPP | Measured vapor pressure (kilopascals) |
| SOLR | Measured solar radiation (Langleys) |
| | **Water-use data** |
| ExDemand | Total water withdrawal from reach ($ft^3/s$) |
| IRRIGATE | External irrigation withdrawal ($ft^3/s$) or irrigation flag determined by logistic-regression equation |
| IRRD | Simulated irrigation withdrawal by model ($ft^3/s$) |
| SWDL | Reported surface-water withdrawal ($ft^3/s$) |
| DEPL | Streamflow depletion from a pumped well ($ft^3/s$) |
| PUMP | Reported ground-water withdrawal ($ft^3/s$) |
| | **Flow or storage components from PERLNDs and IMPLNDs** |
| PERO | Total runoff (inches) |
| SURO | Surface runoff (inches) |
| IFWO | Interflow (inches) |
| AGWO | Active ground-water flow (inches) |
| UZSN | Upper-zone storage (inches) |
| LZSN | Lower-zone storage (inches) |
| | **Low-flow statistics** |
| 1-dayLF | Annual 1-day low flow ($ft^3/s$) |
| 7-dayLF | Annual 7-day low flow ($ft^3/s$) |
| 30-dayLF | Annual 30-day low flow ($ft^3/s$) |

Irrigation withdrawals for long-term simulations (1960–2001) were simplified by creating two WDM data sets; DSN 150 reflects the pattern of daily irrigation on turf farms, and DSN 160 reflects the pattern of daily irrigation on golf courses as described previously. For days in which the logistic-regression equation predicted irrigation, these distribution patterns were expressed as hourly irrigation rates defined in cubic feet per second as a fractional portion of 2,000 gal/d/acre. The 2,000 gal/d/acre is about the average observed irrigation rate. On days of no irrigation, hourly values were zero. For each reach with irrigation withdrawals, hourly withdrawals were read into the HSPF model by multiplying the irrigated area applicable to that reach, in acres, by an adjustment factor that corrected for the difference between the 2,000 gal/d/acre rate and the measured average withdrawal rate where it exists. For example, direct withdrawals from a reach were made for a 230-acre turf farm with an observed average irrigation of 1,650 gal/d/acre when irrigating. For that reach, the *EXT SOURCES* block read DSN 150 with a multiplier (MFACT) of 189.75 (the fractional difference between 2,000 and 1,650 gal/d/acre times 230 acres) as the withdrawal from the first outflow exit. Irrigation withdrawals were assumed lost to evapotranspiration.

## 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 stream 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 basin. Basin and subbasin boundaries in the model study area were obtained from available USGS and RIGIS sources or digitized from 1:24,000-scale USGS topographic maps when necessary. Other digital data layers used in the discretization process included surficial geology, land use, hydrography, and wetlands. The spatial data were simplified and grouped to obtain categories that were considered important to the basin hydrology. The surficial-geology data layer was simplified from seven types of material into two types on the basis of permeability and storage characteristics: (1) sand and gravel and (2) till. The LULC data layer was combined with the wetland data layer and then simplified from 56 to 10 categories: (1) forest, (2) open, (3) irrigated crop, (4) turf farm, (5) golf course, (6) forested wetland, (7) nonforested wetland, (8) low density residential, (9) moderate to high density residential, and (10) commercial-industrial-transportation (fig. 5).

### Development of Hydrologic Response Units (HRUs)

HRUs were obtained by combining the surficial geology and the simplified land-use data layers, which resulted in 22 unique combinations of land-use and surficial-geology types. Unique surficial-geology and land-use types with areas less than about 1 percent of the basin area were grouped into the HRU with the most similar characteristics. For example, open-space in commercial and industrial areas accounted for about 1 percent of the basin area; therefore, this category was combined with the open space in high density residential areas. From the 22 possible combinations of HRU types, 13 PERLNDs and 2 IMPLNDs were established for the Usquepaug–Queen Basin (fig. 9). The area of each HRU for each subbasin was computed by a GIS script that intersects the HRU types with the subbasin boundaries.

#### Impervious Areas (IMPLNDs)

Impervious areas that drain directly to streams (hydrologically effective impervious areas) are simulated as IMPLNDs. Impervious areas that drain to pervious areas (hydrologically ineffective impervious areas) are incorporated into the PERLNDs representing developed areas. Initial estimates of effective impervious area were determined as a percentage of the area for various developed land-use classes (table 6) as assigned in the original land-use cover (the land-use classes in table 5 are more detailed than the land-use classes used to develop the model HRUs as indicated in fig. 5). The initial percentages of impervious area for various developed land-use types were obtained from similar land-use types reported by Alley and Veenhuis (1983). The final effective impervious area was obtained primarily by calibration of small summer storms that are considered to generate runoff mostly from effective impervious surfaces. Other factors considered in the calibration of the effective impervious area include the overall responsiveness of the hydrograph to precipitation and water budgets. Two IMPLND types were used in the model: (1) commercial, industrial, transportation, and (2) residential. Hydrologically, these two IMPLNDs are similar, but they were given unique HRUs for possible future water-quality applications.

About 9 percent of the basin is classified as developed, but the effective impervious area was estimated to be about 2 percent of the basin area. The estimated total effective impervious area as a percentage of the total basin area is less than 1 percent of the basin area above the QRPB, and about 2 percent of the basin area above QRLY and USQU (fig. 9).

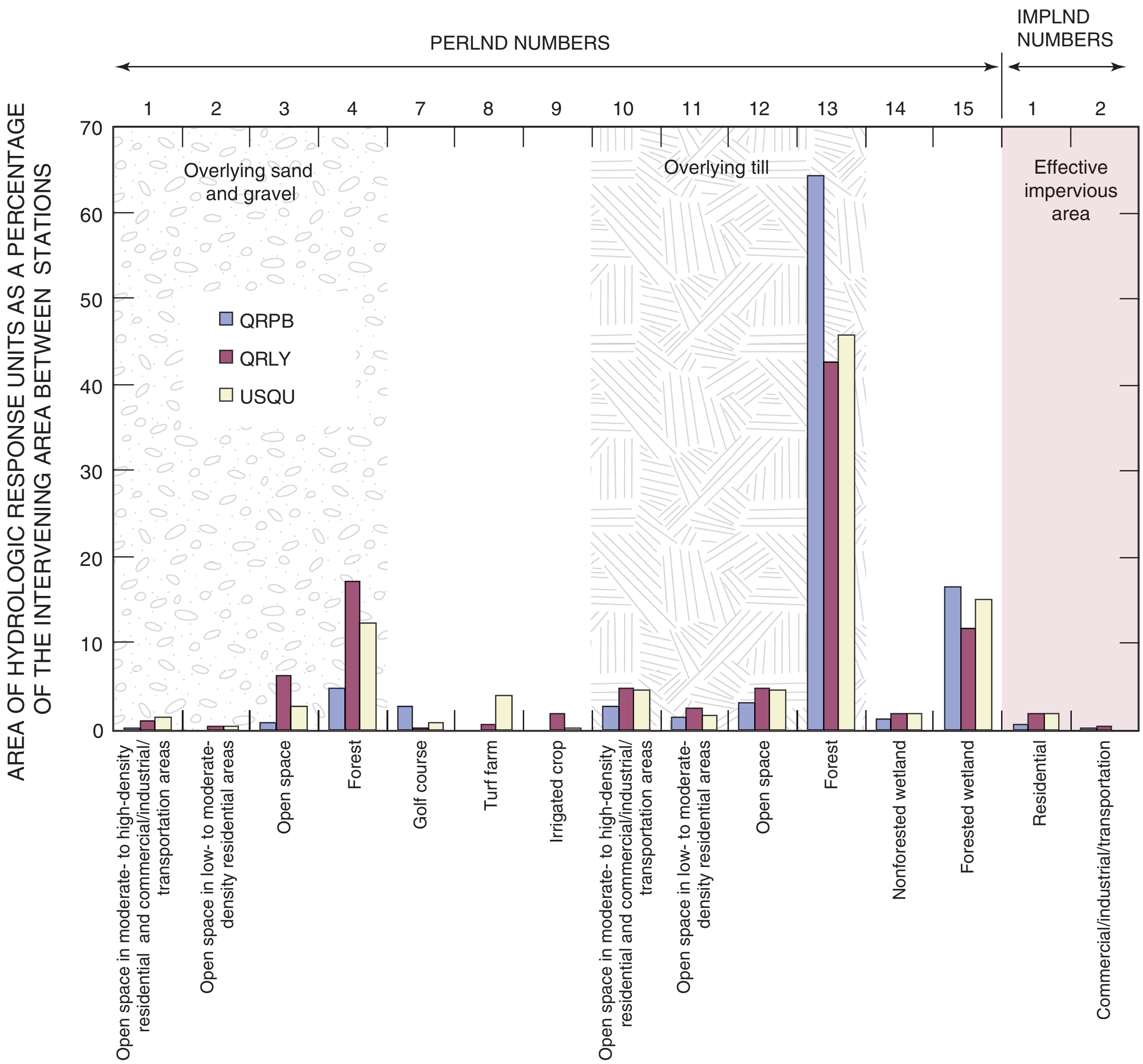



**Figure 9.** Area as a percentage of the intervening basin area between streamflow-gaging stations at Queen River at Exeter (QRPB), Queen River at Liberty (QRLY), and Usquepaug River near Usquepaug (USQU), for hydrologic response units (HRUs) in the Hydrologic Simulation Program–FORTRAN (HSPF) model of the Usquepaug–Queen River Basin, Rhode Island (locations of streamflow-gaging stations shown on fig. 2).

**Table 6.** The percentage of developed area initially estimated as effective impervious area by land-use classification in the Usquepaug–Queen River Basin, Rhode Island.

| Percent impervious | Land-use classification |
|---|---|
| 50 | Medium-high-density residential (0.125- to 0.25-acre lots) |
| 20 | Medium-density residential (0.25- to 1-acre lots) |
| 5 | Medium-low density residential (1- to 2-acre lots) |
| 2 | Low-density residential (2-acre lots or larger) |
| 85 | Commercial |
| 85 | Industrial |
| 60 | Airport |
| 90 | Other transportation |

### Pervious Areas (PERLNDs)

PERLNDs in the basin are represented by four HRUs overlying sand and gravel and four HRUs of similar land use overlying till (fig. 9). For each of these eight HRUs, four represent open space in developed areas (PERLNDs 1,2, 10 and 11), two represent open space in undeveloped areas (PERLNDs 3 and 12), and two represent forested areas (PERLNDs 4 and 13). Other PERLNDs represent the three irrigated HRUs—golf courses, turf farms, and croplands (PERLNDs 8, 9, and 10, respectively), and the two wetland HRUs—nonforested and forested (PERLNDs 14 and 15, respectively). These PERLNDs were not differentiated by underlying surficial material.

Open space in undeveloped areas composes about 9 percent of the total basin area and is about evenly divided between areas overlying sand and gravel, and till. Open space in developed areas composes about 8 percent of the total basin area. Open space associated with development represents the combined area of green space between buildings and the adjacent impervious area that contributes runoff to the pervious area. The additional runoff from impervious areas causes these areas to respond more rapidly to precipitation than similar undisturbed HRUs; therefore, infiltration and soil-water storage was decreased relative to undeveloped open space for similar types of surficial geology.

The dominant HRU in the Usquepaug–Queen Basin (fig. 9) is forest overlying till (PERLND 13), which composes about 47 percent of the total basin area. This HRU composes as much as 75 percent of the area in headwater subbasins and is less common in the subbasins along the lower reaches of the main stem (as little as 12 percent of the subbasin area). PERLND 13 composes about 65 percent of the drainage area to the streamflow-gaging station at QRPB, about 43 percent of the area to QRLY, and about 47 percent of the drainage area USQU (fig. 2).

Three HRUs were established for areas that receive irrigation (fig. 9)—golf courses (PERLND 8), turf farms (PERLND 9), and irrigated crops (PERLND 10). Digital land cover indicated that golf courses occupied 258 acres; however, field investigations indicated that about 29 percent of this area (74 acres) was not irrigated. Areas of golf courses that were not irrigated were reclassified as open space overlying sand and gravel (PERLND 3). Although the underlying surficial material is not defined for the irrigated HRUs, these HRUs are mostly (90 percent) underlain by sand and gravel. Therefore, these HRUs were assigned similar model-variable values as the HRU representing open space overlying sand and gravel. Collectively, irrigated HRUs represent about 4 percent of the total basin area, which is unevenly distributed—irrigated HRUs can compose as much as 20 percent of a subbasin area, but most subbasins contain no irrigated HRUs.

Two HRUs were established to represent wetland areas (fig. 9)—nonforested wetland (PERLND 14) and forested wetland (PERLND 15). The wetland HRUs were not distinguished by their underlying surficial material because this was considered secondary to the soil properties and evaporation potential of the wetlands themselves. Nonforested and forested wetlands are about evenly distributed over sand and gravel deposits and till deposits, however. Forested wetland composes between 4.5 and 20 percent of the subbasin areas and is distributed relatively evenly throughout the basin (median of 10 percent of the subbasin area). Collectively, forested PERLNDs (4 and 13) and forested wetlands (15) compose about 75 percent of the total basin area.

## Stream Reaches (RCHRES)

The basin was segmented into 20 stream reaches (fig. 10). The reach segmentation was based on hydrologic characteristics and the availability of streamflow information. Seven reaches were established along the main stem of the Queen and Usquepaug Rivers and 13 reaches were established on tributaries (table 7). Three tributaries (Fisherville Brook, Locke Brook, and an unnamed tributary, reach 11) were subdivided to create nodes at streamflow-gaging stations. Fisherville Brook was further subdivided because of its size. The upper Queens Fort Brook reach (RCHRES 7) was established to account for the area of this basin that is reported to have subsurface discharge to the HAP Basin (Dickerman and others, 1997; Barlow and Dickerman, 2001). The water-table map by Allen and others (1966) also indicates that ground water may discharge from a portion of the upper part of the drainage area to RCHRES 8 to the Chipuxet River Basin.

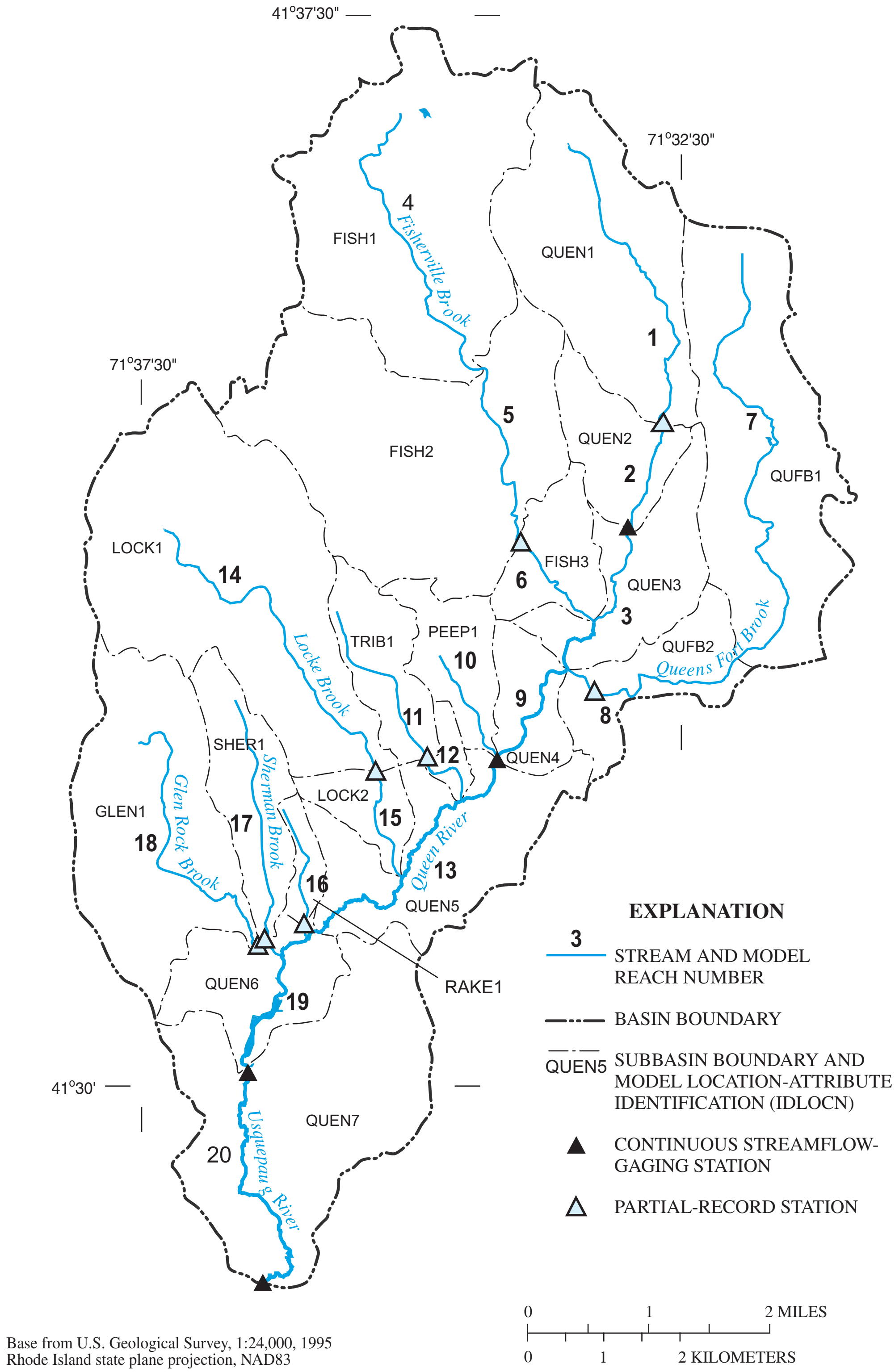



**Figure 10.** Model reaches and subbasin boundaries developed for the Hydrologic Simulation Program–FORTRAN (HSPF) model of the Usquepaug–Queen River Basin, Rhode Island (basin location shown on fig. 1).

**Table 7.** Stream reaches (RCHRES) in the Hydrologic Simulation Program–FORTRAN (HSPF) model of the Usquepaug–Queen River Basin, Rhode Island.

[Location shown in figure 10. IDLOCN, attribute in the Watershed Data Management (WDM) system that identifies the reach; USGS, U.S. Geological Survey; --, no station]

| Model-reach number | IDLOCN | Reach name and IDLOCN of streamflow-gaging station | Direct drainage area (acres) | Total drainage area (acres) | Upstream reach numbers | USGS station number |
|---|---|---|---|---|---|---|
| 1 | QUEN1 | Queen River (QECC) | 1,794 | 1,794 | -- | †01117354 |
| 2 | QUEN2 | Queen River at Exeter (QRPB) | 556 | 2,350 | 1 | 011173545 |
| 3 | QUEN3 | Queen River (QREX) | 802 | 3,152 | 2 | †01117355 |
| 4 | FISH1 | Fisherville Brook | 2,532 | 2,532 | -- | -- |
| 5 | FISH2 | Fisherville Brook (FBEX) | 2,742 | 5,274 | 4 | †01117360 |
| 6 | FISH3 | Fisherville Brook | 472 | 5,746 | 5 | -- |
| 7 | QUFB1 | Queens Fort Brook | 2,131 | 2,131 | -- | -- |
| 8 | QUFB2 | Queens Fort Brook (QFBK) | 623 | 2,754 | 7 | †01117367 |
| 9 | QUEN4 | Queen River at Liberty (QRLY) | 402 | 12,054 | 3,6,8 | 01117370 |
| 10 | PEEP1 | Peeper Pond Brook | 471 | 471 | -- | -- |
| 11 | TRIB1 | Unnamed tributary (QRTR) | 526 | 526 | -- | †01117375 |
| 12 | TRIB1a | Unnamed tributary | 110 | 636 | 11 | -- |
| 13 | QUEN5 | Queen River | 1,227 | 14,388 | 9,10,12 | -- |
| 14 | LOCK1 | Locke Brook (QRDR) | 2,786 | 2,786 | -- | †01117380 |
| 15 | LOCK2 | Locke Brook | 290 | 3,076 | 14 | -- |
| 16 | RAKE1 | Rake Factory Brook (RFBK) | 149 | 149 | -- | †01117385 |
| 17 | SHER1 | Sherman Brook (SBGR) | 665 | 665 | -- | †01117400 |
| 18 | GLEN1 | Glen Rock Brook (GRGR) | 1,805 | 1,805 | -- | †01117390 |
| 19 | QUEN6 | Queen River below Glen Rock Reservoir (URUS) | 704 | 20,787 | 13,15,16, 17,18 | 01117410 |
| 20 | QUEN7 | Usquepaug River near Usquepaug (USQU) | 2,329 | 23,116 | 19 | 01117420 |

† Indicates a partial-record station.

The linkage of reaches in the *SCHEMATIC* block to one another, in most cases, is easily identified in figure 10. For example, reach 4 flows into reach 5, which flows into reach 6. Linkages between some tributaries and the main stem are less obvious where the confluence does coincide with a reach junction (node). These reaches include: reach 6, which together with reaches 3 and 8 flow into reach 9; reach 12, which together with reaches 9 and 10 flow into reach 13; and reaches 15, 16, 17, and 18, which together with reach 13 all flow into reach 19.

The first outflow gate is used to route water from one reach to another in reaches where no withdrawals are specified. In reaches where there are withdrawals (reaches 2, 3, 7, 8, 17, 19, and 20), the withdrawals are taken from the first exit gate and flow is routed from one reach into another through the second exit gate. In reach 7 (upper Queens Fort Brook), only a portion of the subsurface flow is routed downstream to account for ground-water discharge to the HAP Basin; the second exit gate is used to route surface runoff and a portion of the interflow downstream to reach 8. The flow routing in Queens Fort Brook is described further in the calibration section of the report.

**Hydraulic Characteristics (FTABLES):** Stage-storage-discharge characteristics (FTABLES) were developed for the outflow gate used to route water from each of the 20 reaches. The FTABLE characterizes the hydraulic properties of the reach by defining the relation between depth, storage, and discharge. This relation is usually defined by the hydraulic properties at the downstream end of the reach, but the discharge-volume relation is a function of the properties of the entire reach.

The channel-geometry analysis program (CGAP) by Regan and Schaffranek (1985) was used to define the relations among depth, surface area, and volume. A supplemental program, GENFTBL, reads the channel-geometry output from CGAP to calculate the stage-storage-discharge relation by solving Manning's equation for open-channel flow. CGAP requires cross-section channel geometry, which was obtained from discharge-measurement notes at each of the continuous- and partial-record streamflow-gaging stations and from USGS 1:24,000-scale digital topographic maps. At minimum, three cross sections were used to define the storage-discharge relations for each reach. GENFTBL requires Manning's roughness coefficients for each cross section; these coefficients were estimated from guidelines by Coon (1998) and Arcement and Schneider (1989).

## Model Calibration

The Usquepaug–Queen Basin model was calibrated to the period January 1, 2000, to September 30, 2001, by using an hourly time step and the FBWR climate-station data. The short calibration period was necessary because water-withdrawal information was available only for this period. Withdrawal information is needed to fit model variables for the calibration process. Unaccounted-for withdrawals or inaccurate withdrawal information can skew variable values to compensate for the effects of these deficiencies.

Estimates of variable values were determined from spatial data to the extent possible. For example, the average PERLND slope could be measured from digital-elevation data. Most model variable values could not be measured directly, however. These variables were initially assigned values similar to those used for comparable HRUs in the Ipswich River Basin HSPF model (Zarriello and Ries, 2000). An iterative process was then used to adjust these values to minimize the difference between simulated and observed flows. The calibrated-model variable values are given in the partial listing of the *uci* file in Appendix 1.

Discharge measured at three continuous streamflow-gaging stations, QRPB, QRLY, and USQU, (fig. 2) provided the main model-calibration points. Stations QRPB and USQU correspond to outflow points for RCHRES 2 and 20, respectively. QRLY represents the combined flow from RCHRES 9 (main stem Queen River) and RCHRES 10 (Peeper Pond Brook tributary); the flow from these reaches is combined by use of the HSPF *COPY* operation. In general, standards for the model performance were relaxed slightly at the upstream stations (QRPB and QRLY) to achieve the best fit between simulated and observed flow at the downstream station (USQU).

The model was calibrated in accordance with guidelines by Donigian and others (1984) and Lumb and others (1994a). Calibration generally entailed adjusting the variable values to fit the model output to total and seasonal water budgets, then adjusting values to improve the model fit for daily flows while maintaining the total and seasonal water budgets. The model was calibrated by first adjusting variable values as a group for PERLNDs overlying sand and gravel, till, and wetlands. Once reasonable simulation results were obtained, further adjustments were made to variable values for PERLNDs representing different land-use types within each of these geologic groups. Storm runoff and snowmelt were not given detailed consideration because the primary purpose of the model is to simulate the effects of withdrawals during low-flow periods. Snow rarely remains on the ground for appreciable periods; thus, the snow-buildup and melt process routines were included primarily to adjust precipitation data (by a factor of 1.30) to compensate for precipitation-gage measurement inefficiencies during periods of snow.

The quality of the model fit was determined by visual inspection of the simulated and observed hydrographs, flow-duration curves, and scatter plots, and by mathematical summary statistics provided by the *SERIES_COMPARE* utility in the model-independent parameter-estimation program (PEST) Surface-Water Utilities (Doherty, 2003) and HSPEXP (Lumb and others, 1994a). The *SERIES_COMPARE* utility provides fit statistics computed from hourly discharge and total monthly runoff values. These statistics include model bias, standard error, relative bias, relative standard error, Nash-Sutcliffe coefficient (which, as applied, is the same as the coefficient of the model-fit efficiency), and index of agreement (equations for these statistics are provided in Appendix 2). The *SERIES_COMPARE* utility provides relative measures of model fit and is most useful in comparing alternative models. Model-fit statistics computed by *SERIES_COMPARE* are summarized in table 8.

**Table 8.** Model-fit statistics computed by the Parameter Estimation (PEST) Surface Water Utilities program for flows simulated by the Hydrologic Simulation Program–FORTRAN (HSPF) and observed flows at three continuous streamflow-gaging stations in the Usquepaug–Queen River Basin, Rhode Island, January 2000 through September 2001.

[Streamflow-gaging station locations shown on figure 2. Equations for model-fit statistics are given in Appendix 2]

| Model-fit statistic | Streamflow-gaging station | | | | | |
|---|---|---|---|---|---|---|
| | Queen River at Exeter (QRPB) | | Queen River at Liberty (QRLY) | | Usquepaug River near Usquepaug (USQU) | |
| | Hourly discharge | Monthly volume | Hourly discharge | Monthly volume | Hourly discharge | Monthly volume |
| Number of series terms | 15,289 | 21 | 15,289 | 21 | 15,289 | 21 |
| Bias | .01 | $2.24 \times 10^4$ | -1.22 | $-3.19 \times 10^6$ | -1.22 | $-3.20 \times 10^6$ |
| Standard error | 5.07 | $4.53 \times 10^6$ | 23.8 | $2.31 \times 10^7$ | 35.8 | $2.69 \times 10^7$ |
| Relative bias | .001 | .001 | -.029 | -.029 | -.015 | -.014 |
| Relative standard error | .456 | .251 | .523 | .288 | .448 | .179 |
| Nash-Sutcliffe coefficient | .793 | .937 | .726 | .917 | .799 | .968 |
| Index of agreement | .940 | .983 | .920 | .976 | .946 | .991 |

The coefficient of determination ($r^2$) and the Nash-Sutcliffe coefficient are similar because both provide a measure of the variation in the simulated value explained by the observed value. The Nash-Sutcliffe coefficient, however, provides a more rigorous evaluation of the fit quality than does the $r^2$ because the Nash-Sutcliffe coefficient is sensitive to differences between the observed and simulated means and variances, whereas $r^2$ measures the differences between mean values (Legates and McCabe, 1999). In cases where the observed values and model residuals are normally distributed, the value of $r^2$ and the Nash-Sutcliffe coefficient should be equal (Duncker and Melching, 1998).

HSPEXP provides overall model-fit information in terms of the error between various measures of simulated and observed values. These measures include error over the calibration period in the total and seasonal runoff volumes, flows above the 10th percentile (high flows) and below the 50th percentile (low flows), and the base-flow-recession constant, which is the difference in the ratio of the current day’s discharge to the previous day’s discharge for simulated and observed flows. Errors are also computed for selected storm volumes and peak discharges for summer-storm runoff volume. These statistics were designed to work with the “expert” advice feature of HSPEXP.

Model-fit statistics computed by HSPEXP are summarized in table 9. In general, the errors in the various model-fit metrics are well within the criteria for acceptable model performance (Donigian and others, 1984) and the default criteria in HSPEXP. For example, total simulated runoff volume differed from the observed by 0.7, -6.5, and -1.4 percent at QRPB, QRLY, and USQU, respectively. Only the lowest 50-percent flows at the upstream stations (QRPB) had an error (13 percent) greater than the HSPEXP default criteria. This error could be attributed to ground-water underflow (discharge from the basin that bypasses the streamflow-gaging station as ground-water flow), but could be appreciable given the aquifer properties and hydraulic gradient of the water table at this location.

Other model-fit statistics were computed from simulated and observed mean daily discharge and mean monthly runoff volume. These statistics include (1) standard error, (2) root mean square error, (3) coefficient of determination, (4) percent of time differences between simulated and observed discharges were within 10 percent, (5) percent of time these differences were within 25 percent, (6) median percent error, (7) minimum percent error, and (8) maximum percent error. These model-fit statistics are summarized in table 10. The standard error and the root-mean-square error increase as the magnitude of the flow increases downstream. At the basin outlet, the simulated daily mean discharge differed from the observed discharge by less than 10 percent about 30 percent of the time and was within 25 percent of the observed values 73 percent of the time.

**Table 9.** Model-fit statistics computed by the HSPEXP program for simulated flows by the Hydrologic Simulation Program–FORTRAN (HSPF) and observed flows at three continuous streamflow-gaging stations in the Usquepaug–Queen River Basin, Rhode Island, January 2000 through September 2001.

[Streamflow-gaging station locations shown on figure 2. %, percent]

| Model-fit statistic | Percent error between simulated and observed flows at streamflow-gaging station | | |
|---|---|---|---|
| | Queen River at Exeter (QRPB) | Queen River at Liberty (QRLY) | Usquepaug River near Usquepaug (USQU) |
| Total volume | 0.7 | -6.5 | -1.4 |
| Base-flow recession | -.01 | 0 | -.01 |
| Total of lowest 50% flows | 13 | -5.2 | -4.1 |
| Total of highest 10% flows | -5.6 | -6.7 | .7 |
| Storm volume | 9.5 | 7.2 | 7.7 |
| Seasonal volume | 8.2 | 4.1 | .5 |
| Summer storm volume | .4 | 5.2 | .6 |

Statistical measures do not adequately describe all aspects of a model fit; visual inspection of the hydrographs, flow-duration curves, and scatter plots of simulated and observed discharges provide additional information to assess model performance. Hydrographs of simulated and observed hourly discharges indicated that the model performed well seasonally over a range of discharges that spanned about two log cycles at each of the three calibration sites (fig. 11). In general, it was found that any improvement in the model error for one period or one location, or both, resulted in a deterioration of the model fit at another location or another period. For example, further adjustments to the ground-water-recession variables (AGWRC and KVARY) and evapotranspiration losses from active ground water (AGWETP) improved the model fit during the lowest flow period in September 2001. Adjustments that improved model fit in September 2000 increased the model error in other recession periods, in particular, the April and May 2001 recession, which was the longest continuous period of no precipitation during the calibration period. In some instances, further adjustments to the model were not made because of uncertainty in the observed data. For example, discharges at USQU were undersimulated in October 2000, but this discrepancy could be a result of a variable shift applied to the stage-discharge relation during this time because of an obstruction on the control. Thus, the model fit was given less emphasis for this specific time because the magnitude of the shift could be affected by streamflow-measurement error and uncertainty in the period over which the shift was applied.

**Table 10.** Summary of daily and monthly model-fit statistics for flows simulated by the Hydrologic Simulation Program–FORTRAN (HSPF) and observed flows at three continuous streamflow-gaging stations in the Usquepaug–Queen River Basin, Rhode Island, January 2000 through September 2001.

[Streamflow-gaging station locations shown on figure 2. $ft^3/s$, cubic feet per second; %, percent]

| Model-fit statistic | Streamflow-gaging station: Queen River at Exeter (QRPB) | | Queen River at Liberty (QRLY) | | Usquepaug River near Usquepaug (USQU) | |
|---|---|---|---|---|---|---|
| | Daily mean discharge | Monthly mean volume | Daily mean discharge | Monthly mean volume | Daily mean discharge | Monthly mean volume |
| Number of series terms | 639 | 21 | 639 | 21 | 639 | 21 |
| Standard error ($ft^3/s$) | 3.5 | 1.6 | 17 | 7.7 | 31 | 9.4 |
| Root-mean-square error ($ft^3/s$) | 3.3 | 1.7 | 19 | 8.6 | 29 | 10 |
| Coefficient of determination ($r^2$) | .93 | .97 | .91 | .96 | .91 | .98 |
| Percent time model error within 10% | 36 | 38 | 33 | 33 | 30 | 48 |
| Percent time model error within 25% | 65 | 86 | 69 | 81 | 73 | 90 |
| Median percent error | 4.6 | 1.5 | -5.0 | -9.3 | -7.0 | -5.4 |
| Minimum percent error | -64 | -21 | -54 | -26 | -47 | -23 |
| Maximum percent error | 279 | 107 | 260 | 63 | 212 | 61 |

Scatter plots of simulated and observed daily mean and monthly mean discharges generally clustered around the line of unity over the range of values (fig. 12). Correlation coefficients indicate that at a minimum, the model-simulated discharges explained 91 percent of the daily mean discharge and 96 percent of the monthly mean discharge at each site. Deviations from the line of unity are apparent in the extreme daily mean low flows that reflect the model error during the September 2001 period.

Flow-duration curves show the percentage of time a specified discharge is equaled or exceeded and represent the combined effects of climate, topography, and hydrogeologic conditions on the distribution of flow magnitude through time (Searcy, 1959). The flow-duration curve of simulated daily mean discharge generally closely matches the observed at QRPB, QRLY, and USQU (fig. 13). At extreme low flows (discharge that is exceeded more than 98 percent of the time), the duration curve for simulated discharges deviates from the observed discharges; this deviation reflects the oversimulation of discharge during the lowest flow period in September 2001. At the 99.9-percent flow duration, daily mean discharge was oversimulated by about 33, 50, and 44 percent at QRPB, QRLY, and USQU, respectively. Simulated discharges generally closely match the observed discharges for durations less than 98 percent.

## Tributary Streams

The six partial-record stations with estimated daily mean streamflows were also used to evaluate the model performance. The model fit at these stations often indicated that the initial estimates of channel storage were low and increases were justified to account for storage in riparian wetlands and small ponds. Increases in the FTABLE storage for these stations were made; however, no further adjustments were made to the PERLND variables on the basis of the model fit at these stations.

The upper Queens Fort Brook subbasin has a complex subsurface drainage pattern that differs from its surface drainage pattern and likely changes seasonally as the water table responds to recharge. Initial calibration results indicated that routing only surface runoff (SURO and SURI) into RCHRES 7 undersimulated discharge during wet periods and routing all flow components into RCHRES 7 (SURI, SURO, IFWO, AGWO) oversimulated discharge at the Queens Fort Brook partial record-station (QFBK; fig. 2). These results indicate that during wet periods (particularly February through April, when evapotranspiration is low), the water table is above the streambed elevation and at least a portion of the subsurface flow discharges to Queens Fort Brook. During most periods in this study and in a study previously reported by Kliever (1995), the upper Queens Fort Brook (RCHRES 7) rarely flowed. Thus, the water table is likely below the streambed most of the time and ground water likely discharges to the HAP Basin (fig. 2), or flows sublaterally down into the Queens Fort Brook Valley, or both. Similarly, ground water in the upper RCHRES 8 subbasin may discharge to the Chipuxet River Basin (fig. 2), to Queens Fort Brook, or both if the water-table configuration varies with recharge.

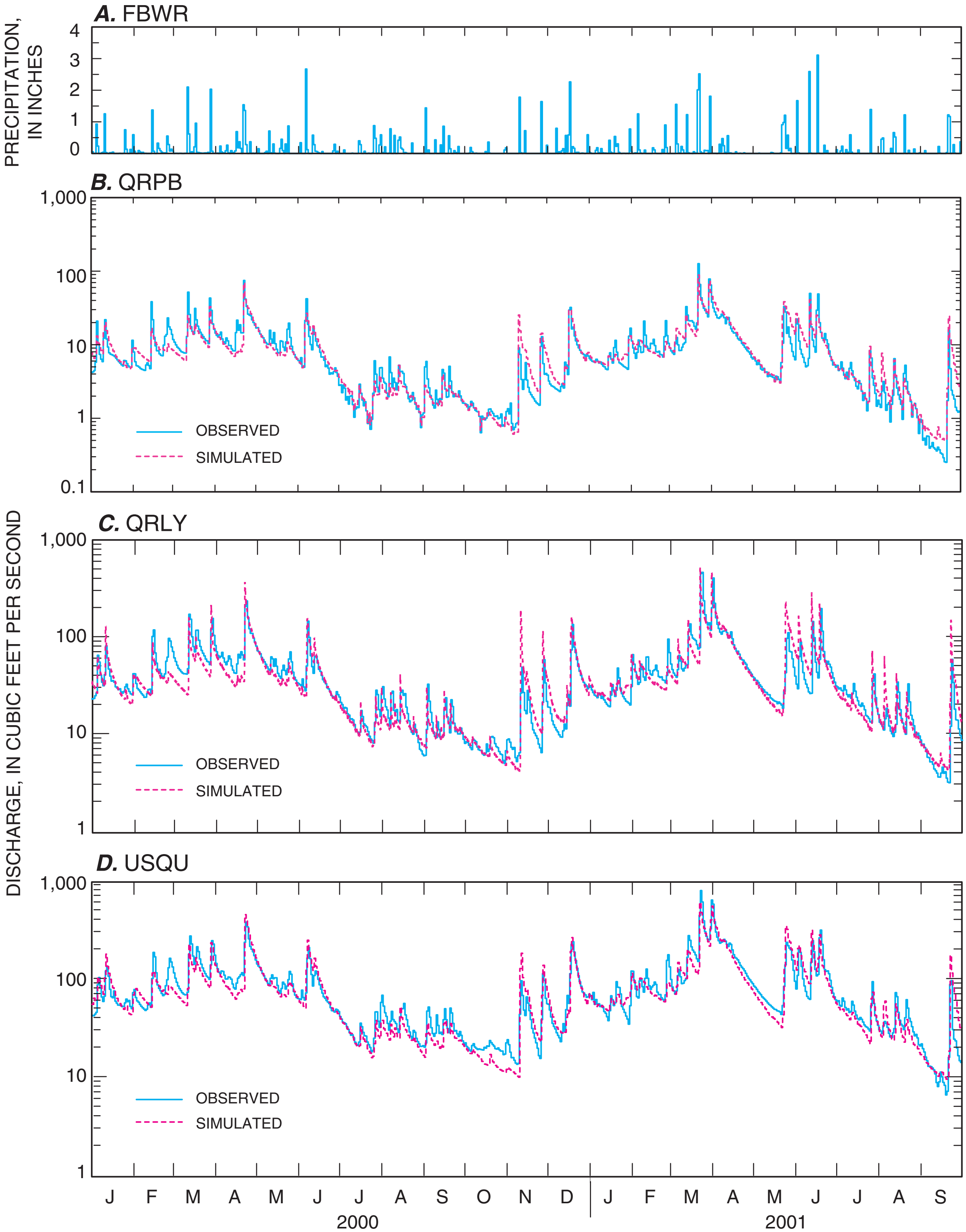



**Figure 11.** Precipitation at *A*, FBWR, and daily mean discharge simulated by the Hydrologic Simulation Program–FORTRAN (HSPF) and observed discharge at streamflow-gaging stations; *B*, Queen River at Exeter (QRPB); *C*, Queen River at Liberty (QRLY); and *D*, Usquepaug River near Usquepaug (USQU) in the Usquepaug–Queen River Basin, Rhode Island, January 2000 through September 2001 (locations of streamflow-gaging stations shown on fig. 2).

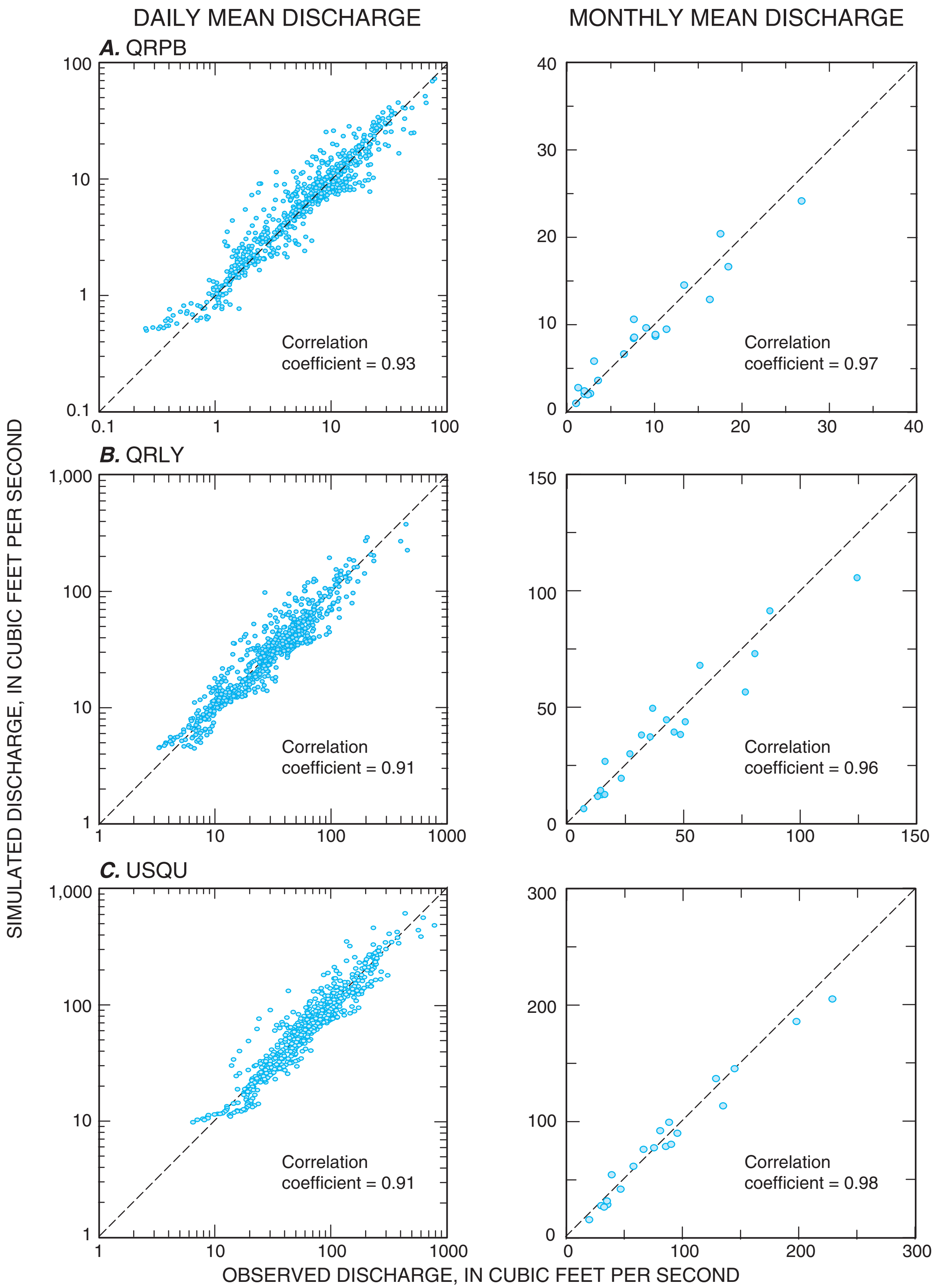



**Figure 12.** Relation of Hydrologic Simulation Program–FORTRAN (HSPF) simulated discharge to observed discharge at streamflow-gaging stations *A*, Queen River at Exeter (QRPB); *B*, Queen River at Liberty (QRLY); and *C*, Usquepaug River near Usquepaug (USQU), Usquepaug–Queen River Basin, Rhode Island, January 2000 through September 2001 (locations of streamflow-gaging stations shown on fig. 2).

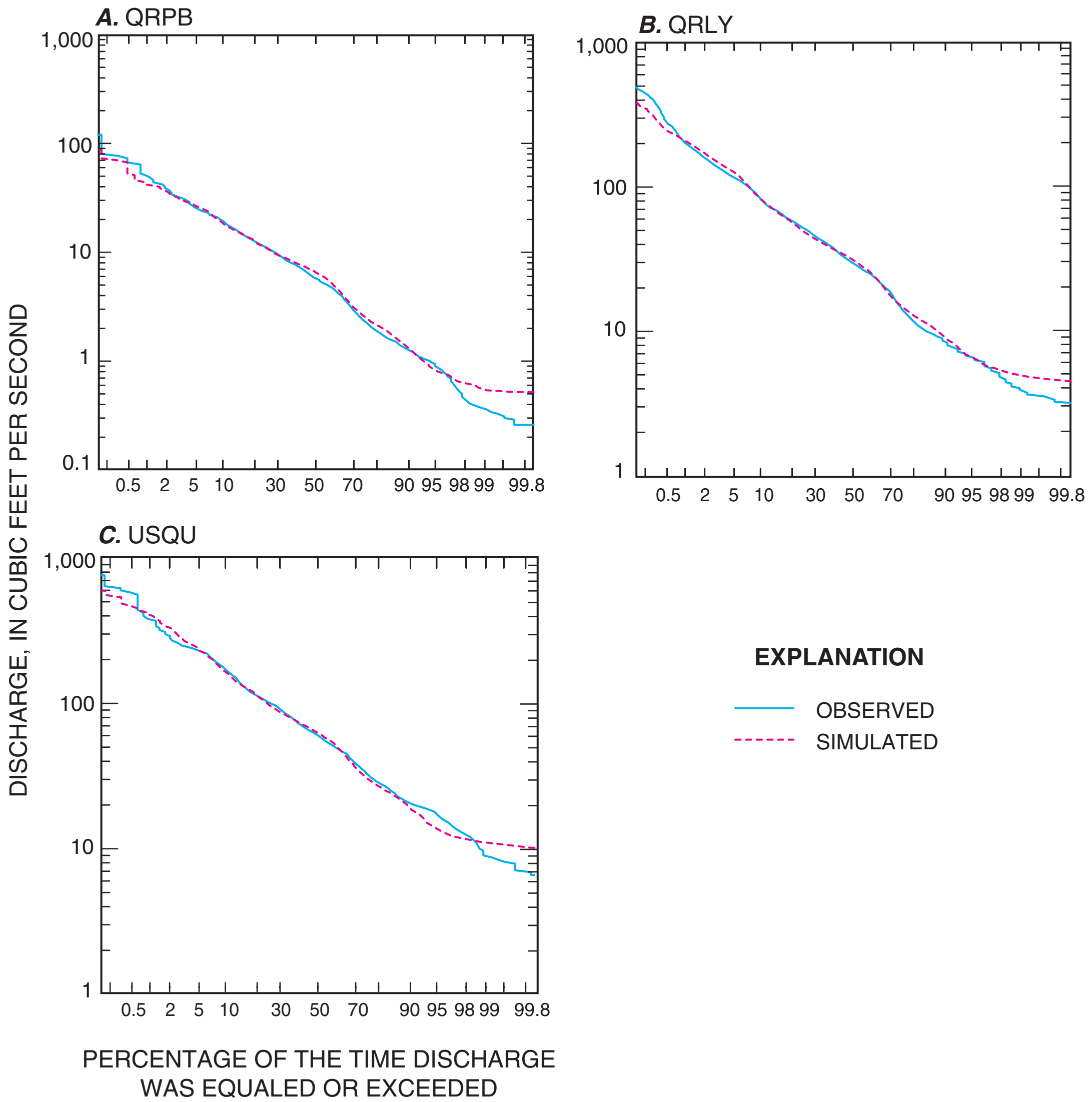



**Figure 13.** Flow-duration curves of daily mean discharges simulated by the Hydrologic Simulation Program–FORTRAN (HSPF) and observed discharges at streamflow-gaging stations *A*, Queen River at Exeter (QRPB); *B*, Queen River at Liberty (QRLY); and *C*, Usquepaug River near Usquepaug (USQU), Usquepaug–Queen River Basin, Rhode Island, January 2000 through September 2001 (locations of streamflow-gaging stations shown on fig. 2).

The subsurface discharge to Queens Fort Brook was estimated by empirically decreasing AGWO and IFWO components routed into RCHRESs 7 and 8 through the *MASSLINK* Block of the *uci* file until the difference in simulated and estimated runoff at QFBK was minimized. IFWO was decreased by 80 percent in RCHRES 7 and by 30 percent in RCHRES 8. AGWO was not routed into RCHRES 7 and varied seasonally through a special-actions assignment of the variable DEEPFR (fractional loss of active ground water from the basin) value in RCHRES 8. Special actions extend the flexibility of the HSPF model by allowing fixed model-variable values to change during the simulation according to user-defined limits. Special actions required assigning unique PERLNDs to this reach so that adjustments to DEEPFR would affect only this reach. These PERLNDs are identified in the model by adding 700 to the identification number for similar PERLND types and were assigned the same variable values, except for the value of DEEPFR. DEEPFR was assigned a value of 0.4 from January through May, 0.99 from June through October, and 0.70 in November. DEEPFR values were assigned to the first day of the month; the special actions changed values linearly between assigned values.

Although the loss to DEEPFR described above for RCHRES 8 minimized the differences between simulated and estimated flow at QFBK (fig. 14), DEEPFR was not assigned in the final model because it was assumed that ground-water underflow at the QFBK could be a large cause of model error. Thus, the added complexity of seasonally varied subsurface losses from the basin was not justified in the final model calibration. The difference between the ground-water and surface-water divides in this reach is believed to be small relative to the amount of water that can bypass the streamflow-gaging stations as underflow. In HSPF, the flow components from PERLNDs are typically assigned to the upstream end of a RCHRES associated with that PERLND; therefore, AGWO that bypasses a streamflow station as underflow results in an oversimulation of streamflow at that station. Although the model structure could have been modified to direct AGWO further downstream, this was not done because further geohydrologic information is needed to determine the extent and variation in the ground-water and surface-water divides and the magnitude of underflow at QFBK.

## Ground-Water Underflow

The HSPF model structure of the Usquepaug–Queen Basin, with the exception of upper Queens Fort Brook as previously described, is based on the assumption that precipitation that enters active ground water eventually discharges to the stream within its subbasin. Thus, if ground-water underflow bypasses a streamflow station, the simulated flow at that station, particularly low flows, would be oversimulated. Ground-water underflow that bypasses a streamflow station typically discharges to the stream further downgradient, and the perceived model error can be attributed to uncertainty in the location where ground water discharges to the stream. This possibility could be a factor at streamflow-gaging stations located in areas underlain with permeable valley-fill deposits and should be considered in the evaluation of the model performance.

The ground-water-flow model developed for the Usquepaug–Queen Basin (Dickerman and others, 1997) simulates the aquifer as a closed basin with a no-flow boundary at the outlet. This boundary was likely chosen because the water-table configuration mapped by Allen and others (1966) indicated that ground-water flow is perpendicular to the river near the outlet. Ground-water-flow lines in a stream-valley aquifer are typically toward the stream and downgradient in the valley. Contouring of the water-table surface in the valley near the basin outlet is complicated by terrain with low relief and extensive wetlands.

A small amount of ground-water underflow is reported for adjacent or nearby basins with similar characteristics (Barlow and Dickerman, 2001; Granato and others, 2003). Ground-water underflow at the Concumcussoc Brook Basin (northeast of the Usquepaug–Queen Basin) outlet is estimated at 0.28 $ft^3/s$ (P.M. Barlow, USGS, oral commun., 2003), but the valley of the Annaquatucket River Basin (northeast of the Usquepaug–Queen Basin; fig. 2), which has a width of about 0.5 mi at its outlet, has an estimated underflow of 1.0 $ft^3/s$ (Barlow and Dickerman, 2001). Underflow in the Mishnock River Valley (northwest of the Usquepaug–Queen Basin), with a nearly flat gradient, is about 0.1 $ft^3/s$ (Granato and others, 2003).

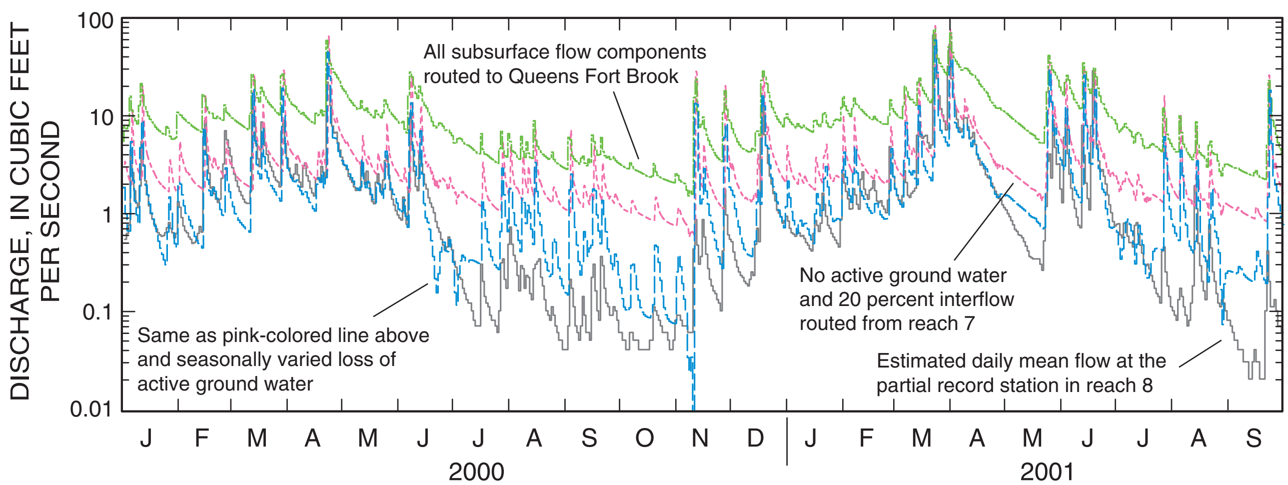



**Figure 14.** Simulated and estimated daily mean discharge at Queens Fort Brook (model reach 8), Usquepaug–Queen Basin, Rhode Island, January 2000 through September 2001 [location of reach 8 shown on fig. 10].

At least a small amount of ground-water underflow is likely at the Usquepaug–Queen Basin outlet given the extensive coarse-grained valley-fill deposits in this area. The aquifer geometry shown on plate 1 by Dickerman and others (1997) indicates that the valley near the outlet is about 1.3 mi wide with about 50 ft of saturated coarse-grained material. Given this geometry and a horizontal conductivity of 100 ft/d for coarse-grained material (Dickerman and others, 1997), a water-table gradient of about 0.0076 is needed to account for the 3 $ft^3/s$ that is oversimulated during the lowest flow period (fig. 13*C*) at the basin outlet.

The model error at QRPB is about 0.2 $ft^3/s$ during the lowest flows (fig. 13*A*). This amount of flow could easily be accounted for as ground-water underflow given the water-table gradient and aquifer characteristics reported by Dickerman and others (1997) near this station. Ground-water underflow could also account for some of the error at the QRLY. Underflow at this streamflow-gaging station is believed to be small, however, because Dickerman and others (1997) show that bedrock rises and nearly contacts the fine-grained deposits about 0.3 mi upstream of this station. Oversimulation of low flows at QRLY is more likely related to uncertainty in the seasonally varied ground-water discharge in the Queens Fort Brook subbasin, which enters the Queen River about 1.1 mi above the QRLY, than to underflow at the station.

## Simulated Hydrologic Budgets and Flow Components

Model variable values assigned to HRUs largely control the flow paths and rate of water movement to streams and the loss of water to evapotranspiration. Hydrologic budgets computed for various flow components by the model illustrate the hydrologic-response characteristics of different HRUs and the influence of various HRUs in the Usquepaug–Queen Basin model. Hydrologic budgets were examined for the 21-month calibration period (January 1, 2000, through September 30, 2001), a wet month (March 2001), and a dry month (October 2000).

Hydrologic budgets are similar for HRUs with similar surficial materials, but are distinctly different for sand and gravel, till, and wetlands (fig. 15*A*). Discharge per unit area by component to streams from PERLNDs overlying sand and gravel averaged about 96 percent from active ground-water flow (AGWO), about 4 percent from interflow (IFWO), and a negligible amount from surface runoff (SURO). Discharge to streams from PERLNDs overlying till averaged about 55 percent from active ground-water flow (about half that from PERLNDs overlying sand and gravel), about 38 percent from interflow, and about 7 percent from surface runoff. Discharge components to streams from wetland PERLNDs were about equally distributed between active ground-water flow and interflow (37 and 39 percent, respectively) with slightly less contributed from surface runoff (24 percent). All discharge to streams from IMPLNDs is from surface runoff.

The simulated discharge to streams over the 21-month period was 59.9 in., of which 70 percent was from forested areas and most came from active ground water (fig. 15*B*). Discharge to streams from forested areas came predominantly from areas overlying till (26.2 in.) and about equal amounts from forested areas overlying sand and gravel and forested wetlands (about 8.0 in. each). Forested areas accounted for about 84 percent (35.4 in.) of the total evapotranspiration losses from the basin (42.2 in. for the 21-month period).

Discharge to streams per unit area during a wet month (March 2001; fig. 16*A*) was generally similar with respect to the proportions of flow components during the calibration period (fig. 15*A*). Discharge to streams from PERLNDs overlying sand and gravel averaged about 86 percent from active ground-water flow, 14 percent from interflow, and a negligible amount from surface runoff. Discharge to streams from PERLNDs overlying till averaged 35 percent from active ground-water flow, 48 percent from interflow, and 17 percent from surface runoff. Discharge to streams from wetland PERLNDs was about evenly distributed between active ground-water flow, interflow, and surface runoff (24, 34, and 42 percent, respectively). All discharge to streams from IMPLNDs is from surface runoff.

During March 2001, the water supply (13.8 in.), mostly from precipitation, was mainly divided between discharge to streams (7.5 in.) and inflow to storage (about 5.7 in.), most of which was into active ground-water storage, and a small amount (about 0.6 in.) was lost to evapotranspiration. About half the water discharged to streams during March 2001 came from forest PERLNDs overlying till (fig. 16*B*); this PERLND contributed about an equal amount of discharge from active ground water and interflow. The PERLND representing forest overlying sand and gravel did not contribute appreciably to streamflow because much of the available moisture went into active ground-water storage during this month.

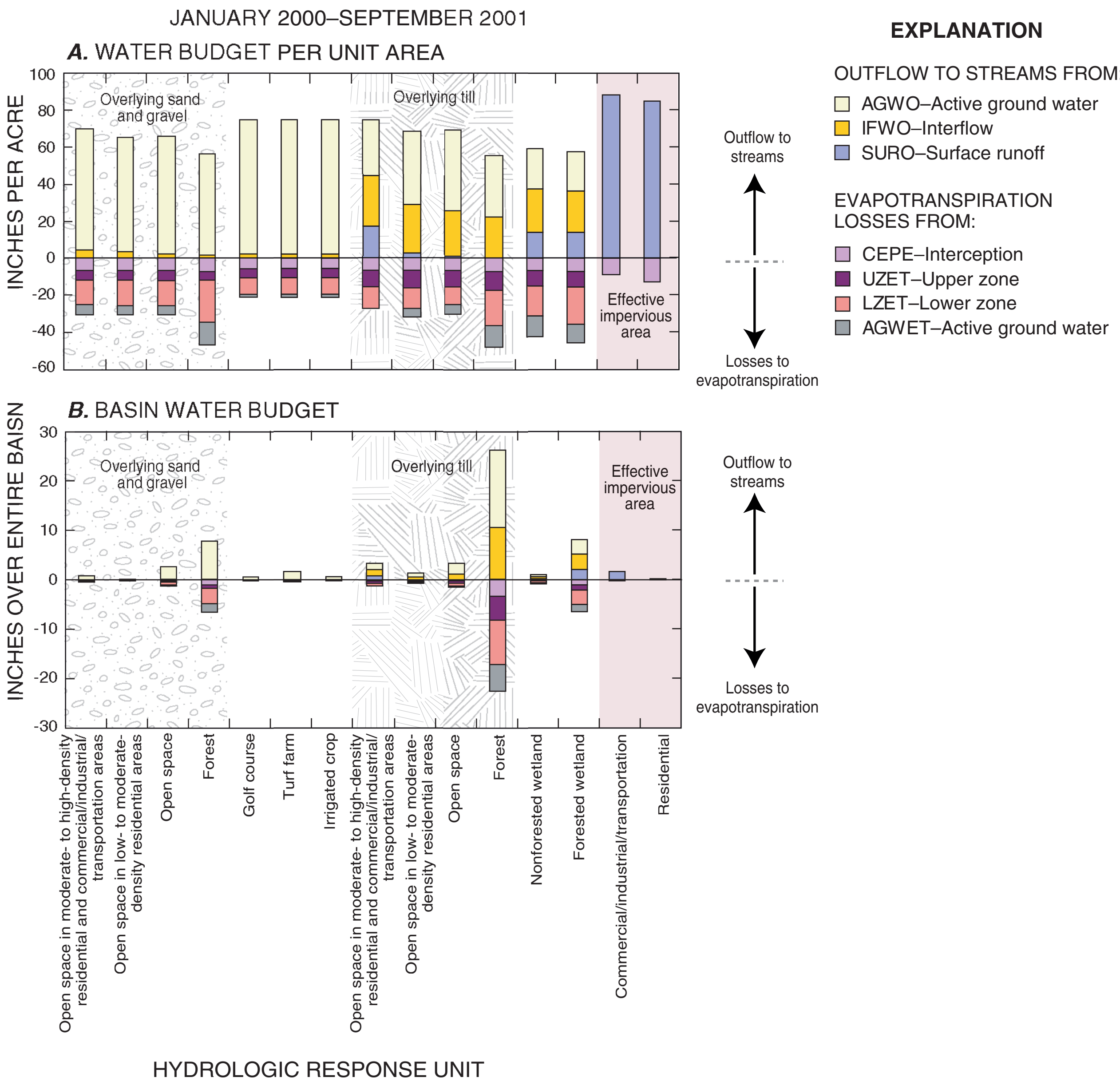



**Figure 15.** Calibration-period water budget by component from each hydrologic response unit simulated by the Hydrologic Simulation Program–FORTRAN (HSPF) model of the Usquepaug–Queen River Basin, Rhode Island, in inches *A*, per acre; and *B*, over the entire basin, January 2000 through September 2001.

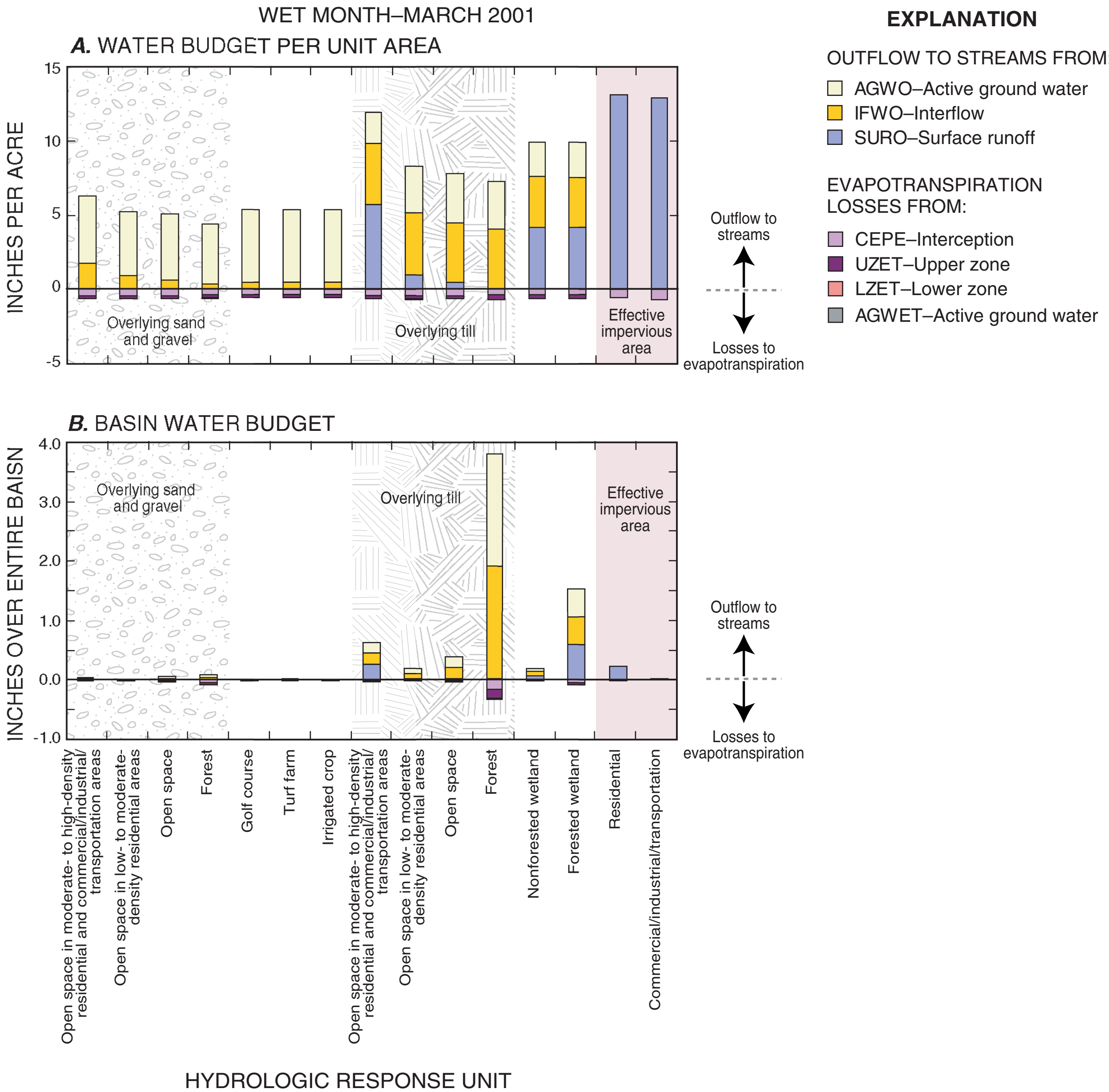



**Figure 16.** Wet-month water budget by component from each hydrologic response unit simulated by the Hydrologic Simulation Program–FORTRAN (HSPF) model of the Usquepaug–Queen River Basin, Rhode Island, in inches *A*, per acre; and *B*, over the entire basin, March 2001.

Discharge to streams per unit area during a dry month (October 2000; fig. 17*A*) was markedly different from the calibration-period (fig. 15*A*) and wet-month (fig.16*A*) water budgets. Nearly all the discharge to streams was from active ground water from storage during this month. Evapotranspiration losses greatly exceed discharge to streams in forested areas overlying till and wetlands and slightly exceed discharge to streams from forested areas overlying sand and gravel. Forested PERLNDs have greater losses to evapotranspiration per unit area relative to other PERLNDs because these PERLNDs are simulated as having larger losses from lower zone storage (LZET) and active ground water (AGWET). Simulated losses to evapotranspiration from forested PERLNDs are the dominant part of the basin water budget during this dry month (fig.17*B*).

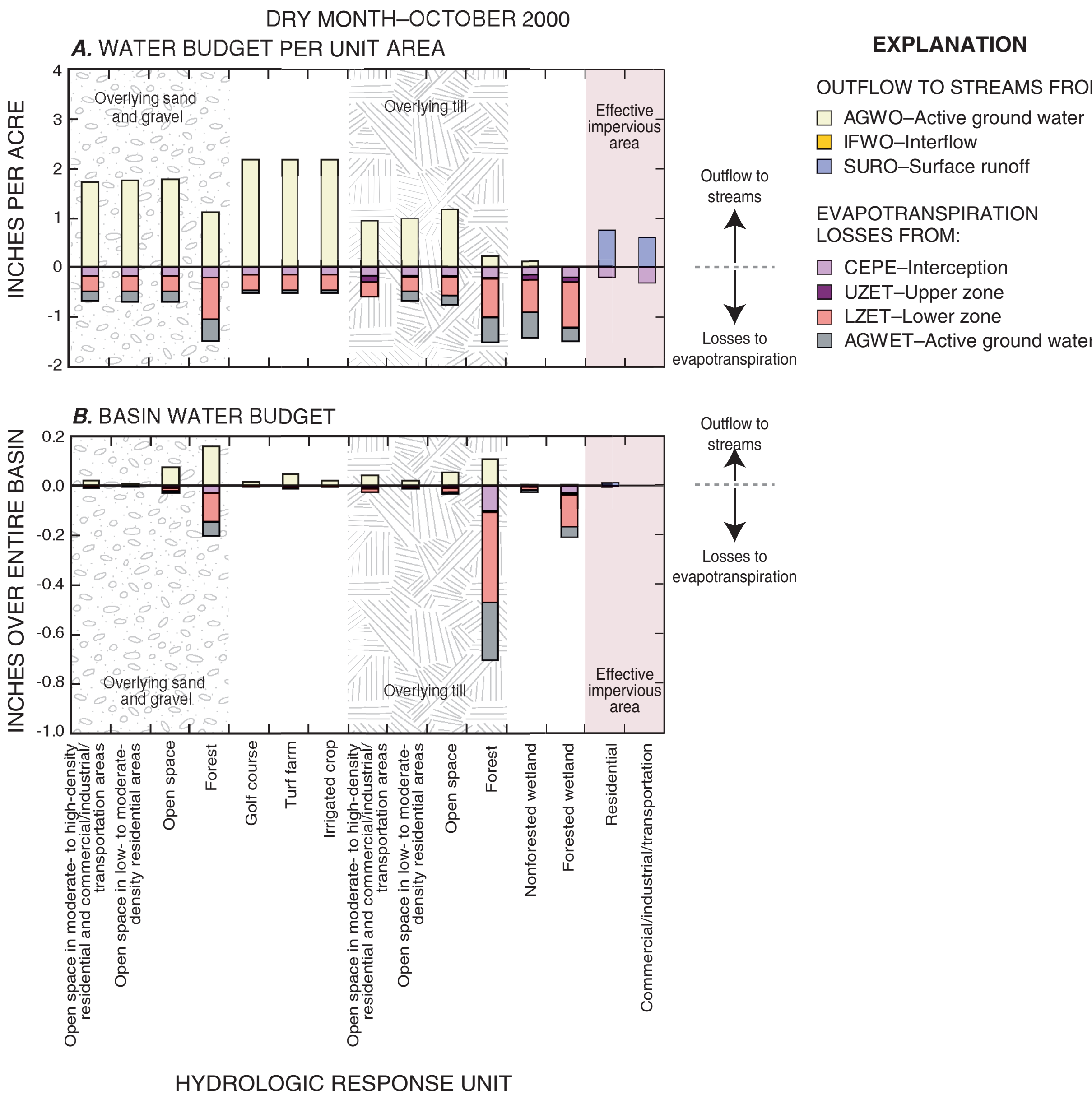



**Figure 17.** Dry-month water budget by component from each hydrologic response unit simulated by the Hydrologic Simulation Program–FORTRAN (HSPF) model of the Usquepaug–Queen River Basin, Rhode Island, in inches *A*, per acre; and *B*, over the entire basin, October 2000.

Contrasts in the distribution and magnitude of the simulated outflow components to streams and losses to evapotranspiration for the 21-month calibration period, a wet month, and a dry month are apparent when summarized for the entire basin (fig. 18). For the calibration period, about 61 percent (59.9 in.) of the moisture supply (mostly precipitation) to the basin (about 98.6 in.) was discharged to streams and about 42 percent (42.2 in.) was lost to evapotranspiration (fig. 18*A*). Note, during this period, there was a net loss of about 3.5 in. from storage; hence, the discharge to streams and evapotranspiration is slightly greater than the moisture supply to the basin.

Discharge to streams during the 21-month calibration period was composed of about 8.5 percent (5.1 in.) surface runoff and about 91.5 percent (54.8 in.) subsurface discharge (17.6 in. of interflow and 37.2 in. of active ground water). During March 2001, the moisture supply that did not go into storage was mostly discharged to streams and a small amount was lost to evapotranspiration (fig. 18*B*). Discharge to streams during this period was composed of about 17 percent (1.3 in.) surface runoff, 40 percent (3.0 in.) interflow, and 43 percent (3.2 in.) active ground water. During October 2000, water loss to evapotranspiration was about twice the discharge to streams (fig. 18*C*) and exceeded the moisture supply to the basin by about 30 percent. Nearly all the discharge to streams during this period was from active ground-water storage.

## Sensitivity Analysis

Sensitivity analysis measures the response of the model-simulated discharge to changes in variable values representing the basin. Thus, for the model structure under consideration, the most influential variables are revealed and the range of feasible values is indicated by perturbing model variables. The simplest sensitivity analysis is typically an iterative process whereby the value of a given variable is perturbed while all other variable values are held constant and the response in the model performance is measured. This type of analysis provides information about variable values as independent quantities, but the approach is not sufficient to distinguish variable values that interact with each other (Wagener and others, 2003). For example, the sensitivity of the active ground-water-recession variable (AGWRC) is highly dependent on the soil-infiltration rate (INFILT), but covariance between variables was not considered in this analysis.

The sensitivity of 10 selected PERLND variables to 4 indices of model fit were evaluated. The PERLND variables soil-infiltration rate (INFILT), nominal lower-zone storage (LZSN), decay coefficient that makes active ground-water recession nonlinear (KVARY), active ground-water recession rate (AGWRC), active ground-water evapotranspiration rate

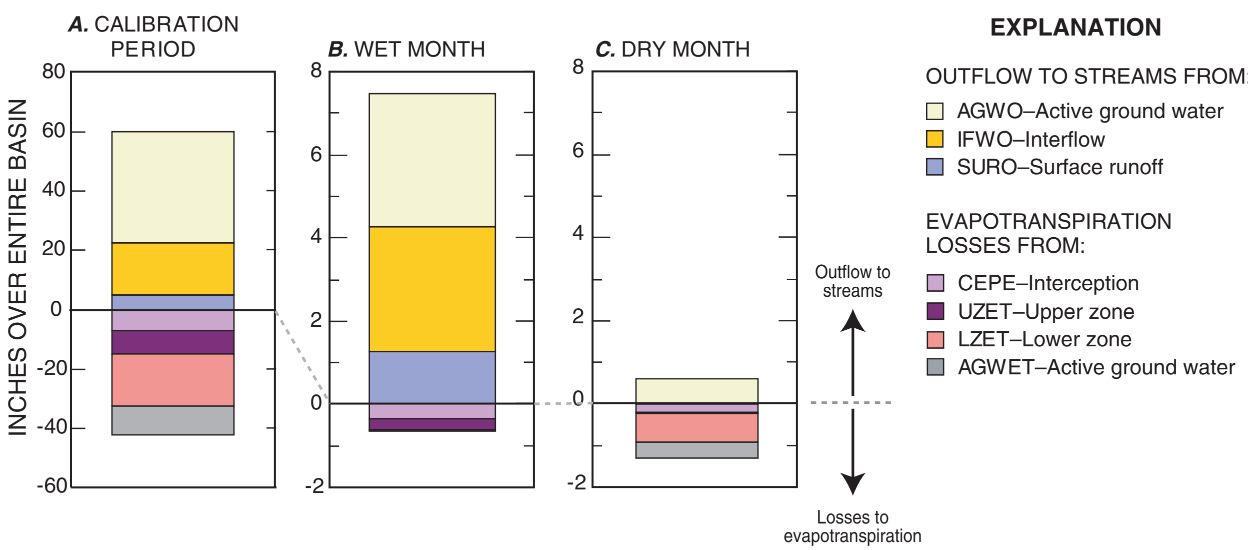



**Figure 18.** Summary of water budgets by component averaged over all hydrologic response units simulated by the Hydrologic Simulation Program–FORTRAN (HSPF) model of the Usquepaug–Queen River Basin, Rhode Island, for *A*, the calibration period—January 1, 2000, through September 30, 2001; *B*, wet month—March 2001; and *C*, dry month—October 2000.

(AGWETP), monthly interception storage (MON-INTERCEP), monthly nominal upper-zone storage (MON-UZSN), monthly interflow (MON-INTERFLW), monthly interflow-recession rate (MON-IRC) and monthly lower-zone evapotranspiration rate (MON-LZETP) were evaluated. Other PERLND variables were not evaluated because they were not used in the Usquepaug–Queen model or because they were found to have little effect during the model calibration. Changes in these variables values were measured against changes in the model fit as measured by the relative bias, the relative standard error, the Nash-Suttcliffe coefficient, and the index of agreement. These measures provide a range of performance criteria, but do not reflect all the criteria used in the selection of calibrated values, which also include visual evaluation of model results and other statistical measures of model performance. The calibrated values were the initial values used in the sensitivity analysis.

Small changes in the ground-water and interflow-recession rates (AGWRC and MON-IRC, respectively) generally resulted in the largest changes in all measures of model fit (figs. 19*A* and 19*B*). The responses of these variables to changes indicate that they have a narrow feasible parameter space, particularly AGWRC. Decreases in the soil-infiltration rate (INFILT) and the interflow variable (MON-INTERFLW) also resulted in large changes in the relative standard error and index of agreement for hourly discharge values. Increases in INFILT and MON-INTERFLW indicated a slightly better model fit for hourly discharge, but also resulted in a slight decrease in the model fit for total monthly runoff. Changes in lower zone storage (LZSN) and evaporation from lower zone storage (MON-LZETP) resulted in large changes in the model bias relative to most other variables tested, but did not result in corresponding changes in the other fit statistics tested relative to other variables. Other variables tested are relatively insensitive to changes in their calibrated (base) value.

## Model Uncertainty and Limitations

Numerical simulation models are, at best, approximations of hydrologic systems because of the necessity to simplify the complex processes and physical characteristics of a basin. Despite these limitations, models can be useful tools to evaluate the hydrologic responses of a basin, provided that the model structure and variable values adequately reflect the hydrologic responses of the system to the stresses being evaluated. The uncertainty associated with data and the possibility of alternative model structures and variable values that can produce equally acceptable results is an important research issue still in its infancy. The adequacy of the available data to distinguish between alternative models (model structures and variable values), and the realization that alternative structures and variable values can only be rejected as acceptable models is a condition that has been described as equifinality (Beven, 1993; Beven and Binley, 1992). The calibrated Usquepaug–Queen HSPF model and its use as a predictive tool should be viewed with an understanding of this inherent uncertainty.

The uncertainty associated with the data used to calibrate the model is compounded by the short period (21 months) used for model calibration, which was constrained by the availability of water-use information. Donigian and others (1984) suggest 3 to 5 years as an optimal period for calibration to evaluate variables under a variety of climatic conditions. Gupta and Sorooshian (1985) conclude that the optimal calibration period is as little as 3 years, but Yapo and others (1996) conclude that 8 years of data are needed to minimize the sensitivity of the calibration period for identification of the best variable values. A consequence of the short calibration period is that the testing and identification of the variable values is limited to a narrow range of climatic conditions, albeit comparable to average long-term conditions.

Extrapolation of a point measurement to define spatially varied precipitation and potential evapotranspiration over the basin adds uncertainty to the identification of the best-fit variable values. For example, the lowest flows during the calibration period were in early September 2001. Precipitation between August 26 and September 26 totaled 0.48 in. at the FBWR station (data used for model calibration), but precipitation was only about half this amount at the NEWPORT and PROVID (0.24 and 0.20 in., respectively) stations. Therefore, the errors associated with low flows during this period could be related to the spatial variability of precipitation. A longer calibration period would help minimize this type of uncertainty because a longer period could include additional extreme events that might constrain the best-fit variable values.

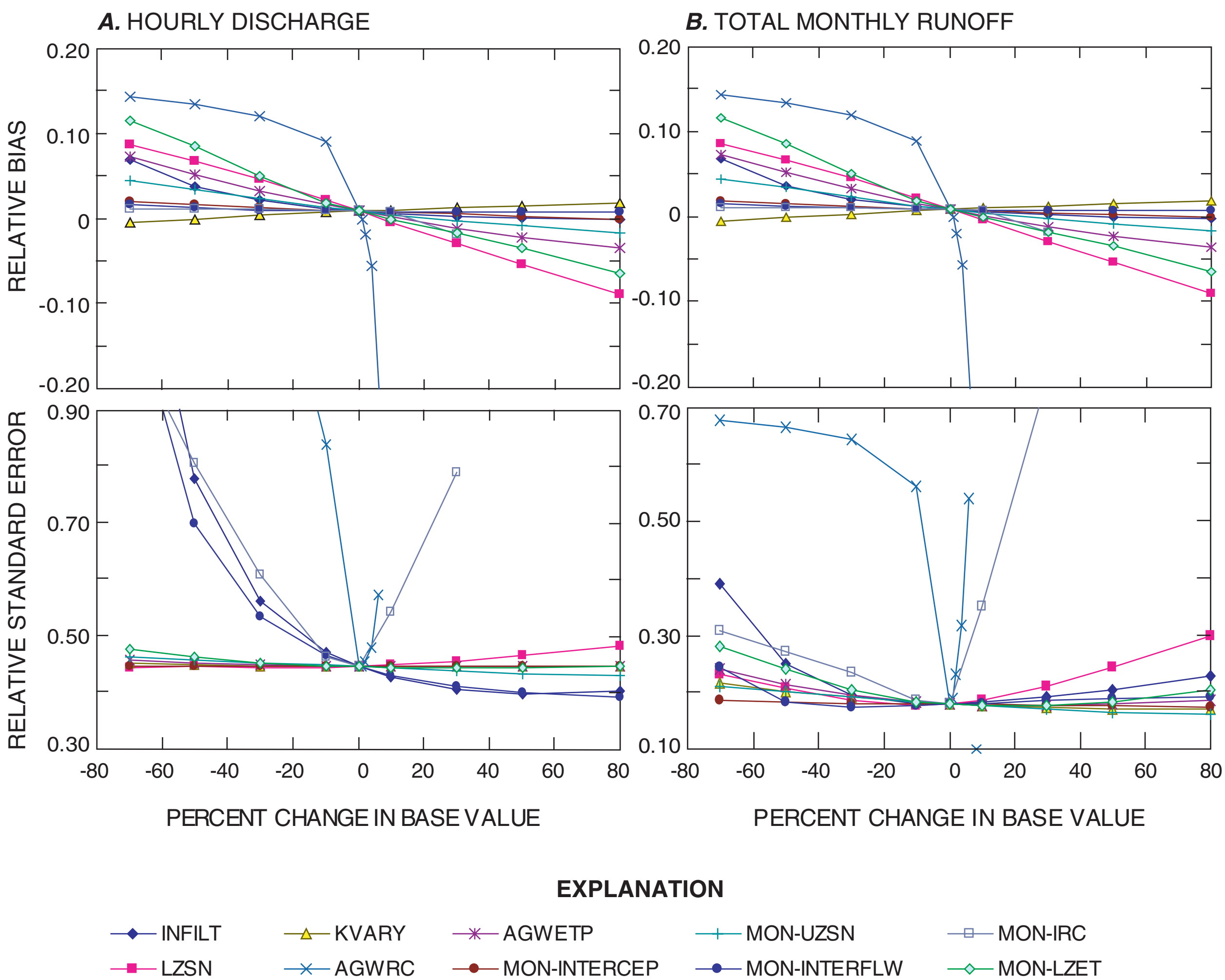



**Figure 19.** Sensitivity of selected Hydrologic Simulation Program–FORTRAN (HSPF) pervious area (PERLNDs) hydrologic variables to four indices of model fit for *A*, hourly discharge; and *B*, total monthly runoff, Usquepaug–Queen River Basin, Rhode Island (fit statistics calculated for the basin outlet—USQU, fig. 2).

Another example of the uncertainty in the extrapolation of a point measurement is the use of climatic data from PROVID, about 15 mi northeast of the basin (fig. 1), for long-term simulations. During December 1, 1999, through September 30, 2001, total precipitation was 11 percent less and total potential evapotranspiration was 14 percent more at the PROVID than at the FBWR stations. About one-third of the time, however, total monthly precipitation was less and total monthly potential evapotranspiration was greater at the FBWR than at PROVID stations. Although the differences in total monthly precipitation and evaporation varied between these two stations, the differences were more consistent during the winter months than at other times of year. These differences illustrate the problems of applying a point measurement to represent spatially varied data, regional differences in climate, systematic measurement bias, or a combination of these factors. Although measures were taken to adjust the PROVID data (the data used to simulate the response of the basin to long-term climatic conditions typical of the region) to match the FBWR data better, the climatic differences between these two stations underscore that simulations made with the PROVID data may not reproduce the observed day-to-day streamflow in the basin. Nevertheless, long-term simulations of water-management alternatives are assumed to reflect response of the basin to regional climatic conditions.

Water-use information is another area of data uncertainty. Known water withdrawals are subtracted directly from simulated streamflow. Once withdrawals are accounted for, the model variable values are adjusted to calibrate the basin's response to precipitation and evapotranspiration. Thus, variable values can be skewed during the calibration process to compensate for inaccuracies or unknown water withdrawals. Withdrawals for irrigation can vary widely because they depend on climate, plant type and root depth, soil characteristics, and

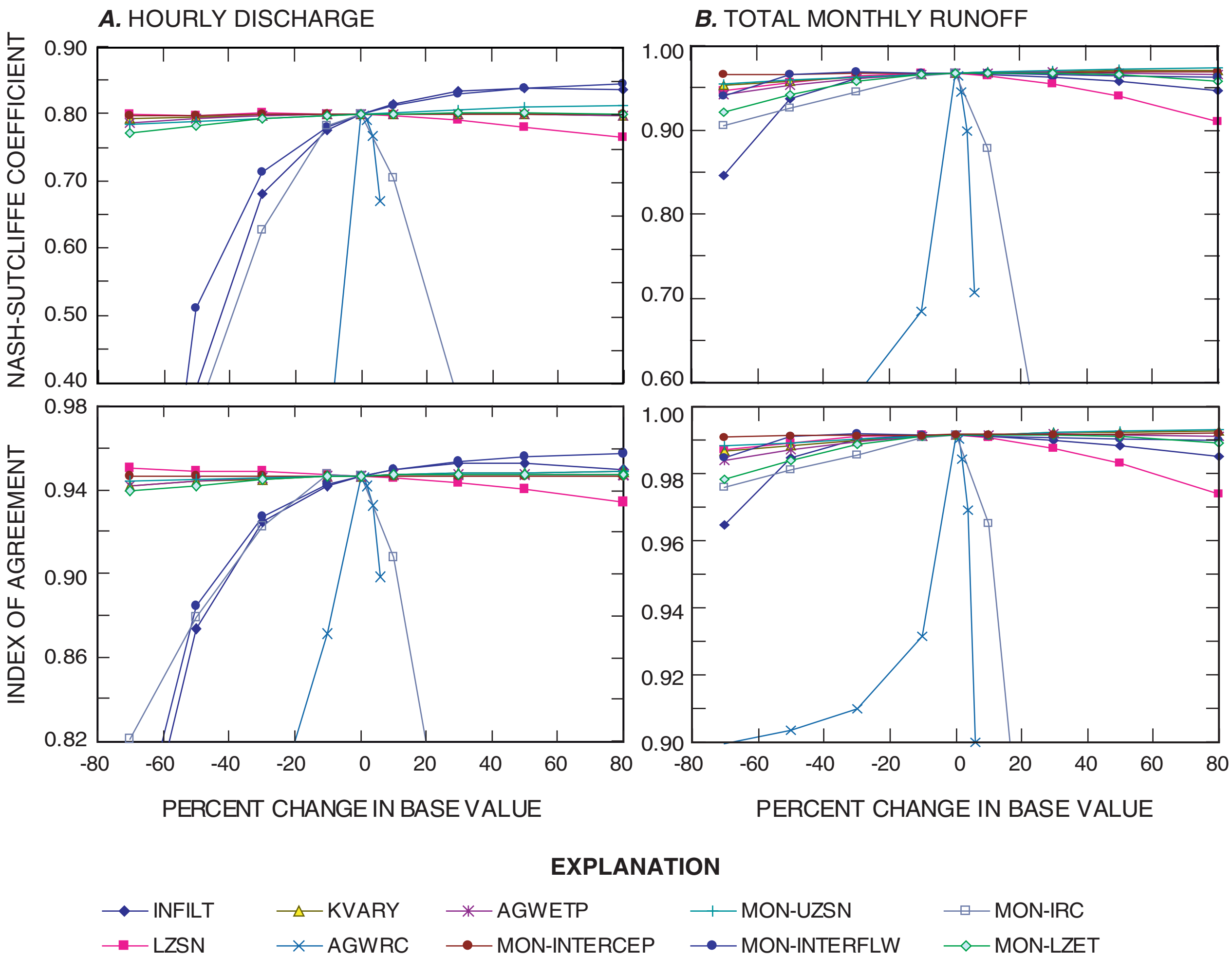



**Figure 19—Continued.** Sensitivity of selected Hydrologic Simulation Program–FORTRAN (HSPF) pervious area (PERLNDs) hydrologic variables to four indices of model fit for *A*, hourly discharge; and *B*, total monthly runoff, Usquepaug–Queen River Basin, Rhode Island (fit statistics calculated for the basin outlet—USQU, fig. 2).

management practices. While irrigation was measured to the extent allowed, withdrawals for several known irrigation uses could only be estimated. In addition, long-term irrigation is estimated from a logistic-regression equation developed from irrigation patterns observed during 2000–01. The irrigation patterns and rates observed during this short time may not be representative of past or future irrigation withdrawals, however.

The model calibration reflects the combined effects of various HRUs (PERLNDs and IMPLNDs) and reaches. Hydrologic judgment was used to represent the responses of different PERLNDs and IMPLNDs. Although a good fit was obtained between simulated and observed flows over a wide range of conditions, information was not available to calibrate individual HRUs explicitly. Thus, simulation results from ungaged areas or results that change one type of HRU to another (such as buildout simulations) have a high degree of uncertainty, and, therefore, 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 river reach, could not be measured. The stage, storage, and, discharge characteristics of a reach affect the flow and the stream stage.

The Usquepaug–Queen Basin HSPF model was conceptualized and calibrated to evaluate the effects of withdrawals on streamflow. Many water-resource-management questions can be addressed by model simulations, but the model may not be appropriate to for some analyses. Thus, care should be taken to consider the model uncertainties and limitations to ensure that the simulation results do not lead to inaccurate conclusions.

# Hydrologic Effects of Water Withdrawals and Land-Use Change

The Usquepaug–Queen Basin HSPF model was developed as a tool to evaluate the effects of various withdrawal practices and land-use change on streamflow. Results are intended to provide government officials and citizen-interest groups information for making current and future water-resources-management decisions. The Pawcatuck Watershed Partnership Water-Use Stakeholders Group (WUSG) in December 2002, in conjunction with the USGS, agreed that the following simulations would be conducted to evaluate the effects on streamflow:

1. No-withdrawals and current withdrawal practices—to provide baseline information on the differences in long-term streamflow (1960–2001) under these contrasting conditions;
2. Conversion from direct stream withdrawals to ground-water withdrawals—to provide information on the effects of streamflow depletion by ground-water withdrawals relative to the effects of direct stream withdrawals;
3. Ladd School withdrawals—to provide information on the effects of past and potential withdrawals at the former Ladd School water-supply wells;
4. Land-use change—to provide information on the effects of potential build-out conditions in the basin.

Each of these simulations required new model-run (*uci*) files that altered input data or model structure, or both, and are uniquely identified by the prefix of the *uci* file name and the IDSCEN attribute in the WDM file. Output generated by each simulation was assigned to a unique data set in the WDM file to enable comparisons among the scenarios.

Long-term simulations (1960–2001) were made by using the PROVID stations' climatic data adjusted to match the concurrent data (2000–2001) at the FBWR station. The PROVID data was adjusted by use of the MFACT variable in the *EXTERNAL SOURCE* block by a factor of 1.14 for precipitation and by 0.94 for PET as previously discussed.

## Current Withdrawals and No Withdrawals

Streamflow under current withdrawals and no withdrawals over long-term climatic conditions (1960–2001) was evaluated as a baseline condition for other simulations. Because of uncertainty in irrigation withdrawals, climatic data, and model performance at extreme low flows, simulations were made by three alterative models. Alternative model structures provided information on the extent to which these uncertainties affect baseline simulation results. Alternative models included a model recalibrated to (1) extreme low flows, (2) modified irrigation withdrawals, and (3) unadjusted long-term climatic data. Model-run file names and target data-set numbers for the output results associated with these run files are summarized in table 11.

Simulated and observed flow-duration curves (fig. 13) indicate that the model oversimulated the lowest flows (flows greater than the 98-percent flow duration) at the basin outlet (USQU) by about 3 $ft^3/s$. If this oversimulated flow is related to error in variable values and not other factors previously discussed (such as error in the precipitation data), then the model would oversimulate other low-flow periods, which systematically underestimates the effects of withdrawals on low flows. To evaluate the potential effect of this uncertainty,

**Table 11.** Summary of model-run files (*uci*) and target data-set numbers (DSNs) for Hydrologic Simulation Program–FORTRAN (HSPF) simulations of the Usquepaug–Queen River Basin, Rhode Island.

[IDSCEN, scenario-identification attribute in the Watershed-Data-Management (WDM) database; PROVID, National Weather Service climate station at Providence, Rhode Island; Mgal/d, millions of gallons per day]

| *uci* and IDSCEN name | Output DSN | Description |
|---|---|---|
| Baseline simulations | | |
| QUUS-NoW | 6002–6020 | Calibrated model, no withdrawals |
| QUUS-lgW | 6102– 6120 | Calibrated model, current withdrawals |
| QU-lgW2 | 6302–6320 | Calibrated model, concentrated peak withdrawals |
| QU2-NoW | 6502–6520 | Model calibrated to lowest flows, no withdrawals |
| QU2-lgW | 6402–6420 | Model calibrated to lowest flows, current withdrawals |
| QU3-NoW | 6702–6720 | Calibrated model, unadjusted PROVID data, no withdrawals |
| QU3-lgW | 6602–6120 | Calibrated model, unadjusted PROVID data, current withdrawals |
| Simulated withdrawals at former Ladd School supply wells | | |
| QUUS-P1 | 7101–7120 | 0.20 Mgal/d—historical peak withdrawal rate |
| QUUS-P2 | 7201–7220 | 0.90 Mgal/d—current operational pump capacity |
| QUUS-P3 | 7301–7320 | 1.78 Mgal/d—maximum capacity |
| Simulated buildout conditions | | |
| QUUS-B1 | 8101–8120 | Fully developed land use, current water withdrawals |
| QUUS-B2 | 8201–8220 | Fully developed land use, 20 percent of self-supply withdrawals |
| QUUS-B3 | 8301–8320 | Fully developed land use, 100 percent of self-supply withdrawals |
| QUUS-B4 | 8401–8420 | Current land use, 100 percent of self-supply withdrawals |
| QUUS-B5 | 8501–8520 | Partially developed land use, current water withdrawals |

baseline simulations also included an alternative model calibrated to the August-September 2001 low flows by increasing the RCHRES surface area (FTABLES) to increase evapotranspiration. It was assumed that riparian wetlands in the basin could lose more water through evapotranspiration (ET) than the calibrated model structure allows because the available moisture supply for ET in these wetlands was limited to direct precipitation. Upgradient land segments, and streamflow itself, likely contribute to the moisture supply in low-lying riparian wetlands, and thus, the total evapotranspiration loss in riparian wetlands is not restricted to the moisture supply from direct precipitation. Increasing the surface area of reaches is a proxy for simulating evapotranspiration loss through riparian wetlands. A similar approach was used in a HSPF model to simulate wetland evapotranspiration loss to achieve a low-flow calibration in the Ipswich River Basin in northeastern Massachusetts to (Zarriello and Ries, 2000). This alteration resulted in faster hydrograph recessions than previously simulated. The simulated flows during September 2001 closely matched the observed flows (fig. 20*A*) and the lowest flows (those greater than the 98-percent flow duration) are nearly identical to the observed flows at the basin outlet (fig. 20*B*). The model fit during other periods was not as good as previously simulated, as indicated by the deviation in flows between the 60- and 98-percent flow durations (fig. 20*B*). Alternative model simulations made with changes to the RCHRES area are identified as QU2-lgW and QU2-NoW (current withdrawals and no withdrawals, respectively).

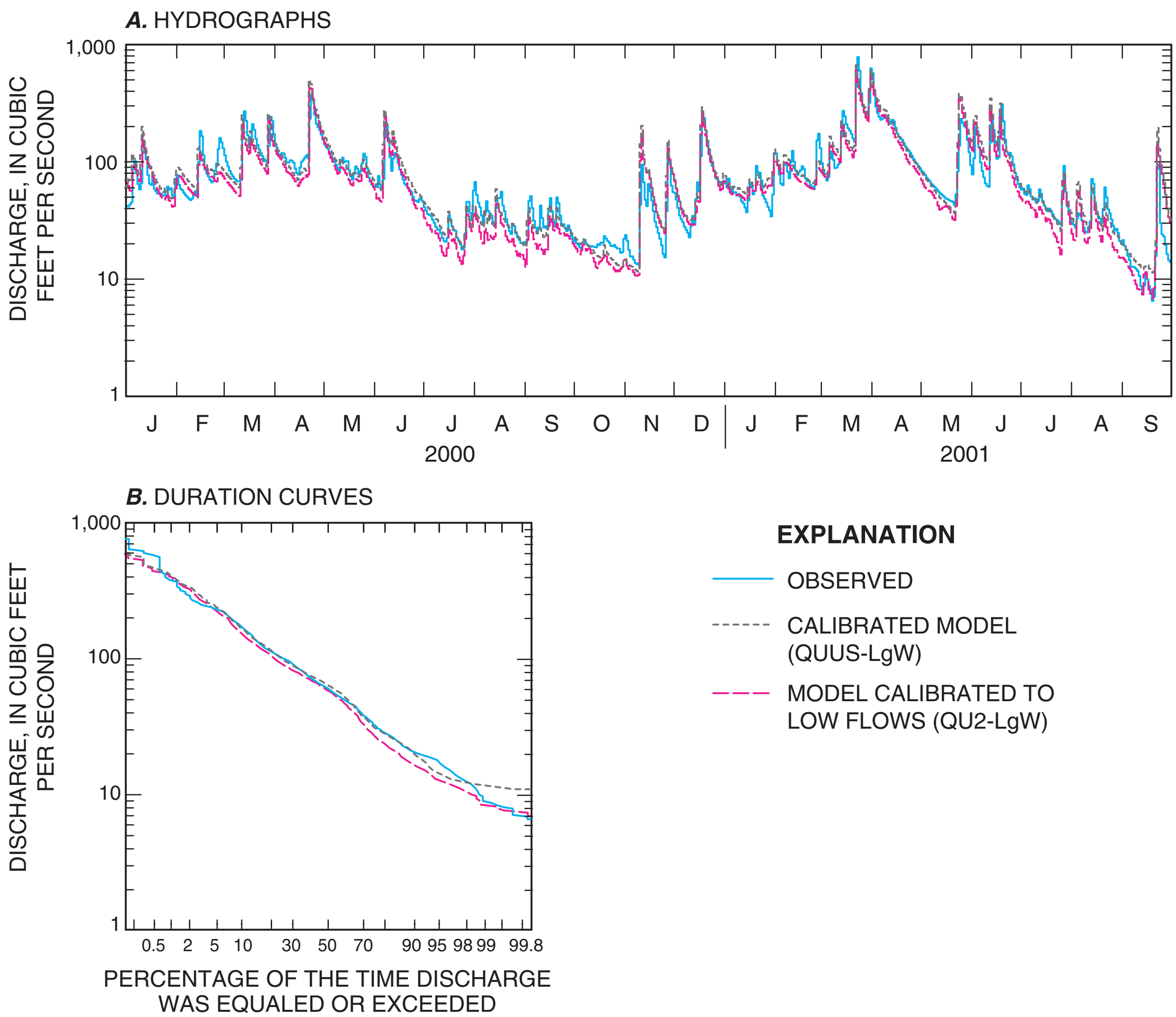



**Figure 20.** Daily mean discharge *A*, hydrographs; and *B*, flow-duration curves at the outlet (USQU) of the Usquepaug–Queen River Basin, Rhode Island, for observed flows and flows simulated with the calibrated Hydrologic Simulation Program–FORTRAN and an alternative HSPF model calibrated to low flows, January 2000 through September 2001 (location of USQU shown on fig. 2).

Irrigation on golf courses is typically limited during daylight hours, but no such constraints exist for turf-farm or other irrigation uses. If all irrigation withdrawals coincide, the peak hourly withdrawal can be higher than that simulated by the average distribution pattern. During June and July 2000, observed hourly withdrawals in RCHRES 20 ranged between about 0.5 and 3.0 $ft^3/s$, but the simulated average withdrawal peaked at about 1.0 $ft^3/s$ (fig. 21*A*). Therefore, the effects of irrigation withdrawals on hourly streamflow could be at least three times greater than initially simulated. To evaluate the effects of concentrated peak withdrawals, the peak turf-farm withdrawal (1:00 p.m., fig. 7*B*) was simulated to coincide with the peak golf-course withdrawal (at about 5:00 a.m., fig. 7*B*). This simulation resulted in a cumulative peak withdrawal of about 2.5 $ft^3/s$ and better reflects (compared to the average irrigation withdrawal distribution) some periods of peak withdrawals observed in RCHRES 20 during June and July 2000 (fig. 21*A*) and during periods in the 2001 irrigation season (fig. 21*B*). Larger peak withdrawals are possible, which would affect short-term streamflows more than the concentrated irrigation pattern. The simulation made with the alternative irrigation pattern is identified as QU-lgW2 (table 11).

Adjustments to the long-term climatic data were made on the basis of concurrent records at FBWR and the PROVID over a 21-month period as previously described. Differences between total monthly precipitation and potential evapotranspiration at the two stations varied, however. This variation indicates that the differences in climatic data between these two stations are not uniform; thus, globally increasing the PROVID data (by the multiplier 1.14) may oversimulate some low-flow periods. To evaluate the effect of this uncertainty, simulations were made with unadjusted PROVID data in the calibrated model. These simulations are identified as QU3-lgW and QU2-NoW (current withdrawals and no withdrawals, respectively; table 11).

The results of simulations with the calibrated model (QUUS-lgW and QUUS-NoW) for the 1960–2001 period indicate that current withdrawals decrease the lowest mean daily streamflows at the basin outlet by about 20 percent relative to no withdrawals. Flow-duration curves of simulated daily mean discharge developed from the calibrated model results indicate that the flows greater than the 99.8-percent flow duration (lowest flows) are about 5 $ft^3/s$ under no withdrawals and about 4 $ft^3/s$ under current withdrawals (fig. 22). Streamflows less than the 90-percent flow duration are minimally affected by current withdrawals.

The alternative models tested indicate a similar percentage of decrease in flows at the 99.8-percent flow duration (fig. 22), although the magnitude of the decrease varied. The absolute discharges simulated by the alternative models are an indication of the range of model uncertainty; thus, differences between simulated flows under current withdrawals and no withdrawals are best viewed as relative changes. Simulations made with the models calibrated to the lowest flows (QU2-lgW and QU2-NoW) indicate that flows greater than the 99.8-percent flow duration are slightly less 4 $ft^3/s$ under no withdrawals and about 3 $ft^3/s$ under current withdrawals (fig. 22). Simulations made with the unadjusted climatic data models (QU3-lgW and QU3-NoW) indicate that flows greater than the 99.8-percent flow duration are about 3 $ft^3/s$ under no withdrawals and about 2.2 $ft^3/s$ under current withdrawals (fig. 22). Simulations with and without withdrawals indicate little difference in discharge for flow less than the 90-percent flow duration for similar model structures.

Simulations with concentrated peak withdrawals (QU-lgW2) affect hourly flows, which affect the minimum daily flows, but concentrated peak withdrawals have no effect on the daily mean flow because of averaging. The effect of the concentrated withdrawals on minimum daily flow was less than expected, however. Concentrated peak withdrawals in RCHRES 20 (fig. 21*A*) indicate that the hourly peak withdrawals (2.5 $ft^3/s$) were about 1.5 times greater than the peak withdrawals obtained from the average of the observed data (1.0 $ft^3/s$). The minimum daily streamflow was expected to decrease proportionally by about 1.5 $ft^3/s$, but decreased by about half this amount.

The effects of daily withdrawal patterns are exemplified by one of the lowest recorded flows at USQU (basin outlet) in late August and early September of 1995. The observed fluctuations in hourly flow over that period were generally about 4 to 5 $ft^3/s$, but occasionally fluctuated by as much as 10 $ft^3/s$ (fig. 23*A*). Hourly flows for this period fluctuated during the day by about 1 $ft^3/s$ for simulations made with average daily distribution withdrawals (QUUS-lgW), but by only about 1.7 $ft^3/s$ for simulations made with concentrated peak withdrawals (QU-lgW2). The less-than-expected changes in minimum streamflow simulated by concentrated peak withdrawals is attributed to the fact that the average daily withdrawals peaked during the period of peak evapotranspiration, whereas the concentrated withdrawals peaked earlier in the day, and offset some of the difference between the average and concentrated peak withdrawals. Diurnal fluctuations in evapotranspiration ranged by about 0.5 $ft^3/s$. Neither the simulations of averaged nor concentrated peak withdrawals were able to match the observed minimum flows during this period, however.

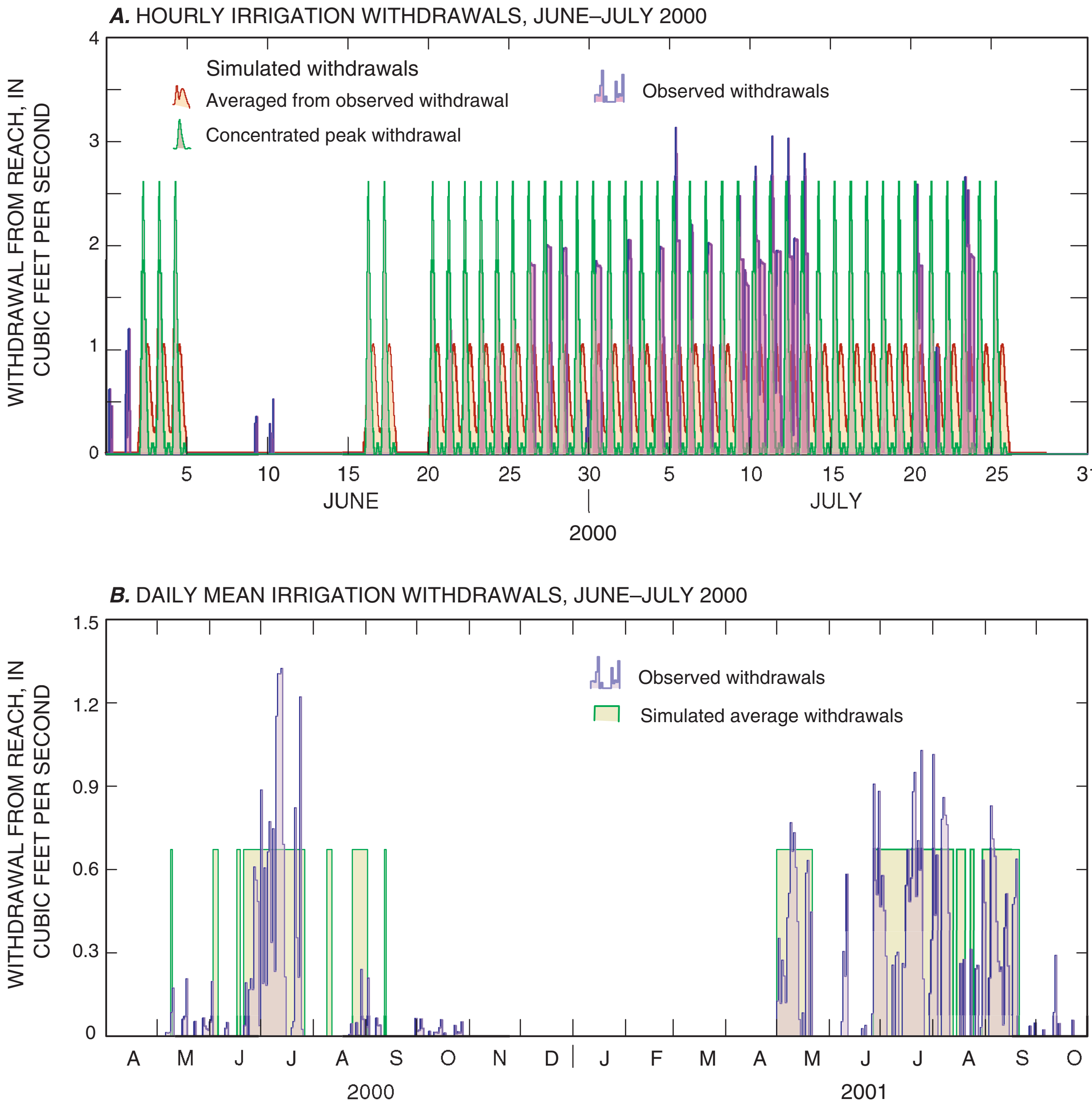



**Figure 21.** Irrigation withdrawals measured and simulated by the logistic-regression equation and the mean daily distribution pattern for *A*, June and July 2000; and *B*, 2000–01 irrigation season, reach 20, Usquepaug–Queen River Basin, Rhode Island (location of reach 20 shown on fig. 10).

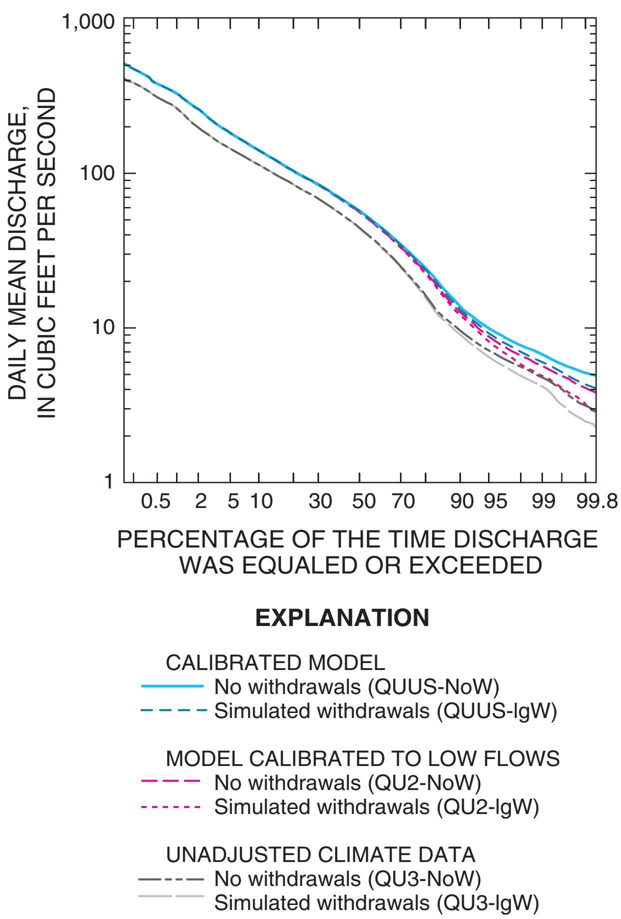



**Figure 22.** Flow-duration curves of daily mean discharge at the outlet (USQU) of the Usquepaug–Queen River Basin, Rhode Island, with withdrawals and without withdrawals simulated by the calibrated Hydrologic Simulation Program–FORTRAN (HSPF) and alternative models, 1960–2001 (location of USQU shown on fig. 2).

Results from the calibrated and alternative models were compared to the observed hydrograph at USQU for the period August–September 1995. Simulations made with the calibrated model and no withdrawals (QUUS-NoW), average daily withdrawal distribution (QUUS-lgW), and concentrated withdrawal distribution (QU-lgw2) generally compare well to the observed hydrograph (fig. 23*A*). The simulated discharge with no withdrawals (QUUS-NoW) generally follows the observed maximum daily discharge, and simulations with withdrawals (QUUS-lgW and QU-ldW2) generally follow the observed daily minimum discharge. During periods in late August and early September, the observed discharge abruptly drops, which the simulations were unable to reproduce. Simulations made with the model calibrated to low flows (QU2-lgW) were better able to reproduce many of the minimum daily flows during late August and early September, but this model undersimulated the maximum daily flows during this period and all flows during other times (fig. 23*B*). Simulations made with the low-flow calibrated model, unadjusted climate data, and concentrated peak withdrawals (QU3-lgW2) produced the lowest flows of all the models tested (about 1 $ft^3/s$ in mid-September). This model also undersimulated the maximum flows during late August and early September and all flows during other periods. These results and observed data suggest that peak withdrawals were in excess of 5 $ft^3/s$ during this time, but the instability of the stage-discharge relation at low flows at USQU casts uncertainty on the accuracy of these extreme low-flow values.

The simulated effects of current withdrawals on long-term daily mean streamflow made with the calibrated model (QUUS-NoW and QUUS-lgW) at QRPB and QRLY are less pronounced than at USQU (fig. 24*A*), but withdrawals have a marked effect on minimum daily flows at QRPB (fig. 24*B*). The simulated minimum daily flows with the calibrated model under current withdrawals indicate that the river would stop flowing at QRPB during part of the day about 5 percent of the time, but under no withdrawals this reach would sustain a minimum flow of about 0.2 $ft^3/s$. Note that the river stops flowing only part of the day because simulated daily mean flows in this reach are about 0.3 $ft^3/s$. Simulation results indicate that flow at QRLY is not appreciably affected by withdrawals because withdrawals in the intervening area between QRPB and QRLY occur mostly in the Queens Fort Brook subbasin, and the low-flow contribution from this tributary is greatly diminished by the ground-water discharge to the HAP Basin.

The minimum flows that can be expected annually for 1-, 7-, and 30-consecutive-day periods, for recurrence intervals between 1 to 100 years, were computed by Log-Pearson type III analysis by the program SWSTAT (Lumb and others, 1994b) for simulated long-term (1960–2001) daily mean discharges. The Log-Pearson Type III analysis fits the annual n-day low-flow values to a theoretical distribution to calculate the magnitude and recurrence interval of the flow statistic. Simulated flows were made with the calibrated model with and without withdrawals. Withdrawals for irrigation were based on the average daily distribution pattern. Low-flow frequency curves developed from simulated daily mean flows indicate little difference at USQU for simulations made with and without withdrawals (fig. 25). The magnitude of flow differed, at most, by about 1 $ft^3/s$ for short duration periods and infrequent recurrence intervals. The low-flow frequency curves developed from daily mean simulated flows at QRPB and QRLY, with and without withdrawals, did not differ appreciably (not shown).

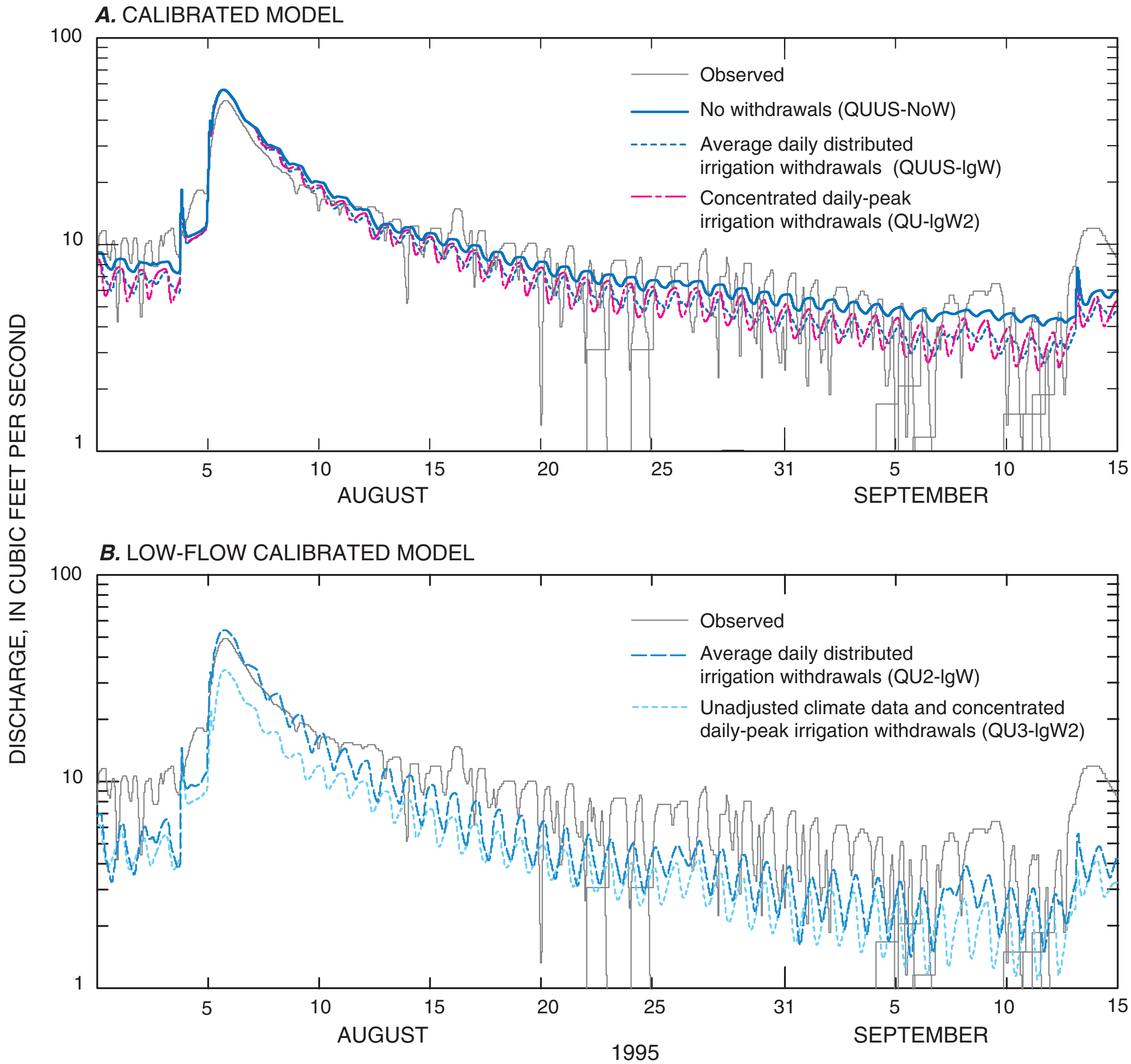



**Figure 23.** Hourly discharge at the outlet (USQU) of the Usquepaug–Queen River Basin, Rhode Island, observed and simulated by the *A*, calibrated Hydrologic Simulation Program–FORTRAN (HSPF); and *B*, an alternative HSPF model calibrated to low flow, August and September 1995 (location of USQU shown on fig. 2).

The magnitudes and frequencies of low flows computed at QRPB, QRLY, and USQU from simulated discharges without withdrawals are summarized in table 12. The 7-day low flow expected to occur once every 10 years (7Q10), normalized for drainage area, increased from 0.08, 0.11, to 0.16 $ft^3/s/mi^2$ at QRPB, QRLY and USQU, respectively. Low flows increase per unit area from upstream to downstream likely because of the increase in aquifer area, which sustains base flow. These low-flow statistics indicate that the river can sustain the default August median aquatic base flow (ABF) of 0.5 $ft^3/s/mi^2$ (U.S. Fish and Wildlife Service, 1981; Lang, 1999) nearly every year at each of these locations under no-withdrawal conditions. Simulation results also indicate that the river can sustain a 0.5 $ft^3/s/mi^2$ base flow nearly every year under current withdrawals.

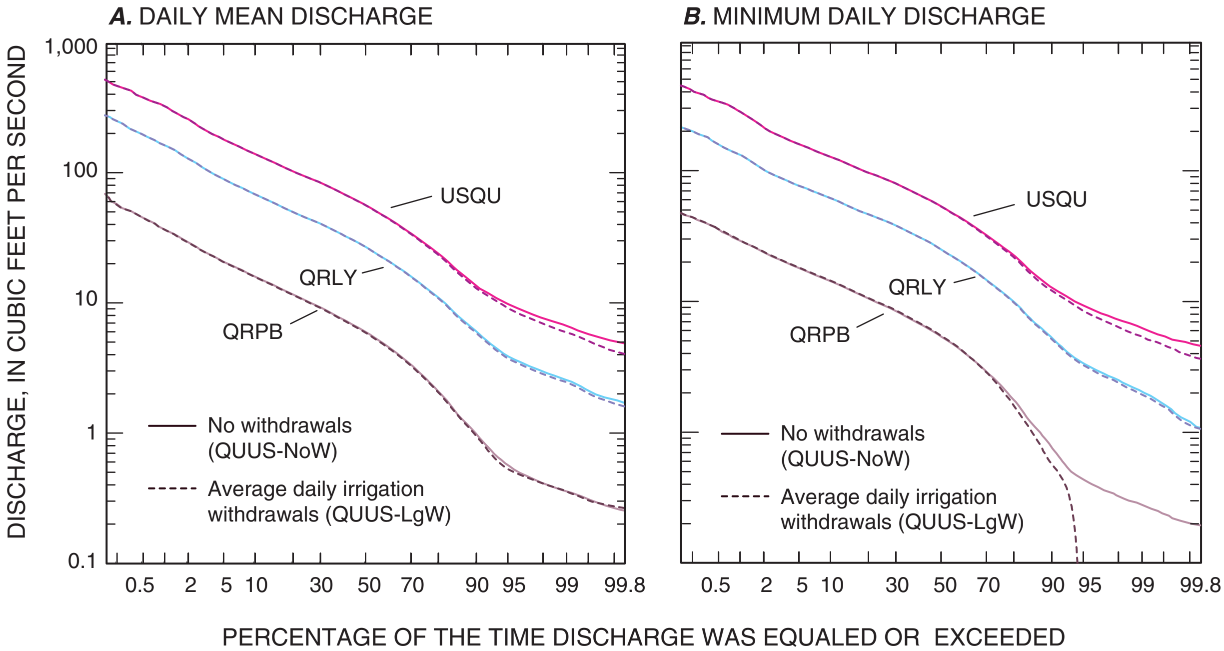



**Figure 24.** Flow-duration curves of simulated *A*, daily mean discharge; and *B*, minimum daily discharge at streamflow-gaging stations—Queen River at Exeter (QRPB), Queen River at Liberty (QRLY), and Usquepaug River near Usquepaug (USQU)—made with the Hydrologic Simulation Program–FORTRAN (HSPF) with and without withdrawals, Usquepaug–Queen River Basin, Rhode Island, 1960–2001 (station locations shown on fig. 2).

The magnitudes and frequencies of low flows computed from observed daily mean flows at USQU from 1976 to 2002 are generally similar to the magnitudes and frequencies of low flows computed from simulated discharges (fig. 25), although there are two notable exceptions. First, the magnitudes of the most extreme 1-day low flows (expected recurrence intervals of 10 years or greater) computed from the observed discharges are about 75 percent less than the flows computed from the simulated discharges. This difference underscores the various sources of uncertainty, including withdrawals that may have been more intensive than simulated, the accuracy of the observed data, and model performance as exemplified by the previously described difference between simulated and observed flow during August and September 1995. Second, the magnitudes of 30-day consecutive low flows computed from simulated discharges deviate from the observed discharges for recurrence intervals less than 1.25 years. This difference reflects the uncertainties mentioned above, but could also result from the previously described global increase in the precipitation data (14 percent) and decrease in potential evaporation data (6 percent) made to the long-term climate data (PROVID).

## Converting from Surface- to Ground-Water Withdrawals

Streamflow depletion from a pumped well with a variable rate is a function of the distance of the well from the stream and of aquifer properties (Jenkins, 1968; Barlow, 2000). Increasing the distance between a pumped well and a stream dampen changes in streamflow depletion during an initial change in withdrawal rate. Similarly, increased aquifer storativity and decreased aquifer transmissivity also dampen changes in streamflow depletion during initial changes in withdrawal rate. A well pumped at a constant rate, however, eventually depletes streamflow at the same rate as pumping because equilibrium is reached between the pumped well and intercepted ground water (water that would have discharged to the stream), or induced infiltration from the stream, or both. Because of the intermittent nature of withdrawals for irrigation and the time-delayed response of streamflow depletion, ground-water withdrawals can minimize the effects of irrigation withdrawals on streamflow. Converting from surface to ground-water sources can be especially beneficial during dry periods by minimizing the effect of peak water withdrawals during periods of naturally occurring low flows.

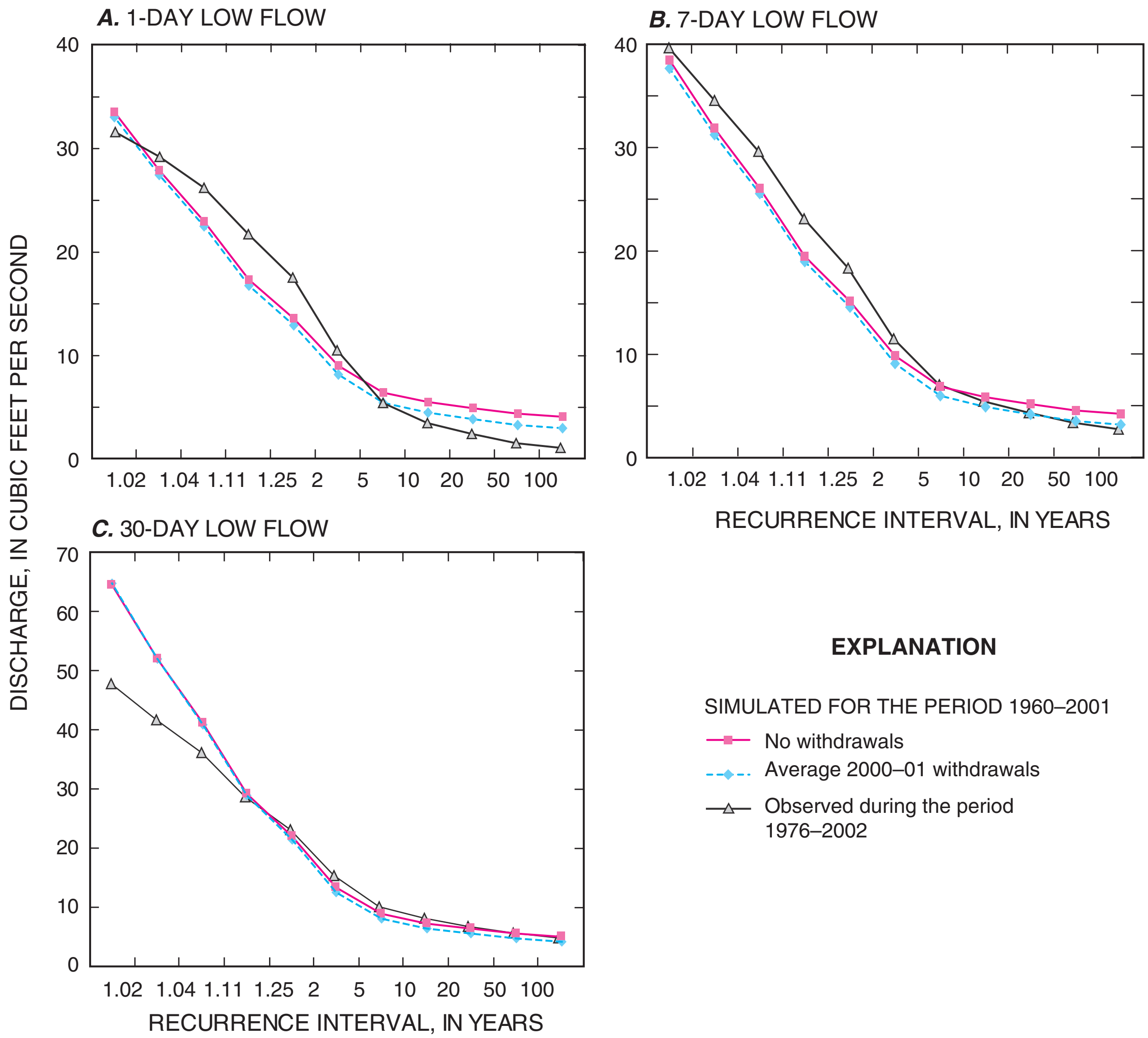



**Figure 25.** Magnitudes and recurrence intervals of *A*, 1-day; *B*, 7-day; and *C*, 30-day minimum daily mean streamflows determined by Log-Pearson Type III analysis of Hydrologic Simulation Program–FORTRAN (HSPF) simulated flows (1960–2001) and observed flows (1976–2002) at the outlet (USQU) of the Usquepaug–Queen River Basin, Rhode Island (location of USQU shown on fig. 2).

The HSPF model was not used to simulate the effect of converting from surface to ground-water sources because the baseline simulations indicated only small differences between average withdrawal and no-withdrawal conditions; therefore, streamflow simulated for withdrawals from pumped wells would differ little from streamflow simulated for the average withdrawal conditions. To illustrate the effects of converting from surface to ground water sources, an observed turf-farm withdrawal was used to compute streamflow depletion. It should be noted that this farm converted its water supply from an off-line pond to three ground-water wells in early 2000. The observed withdrawals were taken directly from the river to illustrate the effects of converting to a ground-water withdrawal from a single well. A single well was simulated because only the combined withdrawals from the three wells were available.

Streamflow depletion was computed by use of the STREAMDEPL program (Barlow, 2000) for a well 2,500 ft from the river (about the average distance of the three wells from the river) and aquifer properties reported by Dickerman and others (1997). Reported hydraulic conductivities ranged from 53 to 330 ft/d with a median of 134 ft/d; therefore, a hydraulic conductivity (K) of 150 ft/d was assumed. Dickerman and others (1997) indicate that the aquifer in the area of the wells has a saturated aquifer thickness (b) of about 50 ft, which was used to compute the aquifer transmissivity (T= Kb). A storativity (S) representative of the specific yield for an unconfined sand and gravel aquifer (0.28) was assumed and, therefore, a diffusivity (D= T/S) of 0.310 $ft^2/s$ was calculated for the aquifer in the area of the pumped well.

**Table 12.** Magnitudes and recurrence intervals of 1-day, 7-day, and 30-day minimum mean daily discharges at streamflow-gaging stations Queen River at Exeter (QRPB), Queen River at Liberty (QRLY), and Usquepaug River near Usquepaug (USQU) by Log-Pearson type III analysis of Hydrologic Simulation Program–FORTRAN (HSPF) simulated flows with no withdrawals, Usquepaug–Queen River Basin, Rhode Island, 1960–2001.

[Station location shown in figure 2]

| Station and recurrence interval (years) | Minimum mean daily discharge for the specified number of days | | | | | |
|---|---|---|---|---|---|---|
| | Cubic foot per second | | | Cubic foot per second per square mile | | |
| | 1-day | 7-day | 30-day | 1-day | 7-day | 30-day |
| Queen River at Exeter (QRPB) | | | | | | |
| 100 | 0.21 | 0.22 | 0.24 | 0.06 | 0.06 | 0.07 |
| 50 | .23 | .24 | .27 | .06 | .06 | .07 |
| 20 | .25 | .27 | .33 | .07 | .07 | .09 |
| 10 | .28 | .31 | .40 | .08 | .08 | .11 |
| 5 | .33 | .37 | .51 | .09 | .10 | .14 |
| 2 | .49 | .57 | .88 | .13 | .16 | .24 |
| 1.25 | .86 | 1.0 | 1.7 | .23 | .28 | .46 |
| 1.11 | 1.2 | 1.4 | 2.5 | .33 | .39 | .68 |
| 1.04 | 1.8 | 2.2 | 3.9 | .50 | .60 | 1.06 |
| 1.02 | 2.5 | 3.0 | 5.3 | .68 | .81 | 1.45 |
| 1.01 | 3.3 | 3.9 | 7.1 | .91 | 1.08 | 1.93 |
| Queen River at Liberty (QRLY) | | | | | | |
| 100 | 1.3 | 1.4 | 1.9 | 0.07 | 0.08 | 0.10 |
| 50 | 1.4 | 1.6 | 2.1 | .07 | .08 | .11 |
| 20 | 1.6 | 1.8 | 2.5 | .08 | .10 | .13 |
| 10 | 1.8 | 2.1 | 2.9 | .10 | .11 | .16 |
| 5 | 2.2 | 2.5 | 3.6 | .12 | .13 | .19 |
| 2 | 3.4 | 3.9 | 5.8 | .18 | .21 | .31 |
| 1.25 | 5.6 | 6.4 | 9.9 | .29 | .34 | .53 |
| 1.11 | 7.4 | 8.5 | 14 | .39 | .45 | .72 |
| 1.04 | 10 | 12 | 19 | .55 | .63 | 1.03 |
| 1.02 | 13 | 15 | 25 | .69 | .79 | 1.32 |
| 1.01 | 16 | 18 | 31 | .85 | .97 | 1.66 |
| Usquepaug River near Usquepaug (USQU) | | | | | | |
| 100 | 4.0 | 4.2 | 5.1 | 0.11 | 0.12 | 0.14 |
| 50 | 4.3 | 4.6 | 5.5 | .12 | .13 | .15 |
| 20 | 4.9 | 5.2 | 6.4 | .13 | .14 | .18 |
| 10 | 5.4 | 5.9 | 7.3 | .15 | .16 | .20 |
| 5 | 6.4 | 6.9 | 8.8 | .18 | .19 | .24 |
| 2 | 9.0 | 9.9 | 13 | .25 | .27 | .37 |
| 1.25 | 14 | 15 | 22 | .37 | .42 | .61 |
| 1.11 | 17 | 19 | 29 | .48 | .54 | .81 |
| 1.04 | 23 | 26 | 41 | .63 | .72 | 1.14 |
| 1.02 | 28 | 32 | 52 | .77 | .88 | 1.44 |
| 1.01 | 33 | 38 | 65 | .93 | 1.07 | 1.79 |

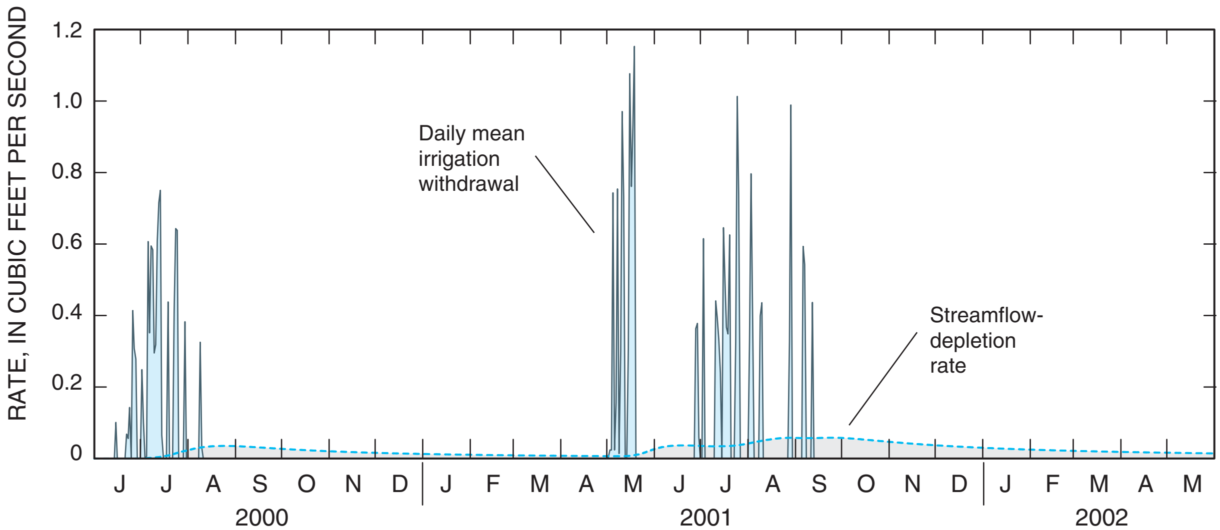



**Figure 26.** Observed daily mean irrigation withdrawals (2000–01) and corresponding streamflow depletions computed with the STRMDEPL program for a well 2,500 feet from the river, Usquepaug–Queen River Basin, Rhode Island.

Streamflow depletion by an irregularly pumped well has a pronounced time-delayed response given the properties defined above (fig. 26). The peak daily mean withdrawal rate (1.153 $ft^3/s$ on May 18, 2001) was about 20 times greater than the peak streamflow-depletion rate (0.058 $ft^3/s$ on September 9, 2001), which occurred 129 days after the peak withdrawal. Streamflow depletion continues well after pumping stops (fig. 26); in fact, streamflow depletion continues, albeit at a low level, from the previous year's withdrawals into the new irrigation season. Because peak hourly withdrawals were about 17 percent greater than the daily mean withdrawals shown in figure 26, the differences between direct stream withdrawals and ground-water withdrawals are even greater than shown.

Analysis of the turf-farm irrigation well demonstrates that streamflow depletion can be greatly diminished by converting from direct stream withdrawals to ground-water wells provided that adequate distance is maintained between the pumped well and the stream. For the aquifer properties described above, the distance of the well from the stream was sequentially decreased from 2,500 to 1,500, 1,000, 500, and 50 ft to evaluate the effects of well distance on streamflow depletion. Computed streamflow-depletion rates for the pumped-well rates for the 2001 irrigation season for various distances of the pumped well from the stream (fig. 27) clearly indicate that streamflow depletion diminishes as distance between the pumped well and the stream increases. Plotting peak streamflow depletion as a fraction of the peak withdrawal rate (fig. 28) indicates that the rate of depletion decreases rapidly within the first 500 to 1,000 ft of the pumped well from the stream, but, thereafter, the rate of depletion levels off and asymptotically approaches zero as distance increases. The peak streamflow depletion, relative to the peak withdrawal, decreased by about 60, 80, and 90 percent as the distance of the pumped well from the stream increased to 500, 1,000, and 1,500 ft, respectively.

## Potential Withdrawals at the Former Ladd School Water-Supply Wells

The former Ladd School facility in Exeter, RI, was being considered for development as an office and technology park by the Rhode Island Economic Development Corporation (RIEDC). The RIEDC plan called for office facilities for about 3,000 employees and a 9-hole golf course, which was expected to use the former facility's water-supply system that pumped water from the underlying aquifer. As part of this effort, the RIEDC prepared a comprehensive study of the former Ladd School water-supply system (Pare Engineering Corporation, 2000). The Pare study reported that the former facility had three production wells; one well is currently not operable (EXW-33, fig. 29), and the other two wells (EXW-39 and EXW-416) can produce 0.9 Mgal/d in their current condition. Aquifer tests indicated that these three wells have a combined capacity of 1.78 Mgal/d; EXW-33—0.33 Mgal/d, EXW-39—0.9 Mgal/d, and EXW-416—0.55 Mgal/d (Pare Engineering Corporation, 2000).

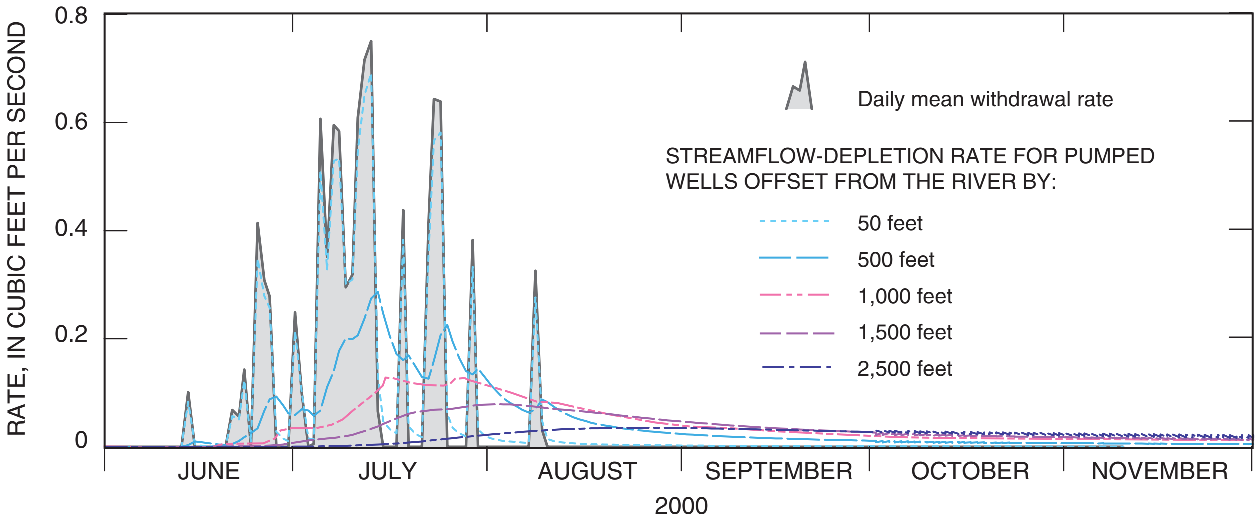



**Figure 27.** Observed daily mean irrigation withdrawals (2000) and corresponding streamflow depletions computed with the STRMDEPL program for hypothetical wells 50 to 2,500 feet from the river, Usquepaug–Queen River Basin, Rhode Island.

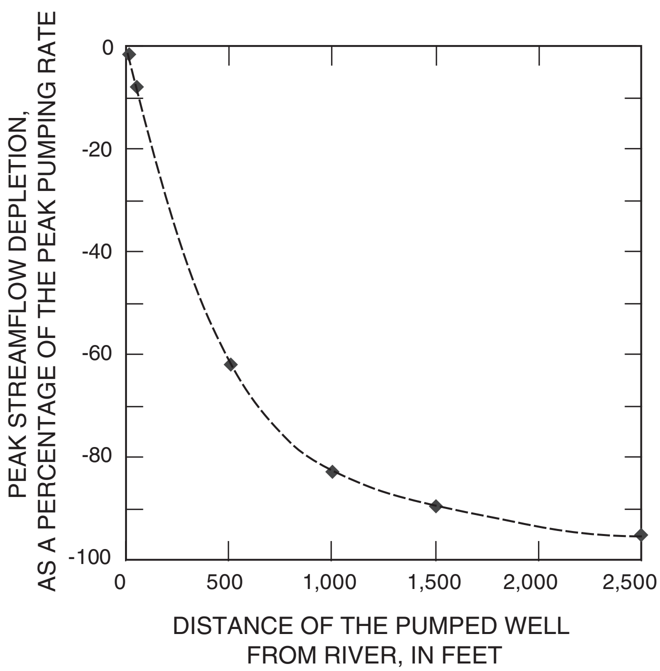



**Figure 28.** Decrease in peak-streamflow depletion as a percentage of the peak withdrawal rate, computed with the STRMDEPL program for an irregularly pumped well offset by distances of 50 to 2,500 feet from the river, Usquepaug–Queen River Basin, Rhode Island.

Although the plans for the office and technology park are not currently (2003) being pursued by RIEDC (M.P. Sams, General Manager, Rhode Island Water Resources Board, oral commun., June 2003), some of the facility has been developed for other purposes. Redevelopment of this facility will likely continue, but the extent and type of development is unknown. In addition, ground-water resources in this area have been identified for possible use by the Town of Exeter and as emergency supply for the Town of North Kingstown (Pare Engineering Corporation, 2000). Therefore, the effects of pumping at the three existing wells on streamflow were evaluated for three withdrawal rates. These rates include withdrawals of

1. 0.20 Mgal/d—This rate represents the average daily withdrawal projected by RIEDC for the formerly proposed fully developed office and technology park (Pare Engineering, 2000). This withdrawal rate may not be indicative of future withdrawals, but it approximates the rate of highest historical withdrawals (1950) that averaged 0.147 Mgal/d and that had a maximum rate of 0.225 Mgal/d (Pare Engineering Corporation, 2000). This simulation is based on the assumption that water is used consumptively (no return flow); historical and future withdrawals are expected to return much of the pumped water to the basin through on-site septic systems, however. Wastewater-return flows lessen the effect of withdrawals on streamflow, but this simulation represents the maximum effect this withdrawal rate could have on

streamflow. This simulation is identified by the prefix QUUS-P1 in the *uci* file and IDSCEN attribute for the output WDM data sets associated with this scenario.

2. 0.9 Mgal/d—This rate is the pumping capacity of the two operational wells in their current condition. This simulation is identified by the prefix QUUS-P2 in the *uci* file and IDSCEN attribute for the output WDM data sets associated with this scenario.
3. 1.78 Mgal/d—This rate is the sustainable yield reported for the three wells by Pare Engineering (2000), and is about equal to the sustainable yield determined by Dickerman and others (1997) for the aquifer (2.0 Mgal/d) in this area. This simulation is identified by the prefix QUUS-P3 in the *uci* file and IDSCEN attribute for the output WDM data sets associated with this scenario.

Withdrawals for scenarios QUUS-P2 and QUUS-P3 were assumed to be for municipal supplies outside of the basin (no return flow to the basin). Output data sets for scenarios QUUS-P1, QUUS-P2, and QUUS-P3 were assigned numbers of 71xx, 72xx, and 73xx, respectively, where xx corresponds to the model-reach number. For each scenario, the wells were assumed to pump at a constant rate and, therefore, time-delayed streamflow depletion was not computed. Another assumption was that the well for the Phoenix House (formerly part of the Ladd School), which has an independent water-supply system, was pumped at the same rate (0.003 Mgal/d) as previously simulated. All other withdrawals were maintained at the same rate as previously simulated (QUUS-lgD), which includes irrigation withdrawals simulated with the average daily distribution. The simulations of water withdrawals at the former Ladd School were run for the period 1960–2001.

Withdrawals from EXW-39 and EXW-416 were taken from the first exit gate of RCHRES 3 and withdrawals from EXW-33 were taken from the first exit gate of RCHRES 8. The results of the initial simulations indicated that, at times, withdrawals exceed streamflow in reach 3 and 8 at the 0.9 and 1.78 Mgal/d rates (QUUS-P2 and QUUS-P3, respectively). When this occurred, the model could not satisfy withdrawals and a mass-balance error was introduced because the withdrawals would need to be satisfied by depleting ground-water storage. To overcome this limitation, a special action (SA) was developed, as was done for a similar condition in the Ipswich River Basin HSPF model (Zarriello and Ries, 2000). The SA developed and adapted to the Usquepaug–Queen Basin HSPF model maintains a mass balance by tracking the volume of withdrawals in excess of streamflow and then subtracts any deficit when streamflow exceeds withdrawals. In effect, the SA adjusts streamflow to replenish water previously lost from ground-water storage when streamflow exceeds withdrawals. The SA maintains at least 50 percent of the streamflow for downstream routing and the remainder goes toward satisfying the cumulative deficit. In effect, this limits the hydrologic connection between the stream and the aquifer so that the stream can begin to flow following precipitation, yet allows a portion of the precipitation to recharge ground-water storage.

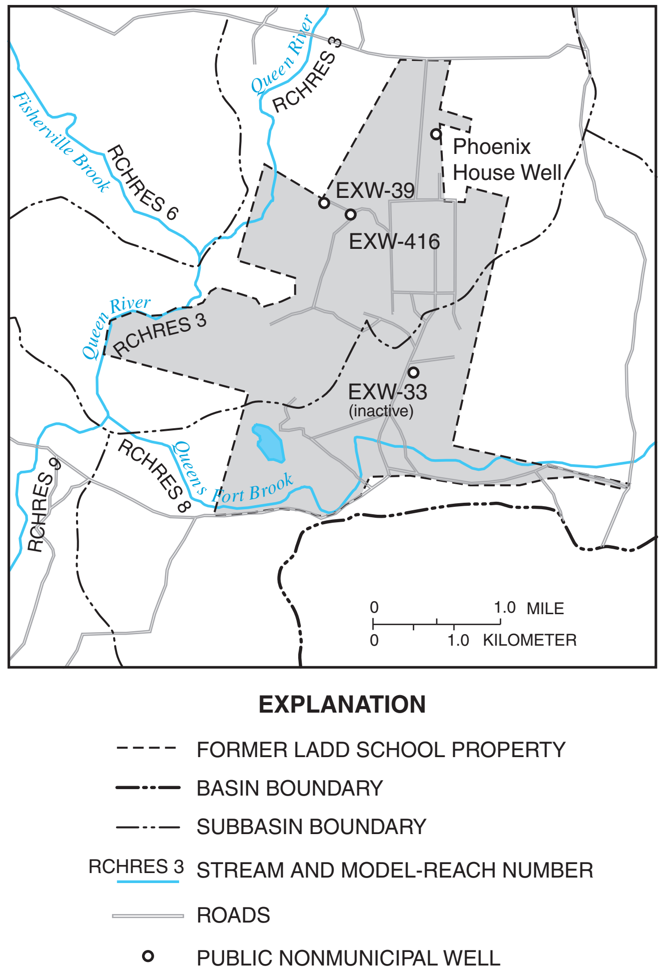



**Figure 29.** Approximate boundary of the former Ladd School facility, locations of water-supply wells, and model-reach numbers, Usquepaug–Queen River Basin, Rhode Island (location within the basin shown on fig. 6).

The effects of the increased withdrawals at the former Ladd School on streamflow were evaluated at model reaches 3, 9, and 20 (fig. 10) by comparison of flow-duration curves under no withdrawals and under current withdrawals. Flow-duration curves for reach 3 (fig. 30*A*) indicated that withdrawals of 0.20 Mgal/d begin to noticeably affect flows that are greater than 70-percent duration (flow less than 5 $ft^3/s$) and that withdrawals of 0.90 and 1.78 Mgal/d affect all flows. The lowest daily mean flows in reach 3 (99.8-percent flow duration) decreased by about 50 percent for withdrawals of 0.20 Mgal/d (from about 0.4 to 0.2 $ft^3/s$) in comparison to current withdrawals. Reach 3 would occasionally stop flowing during part of the day at the 0.20-Mgal/d withdrawal rate because of diurnal fluctuations in streamflow caused by upstream withdrawals (fig. 30*A*, hourly graph) and evapotranspiration. Withdrawal rates of 0.90 and 1.78 Mgal/d would nearly cause reach 3 to stop flowing all day about 10 to 20 percent of the time, respectively (fig. 30*A*, daily mean graph). The flows described above are representative of reach 3 above the confluence of Fisherville Brook and are not representative of the flow in the downstream segment of reach 3 because the confluence with the Queen River is simulated at the juncture of reach 9.

The effects of withdrawals at the former Ladd School on streamflow quickly diminish downstream. In reach 9, streamflow is maintained even under the highest simulated withdrawal rates (fig. 30*B*) because Fisherville Brook (RCHRES 6) and Queens Fort Brook (RCHRES 8) converge with the Queen River above this reach (fig. 29). Fisherville Brook has nearly twice the drainage area of the Queen River at this point and no major withdrawals. Queens Fort Brook has about the same drainage area as the Queen River at this point, but low flows in this tributary are affected by other withdrawals and the subsurface drainage to the HAP Basin. The lowest streamflows in reach 9 (those at the 99.8-percent flow duration) decreased by up to about 50 percent for withdrawals of 1.78 Mgal/d (from about 2 to about 1 $ft^3/s$). In reach 20, the lowest streamflows (those at the 99.8-percent flow duration) were moderately affected (about a 30-percent decrease in streamflow) at the highest withdrawal rate (fig. 30*C*).

The effects of increased withdrawals at the former Ladd School were also evaluated with respect to the magnitude and frequency of 1-, 7-, and 30-day low flows at reaches 3 and 9 by Log Pearson Type III analysis of simulated daily discharges. Simulation results indicated that reach 3 often stops flowing at the higher pumping rates (QUUS-P2 and QUUS-P3). As a result, the theoretical distribution required some manual adjustment to better fit the simulated data. The magnitude and recurrence intervals of low flows for simulations QUUS-P2 and QUUS-P3 at reach 3 (fig. 31) are therefore approximate.

Simulation results indicated that, at the highest withdrawal rate (1.78 Mgal/d), reach 3 stops flowing at least 1 day every year, stops flowing nearly every year for a 7-day period, and stops flowing about every other year for a 30-day period (QUUS-P3). Comparatively, reach 3 is able to maintain slightly more flow at the 0.90 Mgal/d withdrawal rate (QUUS-P2), but still stops flowing about every other year for a 7-day period and about once every 5 years for a 30-day period. In reach 3, the magnitudes of n-day low flows that occur often (recurrence interval less than 1.04 years) for simulated withdrawals of 0.20 Mgal/d (QUUS-P1) do not change appreciably compared to the current withdrawals (QUUS-lgW), but low flows that occur less frequently decrease by about half. For example, the 7-day low flow that is expected to occur once every 10 years (7Q10) is about 0.5 and 0.26 $ft^3/s$ under current withdrawals and the 0.20 Mgal/d withdrawal rate, respectively. In reach 9, the Log Pearson Type III results indicate small changes (less than 20 percent) in the magnitudes of expected n-day low flows as a result of ground-water withdrawals at the former Ladd School, even under the 1.78 Mgal/d withdrawal rate.

These simulation results depict the worse-case scenario of long-term continuous pumping at a constant rate and no return flows. Return flow through on-site septic systems will lessen the effect of withdrawals on streamflow. If the wells are pumped at capacity for only a short period, which is likely if they are used as an emergency supply or for irrigation, the effects of the pumped well on streamflow are diminished. Supply wells EXW-39 and EXW-416 are about 2,000 and 3,100 ft, respectively, from the Queen River and well EXW-33 is about 3,000 ft from Queens Fort Brook (fig. 29). The streamflow depletion that could be expected for short pumping intervals can be estimated from figure 28 because the aquifer properties at the former Ladd School property are similar to those used in developing figure 28. Based on this figure, the peak streamflow-depletion rate resulting from these wells (EXW-39, EXW-416, and EXW-33) for short pumping periods spaced in time would be about 90 percent less than the peak-withdrawal rate.

## Land-Use Change

The hydrologic effects of increased impervious land from urbanization are well known. These include increased storm-runoff volume and peak flows, decreased recharge and base flow, and a decline in water quality. As a result, stream ecosystems often deteriorate as a basin becomes urbanized. Concern over the long-term health of the Usquepaug–Queen River aquatic ecosystem prompted an analysis of the hydrologic effects of land-use change that could be expected under current zoning regulations.

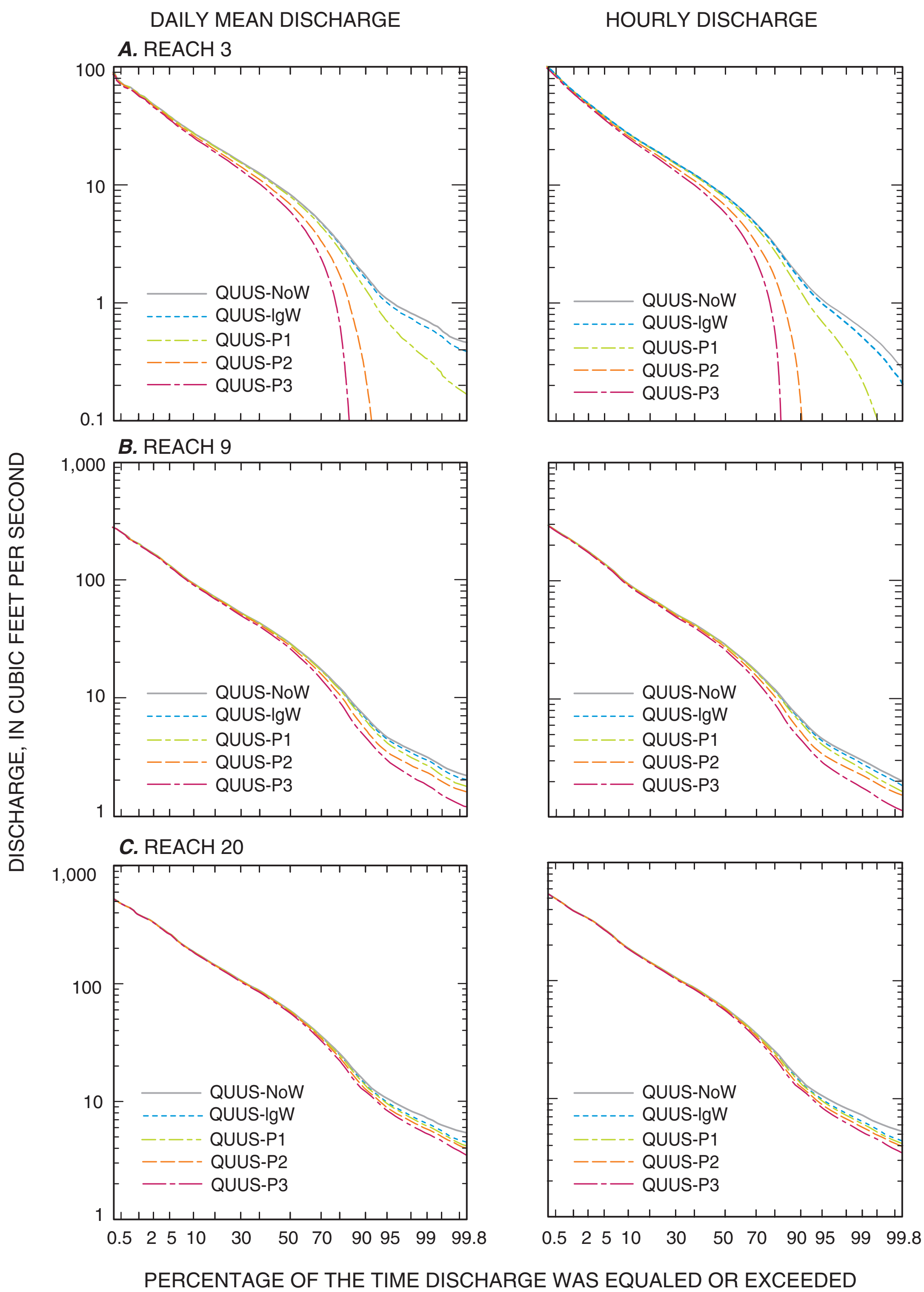



**Figure 30.** Daily mean and hourly flow-duration curves of streamflow simulated with the Hydrologic Simulation Program–FORTRAN (HSPF) under no withdrawals (QUUS-NoW), current withdrawals (QUUS-IgW), and withdrawals of 0.20, 0.90, and 1.78 million gallons per day (QUUS-P1, QUUS-P2, QUUS-P3, respectively) at the former Ladd School water-supply wells for model *A*, reach 3; *B*, reach 9; and *C*, reach 20, Usquepaug–Queen River Basin, Rhode Island, 1960–2001 (reach locations shown on fig.10 and well locations shown on fig. 29).

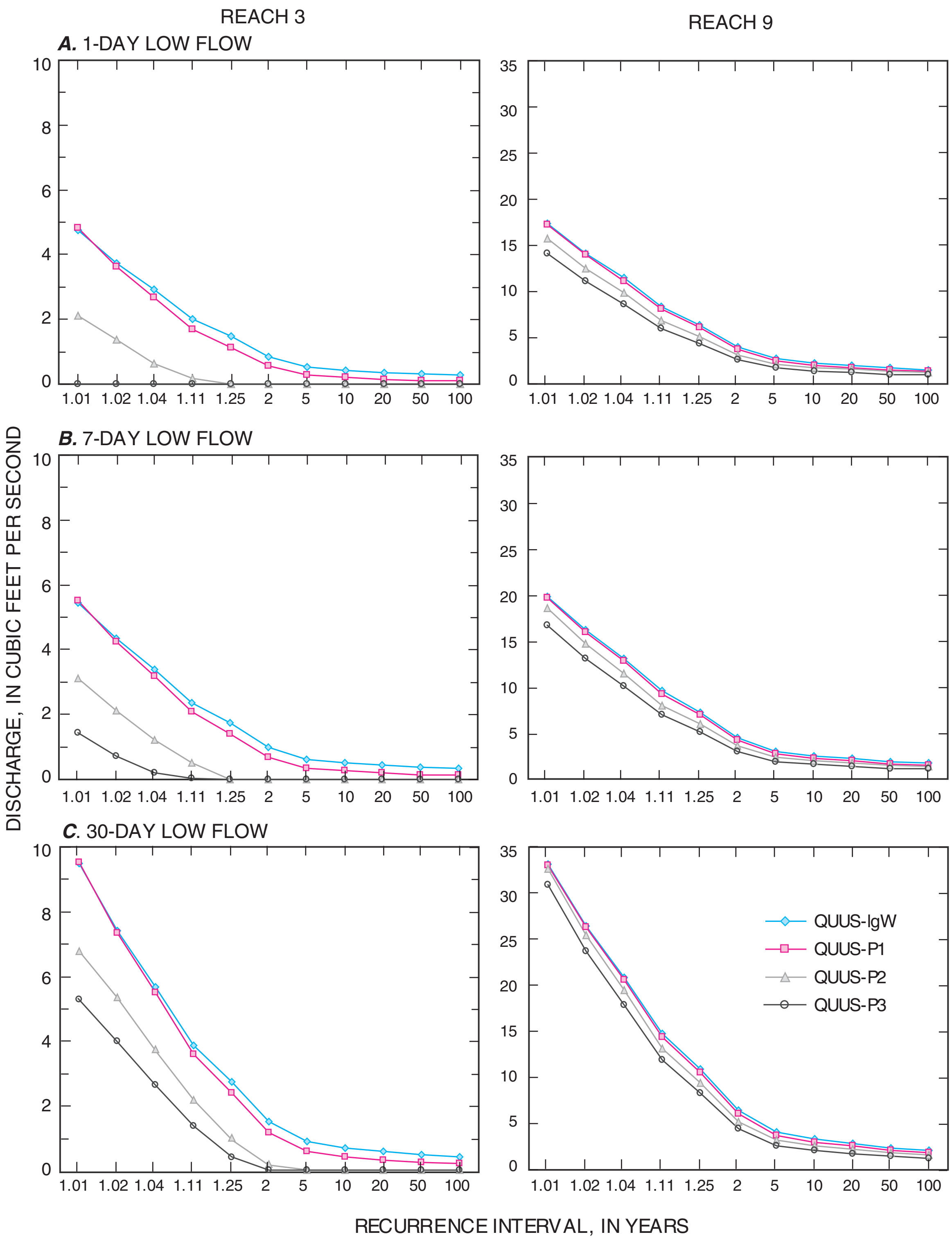



**Figure 31.** Magnitudes and recurrence intervals of *A*, 1-day; *B*, 7-day; and *C*, 30-day low flows at model reaches 3 and 9 by Log Pearson Type III analysis of discharge simulated by the Hydrologic Simulation Program–FORTRAN (HSPF) under current withdrawals (QUUS-IgW), and simulated withdrawals at the former Ladd School water-supply wells of 0.20, 0.90, and 1.78 million gallons per day (QUUS-P1, QUUS-P2, QUUS-P3, respectively), Usquepaug–Queen River Basin, Rhode Island, 1960–2001 (reach location shown on fig. 10 and well locations shown on fig. 29).

Land-use change was simulated by converting HRUs representing undeveloped areas (mainly PERLNDs representing forests) to HRUs representing developed areas (mainly PERLNDs representing moderate to low density housing). The amount of area converted from an undeveloped HRU to a developed HRU was determined on the basis of development suitability and current (2003) town zoning. The development suitability is the area remaining after eliminating (1) wetlands greater than 1 acre, (2) protected open space (lands owned by The Nature Conservancy, Audubon Society of Rhode Island, and State lands that are protected), (3) open water, and (4) currently developed land as indicated by the 1995 land-use map (Scott Millar, Sustainable Watersheds Office, Rhode Island Department of Environmental Management, written commun., 2003). The area suitable for development was decreased in each town by about 10 percent in the calculation of the number of potential new homes (table 13) to account for odd-shaped parcels and other miscellaneous factors that preclude development. For each town, the data layer for the current zoning was overlain with the development suitability map to estimate the potential number of new homes. The total developable area in the basin was estimated at 12,600 acres (55 percent of total basin area), which under the current zoning, allows about 4,300 new homes.

The developable area by subbasin ranged from 6 to 86 percent of the subbasin areas and averaged 52 percent of the subbasin areas. Overall, about 2,300 acres of open, forest, turf-farm, and irrigated agriculture lands (PERLNDs 3, 4, 8, and 9, respectively) overlying sand and gravel were converted into an HRU representing pervious area in low to moderate density residential development overlying sand and gravel (PERLND 2); this conversion entailed about a 25-fold increase in the area of PERLND 2 and decreases in the areas of PERLNDs 3, 4, 8, and 9 of about 63, 40, 54 and 100 percent, respectively. About 10,100 acres of open and forest lands overlying till (PERLNDs 12 and 13, respectively) were converted into an HRU representing pervious area in low to moderate density residential development overlying till (PERLND 11); this conversion entailed about a 22-fold increase in the area of PERLND 11 and decreases in the areas of PERLNDs 12 and 13 of about 83 and 86 percent, respectively. It was assumed that for most of the developable area, 2 percent would become effectively impervious because of the generally low density zoning (table 13). In the upper Queens Fort Brook subbasin (QUFB1 fig. 10), the area that lies in the Town of North Kingstown, about 10 percent of the developable area, is zoned for moderate density residential development, which was assumed to have a 5-percent effective impervious area. Basin-wide, the effective impervious area in residential areas (IMPLND 1) was increased by about 62 percent (from about 400 acres to about 650 acres).

**Table 13.** Town zoning (2003), estimated developable area, and potential number of new homes within the Usquepaug–Queen River Basin, Rhode Island.

[**Number of homes:** Calculated from the allowed zoning in the developable area minus about 10 percent. Town locations are shown on figure 1]

| Town | Town zoning (acres per house) | Developable area (acres) | Number of homes |
|---|---|---|---|
| East Greenwich | 2 | 50 | 20 |
| Exeter | 4–5 | 8,650 | 1,900 |
| North Kingstown | 0. 5 | 140 | 250 |
| Richmond | 2 | 1,800 | 810 |
| South Kingstown | 1 | 710 | 710 |
| West Greenwich | 2 | 1,300 | 580 |
| Total | | 12,650 | 4,270 |

In addition to changes in land use, three alternative water-use scenarios were considered in the hydrologic analysis of land-use change. These analyses include (1) no change in withdrawals, (2) depleting streamflow by 20 percent of the estimated total cumulative withdrawals by private wells for a fully developed basin, and (3) depleting streamflow by the total cumulative withdrawals by private wells for a fully developed basin. These simulations are referred to as QUUS-B1, QUUS-B2, and QUUS-B3, respectively, in the model *uci* file and the IDSCEN attribute for model output saved to the WDM file. Output data sets for scenarios QUUS-P1, QUUS-P2, and QUUS-P3 were assigned numbers of 81xx, 82xx, and 83xx, respectively, where the last two digits (xx) correspond to the model-reach number.

The first analysis (QUUS-B1) considers only the hydrologic effects of land-use change, whereas the other simulations (QUUS-B2 and QUUS-B3) consider the additional effects of increased withdrawals associated with development. The 20-percent decrease in the cumulative withdrawals by private wells was assumed to represent the 15-percent average annual consumptive use reported for domestic supplies in Rhode Island (Solley and others, 1998) plus a slight increase to account for seasonal increases for lawn watering and other consumptive uses. The simulation of total cumulative withdrawals by private wells represents the upper limit of the effects of private withdrawals on streamflow. For example, this simulation could represent the effects of private wells and water transferred from the basin by municipal sewers.

Withdrawals during 1995–99 by private wells are reported to be 0.312 Mgal/d for domestic uses and 0.032 Mgal/d for commercial uses within the basin (Wild and Nimiroski, 2004). These withdrawal rates were apportioned to reaches on the basis of the ratio of the current subbasin developed area to the current total basin developed area. Withdrawals associated with increased development were estimated on the basis of the estimated number of new homes in each subbasin times an average of 3 people per household, times 70 gal/person/d (the average reported water use per person). Future withdrawals from private wells were combined with current domestic and commercial withdrawals, if any, to obtain the total withdrawal from each reach summarized in table 14. The cumulative current self-supply withdrawals with no return flow were estimated at 0.02, 0.32, and 0.53 $ft^3/s$ at QRPB, QRLY, and USQU, respectively. The cumulative current and new self-supply withdrawals with no return flow for a fully developed basin were estimated at 0.16, 0.95, and 1.92 $ft^3/s$ at QRPB, QRLY, and USQU, respectively. The cumulative self-supply withdrawals at the basin outlet (USQU) represent about 2.6 percent of the long-term mean annual discharge.

Cumulative self-supply withdrawals were specified as the flow through the first exit gate of a reach or added to previously specified withdrawals. Previously specified withdrawals for golf-course irrigation and public self-supply wells were maintained at the current average withdrawal rates (QUUS-lgW) for all land-use-change simulations. Withdrawals for turf-farm and crop irrigation were held at current levels (QUUS-lgW) for the simulation of land-use change only (QUUS-B1). This simulation facilitated the evaluation of the effects of changing HRU distribution, but also reflected the response of a nearly fully developed basin with current agricultural withdrawals (2000-01). For simulations QUUS-B2 and QUUS-B3, withdrawals for turf farms and crop irrigation were replaced by the cumulative self-served withdrawals because it was assumed that these areas could be developed. Thus, the net change in the water withdrawal (increase in domestic water withdrawals) is partially offset by the decrease in irrigation withdrawals for these two simulations. Withdrawals from pumped wells at the former Ladd School were specified for the fully developed facility and were simulated at 0.04 and 0.20 Mgal/d for QUUS-B2 (20 percent of the total withdrawal) and QUUS-B3, respectively. Self-supply wells were assumed to pump at a constant rate; therefore, the net streamflow depletion was set equal to the pumping rate. All simulations were run for a 42-year period—1960–2001.

**Table 14.** Summary of self-supply withdrawals for the period 1995–99 and the potential withdrawals by model reach (RCHRES) in the Usquepaug–Queen River Basin, Rhode Island.

[Reach location shown in figure 10]

| RCHRES | Total withdrawals (millions of gallons per day) | | |
|---|---|---|---|
| | Existing | New | Total |
| 1 | 0.008 | 0.076 | 0.084 |
| 2 | .006 | .012 | .018 |
| 3 | .012 | .014 | .026 |
| 4 | .021 | .097 | .118 |
| 5 | .067 | .082 | .149 |
| 6 | .007 | .008 | .016 |
| 7 | .046 | .114 | .160 |
| 8 | .006 | .017 | .023 |
| 9 | .000 | .001 | .001 |
| 10 | .007 | .014 | .021 |
| 11 | .007 | .019 | .026 |
| 12 | .000 | .002 | .002 |
| 13 | .003 | .009 | .012 |
| 14 | .035 | .110 | .145 |
| 15 | .002 | .007 | .008 |
| 16 | .004 | .007 | .011 |
| 17 | .004 | .034 | .037 |
| 18 | .043 | .100 | .143 |
| 19 | .029 | .048 | .078 |
| 20 | .034 | .128 | .162 |
| Total | 0.344 | 0.897 | 1.241 |

Simulation results depicted by the change in the daily mean flow-duration curve from the baseline simulation of current withdrawals (QUUS-lgW) indicate that base flow about doubles at the 99.8-percent flow duration (fig. 32). This result appears counterintuitive to the expected effects of urbanization, but is consistent with the changes in the simulated water budgets from a forested to a developed open-space land use. Water budgets per unit area (fig. 15*A*) indicate that evaporation losses from lower zone and active ground-water storage from forested areas (PERLNDs 4 and 13) are about twice that from open space in developed areas (PERLNDs 2 and 11). There is assumed to be less deep-rooted vegetation in open space in developed areas than in forested areas and, therefore, evapotranspiration losses from these areas is less than from forested areas. Because most of the developable area (83 percent) was converted from forested PERLNDs, the total evapotranspiration losses that directly affect base flow were nearly cut in half by simulating the basin as fully developed. Self-supply wells appear to have only a minor effect on the flow-duration curve relative to similar model structures simulated with current withdrawals (fig. 32).

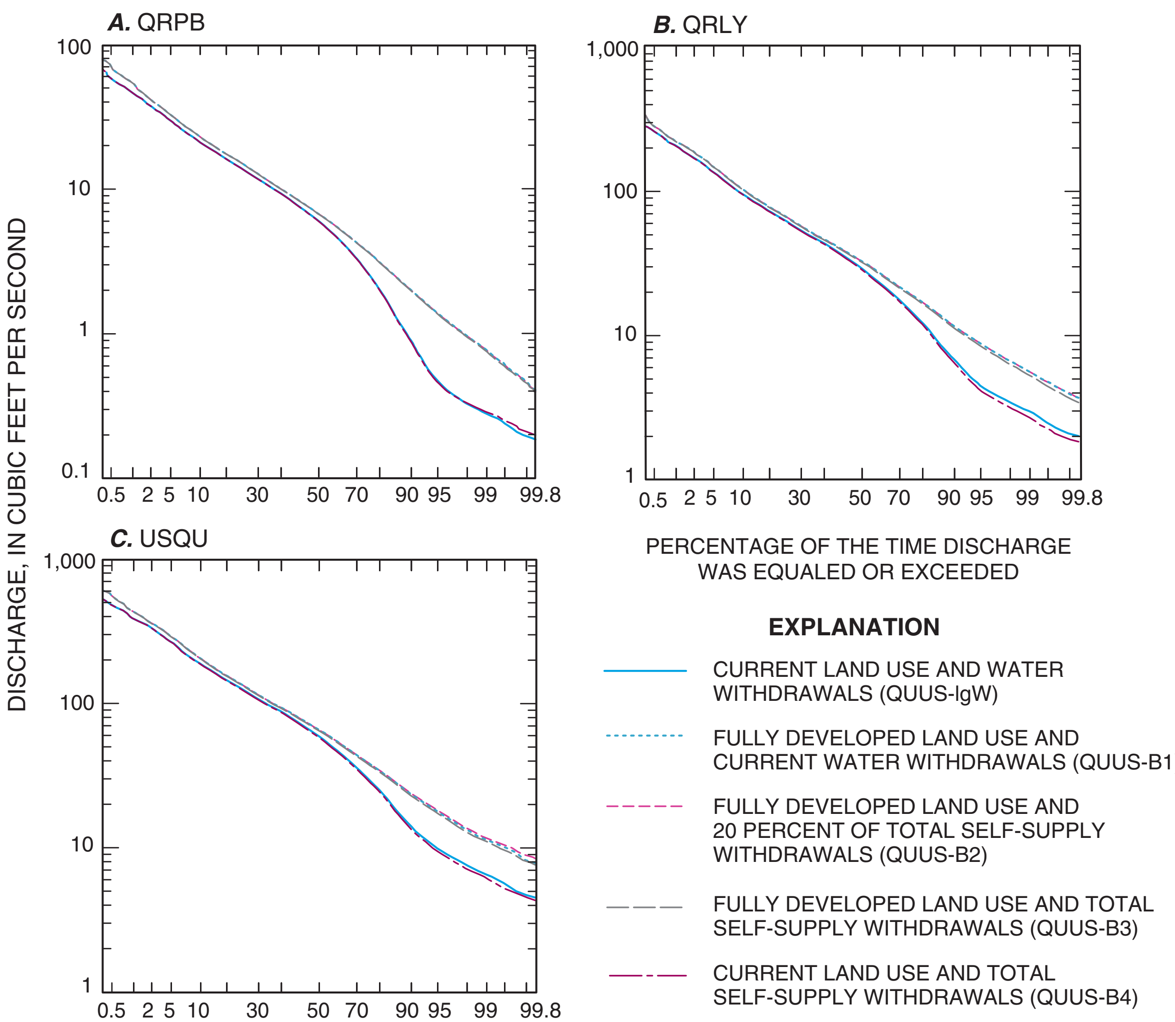



**Figure 32.** Flow-duration curves of simulated daily mean discharges under current (2000–01) withdrawals and buildout with various withdrawals at streamflow-gaging stations *A*, Queen River at Exeter (QRPB); *B*, Queen River at Liberty (QRLY); and *C*, Usquepaug River near Usquepaug (USQU), Usquepaug–Queen River Basin, Rhode Island, 1960–2001 (location of streamflow-gaging stations shown on fig. 2).

These simulations represent an end member where developed areas are entirely converted from their former land-use characteristic to a disturbed open residential land use. The differences between developed and undeveloped land use are likely less than depicted; however, 93 percent of the developable area of the basin is zoned for one house on 2 acres or more (68 percent of the basin area is zoned for one house every 4 acres). As a result, much of the deep-rooted vegetation would likely remain intact after development. If each housing unit is assumed to affect only 0.5 acre, then the area affected by development likely would affect about 2,230 acres or about 10 percent of the basin area. Thus, the flow-duration curve from development would be expected to show little change from the current condition.

Simulations of land-use change are subject to large uncertainties because the model is not explicitly calibrated to unique HRUs. Rather, the model is calibrated to the aggregated response of all HRUs that define the drainage area to a continuous streamflow-gaging station. Thus, the hydrologic responses of individual HRUs are largely unknown. In addition, the hydrologic effects of urbanization can depend on the amount of impervious area directly connected to stream channels (effective impervious area). Increased storm volume and peak discharge and correspondingly decreased base flow are more pronounced in basins where impervious areas directly discharge to streams than in basins where the impervious areas drain to pervious areas. Furthermore, these results do not show the localized effects that can result from urbanization. For example, 86 percent of the Sherman Brook subbasin is developable (zoned for 2-acre lots) and the estimated self-supply withdrawals could increase by about a factor of 10 (from 4,000 to 37,000 gal/d). As a result, streamflow is affected to a greater extent in this basin (fig. 33) than indicated at the three continuous streamflow-gaging stations (fig. 32).

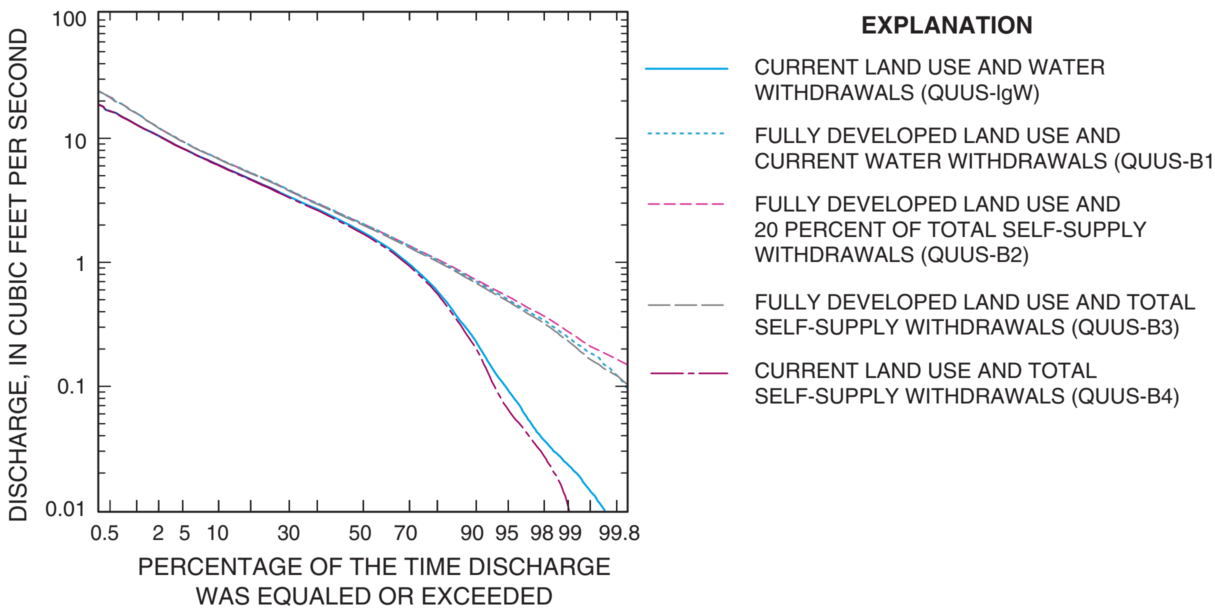



**Figure 33.** Flow-duration curves of simulated daily mean discharges under current (2000–01) withdrawals and buildout with various withdrawals at Sherman Brook (reach 17), Usquepaug–Queen River Basin, Rhode Island, 1960–2001 (location of reach 17 shown on fig. 10).

# Summary

The Usquepaug–Queen River Basin, which encompasses an area of 36.1 $mi^2$ in south-central Rhode Island, is valued for its high-quality water and rich aquatic ecosystem. Streamflow records for periods of low precipitation during the summer months indicate that water withdrawals could be adversely affecting aquatic habitat, water quality, and the value of the river as a scenic and recreational resource. Concern over the effects of withdrawals on streamflow and aquatic habitat prompted the development of a Hydrologic Simulation Program–FORTRAN (HSPF) precipitation-runoff model of the basin by the U.S. Geological Survey in cooperation with the Rhode Island Water Resources Board (RIWRB). The study results will help the RIWRB and others evaluate water-management and land-use change in the basin.

Climate, streamflow, and water-withdrawal data were collected during the study to develop the HSPF model. Climate data included precipitation, air temperature, dew-point temperature, solar radiation, and wind speed; these data were collected at a climate station established for this study in the basin (FBWR) and compiled from the National Oceanic and Atmospheric Administration stations at T.F. Green Airport (PROVID), Newport, and Westerly, and from the University of Rhode Island. Data from FBWR were used for model calibration and data from PROVID were used for long-term simulations. Data from FBWR and PROVID were used to calculate potential evapotranspiration (PET) by the Jensen-Haise method. Streamflow data were collected at four continuous-record stations along the main branch of the Queen and Usquepaug Rivers and at six partial-record sites mostly on the tributary streams. A continuous record was estimated for the partial-record stations to augment streamflow information for model calibration and evaluation of model performance.

Water-use data compiled for the 1995–99 period in the Usquepaug–Queen River Basin included total withdrawals of about 0.841 Mgal/d, which were used mostly for irrigation (56 percent) and domestic (40 percent) purposes. Small amounts of water were withdrawn for commercial (0.013 Mgal/d) and industrial (0.019 Mgal/d) purposes. Water from the basin is used to irrigate an estimated 340 acres of turf farm, 110 acres of golf course, and 210 acres of vegetable, berry, and nursery farms. Accounting for irrigation withdrawals is required for model calibration and to simulate the effects of these withdrawals on streamflow; however, these climatically dependent withdrawals can vary widely from day to day and seasonally. The limited data from measured irrigation withdrawals provided information needed to estimate withdrawals at other locations during the calibration period and to estimate long-term withdrawals.

For long-term simulations, a logistic-regression equation was developed that predicts the likelihood of irrigation on a given day from total potential evapotranspiration in the past 2 days (PET2) and past 20 days (PET20) and total precipitation in the past 10 days (PREC10). A probability of 0.35 or greater provided the best cutoff for predicting when irrigation occurred. In comparison to the measured irrigation withdrawals, the logistic-regression equation correctly predicted turf-farm irrigation 81 percent of the time and golf-course irrigation 74 percent of the time. The number of false positive predictions (equation predicted irrigation when no irrigation was observed) was about equal to the number of false negative predictions (equation did not predict irrigation when irrigation was observed). For long-term simulations (1960–2001), the probability of irrigation was calculated and irrigation was assumed to occur on days when the probability of irrigation was 0.35 or greater. On days when irrigation is predicted, hourly withdrawals were distributed on the basis of the observed irrigation-withdrawal patterns. Daily irrigation on golf courses is bimodal—irrigation typically peaks in the early morning and ends when golf activity begins, then resumes later in the day at a lower rate. The pattern of temporal turf-farm irrigation varied, but on average, withdrawals peaked early in the afternoon. The average turf-farm-irrigation pattern was assumed to represent the daily distribution pattern for unmetered agricultural uses and was used to determine irrigation demands for long-term simulations.

The HSPF model simulates runoff from precipitation and potential-evapotranspiration time-series data. Processes simulate the transport and fate of water for hydrologic response units (HRUs) and stream reaches (RCHRES) that define the hydrologic characteristics of the basin. The Usquepaug–Queen Basin was represented by HRUs composed of 13 pervious areas (PERLNDs), established from combinations of surficial geology and land-use classes, and 2 impervious areas (IMPLNDs). The basin was segmented into 20 reaches to represent junctions at tributaries and availability of streamflow information. A reach was established in the upper Queens Fort Brook subbasin (RCHRES 7) because the subsurface drainage in this area is reported to drain northeast to the Hunt–Annaquatucket–Pettasquamscutt (HAP) Basin.

Limited water-withdrawal data imposed a relatively short calibration period—January 1, 2000, to September 30, 2001. Three continuous streamflow-gaging stations (QRPB, QRLY, and USQU) that monitor flow at 10, 54, and 100 percent of the total basin area, respectively, provided the key model-calibration points. Hydrographs and flow-duration curves of observed and simulated discharges, along with various model-fit statistics, indicated that the model performed well over a range of hydrologic conditions. For example, the total runoff volume for the calibration period simulated at the QRPB, QRLY, and USQU streamflow-gaging stations differed from the observed runoff volume by 0.7, -6.5, and -1.4 percent, respectively.

Simulated flow components indicate that active ground-water flow (AGWO) composed about 96 percent of the discharge from PERLNDs overlying sand and gravel, 55 percent of the discharge from PERLNDs overlying till, and about 37 percent of the discharge from wetland PERLNDs. Interflow (IFWO) composed about 4 percent of the discharge from PERLNDs overlying sand and gravel, 38 percent of the discharge from PERLNDs overlying till, and 39 percent of the discharge from wetland PERLNDs. Surface runoff (SURO) was negligible from PERLNDs overlying sand and gravel, composed about 7 percent of the discharge from PERLNDs overlying till, and about 24 percent of the discharge from wetland PERLNDs. The basin is predominantly forest-covered, and thus, the simulations indicate that 70 percent of the discharge at the basin outlet originated from forested areas—about 44 percent (26.2 in.) from areas overlying till, 13 percent (7.94 in.) from areas overlying sand and gravel, and 13 percent (8.04 in.) from forested wetlands. Forested areas account for about 84 percent (35.4 in.) of the total evapotranspiration losses from the basin; losses from these HRUs can exceed contributions to streamflow during dry periods. Because of the relative importance of ground-water and interflow components, the Usquepaug–Queen Basin model is most sensitive to variables that control these flow processes, particularly for forested PERLNDs overlying till.

The calibrated HSPF model was modified to evaluate the effects of water-withdrawals and land-use changes on streamflow in the basin. These simulations included (1) comparison of streamflows under no withdrawals to streamflow under current withdrawals for long-term (1960–2001) climatic conditions, (2) effects on streamflow of ground-water withdrawals at water-supply wells at the former Ladd School, and (3) the effects on streamflow of fully developed land-use conditions. The effects of converting from direct-stream withdrawals to ground-water withdrawals were also evaluated outside of the HSPF model.

The simulations of streamflow effects under current withdrawals and no withdrawals served as a baseline for other simulations. Simulations included several alterative models to help evaluate uncertainty in model performance with respect to extreme low flows, irrigation withdrawals, and climate data; simulations were made with and without withdrawals with (1) the calibrated model, (2) an alterative model calibrated to extreme low flows, (3) a model with modified peak-irrigation withdrawals, and (4) a model with no adjustments made to the long-term climate data. None of the alternative models reproduced the observed no-flow periods at the basin outlet during August-September 1995, although the calibrated model closely matched the observed maximum daily flow during this period. The alternative models matched the observed minimum daily flow better than the calibrated model, but undersimulated maximum daily flows. These simulations suggest that withdrawals may have been greater in August and September 1995 than during the study period, that model variable values or structure may not represent extreme low-flow conditions, or that precipitation may have been spatially uneven, or that instability in the low-flow stage-discharge relation at USQU resulted in erroneous flow values, or a combination of these factors.

The simulated effects of current withdrawals relative to no withdrawals indicate that withdrawals decrease the lowest daily mean streamflow at the basin outlet by about 20 percent, but withdrawals have little effect on higher flows (those exceeded less than about 90 percent of the time). Results of simulations by the alternative models tested indicate that the lowest daily mean flows ranged from 3 to 5 $ft^3/s$ without withdrawals and from 2.2 to 4 $ft^3/s$ with withdrawals. Changes in the minimum daily streamflows are more pronounced; at QRPB (the upstream station), a minimum daily flow of 0.2 $ft^3/s$ was sustained without withdrawals, but simulations with withdrawals indicate that the reach would stop flowing for part of a day about 5 percent of the time.

The effects of withdrawals on streamflow by pumping supply wells at the former Ladd School were evaluated by simulations that reflect historical peak and future peak withdrawals (0.20 Mgal/d), the operational capacity of existing wells (0.9 Mgal/d), and the sustainable capacity of the aquifer in this area (1.78 Mgal/d). Flow-duration curves for reach 3 (a segment of the Queen River closest to the pumped wells) indicate that withdrawals of 0.20 Mgal/d noticeably affected flows above the 70-percent flow duration (flow less than 5 $ft^3/s$) and that withdrawals of 0.90 and 1.78 Mgal/d noticeably affected all flows. The lowest daily mean flows in reach 3 decreased by about 50 percent for withdrawals of 0.20 Mgal/d (from about 0.4 to 0.2 $ft^3/s$) in comparison to current withdrawals. At the 0.20-Mgal/d withdrawal rate, reach 3 occasionally stopped flowing during part of the day because of diurnal fluctuation in streamflow from upstream withdrawals and evapotranspiration. Withdrawal rates of 0.90 and 1.78 Mgal/d caused reach 3 to stop flowing about 10 to 20 percent of the time. The effects of pumping diminished downstream; reach 9, the next downstream reach from reach 3, receives flow from Fisherville Brook, a major tributary, and thus, even at the 1.78 Mgal/d withdrawal rate, the lowest flows in reach 9 decreased by only about 50 percent (from about 2 to about 1 $ft^3/s$).

Log Pearson Type III analyses indicate that the magnitude and recurrence frequency of 1-, 7-, and 30-day low flows at reach 3 changed little except for infrequent events (high recurrence interval) at withdrawal rates of 0.20 Mgal/d. Withdrawal rates of 0.90 Mgal/d caused reach 3 to stop flowing about every other year for a 7-day period and about once every 5 years for a 30-day period. Withdrawal rates of 1.78 Mgal/d caused reach 3 to stop flowing at least 1 day every year, for a 7-day period for most years, and for a 30-day period about every other year.

Land-use change was simulated by converting HRUs representing undeveloped areas to HRUs representing developed areas on the basis of development suitability and current town-zoning regulations. The total area available for development in the basin was estimated to be 12,600 acres (55 percent of total basin area); this area would accommodate about 4,300 new homes under the current zoning regulations (mostly low density residential development). Buildout simulations also included changing self-supply well withdrawals. Withdrawals from existing and new self-supply wells for a fully developed basin were estimated as 1.2 Mgal/d, which represents about 2.6 percent of the mean annual discharge at the basin outlet.

Simulation results indicate that under fully developed conditions, the lowest flows (99.8-percent flow duration) are about two times greater relative to current conditions. Although this result is not consistent with the hydrologic effects typically associated with urbanization, the result is consistent with simulated water budgets for forested and developed open-space PERLNDs. PERLNDs representing open space in developed areas were assumed to have less deep-root vegetation, and thus, less evapotranspiration loss (about half that of forested PERLNDs). The area of the basin available for development is zoned for low-density residential, which would likely leave much of the deep-rooted vegetation intact and, therefore, the differences between developed and undeveloped land use are likely to be less than simulated. Furthermore, current zoning regulations allow only low-density residential development, which was assumed to increase the effectively impervious area by only 2 percent in the newly developed area. Increases in storm volume and peak discharge and decreases in base flow typically associated with urbanization, thus, are not evident in the simulated build out of the Usquepaug–Queen Basin. Potential increased water withdrawals from new self-supply wells for a fully developed basin indicate only a minor effect on streamflow in the main stem of the Usquepaug–Queen River. The hydrologic effects of urbanization, however, can be more pronounced in localized areas where development is concentrated.

Streamflow depletion rates were calculated for varying distances of a pumped well from a stream on the basis of an actual irrigation record. Peak streamflow depletion relative to the actual irrigation withdrawal decreases rapidly as the well was moved to a distance of 500 ft away from the stream; thereafter, the rate of streamflow depletion declined gradually. For the aquifer conditions tested, streamflow depletion, relative to the peak-withdrawal rate, decreased by about 60, 80, and 90 percent for an irrigation well 500, 1,000, and 1,500 ft from the stream, respectively.

Like many hydrologic models, the HSPF model of the Usquepaug–Queen Basin can be a useful tool for evaluating hydrologic responses to change if model structure and variable values adequately reflect the hydrologic responses of the system to the stresses being evaluated. The uncertainty associated with data and the possible applicability of alternative model structures and variable values should be considered when evaluating the model results for water-resource-management decisions.

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# Appendix 1: Hydrologic Simulation Program–FORTRAN User Control File (*uci*) Input for Pervious-Area Model Variables

```
PERLND
  ACTIVITY
  ### -### 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  ***->
***## -### ATMP SNOW PWAT  SED  PST  PWG PQAL MSTL PEST NITR PHOS TRAC PIVL  PYR
    1   15              4                                                 1   12
  END PRINT-INFO

  GEN-INFO
    <PLS ><-------Name------->NBLKS   Unit-systems   Printer ***
  ###--###                         User  t-series Engl Metr ***
                                          in  out           ***
    1      S&G mod-hi develop     1    1    1    1   15    0
    2      S&G low-mod residen    1    1    1    1   15    0
    3      S&G Open               1    1    1    1   15    0
    4      S&G Forest             1    1    1    1   15    0
    7      S&G Golf course        1    1    1    1   15    0
    8      S&G Turf farm          1    1    1    1   15    0
    9      Irregated crop         1    1    1    1   15    0
   10      Till mod-hi develop    1    1    1    1   15    0
   11      Till low-mod residen   1    1    1    1   15    0
   12      Till Open              1    1    1    1   15    0
   13      Till Forest            1    1    1    1   15    0
   14      Till non-forest wet    1    1    1    1   15    0
   15      Till Forest wetland    1    1    1    1   15    0
  END GEN-INFO

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

  SNOW-PARM1
  ### -###       LAT     MELEV     SHADE    SNOWCF    COVIND ***
    1    3      41.5      290.      0.05      1.30       0.25
    4           41.5      290.      0.50      1.30       0.25
    7   12      41.5      290.      0.05      1.30       0.25
   13           41.5      290.      0.50      1.30       0.25
   14           41.5      290.      0.15      1.30       0.25
   15           41.5      290.      0.50      1.30       0.25
  END SNOW-PARM1

  SNOW-PARM2
  ### -###     RDCSN     TSNOW    SNOEVP    CCFACT    MWATER    MGMELT ***
    1   15      0.15       32.      0.05      0.05      0.90    0.1100
  701  715      0.15       32.      0.05      0.05      0.90    0.1100
  END SNOW-PARM2
```

```
  PWAT-PARM1
***   CSNO=1 snowmelt on   ;   1=varies monthly 0=does not
***## -### CSNO RTOP UZFG  VCS  VUZ  VNN VIFW VIRC VLET IFFC  HWT IRRG
    1    4    1    0    1    1    1    0    1    1    1    0    0    0
    7    9    1    0    1    1    1    0    1    1    1    0    0    0
   10   15    1    0    1    1    1    0    1    1    1    0    0    0
  END PWAT-PARM1

  PWAT-PARM2
   ### -### ***FOREST      LZSN    INFILT      LSUR     SLSUR     KVARY     AGWRC
            ***(none)      (in)   (in/hr)      (ft)    (none)    (l/in)    (l/in)
     1          0.150      7.60     0.400      200.     0.022      0.15     0.992
     2          0.250      8.80     0.440      300.     0.022      0.17     0.994
     3          0.150      8.20     0.480      300.     0.022      0.17     0.994
     4          0.550      8.20     0.520      300.     0.022      0.18     0.994
     7    9     0.050      8.20     0.520      300.     0.022      0.16     0.993
    10          0.150      4.70     0.080      200.     0.024      0.18     0.980
    11          0.250      5.50     0.100      300.     0.024      0.08     0.981
    12          0.150      5.70     0.120      300.     0.024      0.05     0.981
    13          0.450      5.70     0.120      300.     0.024      0.06     0.982
    14   15     0.450      4.70     0.070      100.     0.024      0.04     0.980
   END PWAT-PARM2

   PWAT-PARM3
   ### -### ***PETMAX    PETMIN    INFEXP    INFILD    DEEPFR    BASETP    AGWETP
     1    3       40.       35.       0.5       1.5      0.00     0.000     0.120
     4            40.       35.       0.5       1.5      0.00     0.000     0.280
     7    9       40.       35.       0.5       1.5      0.00     0.000     0.040
    11   12       40.       35.       0.5       1.5      0.00     0.000     0.120
    13            40.       35.       0.5       1.5      0.00     0.000     0.320
    14   15       40.       35.       0.5       2.0      0.00     0.000     0.340
   END PWAT-PARM3

   PWAT-PARM4
     Flag PARM1   VCS       VUZ       VUR       VMN      VIFW       VLE ***
   ### -###     CEPSC      UZSN      NSUR     INTFW       IRC     LZETP ***
                 (in)      (in)    (none)    (none)    (l/da)    (none) ***
     1          0.020      0.21     0.190      1.00      0.75      0.18
     2          0.020      0.21     0.200      1.00      0.75      0.18
     3          0.040      0.21     0.210      1.00      0.75      0.28
     4          0.040      0.21     0.250      1.00      0.75      0.88
     7          0.030      0.21     0.200      1.00      0.75      0.22
     8          0.020      0.21     0.200      1.00      0.75      0.28
     9          0.020      0.21     0.200      1.00      0.75      0.28
    10          0.040      0.12     0.180      1.00      0.75      0.18
    11          0.040      0.12     0.210      1.00      0.75      0.18
    12          0.040      0.12     0.210      1.00      0.75      0.28
    13          0.040      0.12     0.220      1.00      0.75      0.88
    14          0.020      0.12     0.230      1.00      0.75      0.38
    15          0.020      0.12     0.250      1.00      0.75      0.88
   END PWAT-PARM4
```

```
MON-INTERCEP
### -###  JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC ***
  1    3 0.02 0.02 0.02 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.02 0.02
  4      0.02 0.02 0.02 0.02 0.03 0.04 0.04 0.04 0.04 0.04 0.04 0.03
  7    9 0.01 0.01 0.01 0.02 0.02 0.02 0.02 0.02 0.02 0.02 0.01 0.01
 10   11 0.02 0.02 0.02 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.02 0.02
 12      0.02 0.02 0.02 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.02 0.02
 13      0.02 0.02 0.02 0.02 0.03 0.04 0.04 0.04 0.04 0.04 0.04 0.03
 14      0.02 0.02 0.02 0.02 0.03 0.03 0.03 0.03 0.03 0.02 0.02 0.02
 15      0.02 0.02 0.02 0.02 0.03 0.04 0.04 0.04 0.04 0.04 0.03 0.02
END MON-INTERCEP

MON-UZSN
### -###  JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC ***
  1      0.14 0.14 0.14 0.14 0.14 0.14 0.14 0.14 0.14 0.14 0.14 0.14
  2      0.18 0.18 0.18 0.18 0.18 0.18 0.18 0.18 0.18 0.18 0.18 0.18
  3    4 0.23 0.23 0.23 0.23 0.22 0.21 0.20 0.20 0.21 0.22 0.23 0.23
  7    9 0.20 0.20 0.20 0.20 0.20 0.18 0.18 0.18 0.18 0.20 0.20 0.20
 10      0.08 0.08 0.08 0.08 0.08 0.08 0.08 0.08 0.08 0.08 0.08 0.08
 11   12 0.10 0.10 0.10 0.10 0.10 0.10 0.10 0.10 0.10 0.10 0.10 0.10
 13      0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.16 0.15
 14   15 0.06 0.06 0.06 0.06 0.08 0.08 0.08 0.08 0.08 0.06 0.06 0.06
END MON-UZSN

MON-INTERFLW
### -###  JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC ***
  1      1.80 1.80 1.80 1.85 1.85 1.85 1.85 1.85 1.85 1.80 1.80 1.80
  2    3 2.30 2.30 2.30 2.35 2.35 2.35 2.35 2.35 2.35 2.30 2.30 2.30
  4      3.20 3.20 3.20 3.25 3.25 3.25 3.25 3.25 3.25 3.20 3.20 3.20
  7    9 2.20 2.20 2.20 2.25 2.25 2.25 2.25 2.25 2.25 2.20 2.20 2.20
 10      1.70 1.70 1.70 1.75 1.75 1.75 1.75 1.75 1.75 1.70 1.70 1.70
 11   12 1.90 1.90 1.90 1.95 1.95 1.95 1.95 1.95 1.95 1.90 1.90 1.90
 13      3.10 3.10 3.10 3.15 3.15 3.15 3.15 3.15 3.15 3.10 3.10 3.10
 14   15 1.40 1.40 1.40 1.45 1.45 1.45 1.45 1.45 1.45 1.40 1.40 1.40
END MON-INTERFLW

MON-IRC
### -###  JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC ***
  1      0.62 0.66 0.72 0.72 0.70 0.63 0.60 0.60 0.60 0.60 0.60 0.60
  2    3 0.78 0.82 0.88 0.88 0.86 0.79 0.76 0.76 0.76 0.76 0.76 0.76
  4      0.82 0.86 0.92 0.92 0.90 0.83 0.80 0.80 0.80 0.80 0.80 0.80
  7    9 0.80 0.84 0.90 0.90 0.88 0.81 0.78 0.78 0.78 0.78 0.78 0.78
 10      0.56 0.66 0.68 0.68 0.66 0.60 0.55 0.55 0.55 0.56 0.56 0.56
 11   15 0.76 0.76 0.88 0.88 0.86 0.80 0.75 0.75 0.75 0.76 0.76 0.76
END MON-IRC
```

```
  MON-LZETPARM
  ### -###   JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC ***
    1    3  .03  .03  .03  .06  .15  .28  .32  .32  .26  .16  .12  .08
    4       .05  .05  .05  .08  .24  .58  .60  .60  .58  .46  .40  .22
    7    9  .03  .03  .03  .05  .10  .18  .18  .18  .16  .15  .10  .07
   10   11  .03  .03  .03  .05  .15  .28  .30  .30  .24  .16  .10  .06
   12       .03  .03  .03  .04  .12  .24  .24  .24  .22  .18  .16  .04
   13       .06  .06  .06  .08  .24  .58  .60  .60  .58  .46  .40  .22
   14       .04  .04  .04  .07  .26  .42  .45  .45  .40  .42  .32  .16
   15       .06  .06  .06  .08  .28  .60  .64  .64  .60  .52  .42  .22
  END MON-LZETPARM

  PWAT-STATE1
    <PLS > *** Initial conditions at start of simulation
  ### -### ***  CEPS      SURS       UZS      IFWS       LZS      AGWS      GWVS
    1    3      0.02      0.00      0.31     0.001      9.29      8.36      2.98
    4           0.02      0.00      0.19     0.000      8.93      9.90      2.33
    7    9      0.01      0.00      0.26     0.000     10.57      8.06      2.36
   10   13      0.02      0.00      0.24     0.089      6.78      3.03      1.93
   14   15      0.02      0.00      0.14     0.125      6.40      1.09      1.78
  END PWAT-STATE1
END PERLND
```

# Appendix 2: Model-Fit Statistics Computed with the PEST Surface-Water Utilities Program

- Bias: $$B = \frac{1}{N}\sum_{i=1}^{N}(S_i - O_i)$$

- Standard error: $$S = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(S_i - O_i)}$$

- Relative bias: $$B_r = \frac{B}{\overline{O}}$$

- Relative standard error: $$S_r = \frac{S}{S_o}$$

- Nash-Sutcliffe coefficient: $$R^2 = \frac{\sum_{i=1}^{N}(S_i - O_1)^2}{\sum_{i=1}^{N}(O_i - \overline{O}_i)^2}$$

- Index of agreement: $$E_k = 1 - \frac{\sum_{i=1}^{N}\left|S_i - O_i\right|^2}{\sum\left|S_i - \overline{O}\right| + \left|O_i - \overline{O}_i\right|},$$

where

the mean of observed values is given by

$$\overline{O} = \frac{1}{N}\sum O_i$$

and the variance of the observed values is given by

$$S_o = \frac{1}{N-1}\sum(O_i - \overline{O})^2.$$