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Simulation of Surface-Water Conditions in the Nontidal Passaic River Basin, New Jersey

Scientific Investigations Report 2007-5052

U.S. Department of the Interior
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Suggested citation:
Spitz, F.J., 2007, Simulation of surface-water conditions in the nontidal Passaic River Basin, New Jersey: U.S. Geological Survey Scientific Investigations Report 2007-5052, 67 p.

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Conversion Factors, Datums, and Definitions

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic feet (ft^3)	0.02832	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic feet per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic feet per second per square mile [(ft^3/s)/mi^2]	0.01093	cubic meter per second per square kilometer [(m^3/s)/km^2]
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
gallon per day per square mile [(gal/d)/mi^2]	0.001461	cubic meter per day per square kilometer [(m^3/d)/km^2]
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
million gallons per day per square mile [(Mgal/d)/mi^2]	1,461	cubic meter per day per square kilometer [(m^3/d)/km^2]
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 1929).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Simulation of Surface-Water Conditions in the Nontidal Passaic River Basin, New Jersey

By Frederick J. Spitz

Abstract

The Passaic River Basin, the third largest drainage basin in New Jersey, encompasses 950 mi^2 (square miles) in the highly urbanized area outside New York City, with a population of 2 million. Water quality in the basin is affected by many natural and anthropogenic factors. Nutrient loading to the Wanaque Reservoir in the northern part of the basin is of particular concern and is caused partly by the diversion of water at two downstream intakes that is transferred back upstream to refill the reservoir. The larger of these diversions, Wanaque South intake, is on the lower Pompton River near Two Bridges, New Jersey. To support the development of a Total Maximum Daily Load (TMDL) for nutrients in the nontidal part of the basin (805 mi^2), a water-quality transport model was needed. The U.S. Geological Survey, in cooperation with the New Jersey Department of Environmental Protection and New Jersey EcoComplex, developed a flow-routing model to provide the hydraulic inputs to the water-quality model.

The Diffusion Analogy Flow model (DAFLOW) described herein was designed for integration with the Water Quality Analysis Simulation Program (WASP) watershed water-quality model. The flow routing model was used to simulate flow in 108 miles of the Passaic River and major tributaries. Flow data from U.S. Geological Survey streamflow-gaging stations represent most of the model's upstream boundaries. Other model inputs include estimated flows for ungaged tributaries and unchanneled drainage along the mainstem, and reported flows for major point-source discharges and diversions. The former flows were calibrated using the drainage-area ratio method. The simulation extended over a 4+ year period representing a range in flow conditions. Simulated channel cross-sectional geometry in the DAFLOW model was calibrated using several different approaches by adjusting area and top width parameters. The model also was calibrated to observed flows for water year 2001 (low flow) at five mainstem gaging stations and one station at which flow was estimated. The model's target range was medium to low flows--the range of typical intake operations. Simulated flow mass balance, hydrographs (flood-wave speed, attenuation, and spread), flow-duration curves, and velocity and depth values were compared to observed counterparts. Mass balance and hydrograph fit were evaluated quantitatively.

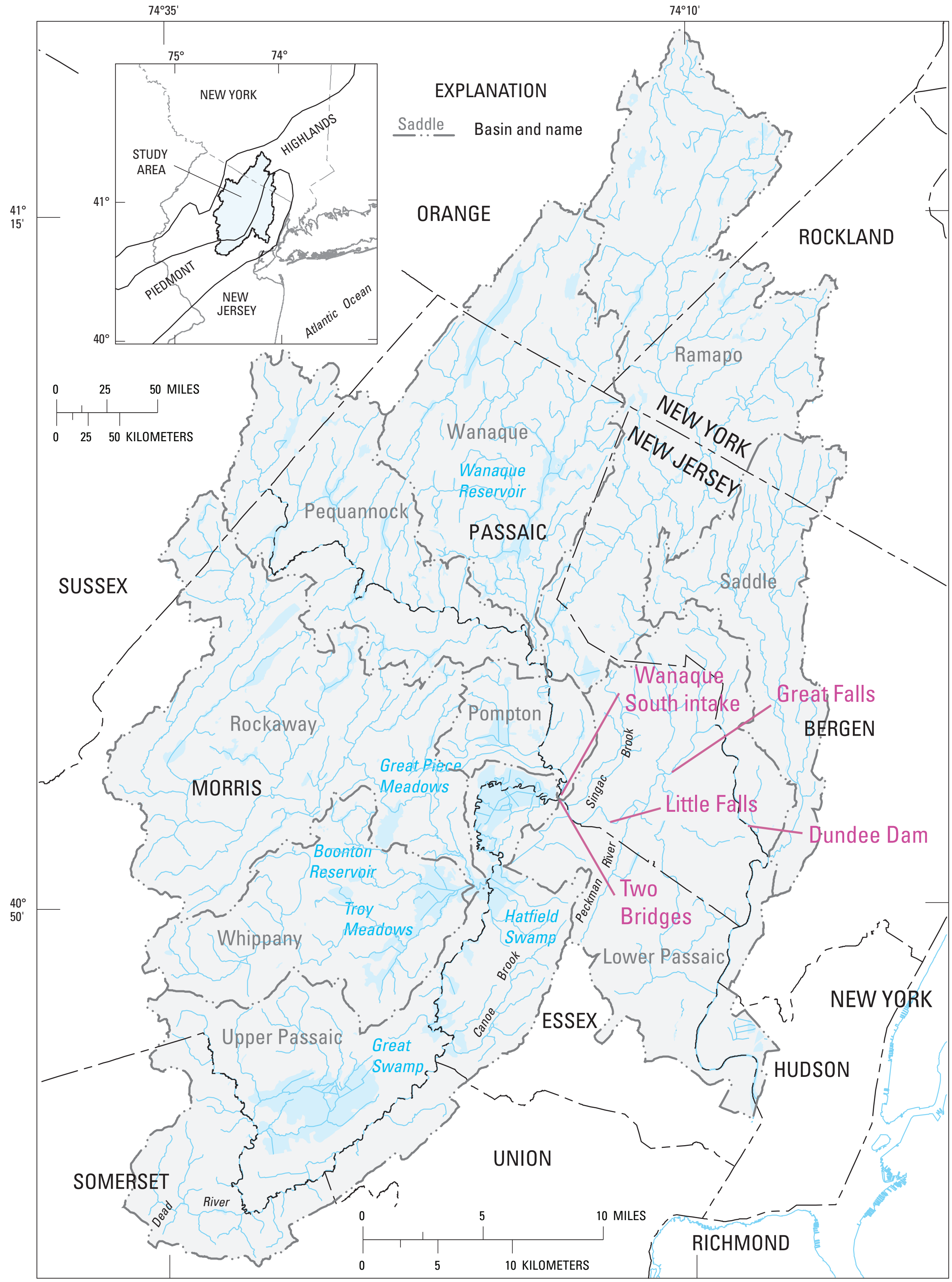
Simulation results generally were within the accuracy of the flow data at the measurement stations. The model was validated to observed flows for water years 2000 (average flow), 2002 (extreme low flow), and 2003 (high flow). Results for 19 of 20 comparisons indicate average mass-balance and model-fit errors of 6.6 and 15.7 percent, respectively, indicating that the model reasonably represents the time variation of streamflow in the nontidal Passaic River Basin.

An algorithm (subroutine) also was developed for DAFLOW to simulate the hydraulic mixing that occurs near the Wanaque South intake upstream from the confluence of the Pompton and Passaic Rivers. The intake draws water from multiple sources, including effluent from a nearby wastewater-treatment plant, all of which have different phosphorus loads. The algorithm determines the proportion of flow from each source and operates within a narrow flow range. The equations used in the algorithm are based on the theory of diffusion and lateral mixing in rivers. Parameters used in the equations were estimated from limited available local flow and water-quality data. As expected, simulation results for water years 2000, 2001, and 2003 indicate that most of the water drawn to the intake comes from the Pompton River; however, during many short periods of low flow and high diversion, particularly in water year 2002, entrainment of the other flow sources compensated for the insufficient flow in the Pompton River.

As additional verification of the flow model used in the water-quality model, a Branched Lagrangian Transport Model (BLTM) was created to simulate historical dye-tracer tests done in the 4-mile subreach between Two Bridges and Little Falls. Dye decay and longitudinal dispersion were calibrated and roughly validated. Concentration mass, time-of-travel, and attenuation and spread of the dye cloud were reproduced by the submodel. The flow and transport models are considered accurate given the indicated limitations.

Introduction

The Passaic River Basin in northeastern New Jersey and a small part of southeastern New York (fig. 1) is the third



Base from U.S. Geological Survey digital line data, 1:24,000
Universal Transverse Mercator Projection, Zone 18, NAD83

Figure 1. Location of the Passaic River Basin, New Jersey. (Dundee Dam divides nontidal from tidal part of basin.)

largest drainage basin in New Jersey (950 mi^2), most of which is in the highly urbanized area outside New York City. Water quality in the basin is affected by many factors, including complex river-system hydraulics, many point-source discharges and diversions, nonpoint-source runoff from mixed land uses, varying geology, river interaction with wetlands and ground water, and water use.

The New Jersey Department of Environmental Protection (NJDEP), in cooperation with the U.S. Environmental Protection Agency (USEPA), has mandated Total Maximum Daily Load (TMDL) requirements for nutrients, mainly total phosphorus, in the nontidal part of the basin (N.J. Department of Environmental Protection, 2001; Cenno and Hirst, 2005). TMDLs establish the load of contaminants a water body can receive without violating applicable water-quality standards. Of particular concern in the Passaic River Basin is eutrophication of the Wanaque Reservoir (fig. 1), a water-supply reservoir in the 90-mi^2 Wanaque River subbasin. The Wanaque South intake, at the downstream end of the Pompton River, diverts water back upstream to the reservoir, thereby contributing additional phosphorus to the reservoir. (The reservoir also receives water diverted from Pompton Lake on the Ramapo River.) Diversion rates are flow-dependent: water typically is not diverted at high flows, when the reservoir storage commonly is near capacity or spilling, and diversion is limited at very low flows, when nearby passing-flow requirements must be met. Therefore, nutrient transfer usually occurs only during medium to low flows.

Treated effluent from Two Bridges Sewerage Authority discharges to the Pompton River just upstream from the intake. Nonpoint-source flows in the basin also contribute nutrient loads. Because streamflows, loadings, and water-quality processes are transient, advanced techniques are required to evaluate these issues. Accordingly, the NJDEP, in cooperation with local watershed advisory committees, determined that a transient water-quality model was needed to support TMDL development efforts. A necessary first step in the development of the water-quality transport model of the watershed was the development of a flow model of the river. The flow model provides a modeling framework, predictive representation of the streamflow hydraulics, and the hydraulic inputs to the water-quality model. Time-of-travel information important for dealing with accidental or intentional spills of soluble contaminants upstream from surface-water intakes also can be approximated from the dye-tracer data used in this study.

Therefore, the U.S. Geological Survey (USGS), in cooperation with the NJDEP and New Jersey EcoComplex (Rutgers University's Environmental Research and Extension Center, or NJEC), developed a Diffusion Analogy Flow model (DAFLOW) to simulate flows in the nontidal Passaic River Basin and for integration with a Water Quality Analysis Simulation Program (WASP) water-quality model. TRC Omni Environmental Corp. (TRC Omni) in Princeton, N.J., developed the WASP model. The water-quality model uses the flow model as a basis for establishing a model network (grid) and to obtain information on mass transport and cross-sectional geometric characteristics throughout the basin.

Purpose and Scope

This report describes a transient flow-routing model developed to provide the hydraulic inputs needed for nutrient TMDL water-quality modeling of the nontidal Passaic River Basin. The flow model provides a time-series of unsteady streamflows as input to a watershed water-quality model being developed by TRC Omni. The model provides predictive capability with respect to the hydraulics of the basin that can be used in future simulations. It simulates mixing near Wanaque South intake because one of the main objectives of the TMDL is to address the effect of phosphorus loads contributed from the intake on the quality of water in the Wanaque Reservoir.

The report documents the development, calibration, and validation of the flow model, which simulates river-system hydraulics over the nontidal Passaic River Basin domain, as well as the development of continuous flow data for all model boundaries, calibration/validation locations, subbasins along the mainstem, and major point sources and sinks. The simulation period (water years 2000-03) represents a range of streamflow conditions, although the focus is on moderate streamflows. The flow model considers constituent transport in addition to flow routing, as it is designed ultimately to interface with and address requirements of the water-quality model (for example, inclusion of sampling stations).

Description of Study Area

The Passaic River Basin lies in the Piedmont and Highlands Physiographic Provinces of northeastern New Jersey and southeastern New York and contains complex and diverse land uses. Approximately half of the basin lies in the Highlands (northwest) and the other half lies in the Piedmont (southeast). The river and its major tributaries drain all of Passaic County, and parts of Morris, Somerset, Union, Essex, Hudson, Sussex, and Bergen Counties in New Jersey; and parts of Orange and Rockland Counties in New York (fig. 1). The population of this area is approximately 2 million.

The six major mainstem tributaries to the Passaic River in the nontidal Passaic River Basin are the Pequannock, Wanaque, Ramapo, Pompton, Rockaway, and Whippany Rivers. A seventh tributary, Saddle River, drains into the Passaic River below Clifton, outside the study area. Many smaller streams drain into these major tributaries. Although the Passaic River ultimately flows southeast into Newark Bay, this study considered only the drainage area upstream from Clifton (805 mi^2), which excludes the tidal reaches downstream from Dundee Dam. Recorded flows at Little Falls (762 mi^2) averaged 1,132 ft^3/s over the 105-year period of record, but can vary widely, as indicated by flows ranging from 37 to 11,300 ft^3/s during August and September 1999. Large wetlands, including Troy Meadows, Hatfield Swamp, and Great Piece

Meadows, are present along the mainstem river and tributaries. The river channel slope is very flat (0.5-1 ft/mi) throughout these areas. Many reservoirs are located within the basin. Ground water is withdrawn along some reaches of the mainstem river and tributaries (for example, Canoe Brook).

Previous Investigations

Anderson and Faust (1973) provided information on water quality and streamflow in the Passaic River upstream from Little Falls, defined relations among various hydrologic characteristics, and evaluated long-term water-quality trends. NJDEP (1987) developed a steady-state river water-quality model using the USEPA's QUAL2E computer program (Brown and Barnwell, 1987) to assess the effect of point-source discharges on the quality of water in the mainstem and to ensure the maintenance of water-quality standards in affected areas. The U.S. Army Corps of Engineers (U.S. Army Corps of Engineers, 1995) regularly updates flood studies of the basin. Storck and Nawyn (2001) reconstructed natural streamflow records in the basin to account for the effects of anthropogenic activities.

Phosphorus loading to the Wanaque Reservoir by instream sources was evaluated by Rosensteel and Strom (1991). NJDEP's current TMDL development process is conducted in cooperation with the USGS and TRC Omni (2004, 2007) for the nontidal Passaic River Basin, Najarian Associates (2005) for Wanaque Reservoir, and Quantitative Environmental Analysis (2005) for Pompton Lake. Work done by Najarian Associates includes a river simulation based on a simple mass-balance model for phosphorus loads.

Surface-Water Flow System

Water enters the mainstem in several ways, including through tributary runoff, unchanneled runoff, ground-water base flow (nonpoint-source flows), and point-source discharges. Water is withdrawn from the mainstem and it's tributaries by diversion. Streamflow consists of both surface- and ground-water components. Separation of the surface-water and ground-water components is not necessary for the flow model. To satisfy the needs of the water-quality model, continuous flows for these components of the surface-water system must be determined at model boundaries and at selected points (model nodes) along the mainstem by measurement or estimation.

Gaged and Ungaged Mainstem Flows

Stream stage is monitored continuously at USGS streamflow-gaging stations. Continuous streamflow is then computed for each station from the stage data using a stage-discharge rating curve developed by relating discharge measurements at each station to stream stage at the time the discharge was measured. The accuracy of continuous-flow records at gaging stations can range from excellent (within 5 percent of actual values) to poor (more than 15 percent from actual values). Gage accuracy can change from year to year and, therefore, can affect computations of discharge per square mile of drainage area. USGS streamflow-gaging stations are identified by numbers that consist of a two-digit major-drainage-basin number followed by a six-digit downstream-order number. Gages relevant to this study are shown in figure 2 and listed in table 1.

The six USGS streamflow-gaging stations that served as model boundaries for this study are 01382500 (Pequannock River at Macopin Intake Dam), 01387000 (Wanaque River at Wanaque), 01388000 (Ramapo River at Pompton Lakes), 01381000 (Rockaway River below reservoir at Boonton), 01381400 (Whippany River near Morristown), and 01379000 (Passaic River near Millington). The accuracy of these gages ranged from 10 to 20 percent for water years 2000-03 (Reed and others, 2001-04).

At certain model boundaries, no gaging station is present and flows must be estimated; these include the Pequannock River, Dead River, Singac Brook, and Peckman River (fig. 1). The gage on the Pequannock River lies upstream from the model boundary, which is located at the site of a former gage (01382800). Equation 1 (below) is used to estimate flow at the boundary and includes the ratio of the drainage areas of the intervening area (20.2 mi^2) to the index-gage subbasin (19.1 mi^2), as well as coefficients C1 and C2. Coefficient C1 is applied to shift the entire hydrograph by some amount, whereas coefficient C2 is applied to shift the low-flow value by some amount. Equations for the boundaries at the Dead River, Singac Brook, and Peckman River, all of which have no upstream gage at the model boundary, also are shown below. The variable Q represents flow in these equations:

$$Q_{01382800} = Q_{01382500} + C1 * 1.06 * Q_{01384500} + C2, \qquad (1)$$

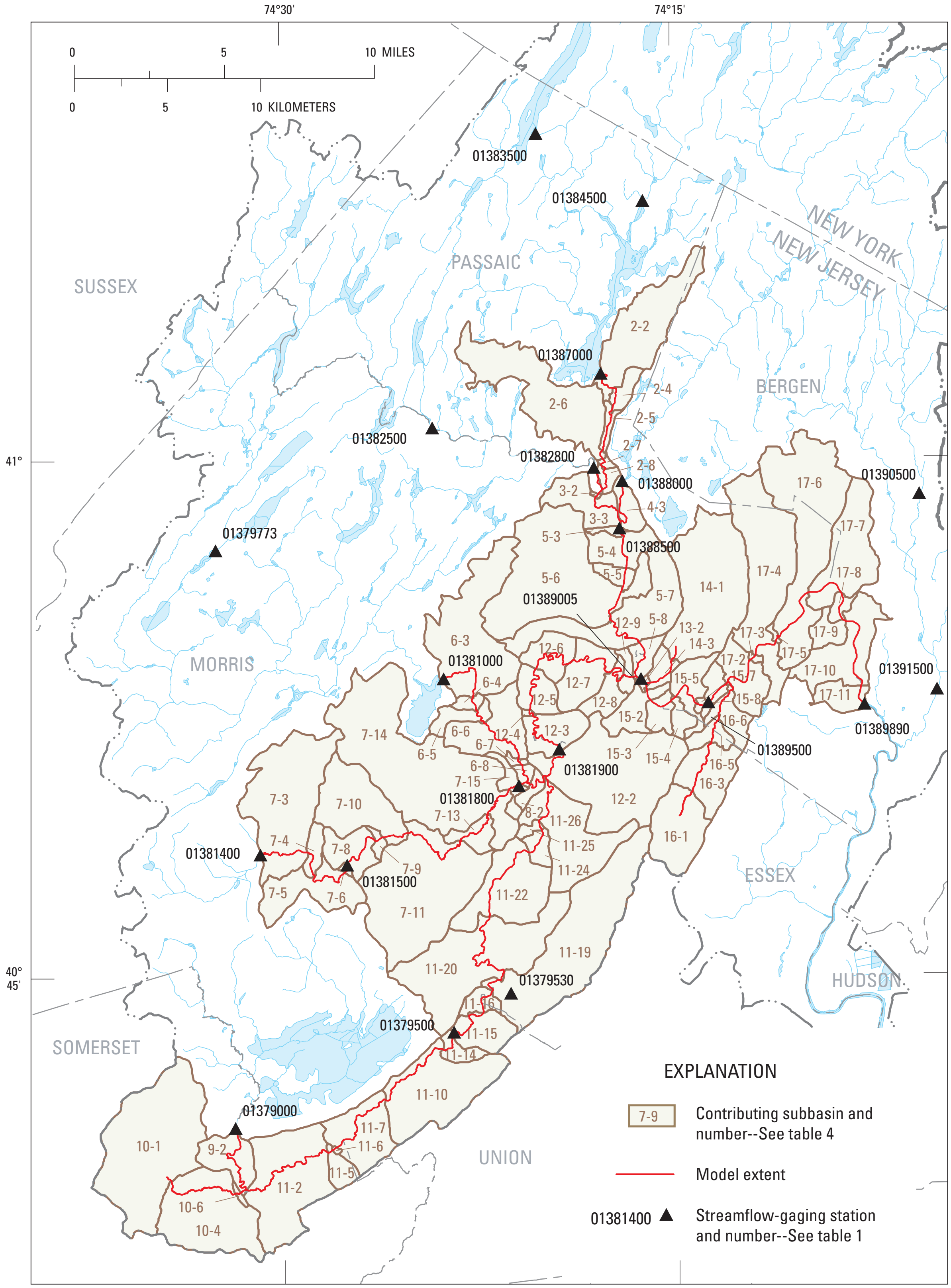
$$Q_{Dead} = C1 * 0.24 * Q_{01379000} + C2, \qquad (2)$$

$$Q_{Singac} = C1 * 0.60 * Q_{01381400} + C2, \qquad (3)$$

and

$$Q_{Peckman} = C1 * 0.13 * Q_{01390500} + C2. \qquad (4)$$

The six USGS streamflow-gaging stations (fig. 2) of importance in model calibration and validation are 01388500 (Pompton River at Pompton Plains), 01381500 (Whippany River at Morristown), 01381800 (Whippany River near Pine Brook), 01379500 (Passaic River near Chatham), 01381900 (Passaic River at Pine Brook), and 01389500 (Passaic River at Little Falls). The accuracy of measurements at these gages ranged from 10 to 20 percent for water years 2000-03



Base from U.S. Geological Survey digital line data, 1:24,000
Universal Transverse Mercator Projection, Zone 18, NAD83

Figure 2. Streamflow-gaging stations and contributing subbasins in the nontidal Passaic River Basin, New Jersey.

Table 1. Streamflow-gaging stations in the nontidal Passaic River Basin, New Jersey.

[mi², square miles; ft³/s; cubic feet per second; ---, not available or not applicable]

Station number[1]	Station name	Drainage area (mi²)	Period of record	Discharge[2] ((ft³/s)/mi²)
	Boundary gages			
01382800	Pequannock River at Riverdale	83.9	1993-97	---
01387000	Wanaque River at Wanaque	90.4	1912-15, 1919-	0.4
01388000	Ramapo River at Pompton Lakes	160.0	1921-	1.6
01381000	Rockaway River below reservoir, at Boonton	119.0	1949-	1.1
01381400	Whippany River near Morristown	14.0	1995-	1.6
01379000	Passaic River near Millington	55.4	1903-06, 1921-	1.3
	Downstream gages			
01388500	Pompton River at Pompton Plains	355.0	1903-04, 1940-	1.3
01381500	Whippany River at Morristown	29.4	1921-	1.7
01381800	Whippany River near Pine Brook	68.5	1992-	2.0
01379500	Passaic River near Chatham	100.0	1903-11, 1937-	1.5
01381900	Passaic River at Pine Brook	349.0	1979-	1.6
01389500	Passaic River at Little Falls	762.0	1897-	1.1
01389890	Passaic River at Dundee Dam at Clifton[3]	805.0	---	---
	Index/other gages			
01379773	Green Pond Brook at Picatinny Arsenal	7.65	1982-	1.5
01382500	Pequannock River at Macopin Intake Dam	63.7	1922-90, 1992-	0.6
01383500	Wanaque River at Awosting	27.1	1919-	1.8
01384500	Ringwood Creek near Wanaque	19.1	1934-78, 1985-	1.6
01379530	Canoe Brook near Summit[4]	11.0	1982-	1.0
01389005	Passaic River below Pompton River at Two Bridges[5]	734.0	1988-	---
01390500	Saddle River at Ridgewood	21.6	1954-74, 1977-	1.4
01391500	Saddle River at Lodi	54.6	1923-	1.8

[1] Locations shown in figure 2.

[2] For water years 2000-03.

[3] Miscellaneous station.

[4] Tributary gaging station.

[5] Unpublished slope (stage only) station.

(Reed and others, 2001-04). Records for stations 01388500, 01381500, 01379500, and 01389500 are considered accurate. Station 01381800 has a short period of record (table 1), is adjacent to wetlands, and is subject to backwater conditions originating at the confluence of the Pompton and Passaic Rivers; station 01381900 is affected similarly by wetlands and backwater. The effect of backwater conditions at these gages is apparent in the delayed hydrograph recession and reduces the accuracy of the gage records. Therefore, these two gages are not considered accurate for model-calibration purposes.

No gage exists at the model outlet, Passaic River at Dundee Dam at Clifton, although a low-flow site (01389890) is present there. Virtually no other flow data are available for the river downstream from Little Falls. In an effort to develop a rating curve for this location, the USGS measured discharge 10 times during the summer of 2004, but no rating curve was developed; continuous stage data recorded at this location for the past several years by United Water New Jersey are inadequate for developing a continuous streamflow record. Therefore, discharge was estimated (R.D. Schopp, U.S. Geological Survey, written commun., 2004), by combining discharge at Passaic River at Little Falls (01389500) with drainage-area-adjusted discharge at nearby Saddle River at Lodi (01391500), which was selected as the index gage. Index gages typically are selected from streams having similar drainage-basin and other characteristics. Hydrologic characteristics of the Saddle River Basin are thought to be similar to those of the drainage area of the Passaic River between Little Falls and Clifton. Like the Passaic River between Little Falls and Clifton, flow at Saddle River at Lodi is affected by both point-source discharges and diversions. This index gage is also best for estimating the intervening discharge because of its proximity and the similar size of its drainage basin. The equation used to estimate flow, accounting for the ratio of the drainage area of the intervening area (43 mi^2) to the drainage area of the index-gage subbasin (54.6 mi^2), is

$$Q_{01389890} = Q_{01389500} + 0.788 * Q_{01391500}. \quad (5)$$

Estimated flows for the Passaic River at Dundee Dam at Clifton compared favorably with discharge measurements made during the summer of 2004.

Minimum passing-flow requirements for streams have been mandated by the NJDEP to protect flow quantity and quality and stream ecology. Passing flows for reservoir releases have been set at the Wanaque River downstream from Wanaque Reservoir (15.5 ft^3/s; 10 Mgal/d) and the Rockaway River downstream from Boonton Reservoir (12.2 ft^3/s; 7.9 Mgal/d). Passing flows for pumped storage have been set at Ramapo River at Pompton Lakes (61.9 ft^3/s; 40 Mgal/d); Pompton River at Pompton Plains (136 ft^3/s; 88 Mgal/d); Passaic River at Chatham (116 ft^3/s; 75 Mgal/d); Passaic River at Two Bridges (143 ft^3/s; 92.6 Mgal/d); and Passaic River at Little Falls (27.2 ft^3/s; 17.6 Mgal/d). Passing flows at the last two stations depend on the operation of Wanaque South intake. A passing flow for hydroelectric use that varies with season and time of day has been set at Passaic River at Great Falls at Paterson (50.0-200 ft^3/s; 32.3-129.3 Mgal/d). A passing flow that varies with the stage of Dundee Lake has been set at Passaic River at Dundee Dam at Clifton (outflow equals inflow).

Gaged, Partial-Record, and Ungaged Flows Along Mainstem

Tributary and unchanneled drainage from subbasins along the mainstem increases mainstem flow. Determination of drainage area and flow for these subbasins is described below.

Subbasin Delineation

Before flows at selected points along the mainstem can be determined, drainage areas along the mainstem must be defined. The methodology used by TRC Omni to define these subbasins (fig. 2) consisted of combining an existing NJDEP geographic information system (GIS) subbasin layer with subbasins delineated automatically using GIS routines. The NJDEP data are based on 14-digit hydrologic unit codes, or HUC14s, for subbasin boundaries (Ellis and Price, 1995; N.J. Department of Environmental Protection, 1996).

Subbasins were delineated for selected points by using GIS routines and a digital elevation model (DEM). The ArcView Spatial Analyst extension AVSWAT2000 was chosen for the delineation of drainage areas for the selected points. The extension allows digitized streams to be defined as preferential flow paths, leading to more accurate subbasin delineation. The methodology for subbasin delineation was divided into three main steps.

The first step was performed using AVSWAT2000 and a 10-meter-resolution DEM. The mainstem was used to define preferential drainage paths and subbasins were automatically delineated for selected points along the mainstem. The preferential drainage paths were a line shapefile derived from county stream layers. A GIS point shapefile contained the location of selected points along the mainstem. DEMs from NJDEP Watershed Management Areas 3 (Pompton, Pequannock, Wanaque, and Ramapo Rivers), 4 (lower Passaic River and Saddle River), and 6 (upper Passaic River and Whippany and Rockaway Rivers) were merged to form a single DEM, which comprised the spatial extent of the entire nontidal Passaic River Basin.

The second step consisted of comparing the automatically delineated subbasin boundaries for selected points with existing subbasin boundaries by overlaying the drainage areas delineated using AVSWAT2000 on the existing HUC14 coverage. There was good agreement between the automatically delineated areas and the HUC14s; however, because automatic delineation is based on gridded data, the boundaries were not as smooth as for the HUC14s. In order to resolve this discrepancy, the HUC14 coverage was edited manually to incorporate the new automatically delineated subbasins. This process increased the resolution of the HUC14 coverage by adding new subbasin boundaries.

The third step consisted of aggregating multiple subbasins that drain to a single point, assigning a unique identifier to the subbasins, and computing the area. This process was performed using the county stream layers as a basis. Large subbasins may include more than one HUC14 drainage area. Drainage areas for subbasins 1-1 and 6-1 were modified to be consistent with USGS delineations. A total of 111 subbasins with a combined area of 286.7 mi^2 were delineated at the resolution needed for the model of the nontidal Passaic River Basin.

Subbasin Flows

There is only one tributary gaging station in the study area, Canoe Brook near Summit (01379530). Partial-record stations exist on a number of other tributaries; however, many drainage areas along the mainstem are ungaged. A simple approach for estimating ungaged subbasin flows was needed. Three methods were considered for estimating continuous flows for tributaries and unchanneled drainage areas. To assess the accuracy of a particular method, total flow mass balance per square mile of aggregate drainage area was computed for gaging stations on the mainstem. (Flow at gages was time lagged, as appropriate, to account for time of concentration.)

The general mass-balance equation is the summation of all major inputs and outputs upstream from a particular gage:

$$Q_{downstream\ gage} - Q_{upstream\ gage} - Q_{tributaries} - Q_{drainage\ areas} - Q_{discharge} + Q_{diversion} = 0. \quad (6)$$

The first method involved estimating flows at partial-record stations using individual measurements and correlation and MOVE.1 regression (Hirsch, 1982) with nearby index gaging stations. Computations of total flow mass balance made using this method indicated that subbasin flows were underestimated, likely because many of the partial-record measurements were made at low-flow sites, which biases results and reduces the accuracy at higher flows.

The second method involved using simulated flows from an existing watershed model that included the study area. This TOPMODEL application (Kennen and others, 2007) inputs precipitation, temperature, ground-water withdrawals, land-surface elevation, and land-surface cover (pervious/impervious) and outputs daily discharges for HUC14 subbasins. Unfortunately, the TOPMODEL simulation did not cover the entire period of the flow model used in this study, so statistical relations between TOPMODEL flows and index-gage flows were used to extend the TOPMODEL results in time. Flows for appropriate TOPMODEL subbasins were compared to flows for 13 index gaging stations using 30 years of record. For example, for rank correlation, the same percentile rank of the best-correlated index-gage flow on that date over the 30 years was applied to the TOPMODEL subbasin flow. Computations of total flow mass balance made using this method indicated that subbasin flows were both under- and overestimated. Better results likely would have been obtained if the TOPMODEL period had covered the entire period of the flow model.

The third method involved estimating flows for ungaged subbasins without partial-record measurements using a drainage-area ratio equation (Perry and others, 2004, p. 18; Sauer, 2002, p. 81; Singh, 1992, p. 86), which determines flows for ungaged subbasins based on flows for comparable gaged subbasins. The method is based on the generally high correlation between discharge and drainage area. The following equation was used to estimate flow for each of the 111 subbasins (excluding Canoe Brook) and includes coefficients that can be adjusted to improve the total flow mass balance:

$$Q_{sb} = C1 * \left(\frac{A_{sb}}{A_{idx}} \right)^{C3} Q_{idx} + C2, \quad (7)$$

where

Q_{sb} = discharge for subbasin,
A_{sb} = drainage area for subbasin,
A_{idx} = drainage area for index gage,
Q_{idx} = discharge at index gage,
$C1$ = multiplicative coefficient,
$C2$ = additive (or subtractive),

and

$C3$ = exponential coefficient.

Coefficients C1 and C2 were assumed to be constant for all subbasins draining to a particular branch for practical reasons. Coefficient C3 was assumed to be 1.0; this coefficient is less important when the drainage areas of subbasins and index gages are of comparable size than when they are different, although differences in underlying geology could still be a factor. A drainage-area ratio in a range from 0.1 to 2.3 was used, which is considered acceptable (for example, Ries and Friesz, 2000, p. 14). Index gages and coefficients were determined during model calibration.

Discharges and Diversions

Discharge and diversion data for October 1999 to November 2003 were collected by both USGS and TRC Omni. Most data were obtained directly from the facility but, when this was not possible, data were derived from NJDEP databases (New Jersey Pollutant Discharge Elimination System Discharge Monitoring Reports, Bureau of Water Allocation Public Water Supply Diversion Reports). The latter NJDEP data were obtained from a provisional New Jersey Water-Transfer database (Domber and Hoffman, 2004). (Limitations associated with the supplemental discharge and diversion data are available from NJDEP in Trenton, N.J.) Daily flows obtained in units of million gallons per day were converted to cubic feet per second (1 Mgal/d equals 1.55 ft^3/s).

There are 25 major point-source discharges and 5 major diversions in the nontidal Passaic River Basin (fig. 3). Discharges and diversions are associated with both municipal and industrial facilities. Flows for most of these facilities (figs. 4a-b) exceed 1 ft^3/s. The Wanaque South intake represents a combined diversion by North Jersey District Water Supply Commission (which also supplies United Water New Jersey) and Passaic Valley Water Commission. Diversions by Marcal Paper, Garden State Paper, and Prime Energy (all pertaining to BWA permit number 4006PS) near Passaic River at Dundee Dam at Clifton were not included in the model because of incomplete data and the expected small effect on the water-quality model.

Values of diurnal variations in discharge and diversion flows are required for modeling purposes (fig. 5). These variations are caused primarily by patterns of water use; for some large diverters, energy costs also play a role. Diurnal variation for North Jersey District Water Supply Commission at Wanaque South for water years 2002 and 2003 was based on the average diurnal variation for the 2 previous water years. Diurnal variation for diversions was based on the limited data obtained from each facility. Because hourly data could not be obtained for most dischargers, diurnal variation was assumed to be similar to that for Livingston Water Pollution Control Facility, which was based on limited data. This assumption ignores differences in facility size, equipment, operation, and other characteristics.

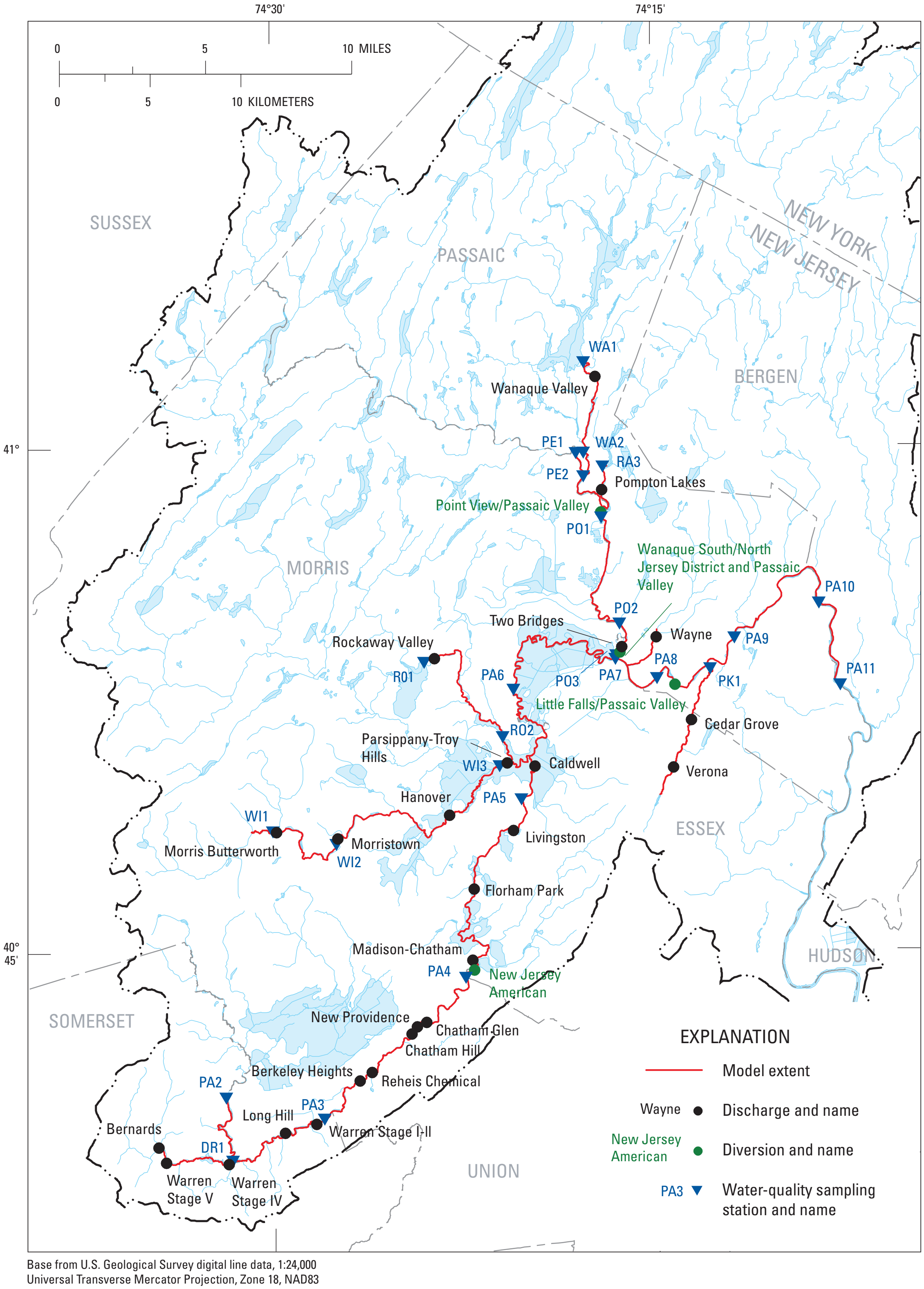
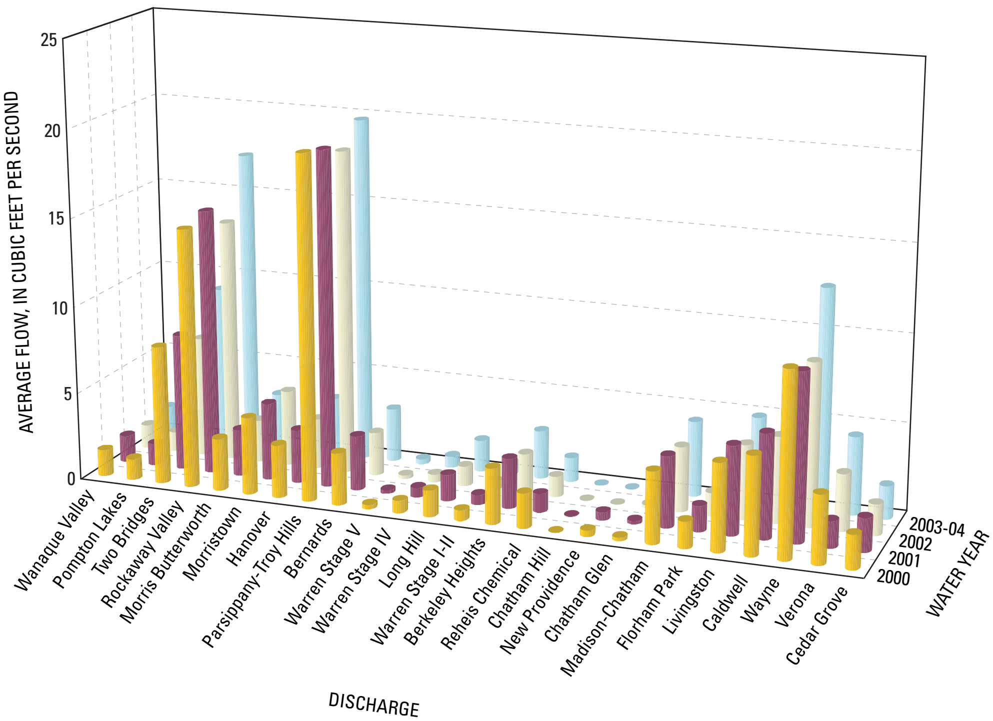


Figure 3. Major discharges and diversions and water-quality sampling stations in the nontidal Passaic River Basin, New Jersey.

(a)



(b)

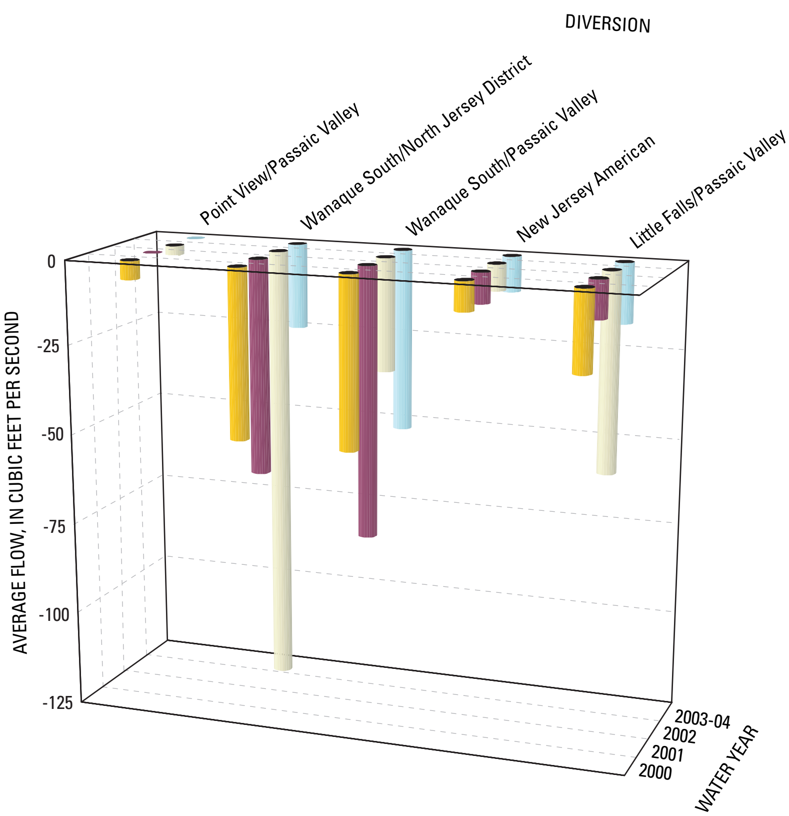


Figure 4. Major (a) discharge and (b) diversion flows in the nontidal Passaic River Basin, New Jersey. (Data obtained from respective facilities.)

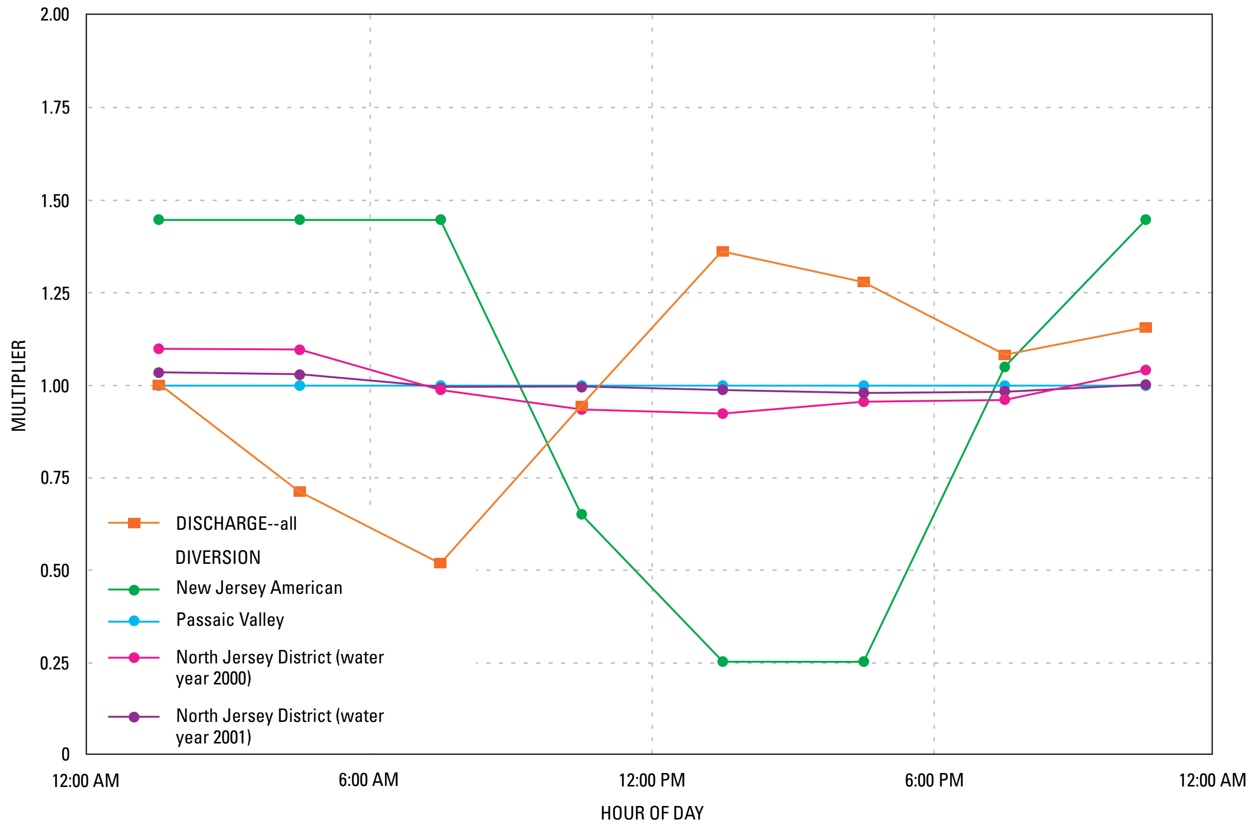


Figure 5. Diurnal variation for discharges and diversions in the nontidal Passaic River Basin, New Jersey.

Simulation of Surface-Water Flow

Water years 2000 through 2003 were selected for simulation of surface-water flow conditions in the nontidal Passaic River Basin. A water year extends from October 1 through September 30 so as to not separate winter stormflows between years, and is designated by the calendar year in which it ends. October and November 2003 (in water year 2004) were simulated with water year 2003 to include the entire period of the water-quality model. These recent years were selected because they cover a broad range of flow conditions, coincide with the timeframe of the water-quality model, and avoid the potential difficulties inherent in obtaining historical discharge and diversion flow data. On the basis of combined data from 12 gaging stations in the study area, discharge averaged 254 ft^3/s in water year 2000, 222 ft^3/s in water year 2001, 74.7 ft^3/s in water year 2002, and 380 ft^3/s in water year 2003, compared to 273 ft^3/s during the periods of record (Reed and others, 2001-04).

Flow Routing Model

Distributed flow routing is a mathematical procedure for predicting the shape and magnitude of a hydrograph at points along a watercourse as well as the time variation of water speed, cross-sectional area, and top width. The simulation of dynamic streamflow movement is based on the St. Venant equations, differential equations of one-dimensional unsteady flow, which are based on flow mass and momentum balances in a one-dimensional open channel (Chapra, 1997). The fully dynamic wave form includes all of the mathematical terms in these equations, but can be unstable and difficult to solve. The dynamic wave form is accurate for a variety of conditions, including mildly sloping channels with slowly rising flood waves, backwater, many tributary inflows, and channel constrictions.

Various simplifications to the momentum equation enable tractable solutions to be achieved; these include the diffusion wave (simpler) and kinematic wave (simplest) forms. The diffusion wave form is generally not accurate for channels with very flat slopes and rapidly rising flood waves, where flow reversals occur, or where the stage-discharge relation is very weak. The kinematic wave form has all of the limitations of the dynamic wave form plus additional restrictions because it ignores the pressure-gradient term as well as the momentum term. For example, the kinematic wave form is not accurate for backwater conditions or when the product of channel slope and time of hydrograph rise is small.

The DAFLOW computer program (Jobson, 1989) was selected for streamflow routing. DAFLOW simulates one-dimensional flow based on the diffusion wave form of the St.

Venant equations. DAFLOW is not fully dynamic because the local and convective acceleration terms are omitted from the momentum balance equation. The resultant flow equation is

$$\frac{\partial Q_s}{\partial t} + C \frac{\partial Q_s}{\partial x} - D_f \frac{\partial^2 Q_s}{\partial x^2} = 0, \qquad (8)$$

where

Q_s = flow under steady conditions,
C = speed of a moving wave,

and

D_f = wave-dispersion coefficient.

DAFLOW routes flow through a system of interconnected upland channels and divides the system into a series of branches that meet at junctions, with each branch divided into a series of subreaches. Each subreach is defined by nodes representing channel cross sections. DAFLOW is accurate for sloped streams, but cannot simulate flow reversals or severe backwater conditions. DAFLOW is intensive in terms of boundary-condition requirements, which makes it reliable. It is practical to apply in a complex river basin because it requires a minimum of channel-geometry data. The use of the diffusion wave form to simulate flow in the Passaic River Basin is justified on the basis of the large scale of the basin and the lack of fine-scale data. For example, the dynamic wave form could closely account for channel variations, but collecting detailed information on such variations is not practical for such a large basin.

DAFLOW uses geomorphic relations to represent channel cross-sectional geometry. Hydraulic-geometry parameters are used in the following equations:

$$A = A0 + A1 * Q_S^{A2}, \qquad (9)$$

where

A = cross-sectional area of flow,
$A0$ = average cross-sectional area at zero flow,
$A1$ = hydraulic-geometry coefficient for area,
$A2$ = hydraulic-geometry exponent for area,

and

$$W = W1 * Q_S^{W2}, \qquad (10)$$

where

W = top width of channel,
$W1$ = hydraulic-geometry coefficient for width,

and

$W2$ = hydraulic-geometry exponent for width.

These empirical relations are based on geomorphic data observed in various locales. Parameter A1 is analogous to parameter W1. Parameters A2 and W2 affect the relation of area and width to flow. Natural streams contain pools and riffles, or inactive and active flow areas, respectively. Parameter A0 applies to the inactive area (dead storage), in contrast to parameters A1 and A2, which apply to the active area (advective flow). For example, values of parameter A0 typically are large upstream from impoundments, such as Beatties Dam at Little Falls. Parameter A0 is not constant with flow; it affects constituent transport (decay and dispersion) but not flow routing, so it could be assumed to equal zero for flow calibration. Because the goal of the TMDL is to address water-quality transport, however, values for parameter A0 must be determined.

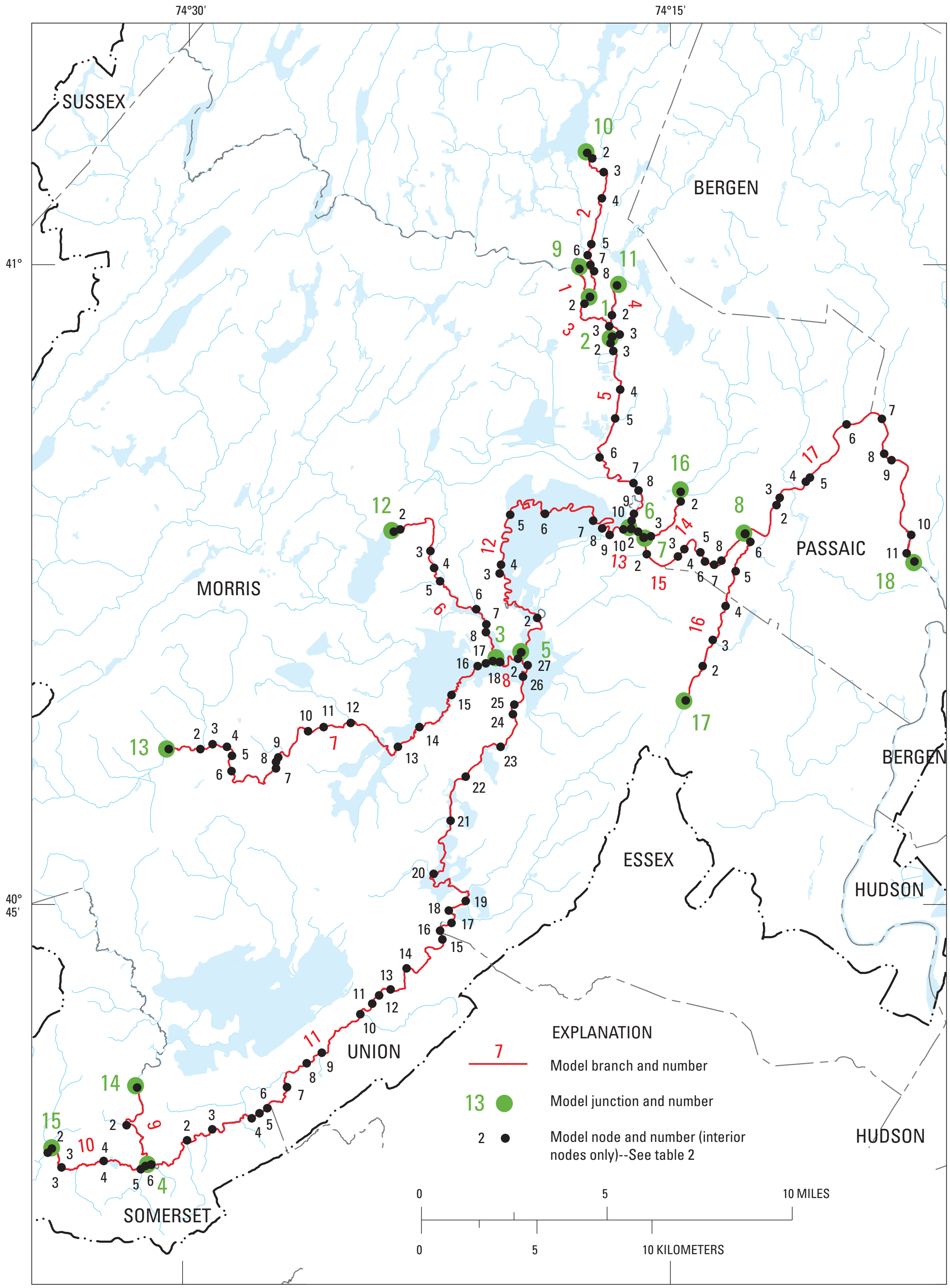
Design

The flow-model network consists of 17 branches, 18 junctions (8 internal), and 145 nodes as shown in (fig. 6; table 2). The model covers 108 total river miles. Nodes were placed at gaging stations, mouths of ungaged tributaries, centroids of unchanneled drainage along the mainstem, and point-source discharges and diversions. A node also was added to represent an off-channel storage boundary condition that was required by two of the validation simulations. Additional nodes were placed at 25 water-quality sampling stations used by the consultant (TRC Omni, 2004, fig. 1). Node density was increased near sampling stations. Node distance along each branch from the upstream end was determined by applying GIS techniques to the 1:24,000 National Hydrography Dataset (USGS, 2004), which is accurate to approximately 40 ft, and checking results against U.S. Army Corps of Engineers (1995) 2-ft-contour flood maps.

Channel slope was computed between gages, between gages and junctions, and between junctions using flood-map elevation and downstream node distance (table 3). The approach was to start simple and add complexity, as needed. Elevation data were derived from paper flood maps and distance between node locations was derived by using GIS. Riverbed slopes were estimated using a constant slope between endpoints. A branch-averaged slope was the most practical design initially, and could be enhanced later, as needed. This approach for determining slopes is appropriate for a large-scale flow model.

The DAFLOW time-step size was 3 hours; the effect of this choice on model sensitivity is discussed farther on. According to guidelines suggested in Jobson and Harbaugh (1999, p. 6), the approximate minimum slope when using a 3-hour time step should be 1 ft/mi. The flow model meets this requirement in most branches.

The flow model was designed to integrate with the water-quality model (TRC Omni, 2007), which uses the Water Quality Analysis Simulation Program, or WASP (Wool and others, 2001). Therefore, subbasin flows were combined to separate nonpoint- from point-source (discharge and diversion) flows. If nonpoint- and point-source flows (which have different concentrations) were in the same node, then a flow-weighted-concentration boundary condition would be needed by WASP for each time step. A maximum 1.5-mi distance between DAFLOW nodes was used to minimize the effect of lumping nonpoint-source flows at nodes. WASP segments had to be created from DAFLOW nodes; network connectivity,



Base from U.S. Geological Survey digital line data, 1:24,000
Universal Transverse Mercator Projection, Zone 18, NAD83

Figure 6. Surface-water model grid of the nontidal Passaic River, New Jersey.

Table 2. Reference information for the surface-water model of the nontidal Passaic River Basin, New Jersey.

[NJPDES, New Jersey Pollutant Discharge Elimination System; BWA, Bureau of Water Allocation; ft^3/s, cubic feet per second; up, upstream; down, downstream; Ave, Avenue; ---, not available or not applicable; shading within table is designed to separate individual model branches]

River	Branch[1]	Node	River mile	Gaging station	Contributing subbasins[2]	Sampling station[3]	Discharge/ diversion[4]	NJPDES/BWA permit number
Pequannock	1	1	0.00	[5]01382800	1-1	PE1	---	---
		2	0.88	---	---	---	---	---
Wanaque	2	1	0.00	01387000	---	WA1	---	---
		2	0.38	---	**2-2**, 2-3	---	---	---
		3	1.09	---	---	---	Wanaque Valley	NJ0053759
		4	1.91	---	2-4	---	---	---
		5	3.33	---	2-5	---	---	---
		6	3.66	---	2-6	---	---	---
		7	4.03	---	2-7	up WA2	---	---
		8	4.31	---	2-8	down WA2	---	---
		9	5.19	---	---	---	---	---
Pequannock	3	1	0.00	---	---	up PE2	---	---
		2	0.19	---	3-2	down PE2	---	---
		3	0.41	---	3-3	---	---	---
		4	1.61	---	---	---	---	---
Ramapo	4	1	0.00	01388000	---	RA3	---	---
		2	0.95	---	---	---	Pompton Lakes	NJ0023698
		3	1.60	---	4-2, **4-3**	---	---	---
		4	1.93	---	---	---	---	---
Pompton	5	1	0.00	---	---	---	---	---
		2	0.19	01388500	---	PO1	Point View/Passaic Valley	BWA 5099
		3	0.41	---	5-2, **5-3**	---	---	---
		4	1.61	---	5-4	---	---	---
		5	2.41	---	5-5	---	---	---
		6	3.63	---	5-6	---	---	---
		7	5.40	---	5-7	up PO2	---	---
		8	5.64	---	**5-8**, 5-9, 5-10	down PO2	---	---
		9	6.44	---	---	---	Two Bridges	NJ0029386
		10	6.63	---	---	---	Wanaque South Intake[6]	
		11	6.87	---	---	PO3	---	---
Rockaway	6	1	0.00	01381000	---	RO1	---	---
		2	0.20	---	---	---	Rockaway Valley	NJ0022349
		3	2.16	---	6-2, **6-3**	---	---	---
		4	2.68	---	6-4	---	---	---
		5	3.24	---	6-5	---	---	---
		6	4.84	---	6-6	---	---	---
		7	5.37	---	6-7	up RO2	---	---
		8	5.59	---	6-8	down RO2	---	---
		9	6.65	---	---	---	---	---
Whippany	7	1	0.00	01381400	---	WI1	---	---
		2	1.13	---	---	---	Morris Butterworth	NJ0024911
		3	1.43					
		4	1.92	---	7-2, **7-3**	---	---	---
		5	2.22					
		6	2.72	---	7-4	---	---	---
		7	4.74	---	7-5	up WI2	---	---
		8	4.95	01381500	**7-6**, 7-7	down WI2	---	---
		9	5.17	---	---	---	Morristown	NJ0025496
		10	6.69	---	7-8	---	---	---
		11	7.16	---	7-9	---	---	---
		12	8.00	---	7-10	---	---	---
		13	10.02	---	**7-11**, 7-12	---	---	---
		14	11.05	---	---	---	Hanover	NJ0024902
		15	12.69	---	7-13	---	---	---

Table 2. Reference information for the surface-water model of the nontidal Passaic River Basin, New Jersey.—Continued

[NJPDES, New Jersey Pollutant Discharge Elimination System; BWA, Bureau of Water Allocation; ft^3/s, cubic feet per second; up, upstream; down, downstream; Ave, Avenue; ---, not available or not applicable; shading within table is designed to separate individual model branches]

River	Branch[1]	Node	River mile	Gaging station	Contributing subbasins[2]	Sampling station[3]	Discharge/ diversion[4]	NJPDES/BWA permit number
		16	14.14	---	7-14	---	---	---
		17	14.39	01381800	**7-15**, 7-16	WI3	---	---
		18	14.58	---	---	---	Parsippany-Troy Hills	NJ0024970
		19	14.80	---	---	---	---	---
Rockaway	8	1	0.00	---	---	---	---	---
		2	0.94	---	8-2	---	---	---
		3	1.25	---	---	---	---	---
Passaic	9	1	0.00	01379000	---	PA2	---	---
		2	1.47	---	9-2	---	---	---
		3	3.38	---	---	---	---	---
Dead	10	1	0.00	---	10-1	---	---	---
		2	0.21	---	---	---	Bernards	NJ0022845
		3	0.88	---	---	---	Warren Stage V	NJ0050369
		4	2.20	---	10-3, **10-4**, 10-5	---	---	---
		5	3.44	---	---	---	Warren Stage IV	NJ0022497
		6	3.60	---	10-6	up DR1	---	---
		7	3.77	---	---	down DR1	---	---
Passaic	11	1	0.00	---	---	---	---	---
		2	1.60	---	**11-2**, 11-3, 11-4	---	---	---
		3	2.63	---	---	---	Long Hill	NJ0024465
		4	4.18	---	---	---	Warren Stage I-II	NJ0022489
		5	4.45	---	11-5	up PA3	---	---
		6	4.70	---	11-6	down PA3	---	---
		7	5.71	---	**11-7**, 11-8, 11-9	---	---	---
		8	6.83	---	---	---	Berkeley Heights	NJ0027961
		9	7.41	---	---	---	Reheis Chemical	NJ0002551
		10	9.19	---	**11-10**, 11-11, 11-12, 11-13	---	---	---
		11	9.76	---	---	---	Chatham Hill	NJ0020281
		12	10.08	---	---	---	New Providence[7]	NJ0021636
		13	10.51	---	---	---	Chatham Glen	NJ0052256
		14	11.50	01379500	11-14	---	---	---
		15	13.39	---	11-15	up PA4	---	---
		16	13.64	---	**11-16**, 11-17, 11-18	down PA4	---	---
		17	14.06	---	---	---	New Jersey American	BWA 5008
		18	14.51	---	---	---	Madison-Chatham	NJ0024937
		19	15.08	[8]01379530	---	---	---	---
		20	17.17	---	**11-20**, 11-21	---	---	---
		21	19.21	---	---	---	Florham Park	NJ0025518
		22	20.67	---	**11-22**, 11-23	---	---	---
		23	22.18	---	---	---	Livingston	NJ0024511
		24	23.28	---	11-24	up PA5	---	---
		25	23.58	---	11-25	down PA5	---	---
		26	24.49	---	**11-26**, 11-27	---	---	---
		27	25.03	---	---	---	Caldwell	NJ0020427
		28	25.52	---	---	---	---	---
Passaic	12	1	0.00	---	---	---	---	---
		2	1.37	01381900	12-2	---	---	---
		3	4.07	---	12-3	up PA6	---	---
		4	4.31	---	12-4	down PA6	---	---
		5	6.33	---	12-5	---	---	---
		6	8.68	---	12-6	---	---	---
		7	10.85	---	12-7	---	---	---

Table 2. Reference information for the surface-water model of the nontidal Passaic River Basin, New Jersey.—Continued

[NJPDES, New Jersey Pollutant Discharge Elimination System; BWA, Bureau of Water Allocation; ft^3/s, cubic feet per second; up, upstream; down, downstream; Ave, Avenue; ---, not available or not applicable; shading within table is designed to separate individual model branches]

River	Branch[1]	Node	River mile	Gaging station	Contributing subbasins[2]	Sampling station[3]	Discharge/ diversion[4]	NJPDES/BWA permit number
		[9]8	11.90	---	---	---	---	---
		9	12.34	---	12-8	---	---	---
		10	12.84	---	12-9	up PA7	---	---
		11	13.05	---	---	down PA7	---	---
Passaic	13	1	0.00	---	---	---	---	---
		2	0.20	---	13-2	---	---	---
		3	0.41	---	---	---	---	---
Singac	14	1	0.00	---	**14-1**, 14-2	---	---	---
		2	0.28	---	---	---	Wayne	NJ0028002
		3	1.71	---	14-3	---	---	---
		4	1.91	---	---	---	---	---
Passaic	15	1	0.00	---	---	---	---	---
		2	0.44	---	15-2	---	---	---
		3	1.49	---	15-3	up PA8	---	---
		4	1.76	---	15-4	down PA8	---	---
		5	2.61	---	**15-5**, 15-6	---	---	---
		6	2.89	---	---	---	Little Falls/Passaic Valley	BWA 5099
		7	3.15	---	15-7	---	---	---
		8	3.44	01389500	15-8	---	---	---
		9	4.44	---	---	---	---	---
Peckman	16	1	0.00	---	**16-1**, 16-2	---	---	---
		2	1.13	---	---	---	Verona	NJ0024490
		3	1.94	---	**16-3**, 16-4	---	---	---
		4	3.09	---	---	---	Cedar Grove	NJ0025330
		5	4.19	---	16-5	---	---	---
		6	5.24	---	16-6	up PK1	---	---
		7	5.53	---	---	down PK1	---	---
Passaic	17	1	0.00	---	---	---	---	---
		2	1.61	---	17-2	up PA9	---	---
		3	1.85	---	17-3	down PA9	---	---
		4	2.85	---	17-4	---	---	---
		5	3.09	---	17-5	---	---	---
		6	5.12	---	17-6	---	---	---
		7	6.24	---	17-7	---	---	---
		8	7.26	---	17-8	up PA10	---	---
		9	7.55	---	17-9	down PA10	---	---
		10	10.11	---	17-10	---	---	---
		11	10.62	---	17-11	up PA11	---	---
		12	10.94	[10]01389890	---	down PA11	---	---

[1] Locations shown in figure 6.

[2] Locations shown in figure 2, except for subbasin 1-1. Subbasins listed in same row are combined in figure 2 using label shown in bold. Flow estimates for contributing subbasins listed in table 4.

[3] For water-quality sample collection (TRC Omni Environmental Corp., 2004).

[4] Locations shown in figure 3. Flow is greater than 1 ft^3/s.

[5] Includes subbasin flow from intervening drainage area between stations 01382500 and 01382800.

[6] Diversion by North Jersey District (BWA 5329) and Passaic Valley (BWA 5099).

[7] Discharges to Berkeley Heights.

[8] Gage in contributing subbasin 11-19. Includes diversion by New Jersey American (BWA 5008).

[9] Model storage balance reservoir.

[10] Miscellaneous site.

Table 3. Channel-slope data for the surface-water model of the nontidal Passaic River, New Jersey.

[ft, foot; mi, mile; ---, not available or not applicable]

River	Branch[1]	Node	Junction	Gaging station	Elevation[2] (ft)	Distance[3] (ft)	Distance (mi)	Slope (ft/ft)	Slope (ft/mi)
Pequannock	1			01382800	195	---	---	---	---
			1	---	179	4659	0.88	3.434E-03	18.13
Wanaque	2			01387000	222	---	---	---	---
			1	---	179	27398	5.19	1.569E-03	8.28
Pequannock	3		1	---	179	---	---	---	---
			2	---	171	10266	1.94	7.792E-04	4.11
Ramapo	4			01388000	179	---	---	---	---
			2	---	171	10174	1.93	7.864E-04	4.15
Pompton	5		2	---	171	---	---	---	---
		2		01388500	169	992	0.19	2.016E-03	10.64
			6	---	161	35267	6.68	2.268E-04	1.20
Rockaway	6			01381000	197	---	---	---	---
			3	---	168.5	35092	6.65	8.122E-04	4.29
Whippany	7			01381400	317	---	---	---	---
		8		01381500	263	26144	4.95	2.066E-03	10.91
		17		01381800	169.5	49823	9.44	1.877E-03	9.91
			3	---	168.5	2162	0.41	4.625E-04	2.44
Rockaway	8		3	---	168.5	---	---	---	---
			5	---	167.5	6587	1.25	1.518E-04	0.80
Passaic	9			01379000	219	---	---	---	---
			4	---	207	17861	3.38	6.719E-04	3.55
Dead	10		15	---	218	---	---	---	---
			4	---	207	18792	3.56	5.853E-04	3.09
Passaic	11		4	---	207	---	---	---	---
		14		01379500	195	60707	11.50	1.977E-04	1.04
			5	---	167.5	74022	14.02	3.715E-04	1.96
Passaic	12		5	---	167.5	---	---	---	---
		2		01381900	166.5	7245	1.37	1.380E-04	0.73
			6	---	161	61649	11.68	8.922E-05	0.47
Passaic	13		6	---	161	---	---	---	---
		2		01389005	160	1045	0.20	9.573E-04	5.05
			7	---	159	1107	0.21	9.035E-04	4.77
Singac	14		16	---	169	---	---	---	---
			7	---	159	10088	1.91	9.912E-04	5.23
Passaic	15		7	---	159	---	---	---	---
		8		01389500	123	18181	3.44	1.980E-03	10.45
			8	---	121	5255	1.00	3.806E-04	2.01
Peckman	16		17	---	340	---	---	---	---
			8	---	121	29204	5.53	7.499E-03	39.60
Passaic	17		8	---	121	---	---	---	---
				01389890	27	57744	10.94	1.628E-03	8.60

[1] Locations shown in figure 6.

[2] From U.S. Army Corps of Engineers (1995) 2-foot-contour flood maps.

[3] Discussed in “Flow Routing Model Design” section of report.

model boundaries, and unit conversions had to be assigned; DAFLOW outputs had to be interpolated to a time step used in WASP; and a WASP hydrodynamic file had to be written. For example, flow output was modified to compute flow volumes in segments. In order to ensure stability and accuracy in WASP, the minimum node distance determines the time-step size (3 min). The difference in time step between DAFLOW and WASP was resolved by linear interpolation. A refined version of the DAFLOW model, based on the same input data, was developed by TRC Omni (2007). A maximum 1,500-ft node distance was used in the refined model to avoid numerical dispersion in WASP.

Boundary and Initial Conditions

Initial estimates for hydraulic-geometry parameters were computed by using the DAFLOW accessory computer program CEL. CEL is designed to help solve non-linear equations 9 and 10. Option 2 was selected to compute parameters from lag times of hydrographs. The Manning equation, which empirically relates flow resistance to channel characteristics, is used in CEL. A Manning's roughness coefficient (n) of 0.05 was input based on average channel characteristics. The assignment of one Manning's roughness coefficient for the entire Passaic River Basin is reasonable because it is not a model input and is used only to generate initial estimates of hydraulic-geometry parameters prior to model calibration. Other inputs to CEL include branch-averaged top width from USGS streamflow measurements at gaging stations. Because only wading measurements were used, results obtained with CEL may be underestimated.

Flow time series for boundary gaging stations, tributaries and unchanneled drainage along the mainstem, and point-source discharges and diversions were input to the model through 112 boundary conditions. These individual time series comprise most of the DAFLOW input file. Because upstream gaging stations do not exist on branches 10, 14, and 16 (fig. 6), upstream flows had to be estimated for these branches using the drainage-area ratio method. Initial conditions for flow were chosen to be consistent with observed flows at gages at the start of a simulation. The duration of initial conditions was less than 2 days in most branches.

Quantitative and Qualitative Measures of Model Accuracy

Flow calibration and validation were evaluated both qualitatively and quantitatively. Qualitative calibration and validation were done visually by comparing observed and simulated hydrographs to evaluate flood-wave speed and attenuation and spread. (Attenuation/spread affects the diffusion and roundness of peaks and troughs.) Quantitative calibration and validation were done by computing various mean and relative error measures for the water year. Mass balance at gage locations was evaluated by minimizing the percent mean error (%ME) in residuals. A residual is the difference between a simulated and observed value. Observed flows at gaging stations represent values at the end of model time steps, whereas simulated flows at corresponding node locations represent average values over model time steps. Although positive and negative residuals can offset each other, the measure does provide information about model bias. A balance in the overall error was sought because the model tended to underpredict flow upstream and overpredict downstream. The results presented herein achieve a balance in overall error.

Model fit at gage locations was evaluated by minimizing mean percent absolute error (M%AE) and root mean square error (RMSE) and maximizing a relative error measure called the coefficient of determination (RSQ). Another relative error measure, the modified index of agreement (MIOA), also was tested. The MIOA is thought to be more robust than RSQ (Legates and McCabe, 1999); however, differences between RSQ and MIOA typically were less than 15 percent and, therefore, RSQ was considered to be an acceptable measure. Associated error equations are

$$\%ME = \frac{\left[1/n \sum_{i=1}^{n} (Q_s - Q_o)_i\right]}{\bar{Q}_o} * 100, \tag{11}$$

$$M\%AE = \left[1/n \sum_{i=1}^{n} \left(\frac{|(Q_s - Q_o)|}{Q_o}\right)_i\right] * 100, \tag{12}$$

$$RMSE = \left[1/n \sum_{i=1}^{n} (Q_s - Q_o)_i^2\right]^{0.5}, \tag{13}$$

and

$$RSQ = \left[\frac{\sum_{i=1}^{n} (Q_o - \bar{Q})_i \; (Q_s - \bar{Q})_i}{\left[\sum_{i=1}^{n} (Q_o - \bar{Q})_i^2\right]^{0.5} \left[\sum_{i=1}^{n} (Q_s - \bar{Q})_i^2\right]^{0.5}}\right]^2, \tag{14}$$

where

Q_s = simulated flow,
Q_o = observed flow,
$\bar{Q}$ = mean observed or simulated flow,
i = summation index,

and

n = number of time steps.

The quality of the gaging-station flow data affects model calibration and validation results. Individual gage accuracy was discussed earlier in this report. Unit values data (15 min) for gages integrated over 3 hours could have been used for calibration and validation; however, daily values data were used instead because these data are quality-assured in the USGS National Water Information System (NWIS) database. Daily values data are the more reliable and complete flow data set available. For example, unit values may have short periods of missing record as a result of equipment problems in the field. The missing daily values record is estimated during subsequent data analysis and computation. Only qualitative calibration and validation was performed for the Passaic River at Dundee Dam at Clifton (01389890) because observed flows had to be estimated for this location, as described earlier. The observed data represent a “best estimate” of flow. Accordingly, the calibration at this location should be interpreted with caution.

Only daily data were available from facilities for discharges and diversions, and some of these data were incomplete and had to be assumed. An estimated diurnal variation was applied to these data, but the computed fine-time-scale data are uncertain. As a result, the model uses a 3-hour time step with flow results integrated over 24 hours for comparison with observed data. The only aspect of the model that might benefit from a finer time scale is the mixing algorithm, but any potential benefit would still depend on the availability of hourly discharge and diversion data. Calibrating the model based on average daily flows is a valid approach. In fact, given the uncertainty and variability associated with many boundary conditions, it can be argued that using average daily flows is the most appropriate temporal resolution.

Model Sensitivity

Certain model inputs affect model accuracy more than others and the effect depends on the sensitivity of model results to these inputs. Flow routing was relatively insensitive to changes in the hydraulic-geometry parameters because the model is controlled mainly by the many boundary conditions, the fact that hydrograph rise and fall in the Passaic River Basin are relatively slow, and the scale and timeframe of the model. If flow is steady, discharge will be constant at all locations, except where step increases in discharge occur, such as where tributaries enter the river, no matter what parameter values are used. In this case, flow routing is totally independent of the parameters, whereas area, depth, and velocity are quite sensitive to them. If flow varies gradually, the effect of flood waves is small, and the system is nearly always in steady state. When discharge changes gradually, detection of errors in wave timing is difficult.

Parameter insensitivity also may be related to the way DAFLOW computes the wave-dispersion coefficient, which is inversely proportional to channel width and slope, and the model limitation that dispersion cannot occur across model junctions. If slopes are flat so that the dispersive length scale (D_L), which is directly proportional to the wave-dispersion coefficient, is large and the branches are relatively short, one wave may quickly traverse an entire branch. Therefore, adjusting the width does not affect D_L because D_L is already longer than the branch length. The model was slightly more sensitive to area than to width hydraulic-geometry parameters.

The breaks in elevation at Little Falls and Great Falls (fig. 1) were not taken into account in the determination of the channel slope. To test the sensitivity of channel slope, the water year 2001 simulation (discussed farther on) was reconfigured and run with a modified slope in branches 15 and 17 to account for the breaks in elevation at Little Falls and Great Falls, respectively. Corresponding flatter slopes were used elsewhere in these branches. Simulation results in these two branches were virtually identical to those based on a reach-averaged slope.

DAFLOW only uses the slope to compute the wave-dispersion coefficient. Slope is not related to wave speed and water velocity. Therefore, slope affects only the rate at which a mound of water in the channel dissipates (the rate at which a peak attenuates). The rate of attenuation of the peak with distance also depends on the wave speed, which has a greater effect than the wave-dispersion coefficient. Given the broad hydrograph peaks in the Passaic River Basin, the wave-dispersion coefficient has little effect on peak attenuation; thus, slope is relatively unimportant. Also, slope has less effect in short reaches because the wave attenuates over the entire reach for every time step, so changes in the wave-dispersion coefficient have little effect. The dissipation of the mound of water in the Passaic River Basin is calibrated reasonably. As a result of not including the two waterfalls in the model, the wave timing may be slightly inaccurate because slopes in those reaches are incorrect, but the total volume of flow within a 1- or 2-day period remain the same. From a water-quality perspective, the wave propagation is minor compared with the total volume of flow.

In contrast, the model was sensitive to changes made to the drainage-area ratio equations (discussed farther on) and time step size. A 3-hour time-step size was used in the model because numerical oscillations (instability) were seen in simulated hydrographs for certain calibration gages when a smaller time step was used. This result is likely caused by accuracy limitations associated with DAFLOW (Jobson and Harbaugh, 1999, p. 5), such as the minimum ratio between advection and dispersion and restrictions relating time-step size to channel slope. The computation of the minimum ratio between advection and dispersion is a function of the time-step size, flow, width, slope, hydraulic-geometry parameters, and whether flow is increasing or decreasing with time. These variables are changing constantly. As long as the computed flows vary smoothly with time, this is not a problem.

An overbank flow simulation also was tested using a preliminary version of the model (May, 1998), and results matched the observed data fairly well, although calibration was not required for overbank flow. Graphs of measured discharge as a function of width at gaging stations helped to determine overbank flow conditions. A formal sensitivity analysis was done to evaluate the mixing algorithm that is discussed farther on.

Calibration of Flow Model

The flow-routing model must be able to simulate accurately a range of flow conditions. Low flows are affected primarily by discharges and diversions, whereas medium and high flows are affected primarily by flooding. Inaccuracy of discharge/diversion data is more important at low flows than high flows. Temporal patterns of runoff also vary with frontal storms that typically occur in the non-growing season and convective storms that typically occur in the growing season.

The model simulates flow under all flow conditions. The target flow range for the Passaic River Basin nutrient TMDL is moderate (medium to low) flow conditions. The model was calibrated over the entire flow range and gave the best results for moderate flows, but did a reasonable job at other flows. For example, even though the cross-sectional formulation cannot represent overbank flows, the model yielded acceptable results at very high flows. From a TMDL perspective, the cross-sectional parameters are less important during overbank flows.

The first step in model calibration was to compare observed and simulated flow mass balance (volume). Simulated mass balance was calibrated to observed mass balance by adjusting coefficients in the drainage-area ratio equations by trial and error. All ungaged subbasins associated with a particular branch were adjusted in the same way to make the procedure practical. The next step in model calibration was to ensure a realistic representation of channel cross-sectional geometry. The final step in model calibration was to evaluate model fit at mainstem gaging stations by comparing simulated and observed hydrographs, flow-duration curves, and graphs of discharge-velocity-depth. Results of the calibration of mass balance and fit are discussed farther on.

Ungaged Subbasin Flows

A drainage-area ratio method, applied to estimate flows in ungaged subbasins and some boundary flows of the Passaic River Basin, also was subject to calibration. The method was applied to estimate flows in 287 mi^2, or 35.7 percent, of the drainage basin (fig. 2). The method estimates subbasin flows based on data from index gages and coefficients used in equations for each subbasin, as described earlier. The method has strengths and weaknesses. Its main strength is its robustness; it provides a good overall estimate of flows. Its main weakness is its dependency on data from index gages in basins whose characteristics may differ from those of the basin for which flow is being estimated.

Index gages were selected as follows. All available gages in northeastern New Jersey were reviewed for use as index gages. Many gages had unique complications due to the effects of regulation or other factors; the best available gages were identified. To help select a particular index gage for a drainage-area ratio equation, daily flows for index gages were correlated for the period of this study, October 1999 to November 2003. This multi-year approach for selecting index gages allowed the effect of dry and wet seasons on flow to be captured.

Channel slope, percent storage (from land-use data), percent impervious surface, and soil permeability for the drainage area of each ungaged subbasin were determined using GIS data and ArcMap Spatial Analyst. Branch-averaged values also were used to simplify the analysis. Values for the same characteristics were also determined for the index gages. The difference in value was computed for each characteristic between each index gage, as well as for proximity and drainage area, and the difference was correlated with correlated daily gage flows. The difference in values between each index gage and each branch was then computed. For each branch, a rank- (for each gage) weighted (to account for the best correlated characteristics) sum (of characteristics) was computed. The lowest rank-weighted sums indicated the best index gages to use for a particular drainage-area ratio equation. Information on subbasins, index stations, and resulting equations is listed in table 4. Additional details can be found in unpublished files available at the USGS Water Science Center in West Trenton, N.J.

Because of error in flow data and the incomplete representation of basin characteristics, this methodology could be used only as a guide in selecting index gages--that is, the best choice did not always result in the best model fit at gaging stations. For example, the selection of index gage could have incorporated additional criteria, such as flashiness, climate, elevation, and ground-water components (for example, geology). Coefficients in equation 7 were calibrated by trial and error; resulting values are shown in table 4. The calibrated values account for a wide range of flows. Observed total flow mass balance at downstream gage locations indicated that associated upstream subbasin flows were reasonable.

Channel Cross-Section Geometry

Hydraulic-geometry parameters were calibrated using a combination of approaches, including (1) assuming values based on empirical data; (2) using DAFLOW accessory computer program FLWOPT to optimize values; (3) matching values to archived USGS streamflow and dye-tracer data; (4) matching values to cross-section surveys, various gage data, and dye-tracer data; and (5) adjusting values in order to improve water-quality-model calibration.

The first three approaches were implemented by USGS and provided initial parameter estimates. The first approach was based on tabulated values for parameters A2 and W2 (equations 9 and 10) given in Jobson (2000). The second approach involved using the FLWOPT program to adjust hydraulic-geometry values by semiautomatically perturbing parameter values up or down in a user-driven procedure to minimize the root mean square error between simulated and observed flows. Calibration of parameters A1 and W1 (equations 9 and 10) was attempted using FLWOPT, but the model was not sensitive to the parameter adjustments, as was discussed earlier.

The third approach was based on archived streamflow data collected by the USGS. Average channel width for an average flow could be determined at gaging stations. Parameter W1 was computed by using equation 10 and assuming a value for parameter W2. Dye-tracer data were available for USGS time-of-travel tests conducted during 1964-75 (Horwitz and Anderson, 1966; Anderson and Faust, 1973; and unpublished files available at the USGS Water Science Center in

Table 4. Flow estimates for contributing subbasins in the surface-water model of the nontidal Passaic River Basin, New Jersey.

[mi^2, square miles; Ars., Arsenal; Q, discharge; ---, not available or not applicable]

River	Subbasin number[2] and drainage area A_{sb} (mi^2)													Index gaging station			Equation coefficients[1]	
														Number	Name	Drainage area A_{idx} (mi^2)	C1	C2
Pequannock	1-1	---	---	---	---	---	---	---	---	---	---	---	---	01384500	Ringwood Creek near Wanaque	19.1	1.3	0.9
	20.2	---	---	---	---	---	---	---	---	---	---	---	---					
Wanaque	**2-2**	2-3	2-4	2-5	2-6	2-7	2-8	---	---	---	---	---	---	01384500	Ringwood Creek near Wanaque	19.1	1.3	0.9
	6.07	0.40	0.82	0.49	8.41	0.16	0.48	---	---	---	---	---	---					
Pequannock	3-2	3-3	---	---	---	---	---	---	---	---	---	---	---	01384500	Ringwood Creek near Wanaque	19.1	1.3	0.9
	0.05	2.69	---	---	---	---	---	---	---	---	---	---	---					
Ramapo	4-2	**4-3**	---	---	---	---	---	---	---	---	---	---	---	01384500	Ringwood Creek near Wanaque	19.1	1.3	0.9
	0.47	0.68	---	---	---	---	---	---	---	---	---	---	---					
Pompton	5-2	**5-3**	5-4	5-5	5-6	5-7	**5-8**	5-9	5-10	---	---	---	---	01381400	Whippany River near Morristown	14.0	1.5	0.4
	0.08	0.20	2.27	0.73	13.08	6.79	0.13	0.74	0.14	---	---	---	---					
Rockaway	6-2	**6-3**	6-4	6-5	6-6	6-7	6-8	---	---	---	---	---	---	01379773	Green Pond Brook at Picatinny Ars.	7.65	0.7	-0.8
	0.10	9.21	0.43	1.08	3.72	0.27	0.56	---	---	---	---	---	---					
Whippany	7-2	**7-3**	7-4	7-5	**7-6**	---	---	---	---	---	---	---	---	01381400	Whippany River near Morristown	14.0	0.8	0.9
	1.15	8.59	0.87	3.90	0.06	---	---	---	---	---	---	---	---					
	7-7	7-8	7-9	7-10	**7-11**	7-12	7-13	7-14	**7-15**	7-16	---	---	---	01379773	Green Pond Brook at Picatinny Ars.	7.65	1.5	-0.8
	0.07	2.12	0.33	5.33	11.80	0.92	1.16	17.29	0.05	0.89	---	---	---					
Rockaway	8-2	---	---	---	---	---	---	---	---	---	---	---	---	01379773	Green Pond Brook at Picatinny Ars.	7.65	0.7	-0.8
	0.55	---	---	---	---	---	---	---	---	---	---	---	---					
Passaic	9-2	---	---	---	---	---	---	---	---	---	---	---	---	01379000	Passaic River near Millington	55.4	1.2	0.0
	2.40	---	---	---	---	---	---	---	---	---	---	---	---					
Dead	10-1	10-3	**10-4**	10-5	10-6	---	---	---	---	---	---	---	---	01379000	Passaic River near Millington	55.4	1.2	0.0
	13.12	0.57	3.10	3.85	0.14	---	---	---	---	---	---	---	---					
Passaic	**11-2**	11-3	11-4	11-5	11-6	**11-7**	11-8	11-9	**11-10**	11-11	11-12	11-13	11-14	01379000	Passaic River near Millington	55.4	1.2	0.0
	3.30	2.47	2.50	0.93	0.06	1.51	1.30	1.13	6.51	0.46	0.16	0.29	0.85					

Table 4. Flow estimates for contributing subbasins in the surface-water model of the nontidal Passaic River Basin, New Jersey.—Continued

[mi², square miles; Ars., Arsenal; Q, discharge; ---, not available or not applicable]

River	Subbasin number[2] and drainage area A_{sb} (mi²)													Index gaging station			Equation coefficients[1]	
														Number	Name	Drainage area A_{idx} (mi²)	C1	C2
	11-15	**11-16**	11-17	11-18	---	---	---	---	---	---	---	---	---	01379000	Passaic River near Millington	55.4	0.7	-0.8
	2.23	0.06	0.60	0.21	---	---	---	---	---	---	---	---	---					
	11-19	---	---	---	---	---	---	---	---	---	---	---	---	[3]01379530	Canoe Brook near Summit	11.0	---	---
	12.19	---	---	---	---	---	---	---	---	---	---	---	---					
	11-20	11-21	**11-22**	11-23	11-24	11-25	**11-26**	11-27	---	---	---	---	---	01379000	Passaic River near Millington	55.4	0.7	-0.8
	8.27	2.40	3.26	2.40	0.85	0.31	4.78	1.47	---	---	---	---	---					
Passaic	12-2	---	---	---	---	---	---	---	---	---	---	---	---	01379000	Passaic River near Millington	55.4	0.7	-0.8
	11.66	---	---	---	---	---	---	---	---	---	---	---	---					
	12-3	12-4	12-5	12-6	12-7	12-8	12-9	---	---	---	---	---	---	01381400	Whippany River near Morristown	14.0	1.5	0.4
	2.47	0.09	1.80	2.02	2.93	1.44	0.59	---	---	---	---	---	---					
Passaic	13-2	---	---	---	---	---	---	---	---	---	---	---	---	01381400	Whippany River near Morristown	14.0	1.0	0.0
	0.14	---	---	---	---	---	---	---	---	---	---	---	---					
Singac	**14-1**	14-2	14-3	---	---	---	---	---	---	---	---	---	---	01381400	Whippany River near Morristown	14.0	1.0	0.0
	8.40	1.87	0.89	---	---	---	---	---	---	---	---	---	---					
Passaic	15-2	15-3	15-4	**15-5**	15-6	15-7	15-8	---	---	---	---	---	---	01381400	Whippany River near Morristown	14.0	1.0	0.0
	1.83	1.01	0.71	1.30	0.67	0.14	0.92	---	---	---	---	---	---					
Peck-man	**16-1**	16-2	**16-3**	16-4	16-5	16-6	---	---	---	---	---	---	---	01390500	Saddle River at Ridgewood	21.6	1.0	0.0
	2.70	1.56	0.79	2.50	0.98	1.46	---	---	---	---	---	---	---					
Passaic	17-2	17-3	17-4	17-5	17-6	17-7	17-8	17-9	17-10	17-11	---	---	---	01390500	Saddle River at Ridgewood	21.6	1.0	0.0
	2.66	0.12	9.55	0.13	11.52	5.46	0.54	1.06	4.59	1.43	---	---	---					

[1] Flow estimated by using drainage-area ratio equation: $Q_{sb} = C1 * (A_{sb}/A_{idx})^{C3} * Q_{idx} + C2$, in cubic feet per second. Coefficient C3 was set equal to 1.

[2] Locations shown in figure 2, except for subbasin 1-1. Subbasins listed in same row are combined in figure 2 using label shown in bold.

[3] Gage in contributing subbasin 11-19. Intervening drainage area below gage is 1.01 mi². Includes diversion by New Jersey American.

West Trenton, N.J.). Rhodamine B and WT dye tracers were used in these tests. Many of the dye tests were conducted during steady flow conditions. (If discharge at the time of a dye study was not available, it was obtained from the NWIS database.) Approximately 66 tests covering 11 of the 17 model branches were available. No dye-tracer data were available for branches 1-4, 14, and 16; parameter values for these branches were inferred from nearby or similar streams with dye-tracer data. Tests did not necessarily cover all of a particular branch, but results were assumed to apply to the entire branch. Computation of area parameters was possible for branches with dye-tracer data. Using two dye tests done in the same branch, these parameters could be computed by solving simultaneous equations using equation 9. For each study, discharge was divided by the velocity of the peak dye concentration to compute the total cross-sectional area. By assuming a value for parameter A2, one equation could be subtracted from the other to eliminate parameter A0, thereby allowing parameter A1 to be computed. Parameter A1 could then be substituted into either of the two equations to compute parameter A0. (Additional information regarding parameter A0 is discussed farther on.)

The fourth approach was implemented by TRC Omni (2007) to refine the above parameter estimates, which were not sufficient for the water-quality model. This approach involved three components based on the type of data used. The first component required developing rating curves and calibrating the hydraulic-geometry parameters to both the rating curve and the physical cross section. This involved comparing the relations between computed flow and cross-sectional area and between depth and width to data from cross-section surveys made at TRC Omni water-quality sampling stations and USGS gaging stations (second component). This approach was developed so these parameters could be represented for a variety of flows using the limited data available. USGS provided data for all types of surface-water stations and TRC Omni made field surveys at water-quality-sampling station locations. The field surveys were performed in order to ensure adequate data to calibrate the cross-sectional parameters. This approach consisted of using measured cross-section geometry, flow, and water-surface elevation to compute the relations between flow and cross-sectional area and between depth and width using a steady-state water-surface elevation computer program HEC-RAS (U.S. Army Corps of Engineers, 2002). HEC-RAS can compute cross-sectional area and top width for a uniform reach given a steady-state flow. The average depth is computed by dividing cross-sectional area by width. The cross-sectional area, width, and depth were computed for a range of flows. The calibration process consisted of finding parameters for the DAFLOW equations by trial and error that fit the geomorphic relations obtained from HEC-RAS.

The second component of this approach involved calibration of hydraulic-geometry parameters to cross-section data at USGS gages. This component was done similarly to the first and did not require the use of HEC-RAS. The third component of this approach involved using cross-sectional areas determined from the dye tests to validate the parameters calibrated using the TRC Omni surveys and USGS gage cross-section data. The areas from the dye tests were compared to the length-averaged areas computed using equation 9 and the calibrated cross-sectional parameters.

The fifth approach, implemented by TRC Omni (2007), involved manual parameter adjustment to facilitate calibration of WASP--for example, to account for the effects of Speedwell Lake and Lake Pocahontas (Morristown) on water-quality transport in the upper Whippany River.

The scope of the work done to determine values of hydraulic-geometry parameters that satisfied calibration of both the flow and water-quality models was substantial. The spatial and temporal extent of data and sites used for cross-section calibration is documented by TRC Omni (2007). Thirty-five cross sections were calibrated to guarantee the parameters were providing a realistic representation of the cross sections. The results shown in this report represent only a subset of all data and sites used for parameter calibration.

The calibrated cross-sectional areas, widths, and depths are summarized in table 5. USGS data from other types of stations also are included in this table. Final hydraulic-geometry parameter values were substituted into equations 9 and 10 to compute simulated cross-sectional area and width, respectively. Simulated hydraulic depth is computed by dividing area by width. Equations 9 and 10 are a theoretical approximation of the stream geometry. Therefore, not all the data obtained using the cross-section survey can be captured by the model. A general measure of accuracy can be obtained by comparing the difference between simulated and measured branch-averaged cross-sectional area, depth, and width, as shown in table 5. Subreaches were modeled using the detailed values that made up those averages. By reviewing the results for each branch, a good approximation can be obtained in most cases.

Values for certain calibrated cross-sectional parameters fall outside the ranges recommended by Jobson and Harbaugh (1999, p. 5), who suggest narrow ranges for parameter values. These ranges are meant to be a guide and not an absolute. Any group of measures contains substantial scatter; investigators look for central tendencies and generally de-emphasize extreme values. These ranges were proposed when DAFLOW was first developed, field experience with it was limited, and less geomorphic literature was available. Further, if the parameter values were limited to the suggested ranges, the relations between flow and cross-sectional area, width, and depth would not be satisfactory. Instead, the parameters were calibrated by observing the relations of flow to area, width, and depth, and of depth to width, that best represent the cross-sectional shape and flow velocities under a variety of conditions. The parameter values are justified because there is good calibration of both the flow and water-quality-transport models.

Table 5. Calibrated channel cross-section geometry in the surface-water model of the nontidal Passaic River Basin, New Jersey.

[wq, water quality; ---, not available or not applicable]

River	Branch[1]	Node	River mile	Measurement station[2]			Measured geometry			Simulated geometry		
				Number	Type	Discharge[3]	Area	Width	Depth	Area	Width	Depth
Pequannock	1			---	---	---	---	---	---	---	---	---
		1	0.00	01382800	gage	65.3	44.4	40.2	1.1	136.3	65.5	2.1
				PE1	survey	209.1	283.5	78.8	5.6	231.9	78.0	3.0
		2	0.88	---	---	---	---	---	---	---	---	---
						Average	***163.9***	***59.5***	***3.3***	***184.1***	***71.8***	***2.5***
Wanaque	2			---	---	---	---	---	---	---	---	---
		1	0.00	01387000	gage	71.3	56.1	41.1	1.4	60.6	32.1	1.9
				WA1	survey	18.0	279.0	116.0	2.4	246.9	112.3	2.2
		2	0.38	---	---	---	---	---	---	---	---	---
		3	1.09	---	---	---	---	---	---	---	---	---
		4	1.91	---	---	---	---	---	---	---	---	---
		5	3.33	---	---	---	---	---	---	---	---	---
		6	3.66	---	---	---	---	---	---	---	---	---
		7	4.03	WA2	survey	41.3	476.1	120.0	4.0	403.8	115.6	3.5
		8	4.31	---	---	---	---	---	---	---	---	---
		9	5.19	---	---	---	---	---	---	---	---	---
						Average	***270.4***	***92.4***	***2.6***	***237.1***	***86.7***	***2.5***
Pequannock	3			---	---	---	---	---	---	---	---	---
		1	0.00	PE2	survey	253.9	84.6	49.9	1.7	84.6	50.9	1.7
		2	0.24	---	---	---	---	---	---	---	---	---
		3	1.64	---	---	---	---	---	---	---	---	---
		4	1.94	---	---	---	---	---	---	---	---	---
						Average	***84.6***	***49.9***	***1.7***	***84.6***	***50.9***	***1.7***
Ramapo	4			---	---	---	---	---	---	---	---	---
		1	0.00	01388000	gage	279.8	202.9	90.7	2.2	300.5	98.7	3.0
				RA3	survey	309.0	339.8	99.6	3.4	322.2	100.7	3.2
		2	0.95	01388100	wq	93.6	571.1	95.1	6.0	514.2	92.0	5.6
		3	1.60	---	---	---	---	---	---	---	---	---
		4	1.93	---	---	---	---	---	---	---	---	---
						Average	***371.3***	***95.2***	***3.9***	***379.0***	***97.2***	***3.9***
Pompton	5			---	dye tests	72.0	222.0	---	---	199.2	---	---
		1	0.00	---	---	---	---	---	---	---	---	---
		2	0.19	01388500	gage	497.9	304.6	98.9	3.1	374.8	153.0	2.5
				PO1	survey	145.0	176.3	120.2	1.5	186.4	121.0	1.5
		3	0.41	---	---	---	---	---	---	---	---	---
		4	1.61	---	---	---	---	---	---	---	---	---
		5	2.41	01388600	wq	91.3	102.8	95.9	1.1	151.1	110.8	1.4
		6	3.63	---	---	---	---	---	---	---	---	---
		7	5.40	PO2	survey	569.5	1165.5	239.4	4.8	693.3	173.0	4.0
		8	5.64	---	---	---	---	---	---	---	---	---
		9	6.44	---	---	---	---	---	---	---	---	---
		10	6.63	01389000	low flow	87.1	297.2	157.7	1.9	440.0	163.5	2.7
		11	6.87	PO3	survey	173.8	11.9	173.1	3.8	504.7	166.9	3.0
						Average	***325.7***	***147.5***	***2.7***	***364.2***	***148.0***	***2.5***
Rockaway	6			---	dye tests	54.2	106.1	---	---	152.9	---	---
		1	0.00	01381000	gage	142.1	75.5	46.9	1.6	181.0	78.2	2.3
				RO1	survey	18.0	88.0	45.5	1.9	88.0	48.6	1.8
		2	0.20	---	---	---	---	---	---	---	---	---
		3	2.16	---	---	---	---	---	---	---	---	---
		4	2.68	---	---	---	---	---	---	---	---	---
		5	3.24	---	---	---	---	---	---	---	---	---

Table 5. Calibrated channel cross-section geometry in the surface-water model of the nontidal Passaic River Basin, New Jersey.—Continued

[wq, water quality; ---, not available or not applicable]

River	Branch[1]	Node	River mile	Measurement station[2]			Measured geometry			Simulated geometry		
				Number	Type	Discharge[3]	Area	Width	Depth	Area	Width	Depth
		6	4.84	---	---	---	---	---	---	---	---	---
		7	5.37	RO2	survey	232.2	303.7	82.5	3.7	282.4	81.6	3.5
		8	5.59	01381200	multi-use	54.7	108.5	63.1	1.7	165.2	71.7	2.3
		9	6.65	---	---	---	---	---	---	---	---	---
						Average	***136.4***	***59.5***	***2.2***	***173.9***	***70.0***	***2.5***
Whippany	7			---	---	---	---	---	---	---	---	---
		1	0.00	01381400	gage	47.3	35.2	19.8	1.8	35.7	23.2	1.5
				WI1	survey	30.2	51.2	27.2	1.9	27.9	21.7	1.3
		2	1.13	---	---	---	---	---	---	---	---	---
		3	1.43	---	---	---	---	---	---	---	---	---
		4	1.92	---	dye tests	42.3	70.0	---	---	95.9	---	---
		5	2.22	---	---	---	---	---	---	---	---	---
		6	2.72	---	---	---	---	---	---	---	---	---
		7	4.74	WI2	survey	67.0	132.6	55.1	2.4	129.9	57.2	2.3
		8	4.95	01381500	gage	54.8	37.8	38.1	1.0	117.5	54.4	2.2
		9	5.17	---	---	---	---	---	---	---	---	---
		10	6.69	---	---	---	---	---	---	---	---	---
		11	7.16	---	---	---	---	---	---	---	---	---
		12	8.00	---	---	---	---	---	---	---	---	---
		13	10.02	01381600	low flow	34.9	36.7	31.4	1.2	90.2	45.5	2.0
		14	11.05	---	---	---	---	---	---	---	---	---
		15	12.69	---	---	---	---	---	---	---	---	---
		16	14.14	---	---	---	---	---	---	---	---	---
		17	14.39	01381800	gage	100.9	96.0	46.6	2.1	163.0	55.1	3.0
				WI3	survey	270.0	316.7	64.8	4.9	296.6	65.7	4.5
		18	14.58	---	---	---	---	---	---	---	---	---
		19	14.80	---	---	---	---	---	---	---	---	---
						Average	***97.0***	***40.4***	***2.2***	***119.6***	***46.1***	***2.4***
Rockaway	8			---	dye tests	68.0	82.0	---	---	90.5	---	---
		1	0.00	---	---	---	---	---	---	---	---	---
		2	0.94	---	---	68.0	---	---	---	90.5	55.8	1.6
		3	1.25	---	---	---	---	---	---	---	---	---
						Average	***82.0***	---	---	***90.5***	***55.8***	***1.6***
Passaic	9			---	dye tests	28.4	48.7	---	---	41.2	---	---
		1	0.00	01379000	gage	93.4	58.0	46.1	1.3	80.9	49.7	1.6
				PA2	survey	124.0	235.2	79.8	2.9	96.3	53.4	1.8
		2	1.47	---	---	---	---	---	---	---	---	---
		3	3.38	---	---	---	---	---	---	---	---	---
						Average	***114.0***	***63.0***	***2.1***	***72.8***	***51.6***	***1.7***
Dead	10			---	dye tests	8.0	38.0	---	---	48.4	---	---
		1	0.00	01379100	low flow	1.6	5.7	10.4	0.6	20.2	24.0	0.8
		2	0.21	---	---	---	---	---	---	---	---	---
		3	0.88	---	---	---	---	---	---	---	---	---
		4	2.20	---	---	---	---	---	---	---	---	---
		5	3.44	---	---	---	---	---	---	---	---	---
		6	3.60	01379200	low flow	12.3	37.1	23.9	1.5	62.5	51.8	1.2
				DR1	survey	60.7	170.3	95.2	1.8	170.3	95.2	1.8

Table 5. Calibrated channel cross-section geometry in the surface-water model of the nontidal Passaic River Basin, New Jersey.—Continued

[wq, water quality; ---, not available or not applicable]

River	Branch[1]	Node	River mile	Measurement station[2]			Measured geometry			Simulated geometry		
				Number	Type	Discharge[3]	Area	Width	Depth	Area	Width	Depth
		7	3.77	---	---	---	---	---	---	---	---	---
						Average	***62.8***	***43.2***	***1.3***	***75.3***	***57.0***	***1.3***
Passaic	11			---	dye tests	47.1	101.2	---	---	104.2	---	---
		1	0.00	---	---	---	---	---	---	---	---	---
		2	1.60	---	---	---	---	---	---	---	---	---
		3	2.63	01379300	low flow	52.1	79.3	51.5	1.5	79.8	52.0	1.5
		4	4.18	---	---	---	---	---	---	---	---	---
		5	4.45	PA3	survey	216.1	377.6	224.2	1.7	130.3	74.6	1.7
		6	4.70	---	---	---	---	---	---	---	---	---
		7	5.71	---	---	---	---	---	---	---	---	---
		8	6.83	---	---	---	---	---	---	---	---	---
		9	7.41	---	---	---	---	---	---	---	---	---
		10	9.19	---	---	---	---	---	---	---	---	---
		11	9.76	---	---	---	---	---	---	---	---	---
		12	10.08	---	---	---	---	---	---	---	---	---
		13	10.51	---	---	---	---	---	---	---	---	---
		14	11.50	01379500	gage	175.7	104.5	72.3	1.4	118.6	73.6	1.6
		15	13.39	PA4	survey	88.0	124.1	57.4	2.2	88.8	70.6	1.3
		16	13.64	---	---	---	---	---	---	---	---	---
		17	14.06	---	---	---	---	---	---	---	---	---
		18	14.51	---	---	---	---	---	---	---	---	---
		19	15.08	---	---	---	---	---	---	---	---	---
		20	17.17	---	---	---	---	---	---	---	---	---
		21	19.21	---	---	---	---	---	---	---	---	---
		22	20.67	01379570	low flow	69.7	147.7	60.6	2.4	144.7	60.4	2.4
		23	22.18	---	---	---	---	---	---	---	---	---
		24	23.28	PA5	survey	121.2	480.0	167.9	2.9	469.8	166.7	2.8
		25	23.58	---	---	---	---	---	---	---	---	---
		26	24.49	---	---	---	---	---	---	---	---	---
		27	25.03	---	---	---	---	---	---	---	---	---
		28	25.52	---	---	---	---	---	---	---	---	---
						Average	***202.1***	***105.6***	***2.0***	***162.3***	***83.0***	***1.9***
Passaic	12			---	dye tests	102.0	296.0	---	---	348.8	---	---
		1	0.00	---	---	---	---	---	---	---	---	---
		2	1.37	01381900	gage	621.4	612.6	163.9	3.7	566.6	135.1	4.2
		3	4.07	PA6	survey	615.3	572.5	136.6	4.2	565.1	134.9	4.2
		4	4.31	---	---	---	---	---	---	---	---	---
		5	6.33	---	---	---	---	---	---	---	---	---
		6	8.68	---	---	---	---	---	---	---	---	---
		7	10.85	---	---	---	---	---	---	---	---	---
		8	11.90	---	---	---	---	---	---	---	---	---
		9	12.34	---	---	---	---	---	---	---	---	---
		10	12.84	PA7	survey	628.3	659.8	273.9	2.4	656.4	273.0	2.4
		11	13.05	01382000	multi-use	165.5	343.9	240.3	1.4	400.2	262.3	1.5
						Average	***497.0***	***203.6***	***2.9***	***507.4***	***201.3***	***3.1***
Passaic	13			---	dye tests	212.0	1191.0	---	---	1092.5	---	---
		1	0.00	---	---	---	---	---	---	---	---	---
		2	0.20	01389005	slope	224.4	451.8	263.1	1.7	557.4	267.4	2.1
			0.41	---	---	---	---	---	---	---	---	---

Table 5. Calibrated channel cross-section geometry in the surface-water model of the nontidal Passaic River Basin, New Jersey.—Continued

[wq, water quality; ---, not available or not applicable]

River	Branch[1]	Node	River mile	Measurement station[2]			Measured geometry			Simulated geometry		
				Number	Type	Discharge[3]	Area	Width	Depth	Area	Width	Depth
						Average	***821.4***	---	---	***824.9***	---	---
Singac	14			---	---	---	---	---	---	---	---	---
		1	0.00	---	---	---	---	---	---	---	---	---
		2	0.28	---	---	---	---	---	---	---	---	---
		3	1.71	01389100	low flow	19.8	54.6	57.2	1.0	56.0	55.7	1.0
		4	1.91	---	---	---	---	---	---	---	---	---
						Average	***54.6***	***57.2***	***1.0***	***56.0***	***55.7***	***1.0***
Passaic	15			---	dye tests	212.0	1191.0	---	---	1092.5	---	---
		1	0.00	---	---	---	---	---	---	---	---	---
		2	0.44	---	---	---	---	---	---	---	---	---
		3	1.49	PA8	survey	1540.0	2345.2	293.3	8.0	2308.1	295.9	7.8
		4	1.76	---	---	---	---	---	---	---	---	---
		5	2.61	---	---	---	---	---	---	---	---	---
		6	2.89	---	---	---	---	---	---	---	---	---
		7	3.15	---	---	---	---	---	---	---	---	---
		8	3.44	01389500	gage	1157.8	512.4	107.1	4.8	513.4	141.7	3.6
		9	4.44	---	---	---	---	---	---	---	---	---
						Average	***1349.5***	***200.2***	***6.4***	***1304.6***	***218.8***	***5.7***
Peckman	16			---	---	---	---	---	---	---	---	---
		1	0.00	---	---	---	---	---	---	---	---	---
		2	1.13	01389534	crest stage	39.5	26.1	29.3	0.9	35.8	30.1	1.2
		3	1.94	---	---	---	---	---	---	---	---	---
		4	3.09	---	---	---	---	---	---	---	---	---
		5	4.19	---	---	---	---	---	---	---	---	---
		6	5.24	01389600	low flow	14.7	26.3	28.9	0.9	28.8	30.1	1.0
		7	5.53	---	---	---	---	---	---	---	---	---
						Average	***26.2***	***29.1***	***0.9***	***32.3***	***30.1***	***1.1***
Passaic	17			---	dye tests	639.0	931.0	---	---	888.1	---	---
		1	0.00	---	---	---	---	---	---	---	---	---
		2	1.61	PA9	survey	2003.9	1103.0	257.1	4.3	1191.2	253.6	4.7
		3	1.85	---	---	---	---	---	---	---	---	---
		4	2.85	01389802	total flow[4]	279.0	184.2	97.6	1.9	217.0	105.4	2.1
		5	3.09	---	---	---	---	---	---	---	---	---
		6	5.12	---	---	---	---	---	---	---	---	---
		7	6.24	---	---	---	---	---	---	---	---	---
		8	7.26	PA10	survey	2069.9	2009.7	293.7	6.8	2028.4	291.4	7.0
		9	7.55	01389870	wq	1232.7	636.7	230.7	2.8	756.1	241.6	3.1
		10	10.11	---	---	---	---	---	---	---	---	---
		11	10.62	dam	survey	4650.0	4806.0	540.0	8.9	4245.3	528.2	8.0
		12	10.94	dam	survey	19700.0	6472.8	558.0	11.6	6650.2	551.6	12.1
						Average	***2306.2***	***329.5***	***6.0***	***2282.3***	***328.6***	***6.2***

[1] Locations shown in figure 6.

[2] Data from USGS stations, cross-section surveys at sampling stations (Marcelo Cerucci, TRC Omni Environmental Corp., written commun., 2005), archived USGS time-of-travel dye tests conducted during 1964-75 (unpublished files available at the USGS Water Science Center in West Trenton, New Jersey), and cross-section surveys at Dundee Dam (Emad Sidhom, United Water New Jersey, written commun., 2004). Dye tests yield a reach-averaged cross-section area for a given discharge.

[3] Estimated at sampling stations (Thomas Amidon, TRC Omni Environmental Corp., written commun., 2005).

[4] Approximate.

Low-Flow Conditions (Water Year 2001)

To some degree, the choice of calibration period for the flow model and water-quality model was a function of project logistics and data availability. The model was calibrated for water year 2001, a low-flow year, which is comparable to the target flow conditions for evaluating river-water quality. (Note that WASP was calibrated for water year 2003.) Water year 2001 included a wide-ranging set of flow conditions for calibration. Simulated and observed results for six downstream gages are shown in figures 7 to 12; error analysis is shown in table 6. (Individual streamflow measurements, also shown in these figures, can indicate anomalies in the rating curve, and therefore, the observed flow record.) Comparison of simulated and observed mass balance yielded a percent mean error that is lower than the observed data error of four of the gages and equal to that of a fifth gage (01381900, Passaic River at Pine Brook). No quantitative comparison is made for station 01389890, Passaic River at Dundee Dam at Clifton, because measured/observed data for this water year are unavailable.

The upper graph in figures 7 to 12 shows simulated and observed flow hydrographs; the middle graph shows simulated and observed flow-duration curves, with the abscissa divided into quartiles. The third quartile (50 to 75 percent) is thought to best represent the target flow range. Table 6 indicates whether the third quartile provides better (+) or worse (-) calibration results than the entire flow range. The lower graph in the figures shows simulated and measured flow velocity and depth. Measured values are computed from measured discharge, area, and width. Because streamflow measurements are typically made in narrow, shallow, channel cross sections, measured velocities are expected to be greater and depths are expected to be smaller than the simulated values. Impoundments may also affect the differences between measured and simulated velocities and depths (fig. 6, branches 4 and 15).

Model fit at the gages was evaluated mainly by using mean percent absolute error; additional statistics also are shown in table 6. The hydrograph matches are good to fair and within the accuracy of gages 01385500, Pompton River at Pompton Plains (fig. 7), and 01381500, Whippany River at Morristown (fig. 8). Calibration for flow duration, velocity, and depth are reasonable (better for 01385500) for these gages. Simulated velocity is underpredicted for gage 01381500; a higher velocity would be expected in a headwaters reach.

The hydrograph match for gage 01379500, Passaic River near Chatham (fig. 9), originally showed a simulated wave speed that was slower than the observed wave speed and, consequently, a large mean percent absolute error. This timing offset propagated downstream. Unlike other subbasins in the model, subbasins in branches 9 through 11 and subbasin 12-2 required use of index gage 01379000, Passaic River near Millington, as other index gages proved inadequate. The drainage area for this index gage is relatively large compared to those of other index gages and contains a large wetland area (Great Swamp), which can delay the downstream flow of water after a storm event. To account for these differences, a 20-hour forward lag was applied to flows at this index gage to increase the velocity of the flood wave as it moves downstream. As a result, calibration results improved at gage 01379500 and downstream gages. The hydrograph match is poor, however, and not within the accuracy of the gage. Calibration for flow duration, velocity, and depth are reasonable.

The hydrograph match is less accurate generally for gage 01381900 (fig. 10), particularly in terms of wave attenuation. Calibration for flow duration matches better for the third quartile than for the entire flow range, whereas calibration for velocity and depth are reasonable. The hydrograph match is more difficult to achieve for gage 01389500, Passaic River at Little Falls (fig. 11). This discrepancy is caused in part by the propagation of model error downstream, the exaggeration of error at low flows, and the effect of nearby diversions at Wanaque South and Little Falls, which are superimposed on the hydrograph in figure 11 (and similar figures farther on). The main reason that peaks are not well captured is that DAFLOW is not able to simulate water storage resulting from overbank conditions. The match at this gage improved after a mixing algorithm (discussed farther on) was added to DAFLOW because the Wanaque South intake could then draw water from the Passaic River. Calibration for flow duration is very good and velocity and depth are reasonable. The corresponding match between simulated and estimated data is reasonable for station 01389890 (fig. 12).

Validation of Flow Model

Three other recent water years, representing other flow conditions, were simulated to ensure the flow model provides the hydraulic framework to support TMDL modeling of the Passaic River. The goal of these simulations was to validate drainage-area ratio equations and values of hydraulic-geometry parameters determined during calibration (water year 2001). Water years 2000 (average flow), 2002 (extreme low flow), and 2003 (high flow) were used for these simulations. No further adjustment to equations or parameters was necessary during these simulations; in fact, combined mass-balance results for each water year were better than for water year 2001. A storage boundary condition needed to be implemented for water year 2002 and the early part of water year 2003, however.

Average-Flow Conditions (Water Year 2000)

The model was validated for water year 2000, an average-flow year. Simulated and observed discharge, flow duration, velocity, and depth for six downstream gages are shown in figures 13 to18; error analysis is shown in table 6. Comparison of simulated and observed mass balance yielded percent mean errors that are less than the accuracy of the gages. The model overpredicted mass balance at gage 01379500, Passaic River at Chatham, compared to mass balance at this gage in water year 2001. No observed data are available for station 01389890, Passaic River at Dundee Dam at Clifton, for water year 2000.

Model-fit results for water year 2000 were compared to results for water year 2001. The hydrograph match is generally within the accuracy of gages 01385500, Pompton River at Pompton Plains (fig. 13), and 01381500, Whippany River at Morristown (fig. 14). Validation for flow duration, velocity, and depth are reasonable (better for 01385500) for these gages, although validated velocity is not as good as expected for gage 01381500. The root mean square error is larger than expected for gage 01388500. The hydrograph match for gage 01379500 (fig. 15) yields an increased mean percent absolute error, although validation for flow duration, velocity, and depth are reasonable. The hydrograph match for gage 01381900, Passaic River at Pine Brook (fig. 16), is less accurate; however, validation for flow duration, velocity, and depth are reasonable. Validation within the target flow range is better. The hydrograph match for gage 01389500, Passaic River at Little Falls, is comparable to that in water year 2001 (fig. 17). Root mean square error is less than expected and validation for flow duration, velocity, and depth are reasonable. The corresponding match between simulated and estimated data also is reasonable for station 01389890 (fig. 18).

Extreme Low-Flow Conditions (Water Year 2002)

The model also was validated for water year 2002, an extreme low-flow year. Simulated and observed discharge, flow duration, velocity, and depth for six downstream gages are shown in figures 19 to 24; error analysis is shown in table 6. Comparison of simulated and observed mass balance yielded percent mean errors that are lower than the accuracy of four of the gages and greater than the accuracy of a fifth gage (01389500, Passaic River at Little Falls). The discrepancy for gage 01389500 is discussed below. The model overpredicted mass balance at gage 01388500, Passaic River at Pompton Plains, compared to the mass balance at this gage in water year 2001. No observed data are available for station 01389890, Passaic River at Dundee Dam at Clifton, for water year 2002.

Model-fit results for water year 2002 were compared to results for water year 2001. The hydrograph match is not within the accuracy of gages 01388500 (fig. 19) and 01381500, Whippany River at Morristown (fig. 20), and velocity validation is not as good as expected for gage 01381500. Validation for flow duration, velocity, and depth are reasonable. Validation within the target flow range is better. The hydrograph match for gage 01379500, Passaic River near Chatham (fig. 21), yields an increased mean percent absolute error, although validation for flow duration, velocity, and depth are reasonable. The hydrograph match is more accurate for gage 01381900, Passaic River at Pine Brook (fig. 22). Validation for flow duration, velocity, and depth are reasonable.

Initially, the model failed to run for the 2002 water year because simulated flow decreased to zero near the Wanaque South and Little Falls intakes during intermittent short periods when river flow was less than 50 ft^3/s locally and the combined diversions exceeded 250 ft^3/s. This discrepancy can be explained by (1) the lack of diurnal diversion data for Wanaque South intake, including a modified diversion pattern that coincided with rainfall events during the drought; (2) model sensitivity to the diversion boundary conditions; (3) fine-scale timing error in the routing; (4) observed-data error that is greater than the residual flow in the river; and (5) inaccurate channel cross-sectional geometry representation at very low flows. A transient storage boundary condition was developed to address this discrepancy.

The storage boundary condition is a surrogate for the extensive wetlands in the vicinity of Two Bridges, which cannot be simulated using DAFLOW. Release of water from storage is a reasonable assumption during very low flows and the effect of this boundary condition is expected to be small over a water year. Accordingly, the DAFLOW program was modified and a mass-balancing procedure was applied to remove a small volume of water from channel storage and store it in an off-channel reservoir (fig. 6, branch 12, node 8) until needed to maintain a minimum flow in the river. Although it is not difficult to determine the volume of water needed to make up the deficit, it is difficult to determine the exact timing and distribution of the addition. No more water was added than was necessary in order to minimize the effect on the water-quality model. A water-storage reservoir of approximately 30 million cubic feet (689 acre-ft) was required. The difference in flow between nodes 5-10 and 5-11 (fig. 6), representing the lower Pompton River, was used as the basis for minimizing the total flow deficit. When the total flow deficit was greater than zero or the volume in the subreach containing the nodes was negative, the difference in flow between the nodes was added manually to the storage boundary condition at leading time steps. The model was run, and the procedure was repeated until the deficit was zeroed. Afterwards, the equivalent flow was subtracted manually at trailing time steps by checking the same criteria. A disadvantage of this approach is that the model is no longer fully predictive. Any future simulations that involve different flow conditions will require rebalancing of the storage flows.

Despite the use of this boundary condition, the resulting hydrograph match is less accurate for gage 01389500 (fig. 23) than for other gages, particularly at low flows. Unfortunately, these results are the best that could be achieved. Validated flow duration highlights the discrepancy. Validation for velocity and depth are reasonable. The corresponding match between simulated and estimated data is better than expected for station 01389890 (fig. 24) when considering the upstream discrepancy at Little Falls.

Table 6. Model calibration and validation error at gage locations, Passaic River Basin, New Jersey.

[%, percent; +, better than overall error; - worse than overall error; ---, not available or not applicable]

					Observed data		Model error measures					
							% Mean error		Mean % absolute error			
Gage	Name	Branch[1]	Node	Water year	Mean discharge	% Error	Overall	50-75% flow duration	Overall	50-75% flow duration	Root mean square error	Coefficient of determination
01388500	Pompton River at Pompton Plains	5	2	2000	561	10-15	-14.3	+	11.8	+	170.7	0.95
				2001	439	10-15	-5.1	+	8.9	+	76.8	0.99
				2002	119	10-15	3.9	-	16.5	+	67.6	0.91
				2003	731	10-15	-8.2	+	8.6	-	149.2	0.99
01381500	Whippany River at Morristown	7	8	2000	49.7	10-20	-0.7	-	13.0	-	14.6	0.87
				2001	46.9	10	-5.9	-	9.8	-	16.0	0.86
				2002	27.8	10	-6.2	-	12.0	+	10.2	0.89
				2003	71.2	10	-0.3	-	12.0	+	21.6	0.90
01379500	Passaic River near Chatham	11	14	2000	144	10-15	2.9	-	23.3	-	51.3	0.83
				2001	146	10-15	-5.5	+	16.5	-	39.5	0.93
				2002	70.2	10-15	-0.7	-	19.2	-	26.7	0.92
				2003	230	10-15	7.9	+	13.7	-	56.3	0.95
01381900	Passaic River at Pine Brook	12	2	2000	590	10-15	-7.2	+	18.4	+	210.3	0.79
				2001	551	10-15	-15.5	+	17.4	+	219.6	0.84
				2002	257	10-15	-10.2	-	16.0	+	125.3	0.84
				2003	898	10-15	-9.0	-	20.2	+	383.7	0.77
01395000	Passaic River at Little Falls	15	8	2000	950	10	10.6	-	21.9	+	308.2	0.84
				2001	822	10	5.3	+	21.4	-	357.6	0.90
				2002	199	10	14.4	-	53.2	-	161.5	0.91
				2003	1526	10	5.7	+	18.6	+	628.4	0.87
01389890	Passaic River at Dundee Dam at Clifton	17	12	2000	1032	---	8.3	+	19.2	+	296.8	0.85
				2001	892	---	4.4	+	18.6	-	362.6	0.91
				2002	241	---	9.6	-	34.5	-	164.5	0.90
				2003	1664	---	5.2	-	17.0	+	591.9	0.90

[1] Locations shown in figure 6.

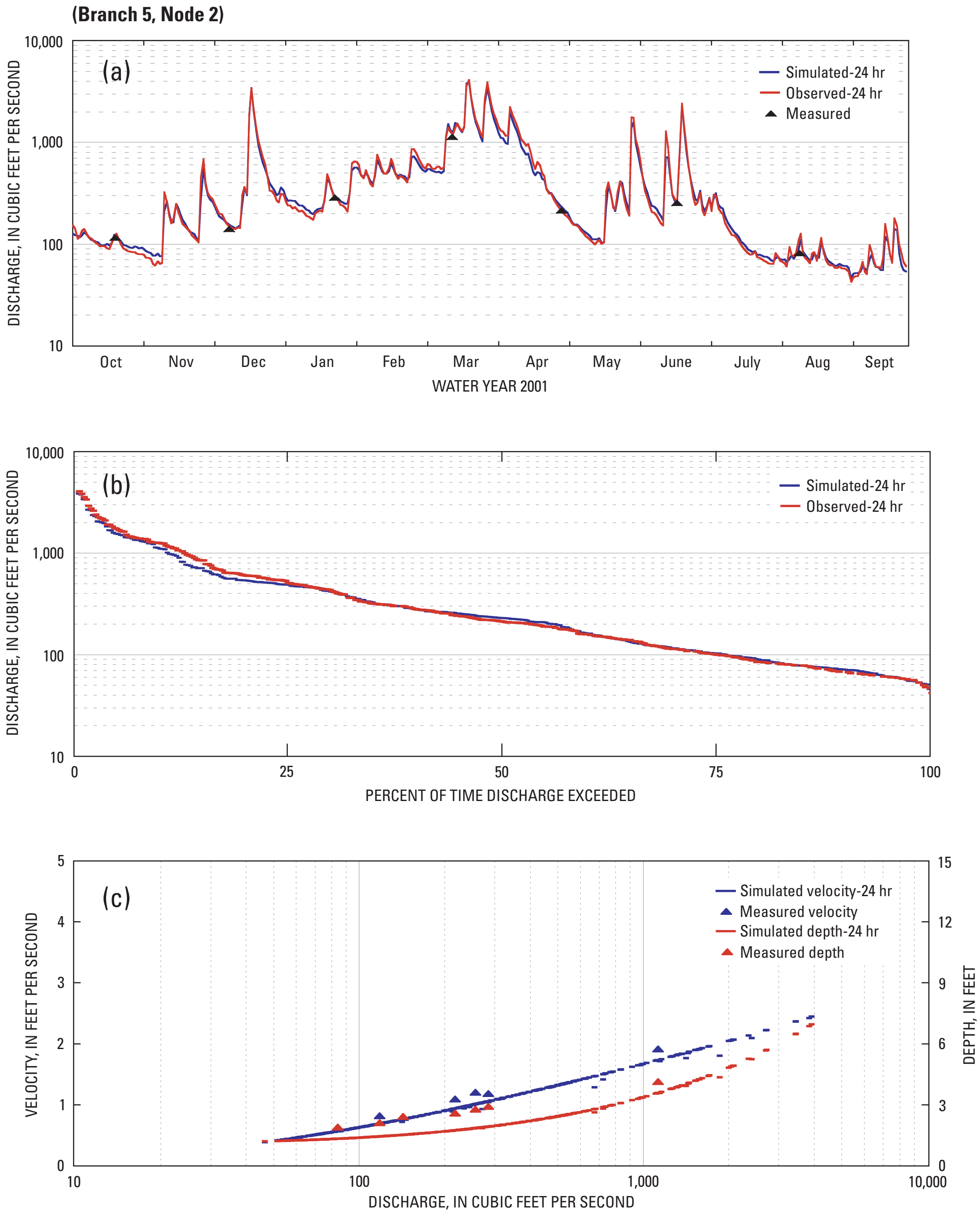


Figure 7. Calibrated (a) discharge, (b) flow duration, and (c) velocity and depth at gage 01388500, Pompton River at Pompton Plains, New Jersey , water year 2001.

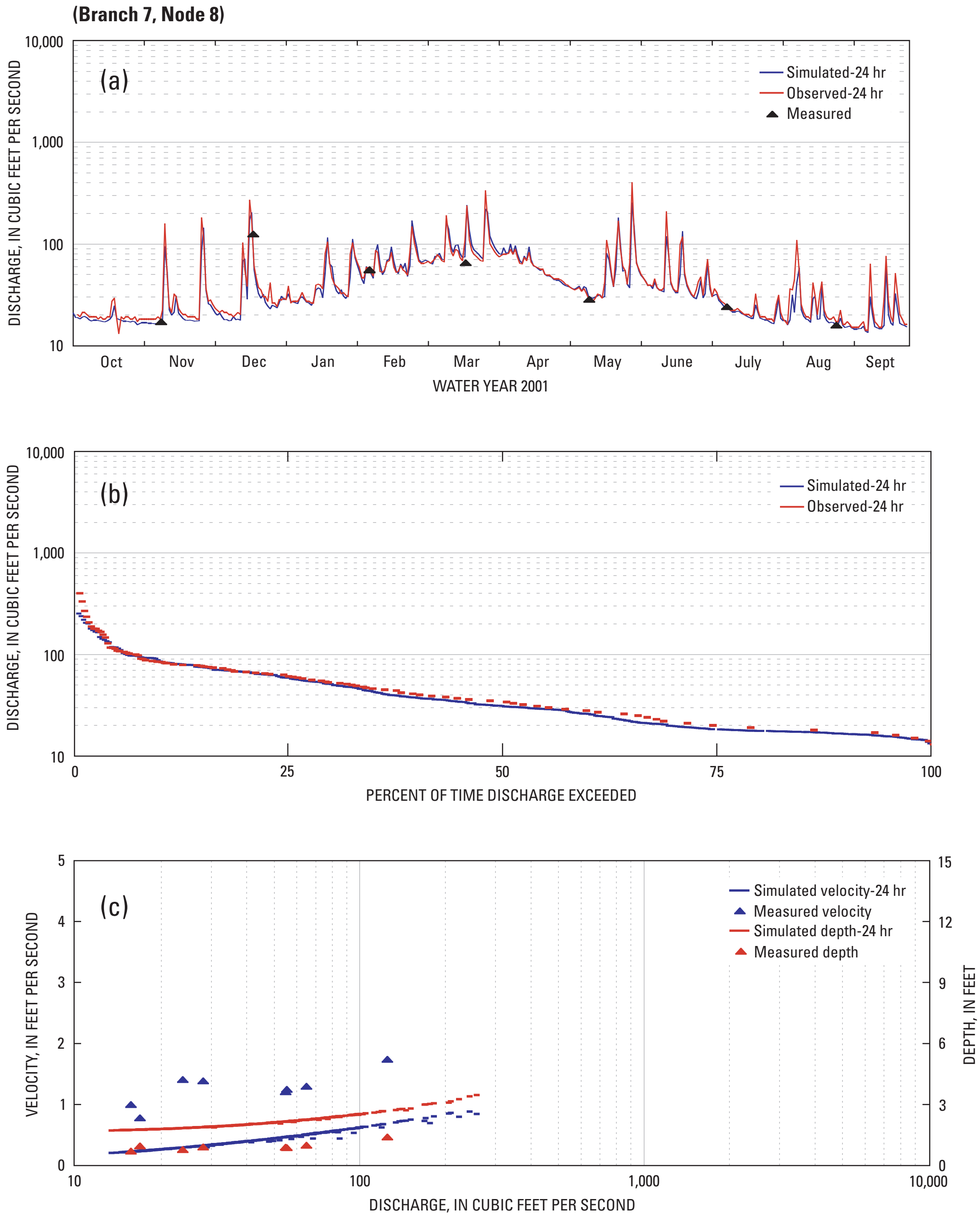


Figure 8. Calibrated (a) discharge, (b) flow duration, and (c) velocity and depth at gage 01381500, Whippany River at Morristown, New Jersey , water year 2001.

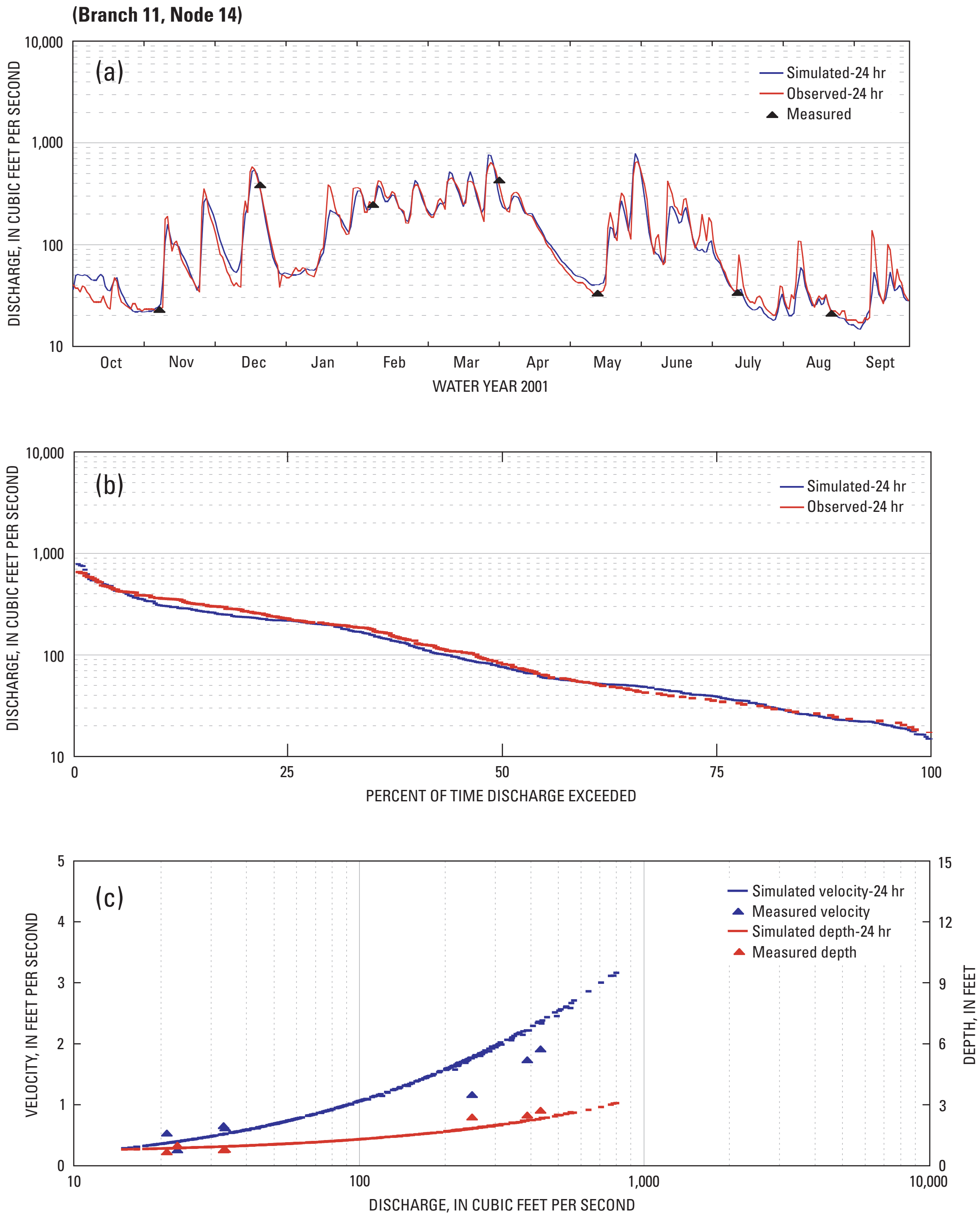


Figure 9. Calibrated (a) discharge, (b) flow duration, and (c) velocity and depth at gage 01379500, Passaic River near Chatham, New Jersey, water year 2001.

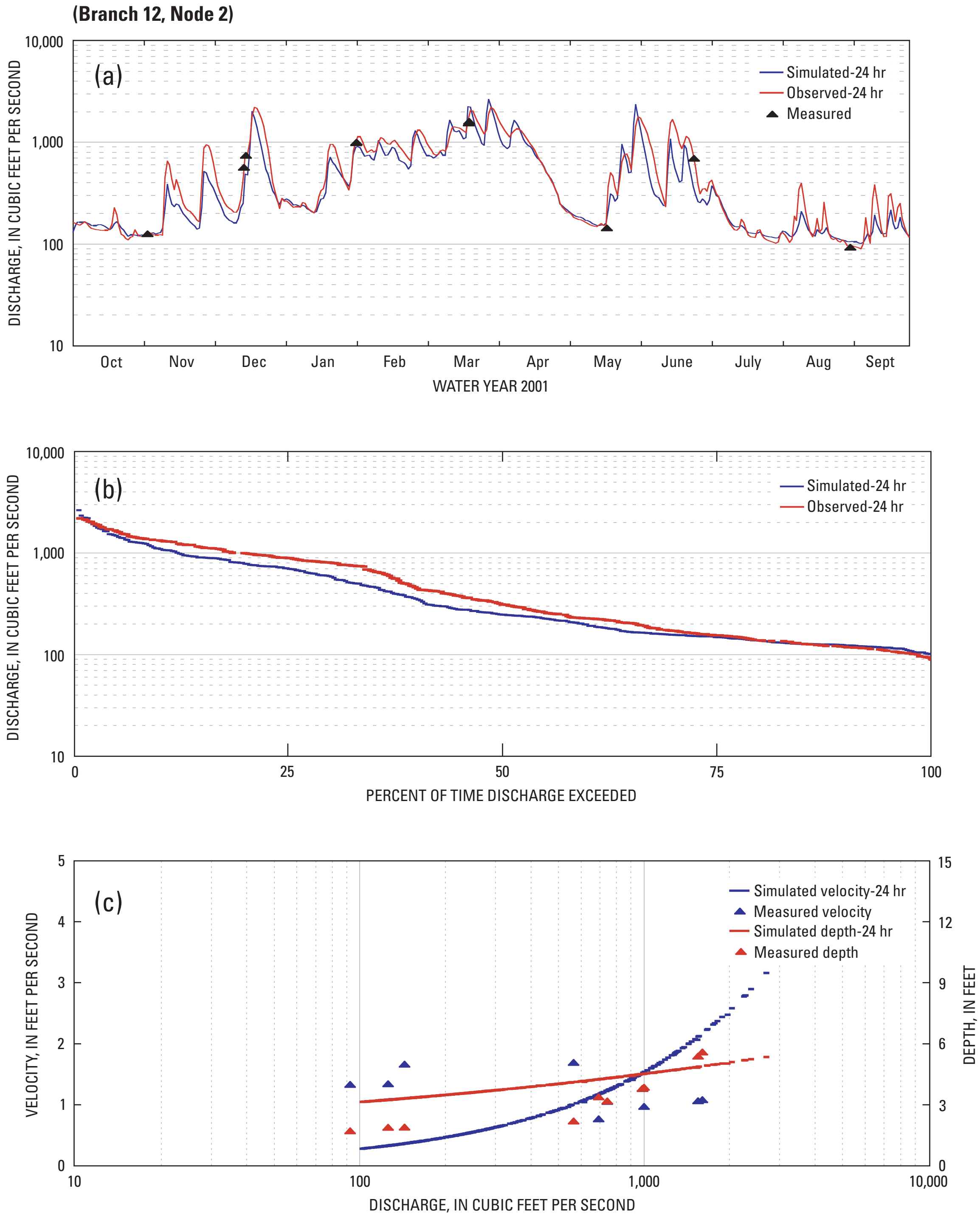


Figure 10. Calibrated (a) discharge, (b) flow duration, and (c) velocity and depth at gage 01381900, Passaic River at Pine Brook, New Jersey, water year 2001.

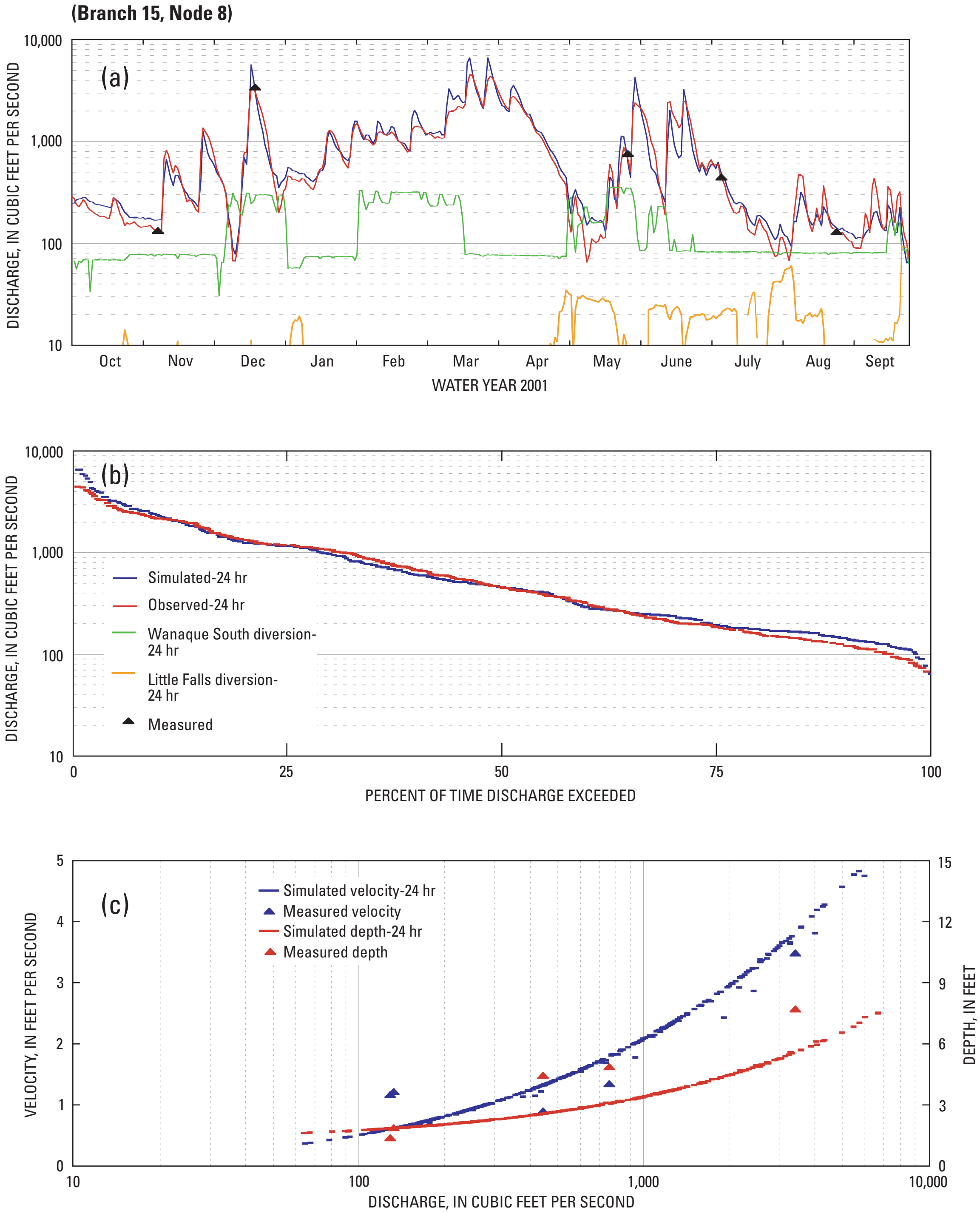


Figure 11. Calibrated (a) discharge, (b) flow duration, and (c) velocity and depth at gage 01389500, Passaic River at Little Falls, New Jersey, water year 2001.

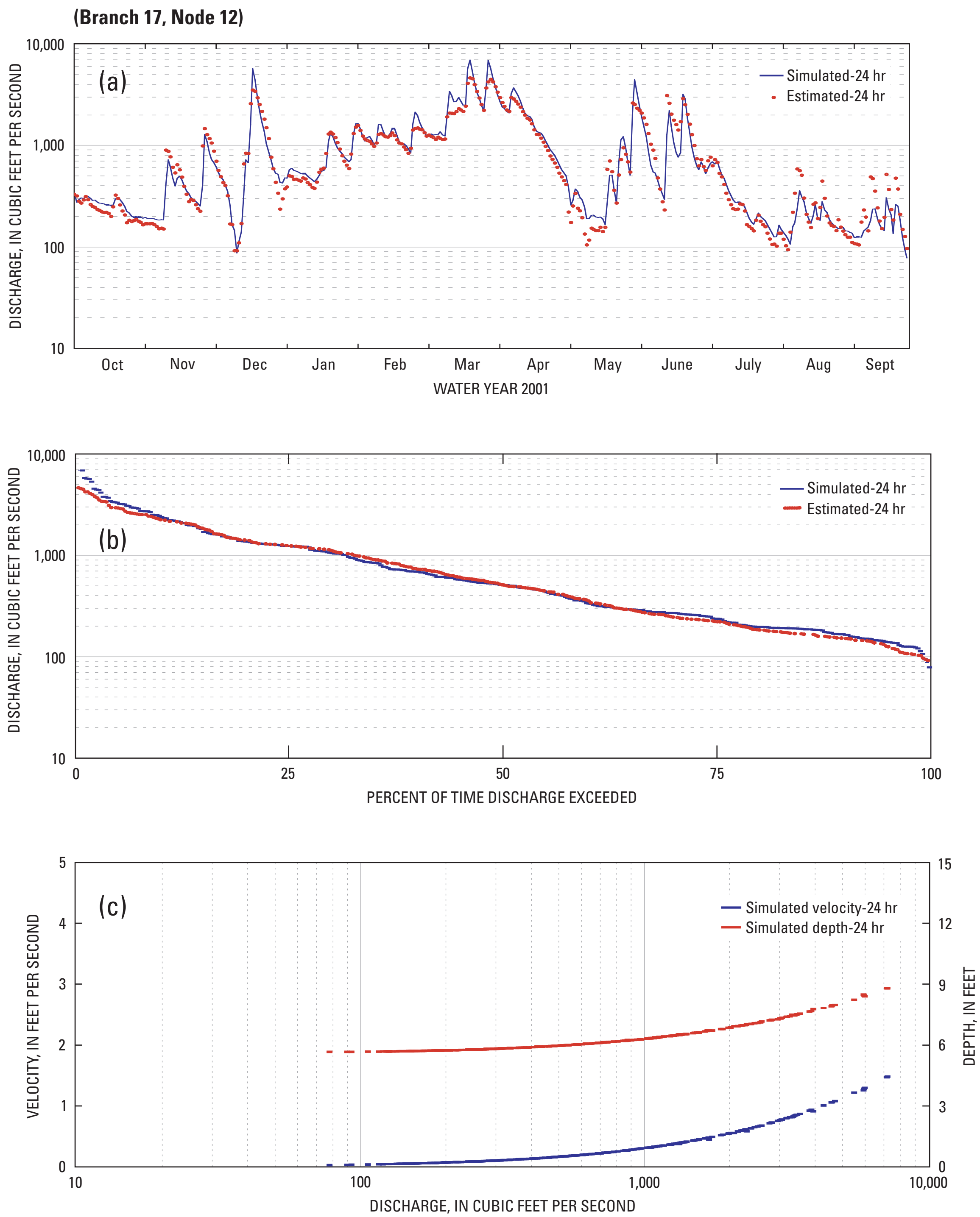


Figure 12. Calibrated (a) discharge, (b) flow duration, and (c) velocity and depth at station 01389890, Passaic River at Dundee Dam at Clifton, New Jersey, water year 2001.

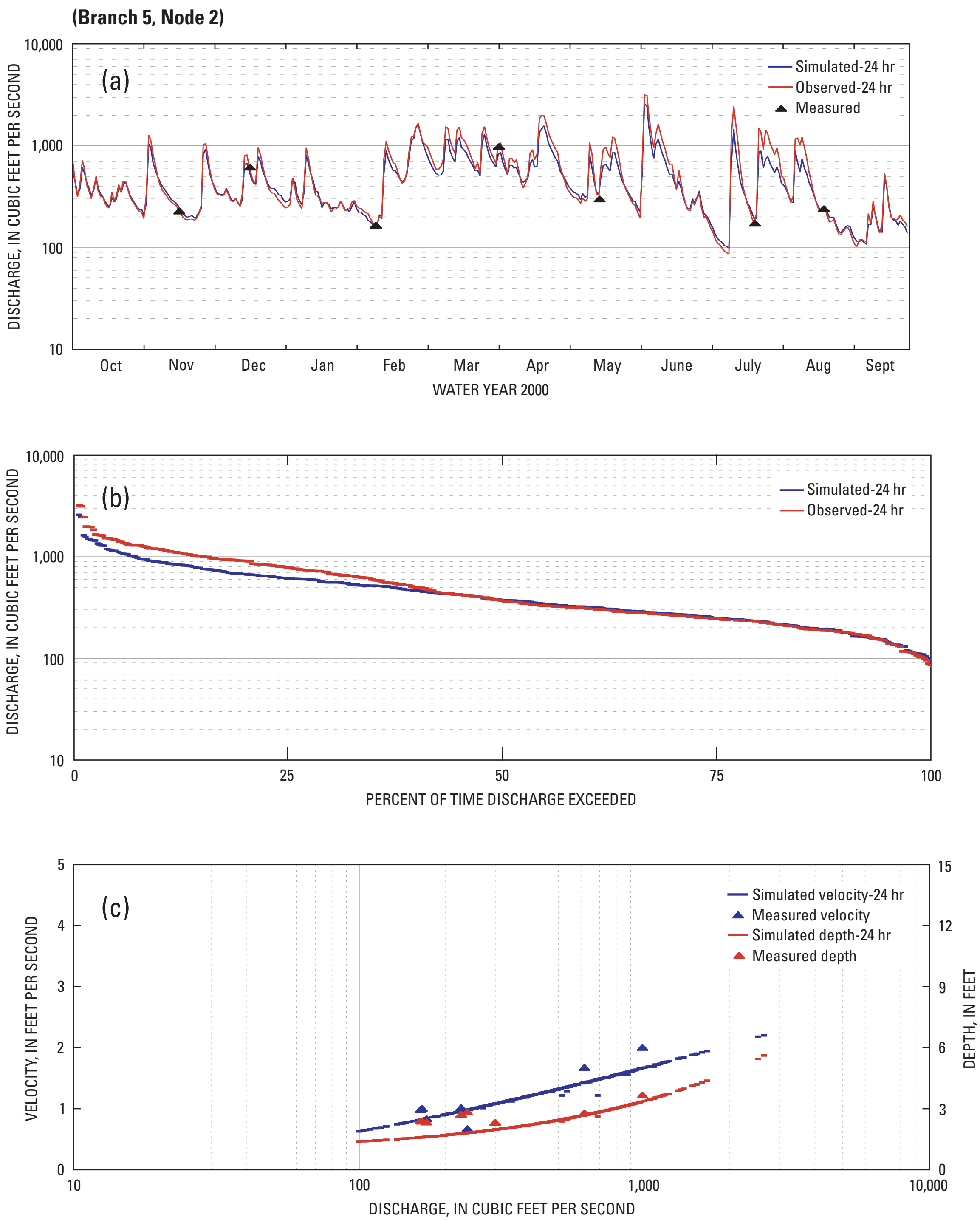


Figure 13. Validated (a) discharge, (b) flow duration, and (c) velocity and depth at gage 01388500, Pompton River at Pompton Plains, New Jersey, water year 2000.

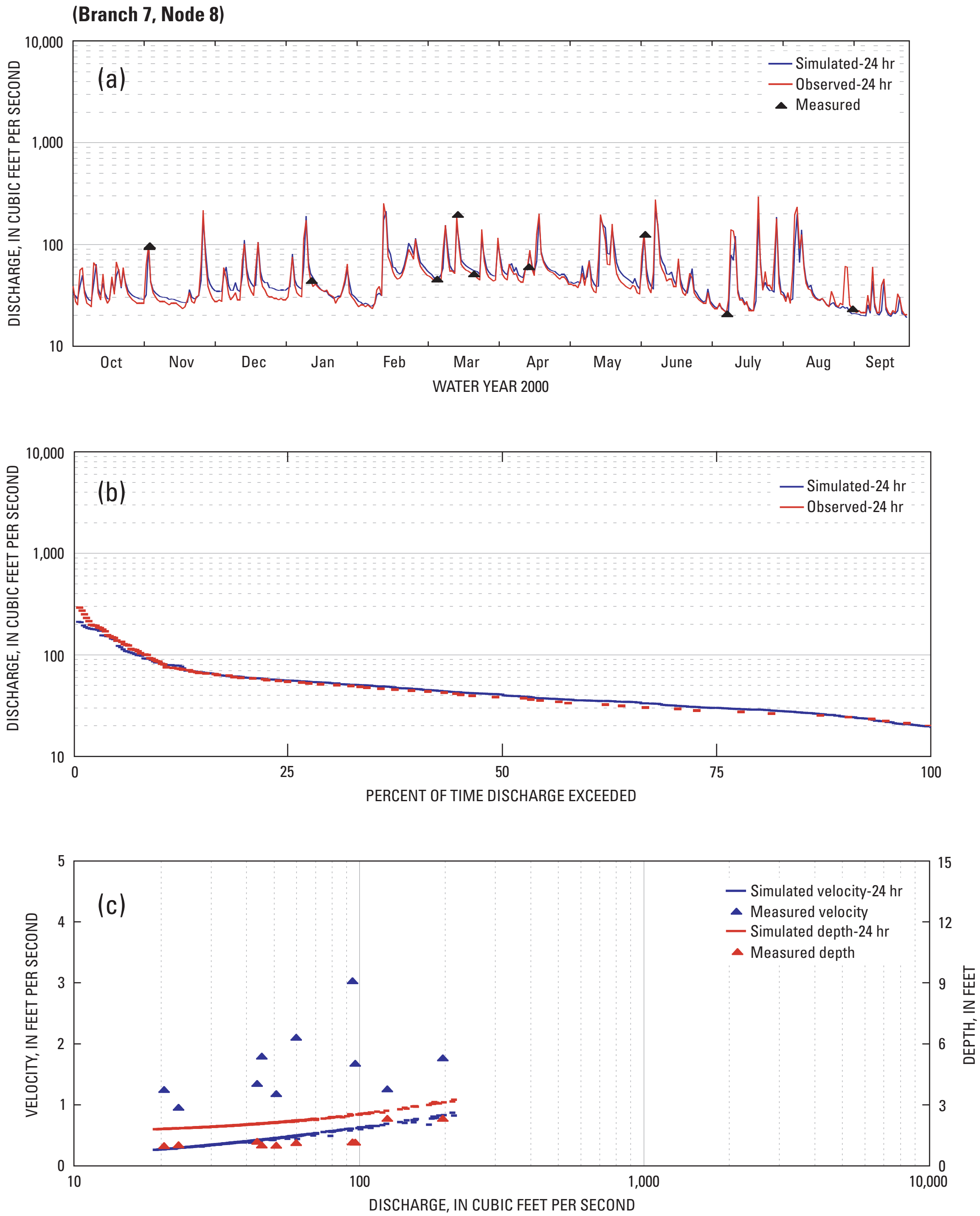


Figure 14. Validated (a) discharge, (b) flow duration, and (c) velocity and depth at gage 01381500, Whippany River at Morristown, New Jersey, water year 2000.

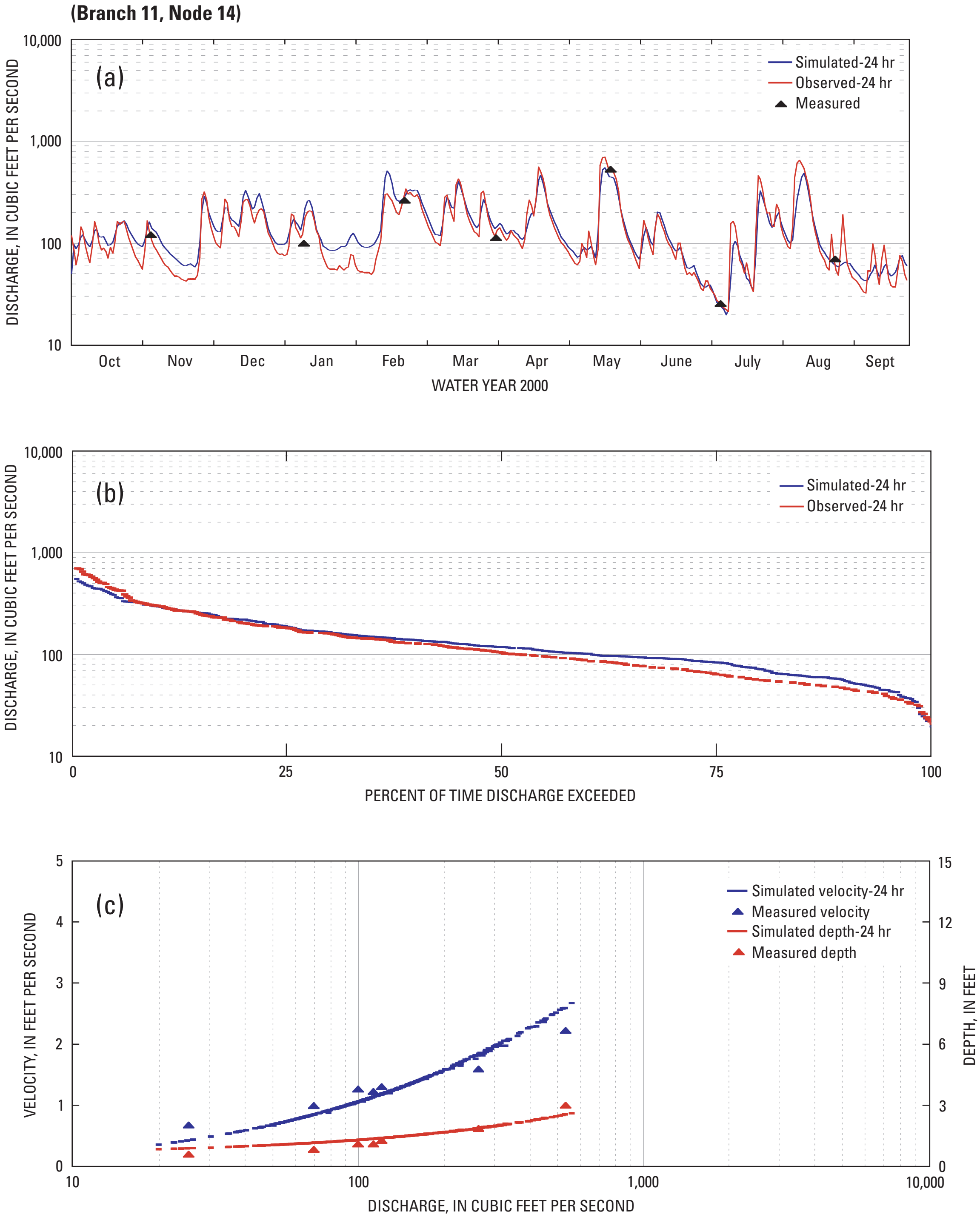


Figure 15. Validated (a) discharge, (b) flow duration, and (c) velocity and depth at gage 01379500, Passaic River near Chatham, New Jersey, water year 2000.

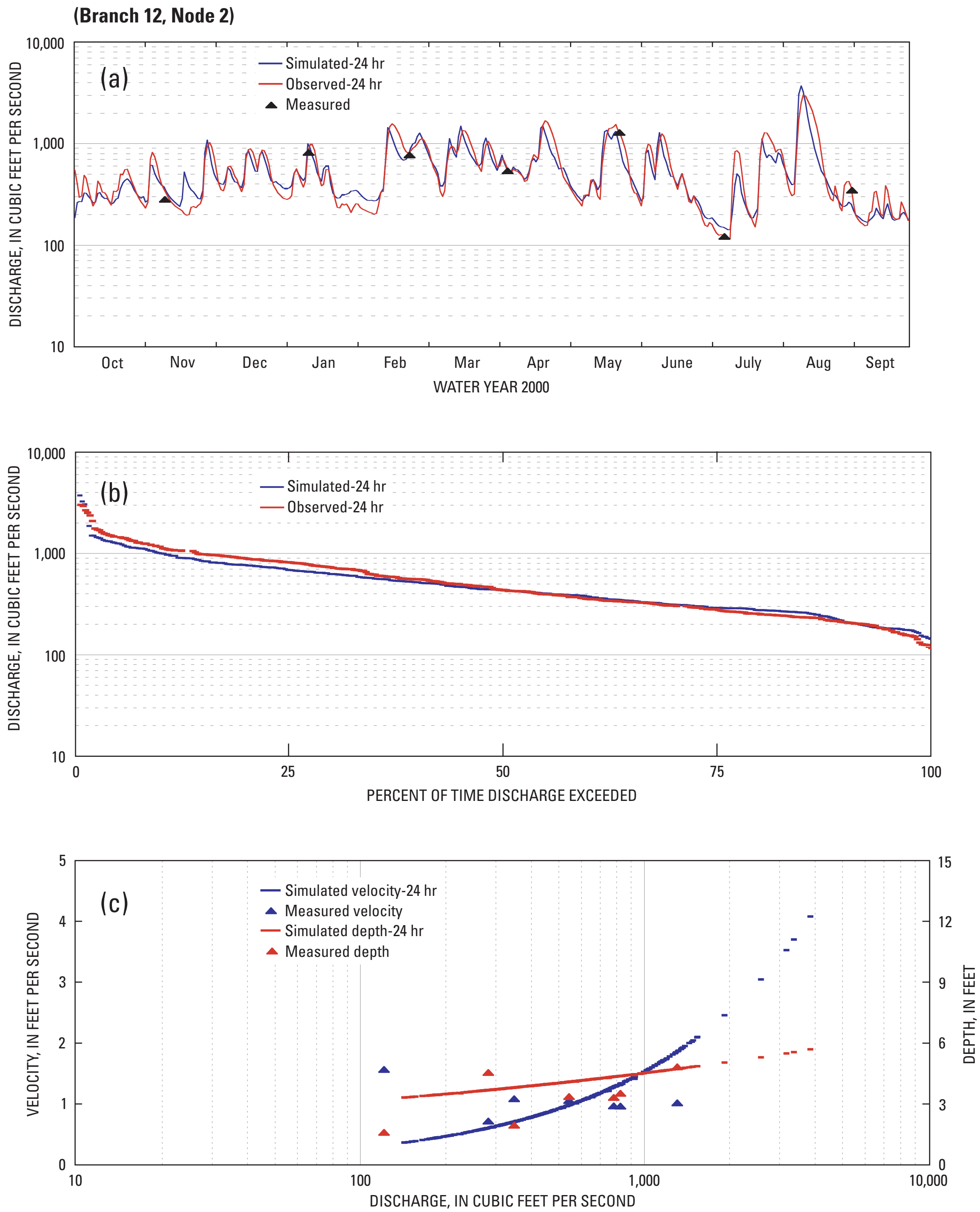


Figure 16. Validated (a) discharge, (b) flow duration, and (c) velocity and depth at gage 01381900, Passaic River at Pine Brook, New Jersey, water year 2000.

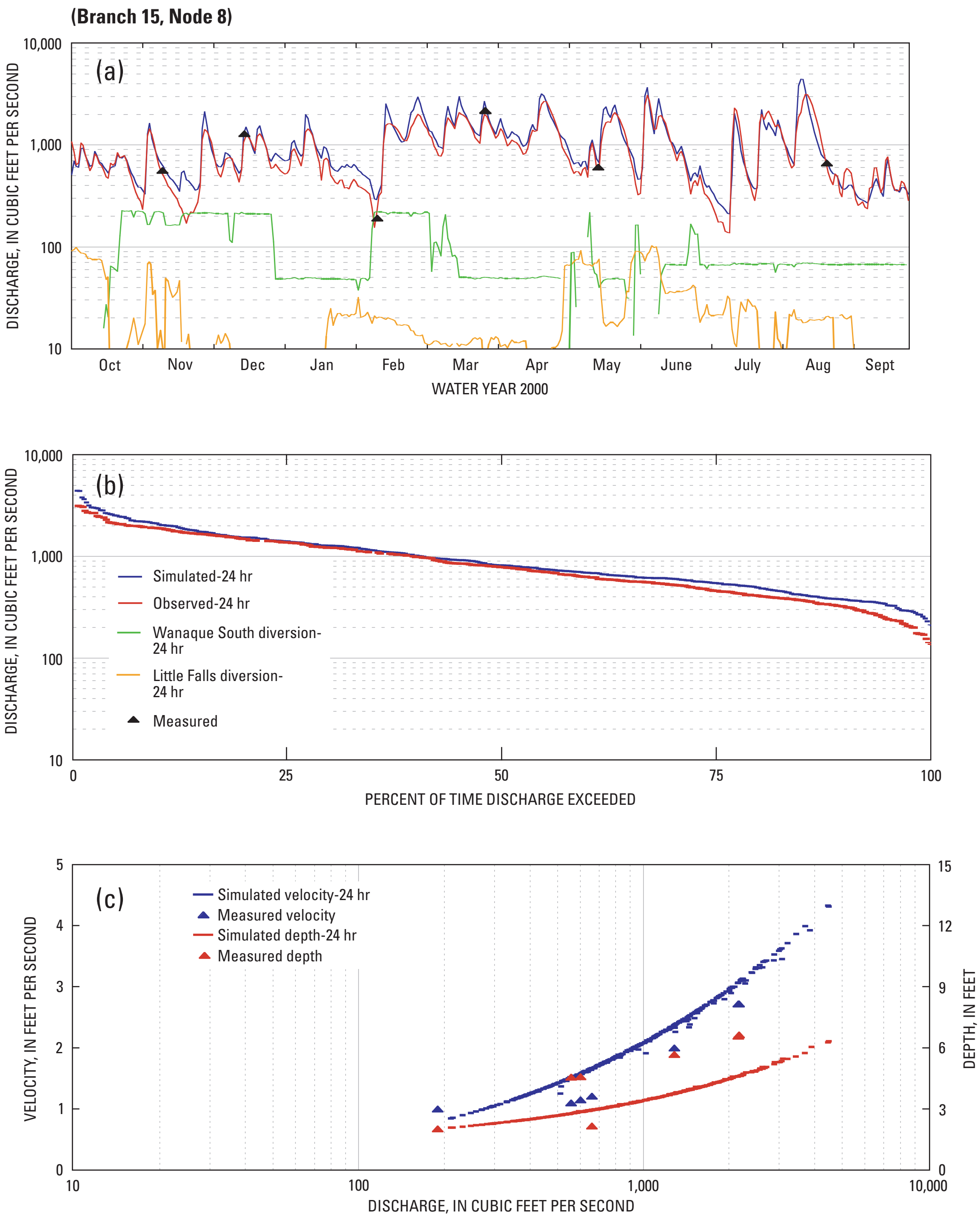


Figure 17. Validated (a) discharge, (b) flow duration, and (c) velocity and depth at gage 01389500, Passaic River at Little Falls, New Jersey, water year 2000.

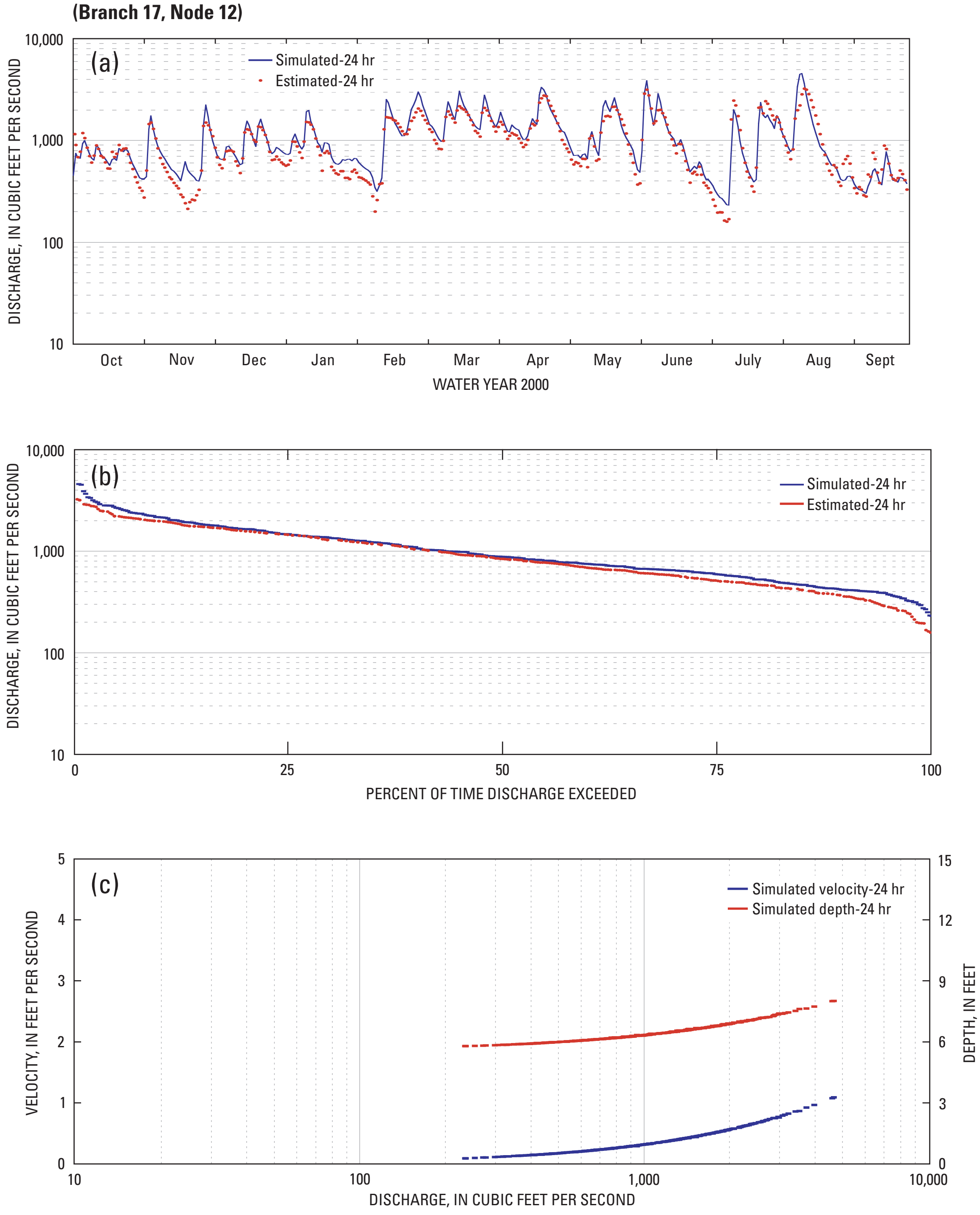


Figure 18. Validated (a) discharge, (b) flow duration, and (c) velocity and depth at station 01389890, Passaic River at Dundee Dam at Clifton, New Jersey, water year 2000.

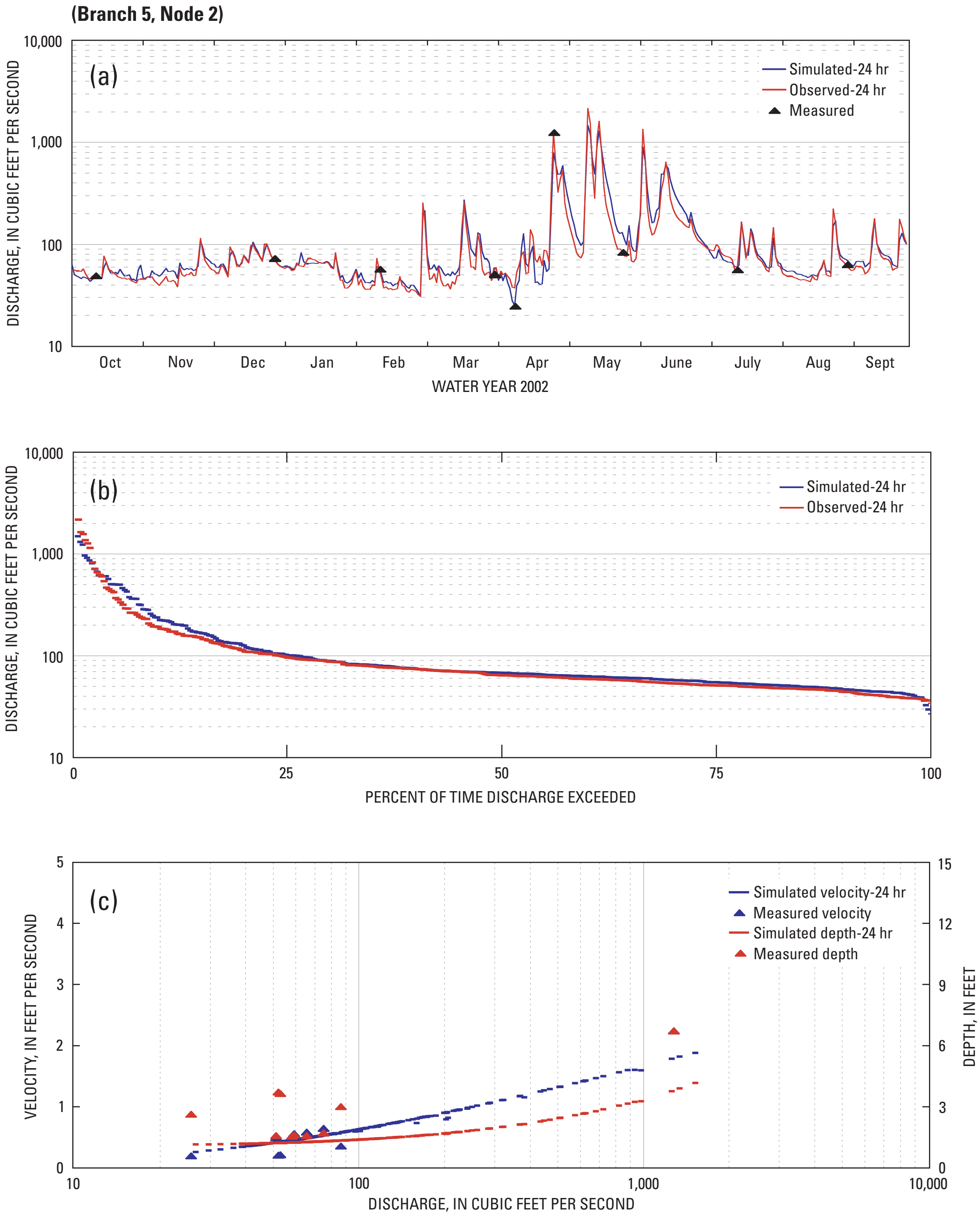


Figure 19. Validated (a) discharge, (b) flow duration, and (c) velocity and depth at gage 01388500, Pompton River at Pompton Plains, New Jersey, water year 2002.

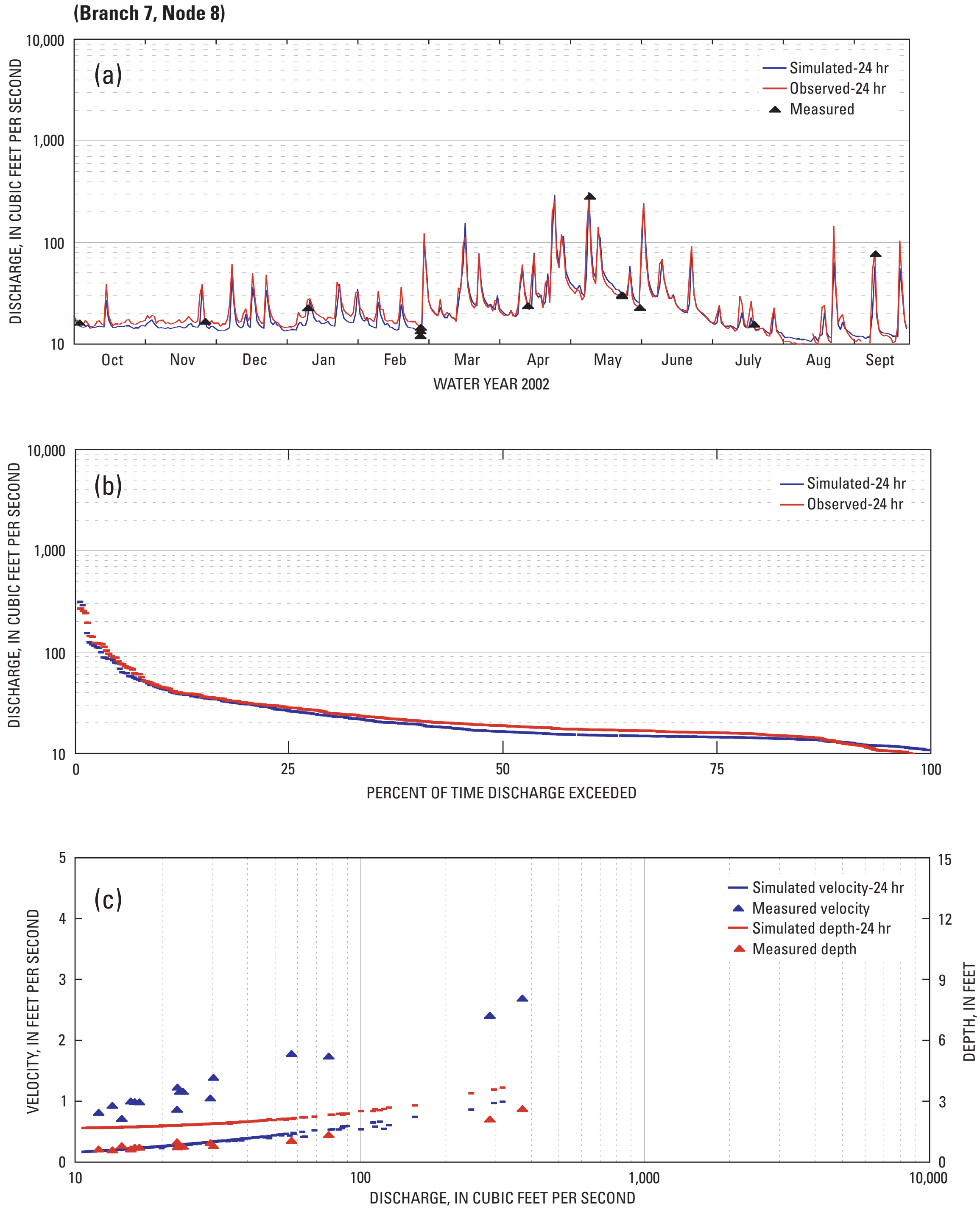


Figure 20. Validated (a) discharge, (b) flow duration, and (c) velocity and depth at gage 01381500, Whippany River at Morristown, New Jersey, water year 2002.

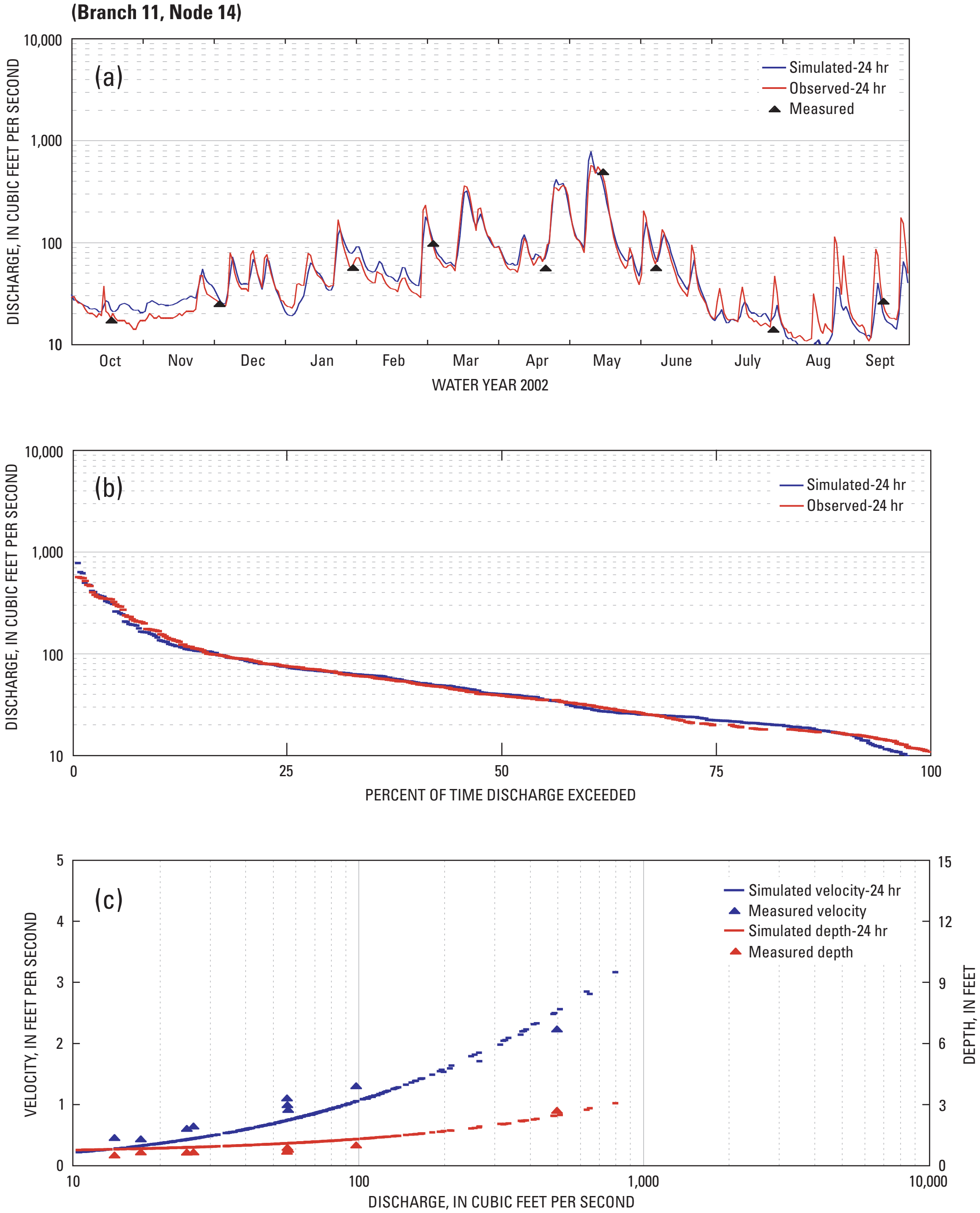


Figure 21. Validated (a) discharge, (b) flow duration, and (c) velocity and depth at gage 01379500, Passaic River near Chatham, New Jersey, water year 2002.

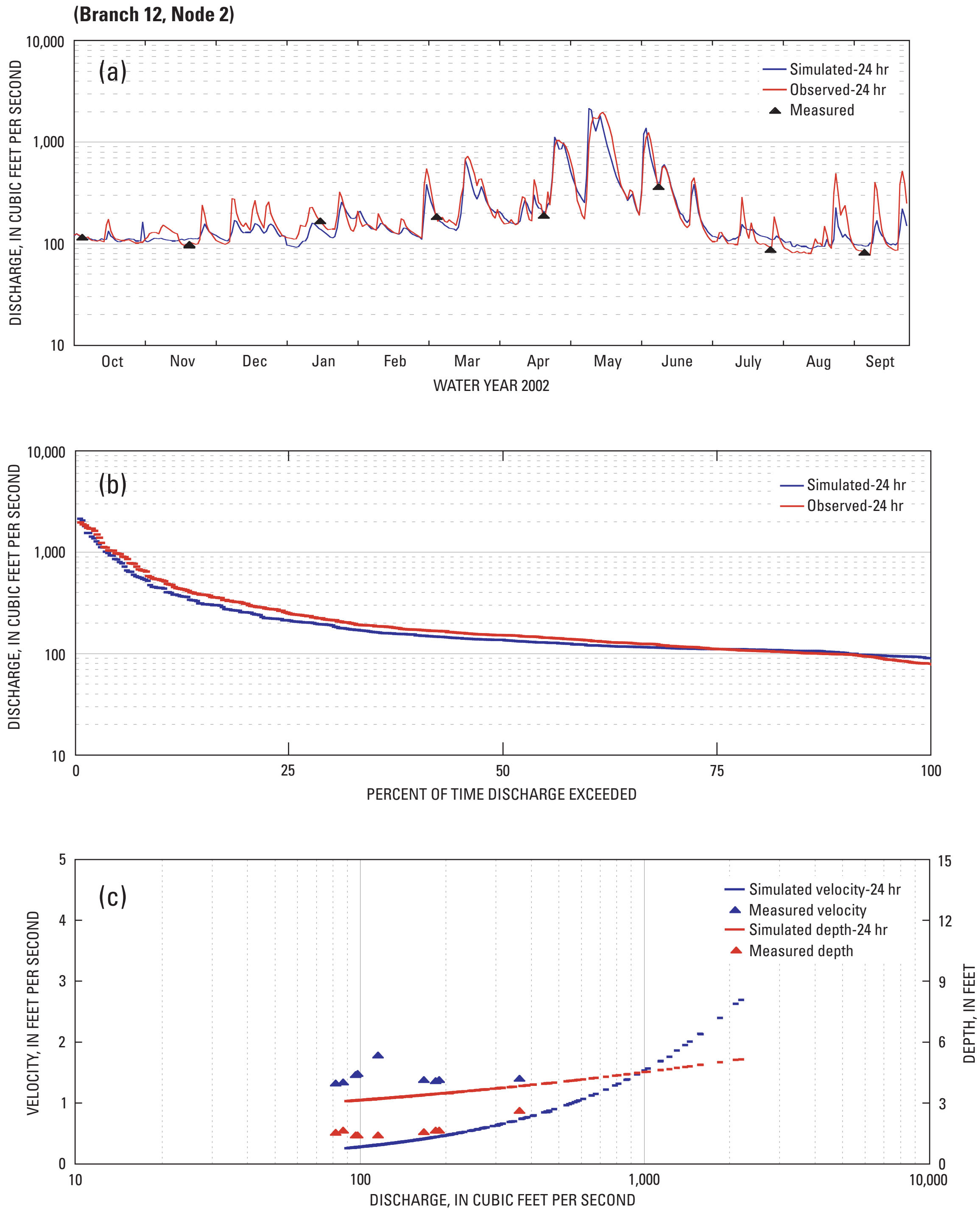


Figure 22. Validated (a) discharge, (b) flow duration, and (c) velocity and depth at gage 01381900, Passaic River at Pine Brook, New Jersey, water year 2002.

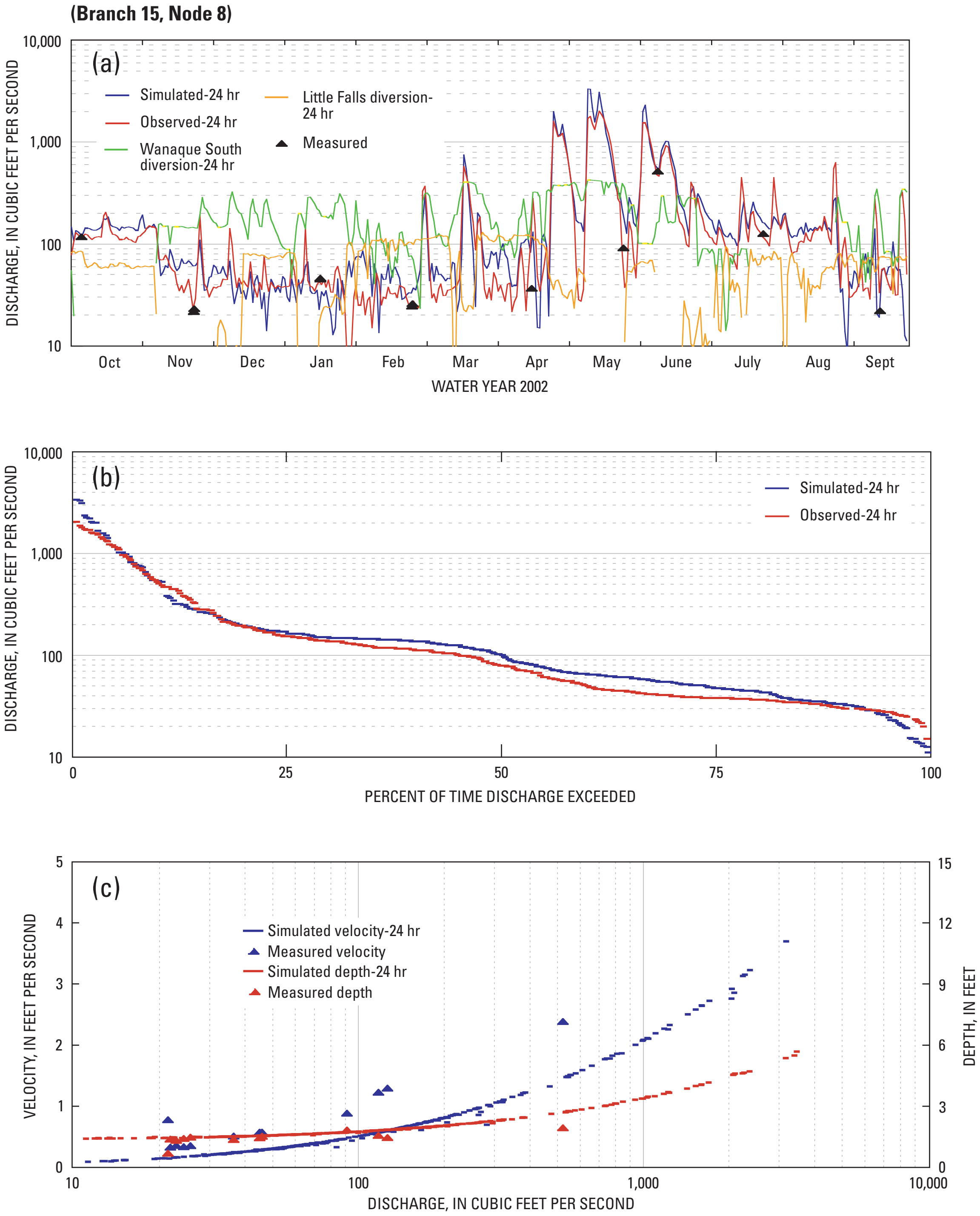


Figure 23. Validated (a) discharge, (b) flow duration, and (c) velocity and depth at gage 01389500,Passaic River at Little Falls, New Jersey, water year 2002.

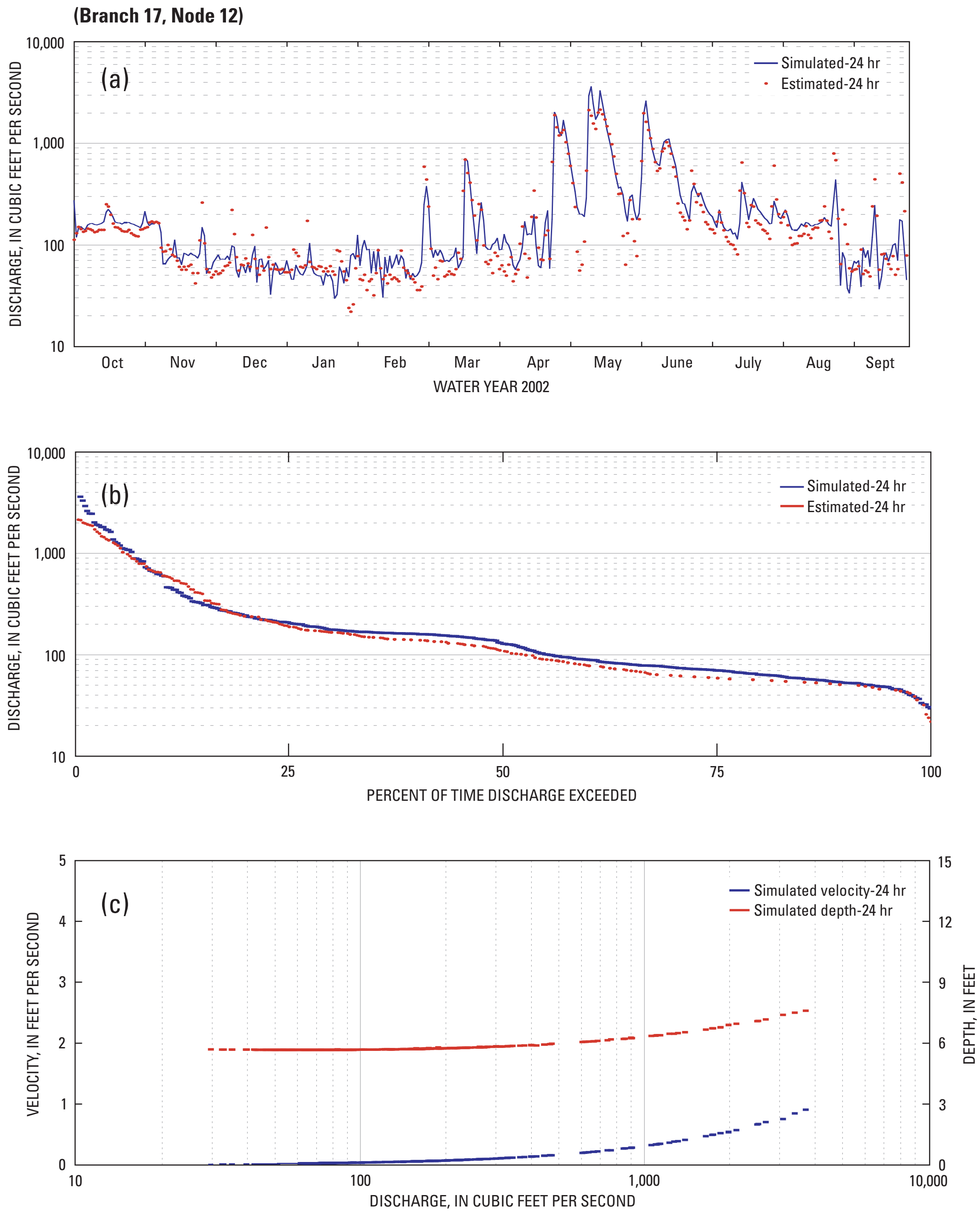


Figure 24. Validated (a) discharge, (b) flow duration, and (c) velocity and depth at station 01389890, Passaic River at Dundee Dam at Clifton, New Jersey, water year 2002.

High-Flow Conditions (Water Year 2003)

The model also was validated for water year 2003, a high-flow year. This simulation included the first 2 months of water year 2004 so as to cover the period of the water-quality model. At the time of validation, streamflow data from gaging stations for the first 2 months of water year 2004 had not yet undergone quality-assurance review by USGS. Validation discrepancies at peak flows also may be affected by reservoir spilling during storm events. The storage-balancing procedure required for water year 2002 was required for a few months at the start of water year 2003. A water-storage reservoir of approximately 3 x 10^6 ft^3 (69 acre-ft) was required.

Simulated and observed results for six gages are shown in figures 25 to 30; error analysis is shown in table 6. Comparison of simulated and observed mass balance yielded percent mean errors that are less than the accuracy of the gages. The model overpredicted mass balance for gage 01379500, Passaic River at Chatham, compared to the mass balance at this gage for water year 2001. No observed data are available for station 01389890, Passaic River at Dundee Dam at Clifton, for this water year.

Model-fit results for water year 2003 were compared to results for water year 2001. The hydrograph match is comparable to the accuracy of gage 01385500, Pompton River at Pompton Plains (fig. 25), and worse than the accuracy of gage 01381500, Whippany River at Morristown (fig. 26). Validation for flow duration, velocity, and depth are reasonable. Velocity validation is not as good as expected for gage 01381500, although validation within the target flow range is better than for water year 2001. The hydrograph match for gage 01379500 (fig. 27) is more accurate, as indicated by the lower mean percent absolute error (table 6). Validation for flow duration, velocity, and depth are reasonable. The hydrograph match is less accurate for gage 01381900, Passaic River at Pine Brook (fig. 28). Validation for flow duration, velocity, and depth are reasonable. Validation within the target flow range is better. The hydrograph match is more accurate for gage 01389500, Passaic River at Little Falls (fig. 29). Validation for flow duration, velocity, and depth are reasonable. The corresponding match between simulated and estimated data is reasonable for station 01389890 (fig. 30).

Mixing Algorithm at Two Bridges, New Jersey

The Pompton River merges with the Passaic River at Two Bridges, New Jersey (fig. 31). The Wanaque South intake is approximately 1,000 ft upstream from the confluence on the left bank of the Pompton River (looking downstream). The Two Bridges Sewerage Authority (TBSA) outfall is approximately 1,000 ft upstream from the intake on the right bank of the Pompton River. As a result of the locally flat topography, reverse flow occurs near the mouth of the Pompton River back up to the intake during certain periods of low flow and high diversion. This effect also can entrain Passaic River flow back up to the intake and contributes to the mixing of water from the Pompton River, Passaic River, and TBSA outfall. This effect may extend a short distance downstream in the Passaic River (Phil Roosa, Passaic Valley Water Commission, oral commun., 2004). A hydroelectric plant at Little Falls, approximately 3 mi downstream from Two Bridges, also may affect the mixing (R.D. Schopp, U.S. Geological Survey, oral commun., 2004).

Because water quality differs among these three local flow sources, nutrient loading of the Wanaque Reservoir is affected by the proportion of flow to the Wanaque South intake that originates from each source. Water quality generally is better in the Pompton River than in the Passaic River (Anderson and Faust, 1973; Hickman, 1997). The surface-water-quality standard for total phosphorus concentration (0.1 mg/L) is often exceeded in the Passaic River (and TBSA effluent). The Passaic River also contained dissolved solids at a concentration approximately 1.5 times that in the Pompton River during 1963-97 (USGS NWIS database). Total phosphorus loads from the three local flow sources in the vicinity of the intake differ greatly (fig. 32). (Only limited data were available for TBSA.)

Description of Algorithm

Because DAFLOW cannot simulate reverse flow, a mixing algorithm (subroutine) was developed (Harvey Jobson, U.S. Geological Survey, written commun., 2005) to account for the entrainment of Passaic River water into the Wanaque South intake under certain flow and diversion conditions. The mixing algorithm is a theoretical estimate of the distribution of water entrained by the Wanaque South intake among its three local sources (Pompton River, TBSA effluent, and Passaic River). The algorithm is based on a flow mass balance. The physics of the equations in the algorithm are based on the theory of diffusion in rivers and the hydrodynamics of streamlines and streamtubes as verified by many research studies (for example, Yotsukura, 1979) on lateral mixing in rivers. The five main equations are linear approximations to segments of theoretical mixing curves defining the relation between intake diversion and entrained TBSA effluent or Passaic River flow. The equations involve five parameters that affect mixing among the three sources as the diversion increases.

The variables used in the equations are defined below. The last five terms represent the mixing parameters.

Q_{sp} = TBSA effluent entrained by intake,
Q_s = effluent,
Q_p = intake diversion,
Q_{in} = Pompton River flow upstream from effluent outfall,
Q_{pam} = Passaic River flow entrained by intake as a result of mixing,
Q_{pap} = Passaic River flow entrained by intake as a result of advection,

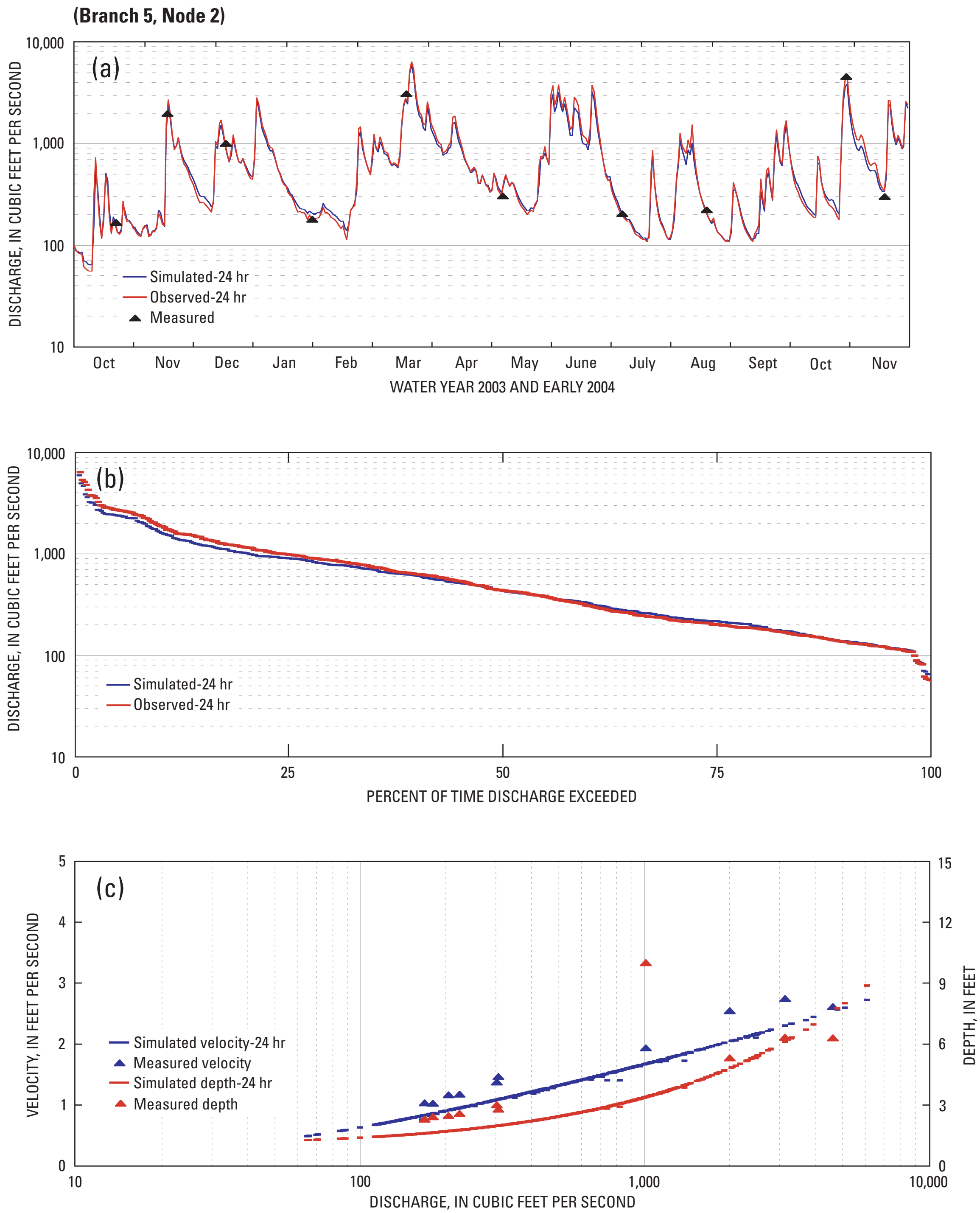


Figure 25. Validated (a) discharge, (b) flow duration, and (c) velocity and depth at gage 01388500, Pompton River at Pompton Plains, New Jersey, water year 2003 and early 2004.

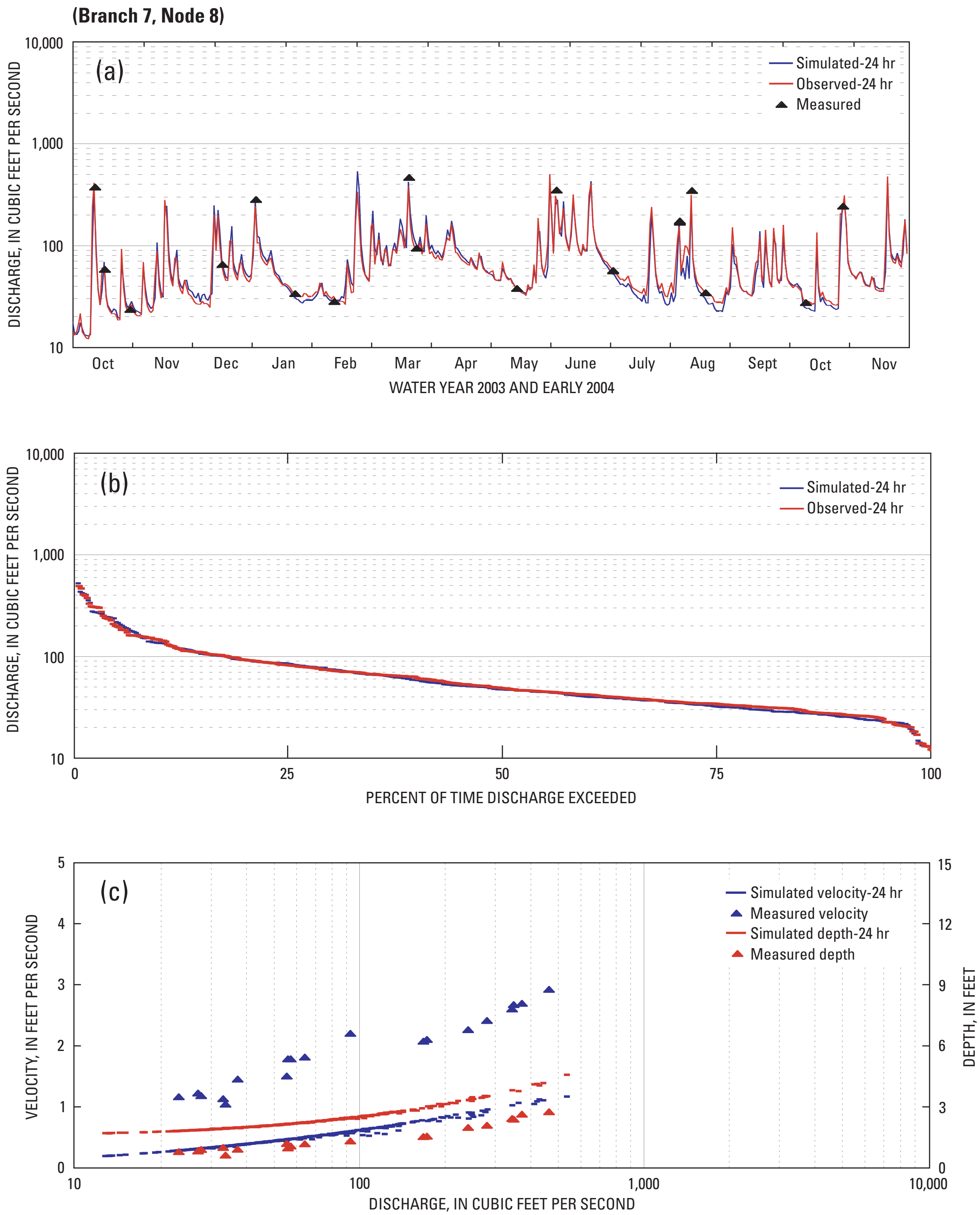


Figure 26. Validated (a) discharge, (b) flow duration, and (c) velocity and depth at gage 01381500, Whippany River at Morristown, New Jersey, water year 2003 and early 2004.

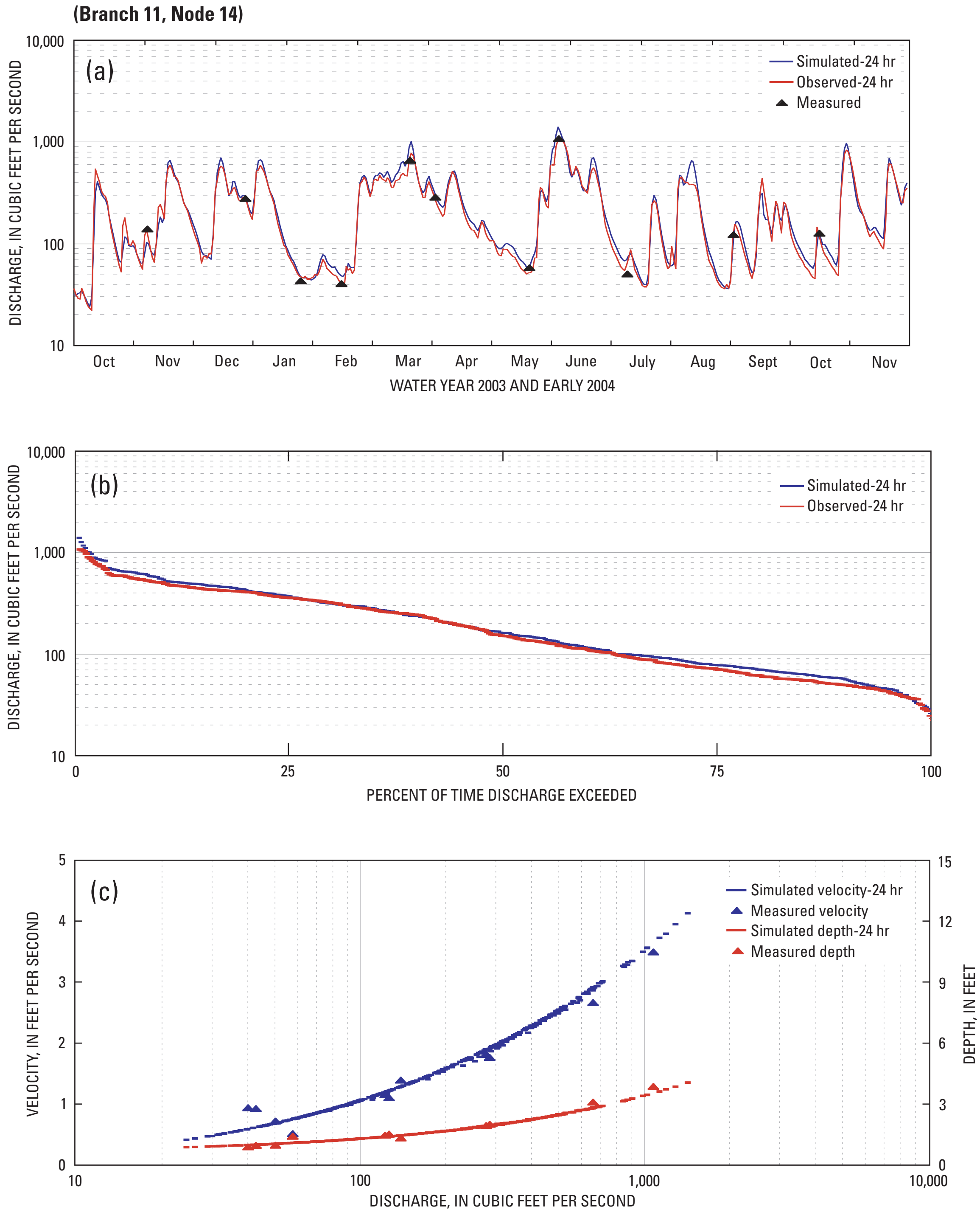


Figure 27. Validated (a) discharge, (b) flow duration, and (c) velocity and depth at gage 01379500, Passaic River near Chatham, New Jersey, water year 2003 and early 2004.

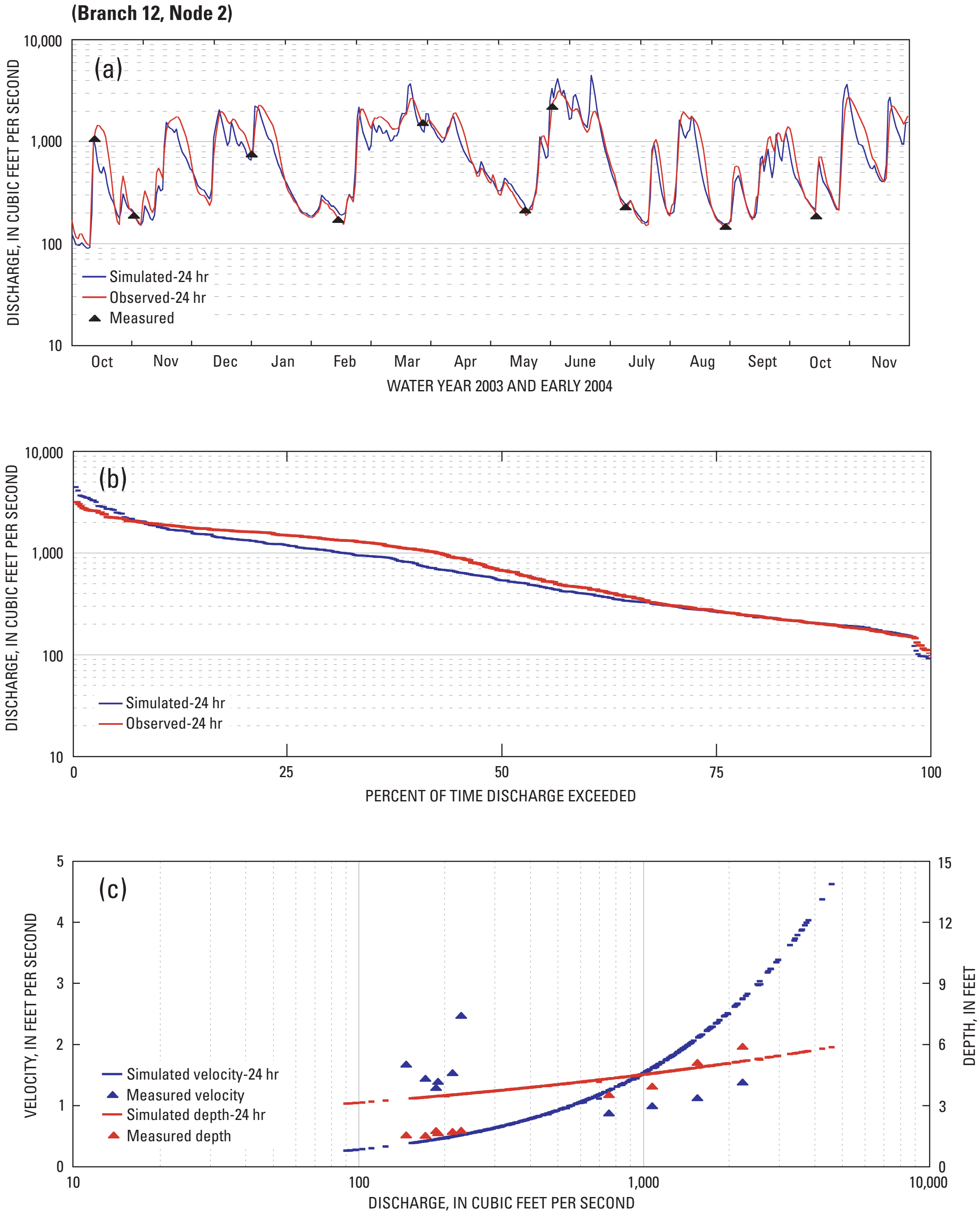


Figure 28. Validated (a) discharge, (b) flow duration, and (c) velocity and depth at gage 01381900, Passaic River at Pine Brook, New Jersey, water year 2003 and early 2004.

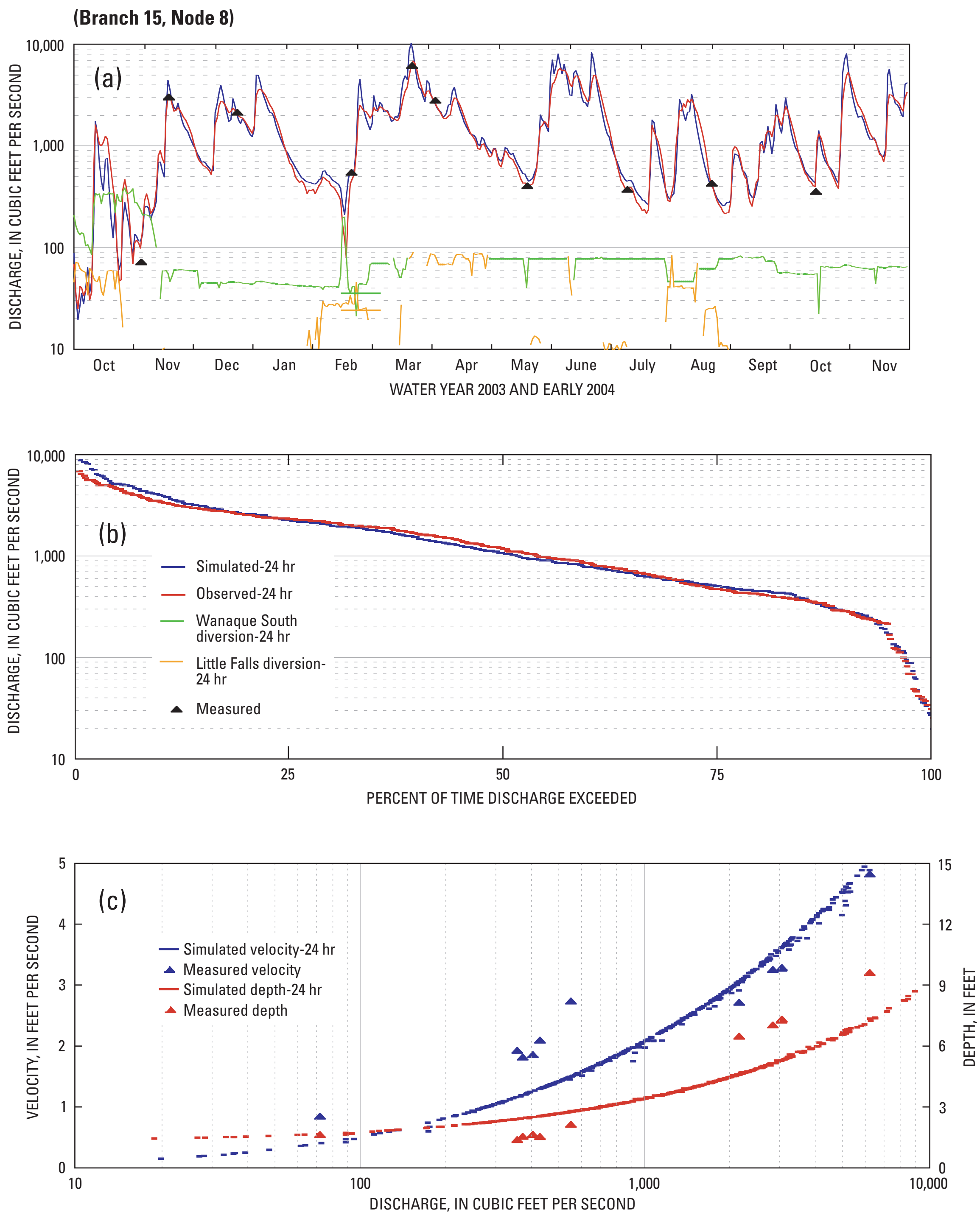


Figure 29. Validated (a) discharge, (b) flow duration, and (c) velocity and depth at gage 01389500, Passaic River at Little Falls, New Jersey, water year 2003 and early 2004.

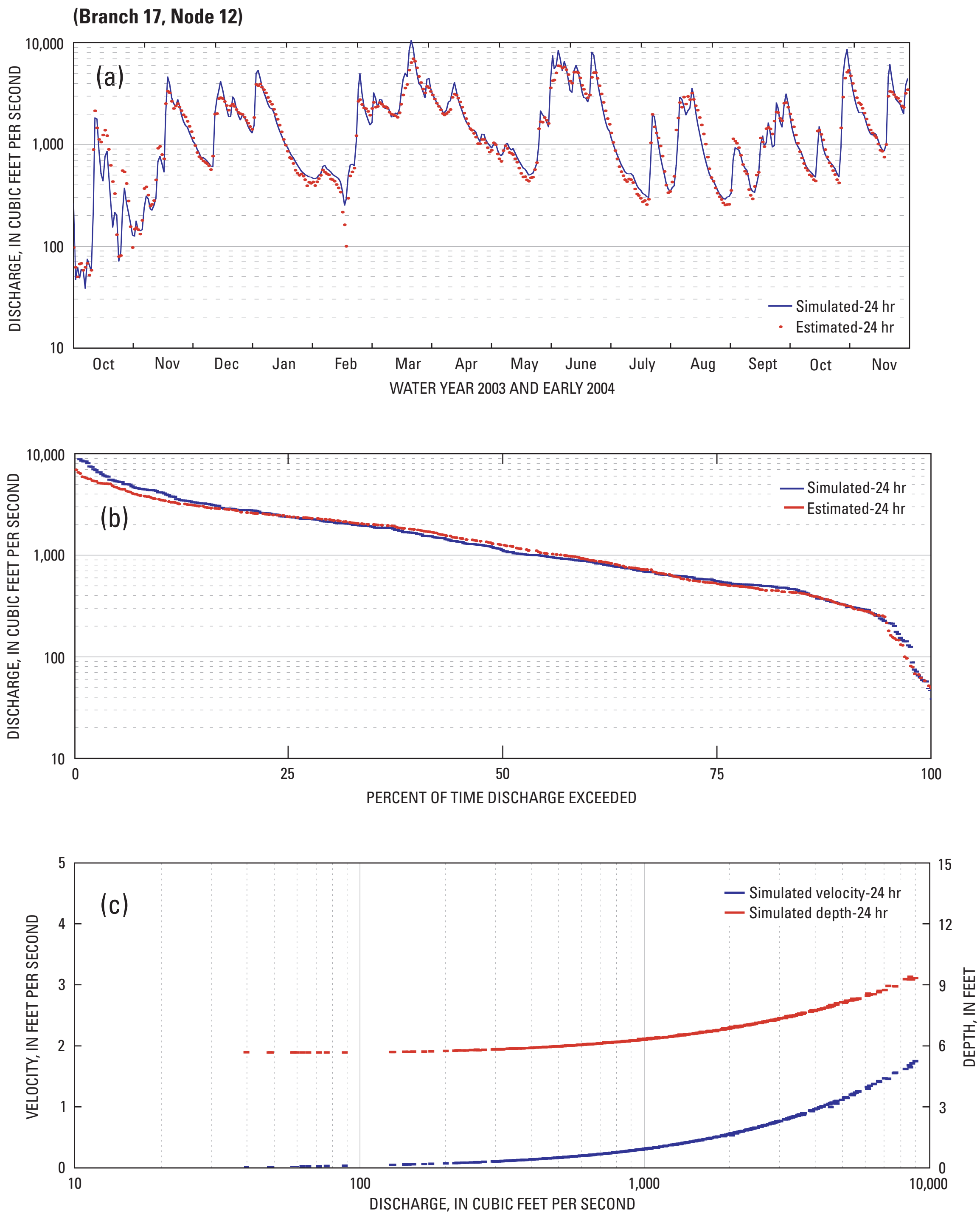


Figure 30. Validated (a) discharge, (b) flow duration, and (c) velocity and depth at station 01389890, Passaic River at Dundee Dam at Clifton, New Jersey, water year 2003 and early 2004.

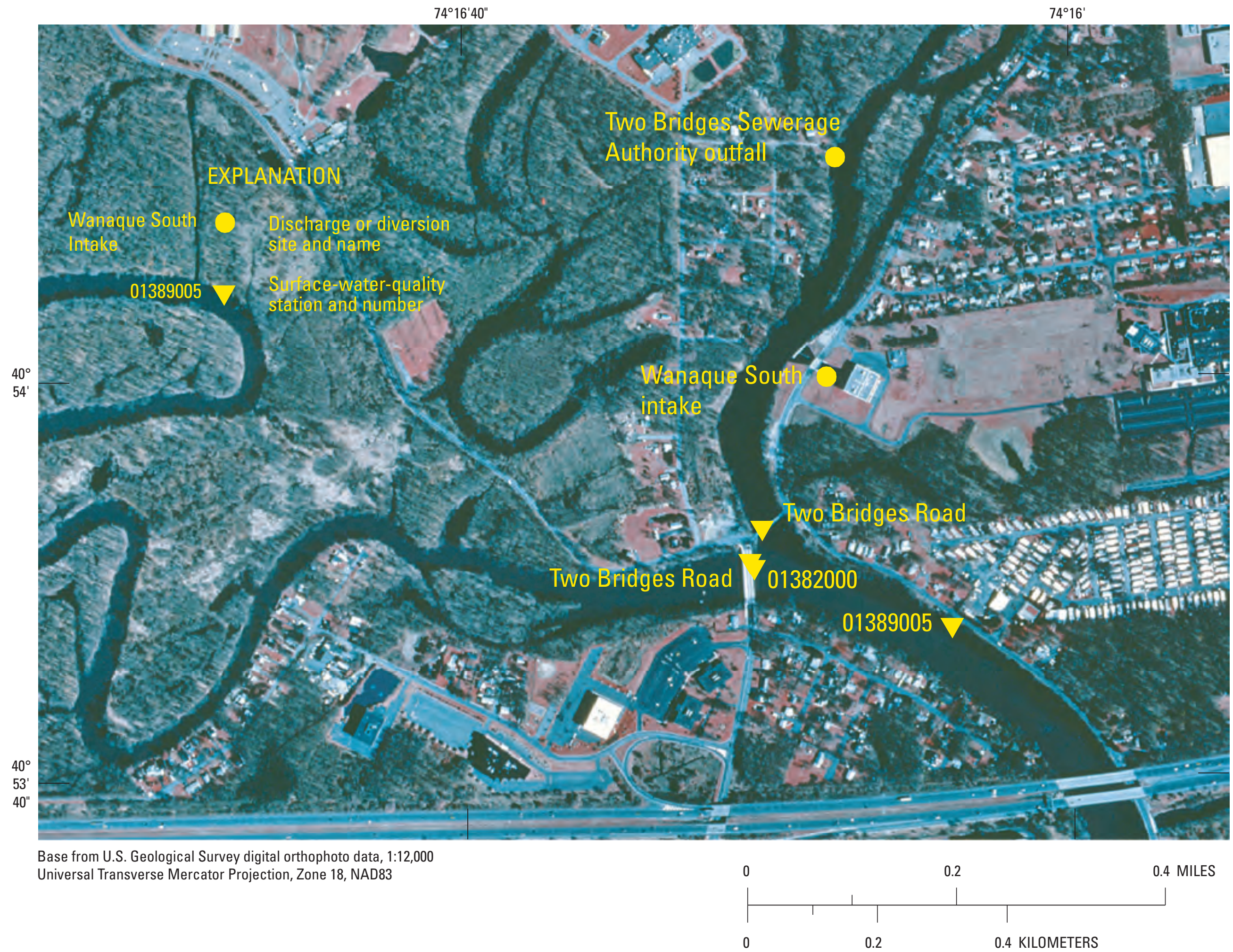


Figure 31. Location of sampling stations and discharge and diversion sites, Two Bridges, New Jersey, and vicinity.

R1 = ratio of intake diversion to Pompton River flow when mixing with effluent begins,

P1 = percent of effluent in total flow when intake diversion equals Pompton River flow,

P2 = percent of effluent in total flow when intake diversion equals Pompton River flow plus effluent,

D1 = flow in the Pompton River (either positive or negative) when the mixing influence is assumed to cease,

and

QM = Passaic River flow entrained by the intake when the net downstream flow in the Pompton River below the intake is zero.

The first three equations define the mixing of Pompton River water and TBSA effluent. The amount of effluent entrained by the intake (Q_{sp}) depends on the intake diversion (Q_p). If Q_p is less than a certain portion (R1) of the Pompton River flow upstream from the sewage outfall (Q_{in}), then no effluent is entrained. If Q_p is greater than R1 times Q_{in}, but less than Q_{in}, then Q_{sp} is determined by equation 15. If Q_p is greater than Q_{in}, but less than Q_{in} plus the effluent flow (Q_s), then Q_{sp} is determined by equation 16. Parameters P1 and P2 control the amount of effluent reaching the intake. If Q_p is greater than Q_{in} plus Q_s, but less than a fixed discharge of D1 plus Q_{in} plus Q_s, then Q_{sp} is determined by equation 17. Finally, if Q_p exceeds Q_{in} plus Q_s by more than D1, then all the effluent is entrained by the intake. A negative value for parameter D1 indicates that flow downstream from the intake is in the upstream direction, toward the intake (reverse flow).

$$Q_{sp} = Q_s * P1 \frac{\left(\frac{Q_p}{Q_{in}}\right) - R1}{1 - R1} \quad (15)$$

$$Q_{sp} = Q_s * P1 + Q_s (P2 - P1) * \frac{(Q_p - Q_{in})}{Q_s} \quad (16)$$

$$Q_{sp} = Q_s * P2 + (1 - P2) * \frac{[Q_p - (Q_{in} + Q_s)]}{D1} \quad (17)$$

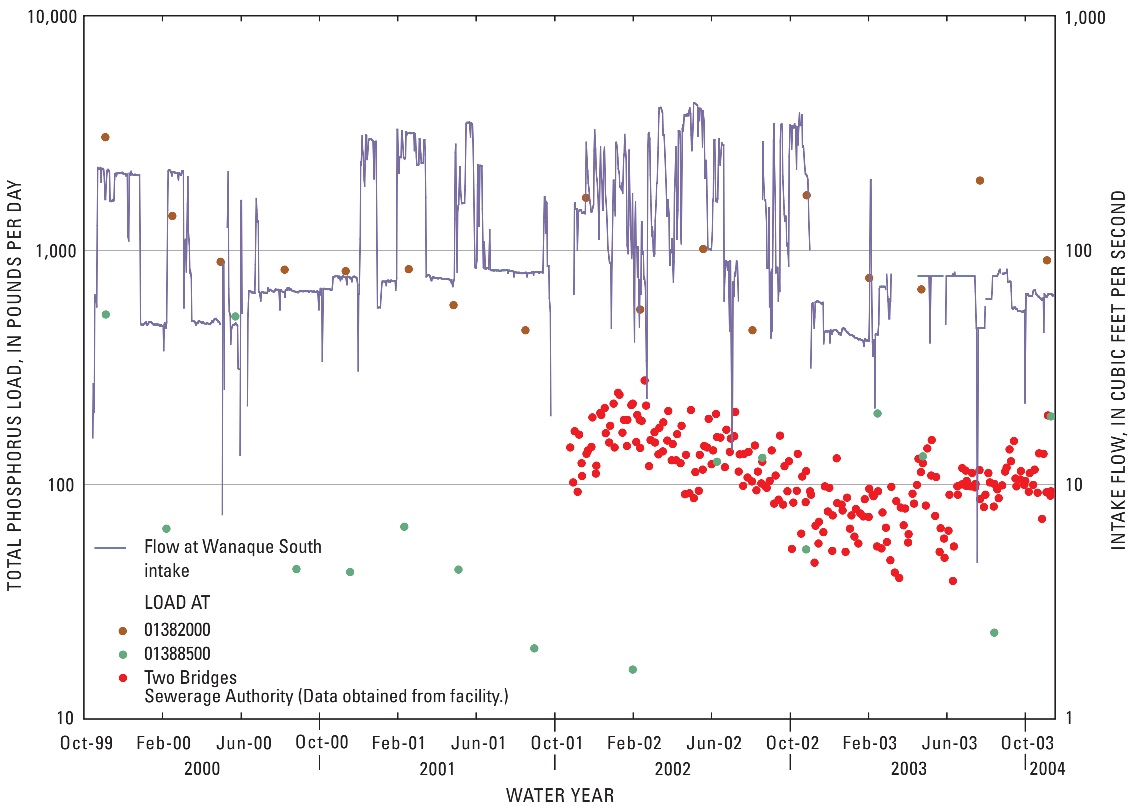


Figure 32. Intake flow and phosphorus loads in the vicinity of Two Bridges, New Jersey, 1999-2003. (Most locations shown in fig. 31)

The last two equations define the mixing between the Pompton and Passaic Rivers. As Q_p approaches Q_{in} plus Q_{sp}, flow in the Passaic River also will begin to move upstream, toward the intake. As the net downstream Pompton River flow below the intake approaches zero, some mixing with Passaic River flow will occur, and some Passaic River flow will be diverted. This entrainment of Passaic River flow is a result of mixing, not advection, because it occurs despite a small net downstream flow. Some Pompton River flow plus effluent moves downstream past the intake, and an equal amount of Passaic River flow moves upstream toward the intake. If the net downstream flow is greater than D1, then no Passaic River flow will be entrained by the intake. If the net downstream flow is greater than zero, but less than D1, then the Passaic River entrained flow (Q_{pam}) is computed using equation 18. When the net downstream flow is zero, parameter QM represents the amount of entrained Passaic River flow. As the intake diversion increases above Q_{in} plus Q_{sp}, additional flow is diverted from the Passaic River by advection (Q_{pap}), which is computed using equation 19. In summary, the Passaic River flow that can move upstream to the intake varies from zero, when the Pompton River flow downstream from the intake is greater than D1, to QM, when the Pompton River flow downstream from the intake is zero.

$$Q_{pam} = QM * \frac{(Q_p + D1 - Q_{in} - Q_{sp})}{D1} \qquad (18)$$

$$Q_{pap} = Q_p - Q_{sp} - Q_{in} \qquad (19)$$

The mixing algorithm applies only during a limited flow range--that is, when Q_p is comparable to the Pompton River flow. Outside this flow range, the algorithm has little or no importance. The algorithm does not apply if Q_p is less than Q_{in} and Q_{sp} equals zero, or if Q_p is greater than Q_{in} plus Q_s plus D1 and Q_{sp} equals Q_s. Also, no flow is diverted from the Passaic River if Q_p is less than Q_{in} plus Q_s plus D1.

Output from Algorithm

Little flow or water-quality data for the vicinity of Two Bridges were available for use in fully calibrating and validating the algorithm. Several types of calibration were attempted, but these attempts often were limited by insufficient data. In one study, a physical model was used in the design of Wanaque South intake (Hydro Research Science, Inc., 1983). Tests done for this study covered a range of flow conditions and indicated that complete mixing may have occurred when Pompton River flow was less than approximately 2,000 ft^3/s. Diversions occur at Wanaque South for higher river flows, however, and that study addressed only specific flow combinations and did not account for TBSA effluent.

Continuously monitored and individual measurement surface-water and water-quality stations are shown in figure 31. The water-quality parameter for which the most data were available was specific conductance (February-September 2002). These data were available from the USGS NWIS database and from North Jersey District Water Supply Commission and Passaic Valley Water Commission. TBSA also provided effluent dissolved-solids concentrations, which were converted to specific conductance by using the method described by Hem (1985) and surface-water-quality data.

The computed ratio of intake diversion to Pompton River flow when mixing with effluent begins (R1) could be approximated from the limited data by checking for times when conductance at the intake was similar to conductance on the opposite side of the river at Two Bridges Road and by checking for corresponding times when Pompton River flow was greater than the intake diversion (for example, during May-June 2002). This approximation yielded a minimum value of 0.5 for parameter R1. The remaining parameter values had to be assumed. It is assumed that TBSA contributes effluent to the intake mainly when the intake diversion is comparable to Pompton River flow. Further, it is assumed that TBSA effluent is only partially mixed across the Pompton River by the time it reaches the intake. General tracer tests indicate that transverse mixing likely occurs slowly when dye is injected at the river bank (Kilpatrick and Wilson, 1989). Accordingly, parameters P1 and P2 were assumed to equal 0.2 and 0.8, respectively. (It is possible that TBSA effluent is fully mixed before reaching the intake, in which case relevant output from the algorithm is not necessary.) Parameters D1 and QM each were assumed to equal 5 ft^3/s; conducting a local dye-tracer test would help to verify these values. A tracer test to help determine mixing parameters was considered in the summer of 2004, but could not be conducted as a result of persistent high flow conditions.

Sensitivity analysis can provide additional information about the choice of mixing-parameter values. The effect of variation in parameter values on the average intake diversion from the local flow sources during water year 2002 is shown in figure 33. This analysis is confined to the limited range of Pompton River flows in which the parameters are relevant. Parameters R1, P1, and P2 are not included on the lower graph because they have little or no effect on the diversion of Passaic River flow. Simulation results generally are more sensitive to changes in parameters D1 and QM than to changes in parameters R1, P1, and P2, although intake diversion from the Pompton River is very sensitive to parameter R1, and intake diversion from TBSA is not sensitive to parameters QM or D1. These results likely are because effluent is only a small portion of the total flow diverted.

The simulated sources of water to Wanaque South intake based on the parameter values used are shown in "pumpographs" (intake diversion as a function of time) for the 4 water years (figs. 34a-d). Daily flows are shown in the figure. As expected, most of the diverted water comes from the Pompton River. During certain periods of low flow and high diversion, however, when the Pompton River flow is insufficient to supply the intake (for example, in water year 2002), TBSA and the Passaic River contribute flow to the intake. These contributions can occur throughout the year depending on local flow conditions.

In another study (Najarian Associates, 2005), cumulative frequency analysis was used to show that Passaic River flow was entrained approximately 55 percent of the time on intake operation days from 1993 to 2002. Water-quality simulation results indicated that, from October 1999 to November 2003, Passaic River water was entrained more than 50 percent of the days that diversion occurred, accounting for almost 20 percent of the flow and more than 42 percent of the phosphorus load to the diversion. These results are consistent with Najarian Associates' (2005) estimates for 1993-2002. Also, the governing assumption used to determine Passaic River entrainment is the same assumption used by Najarian Associates (2005), namely that Pompton River water is used preferentially as long as flow is available to meet the demand; then Passaic River water is used to make up any deficit. Calibration of the mixing algorithm is important only in determining the amount of TBSA effluent entrained by the diversion. This determination is irrelevant when Passaic River water is entrained because all TBSA effluent and Pompton River water are entrained under those conditions. Ultimately, the parameter values used are considered acceptable because (1) adequate field data are lacking, (2) they satisfy the purpose of demonstrating the proof of concept, (3) they affect only local flow routing, and (4) their validity might be better evaluated through use of the water-quality model (that is, the parameter values may not be appropriate from a water-quality perspective).

Simulation of Water-Quality Transport

The water-quality computer program WASP was used by TRC Omni to simulate the dynamics of nutrient cycling and its effect on water-quality constituents. WASP is a dynamic finite-difference program for aquatic systems that includes the time-varying processes of advection, dispersion, point and nonpoint mass loading, and boundary exchange. Input to WASP consists of time series of streamflows, time series of constituent loads, constituent concentrations in streamflow, and several water-quality parameters. Output from WASP provides constituent data that can be used in establishing the Passaic River Basin nutrient TMDL.

In addition to the DAFLOW design considerations for WASP discussed earlier, TRC Omni (2007) developed a graphical user interface, one function of which was to reformulate output flows from DAFLOW for input to WASP. That is, DAFLOW output was converted from a Lagrangian to a Eulerian reference frame. In a Lagrangian reference frame, the computational nodes move with the flow; in a Eulerian reference frame, they are fixed in space. The interface also performs other functions for the water-quality modeling, including data processing and decision support.

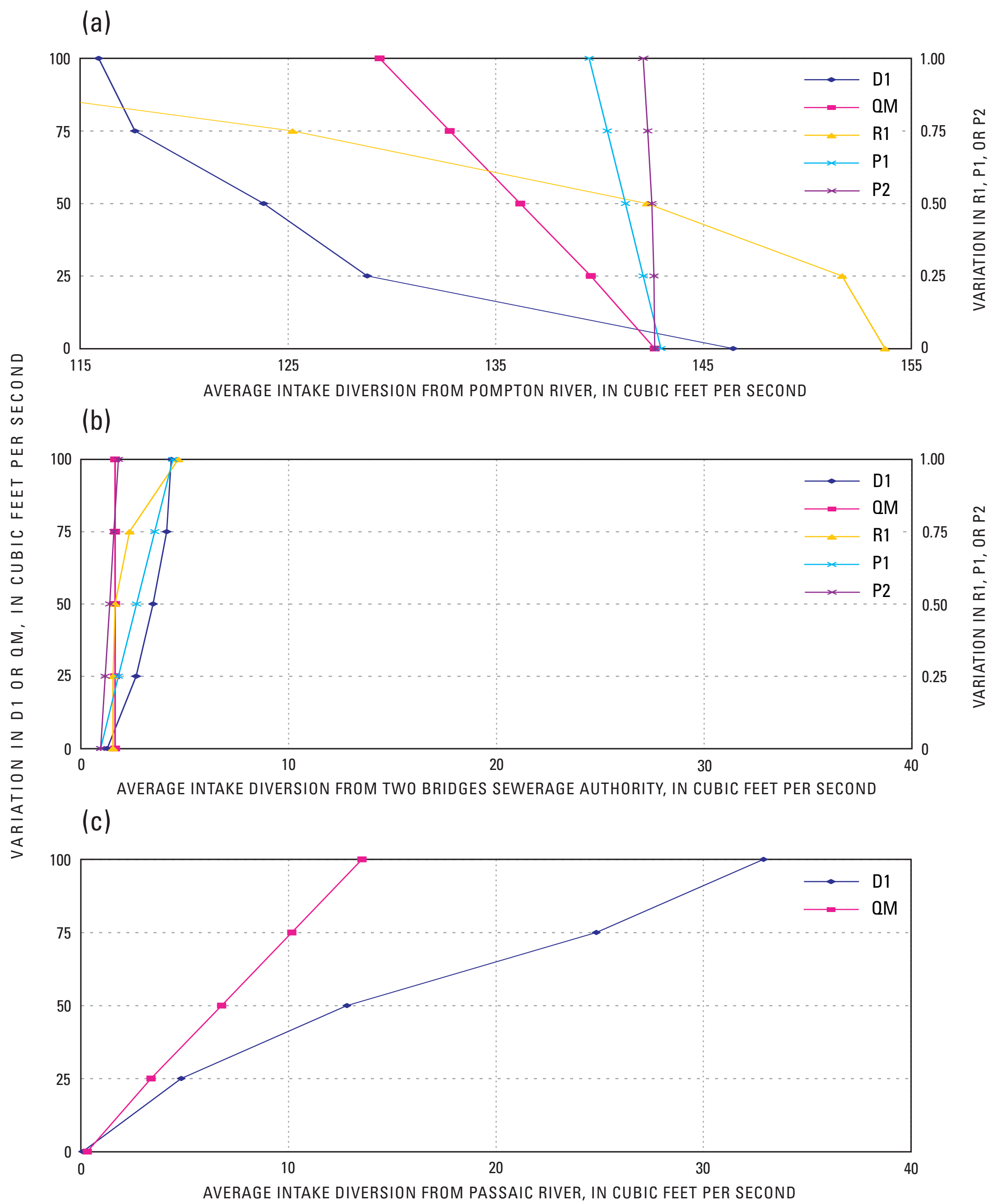


Figure 33. Results of sensitivity analysis on mixing algorithm parameters used in the flow model of the nontidal Passaic River, New Jersey, water year 2002. (Parameters D1, QM, R1, P1, and P2 identified on p. 56)

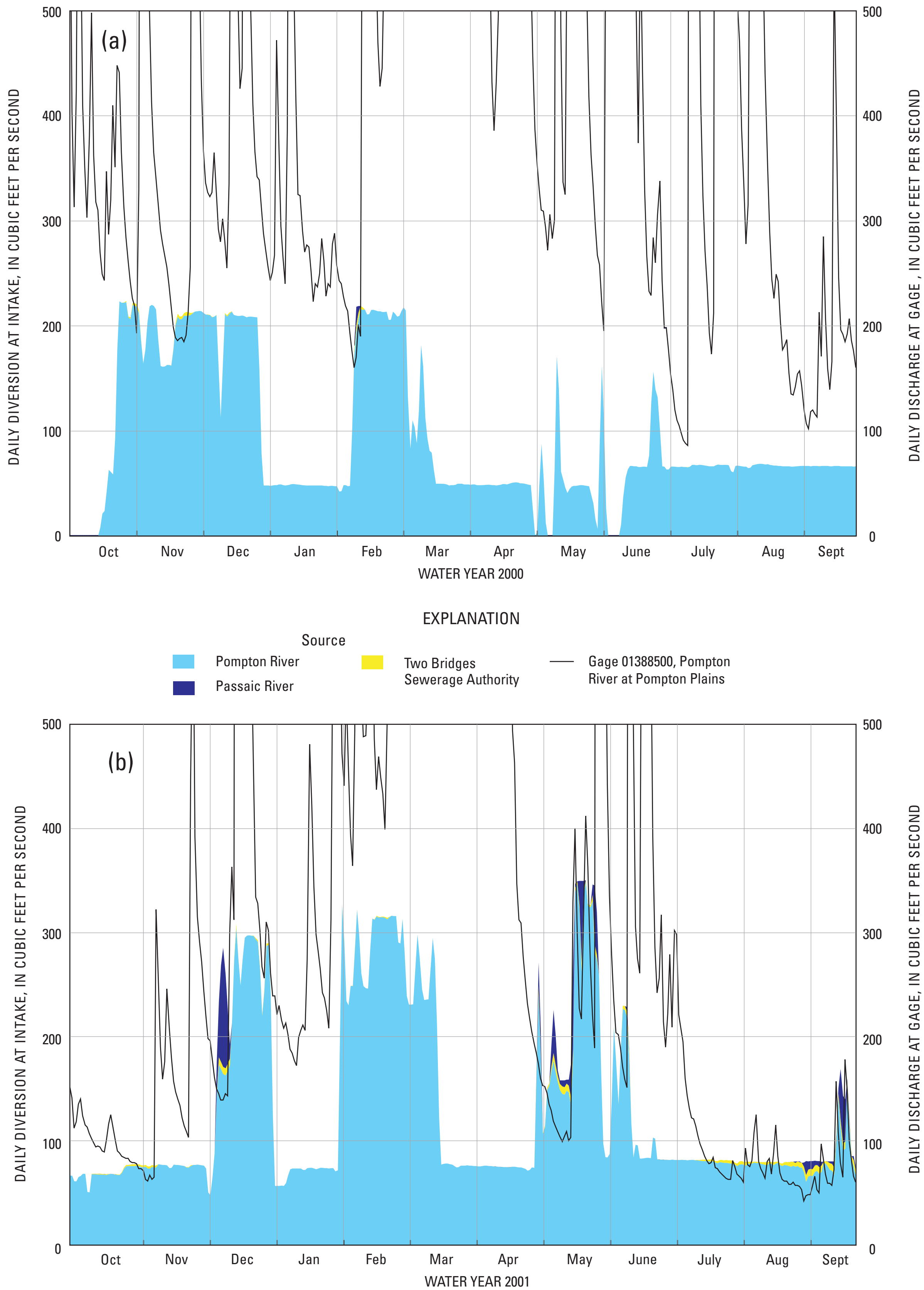


Figure 34. Simulated sources of water to Wanaque South intake, Two Bridges, New Jersey, for (a) water year 2000, (b) water year 2001, (c) water year 2002, and (d) water year 2003 and early 2004.

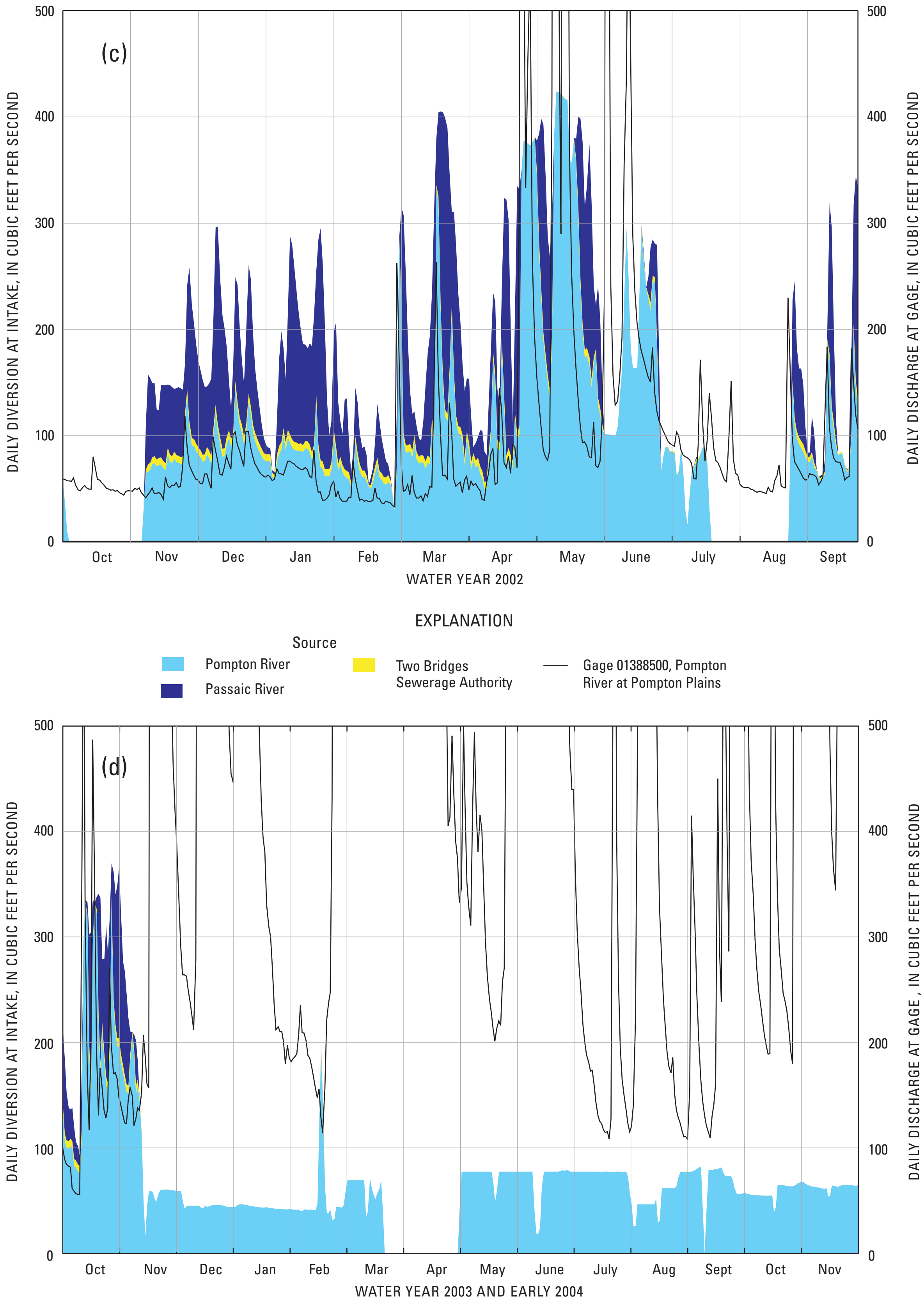


Figure 34. Simulated sources of water to Wanaque South intake, Two Bridges, New Jersey, for (a) water year 2000, (b) water year 2001, (c) water year 2002, and (d) water year 2003 and early 2004.—Continued

Channel Inactive Storage Area

DAFLOW simulates flood wave speed but not constituent transport speed. Accurate determination of hydraulic-geometry parameter A0, average channel cross-sectional area at zero flow, is required for the water-quality model, as discussed earlier in this report. Calibration of parameter A0 also was described earlier by way of equation 9. If continuous concentration data were available at many locations within the model domain, a computer program like the Branched Lagrangian Transport Model (BLTM) could be used (Jobson and Schoellhamer, 1993; Jobson, 1997; Jobson, 2001) to accurately calibrate parameter A0. Such data are not available, although archived dye-tracer data from USGS time-of-travel tests do exist. Unfortunately, most of these data are unpublished. Published data are available for the subreach between Two Bridges and Little Falls, and can be used to validate the parameter A0 values there. Thus, BLTM was applied to simulate constituent transport in that subreach.

Time-of-travel tests involving 29.8 mi of the Passaic River (Horwitz and Anderson, 1966) were available for use in this transport simulation. The tests were conducted under steady flow conditions using fluorescent rhodamine B dye, which was thought to be relatively stable and non-reactive. Dye-concentration data were provided for a moderately low-flow tracer test conducted during June 16-19, 1964, but dye concentration as a function of time, required for BLTM, was given only for the sampling sites at Two Bridges and Little Falls. No pollutographs (concentration as a function of time) were available for an extreme-low-flow tracer test conducted during September 21-25, 1964.

Transport Submodel

The Branched Lagrangian Transport Model (BLTM) simulates dissolved-constituent transport in open channels by solving the one-dimensional advection-dispersion equation. BLTM uses a Lagrangian reference frame; a solution scheme that minimizes numerical dispersion and allows determination of the effect of each physical process on the computed concentrations. BLTM can accept DAFLOW output directly as input, and can route any number of interactive constituents for which the physical and (or) chemical reactions can be defined in a subroutine. The version of the BLTM used herein considers only first-order growth or decay. The transport equation for one constituent is

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial \xi}\left(D\frac{\partial C}{\partial \xi}\right) + S + \Phi + K\,(C - CR), \qquad (20)$$

where

C = concentration,
ξ = Lagrangian distance coordinate,
D = longitudinal dispersion coefficient,
S = rate of production of concentration, which is independent of the concentration,
Φ = rate of change in concentration due to tributary inflow,
K = rate of production of the constituent,
and
CR = equilibrium concentration.

Design and Boundary Conditions

A DAFLOW submodel was needed to drive the BLTM submodel. Accordingly, a three-branch DAFLOW submodel was created from branches 13 to 15 (fig. 6) of the existing DAFLOW model. A 2.5-day simulation using 1-hour time steps was created to coincide with the period of the tracer test done in June 1964. The adequate subreach slope made the smaller time step feasible (Jobson and Harbaugh, 1999). Flow boundary conditions during the tracer test were reconstructed from the limited reported and archived data. Flows were assumed to be constant and no diversion was simulated at Little Falls (data were not available). A three-branch BLTM submodel also was created. A concentration boundary condition determined by discretizing the pollutograph at Two Bridges was input at the upstream end of the submodel. A 1-hour time step was required to represent the variation in dye concentration with time shown in the pollutograph.

Calibration and Validation

A pollutograph showing the match between simulated and measured dye concentration at Little Falls is shown in figure 35. Concentration loss and peak attenuation and spread caused by decay and (or) dilution from inflows are reproduced. Tracers are lost in transit as a result of adhesion on sediments and photochemical decay. Dye loss was calibrated by adjusting a first-order decay coefficient and minimizing the mean error in residuals between simulated and measured concentrations. Peak dye attenuation and spread were calibrated by adjusting a dimensionless dispersion factor, which is based on the longitudinal dispersion coefficient, and minimizing the root mean square error in residuals. The calibrated decay rate of rhodamine B dye of 5.0 percent per hour is comparable to a measured decay rate of 7.5 percent per hour. In contrast, a dye such as rhodamine WT, which is less sorptive than rhodamine B, decays at only 5 percent per day (Wilson and others, 1986; Kilpatrick, 1993). The calibrated dispersion factor of 0.35 could be refined by predicting the peak dye concentration at various points along the river caused by an upstream injection, using the procedure outlined in Jobson (1996), and then adjusting dispersion factors in each subreach to obtain simulated results similar to those predicted.

The timing of the peak dye concentration was approximately 3 hours too slow using the values for parameter A0 from the existing DAFLOW model (fig. 35). This result could be improved by adjusting parameter A0 through trial and error. The submodel was validated using the calibrated transport parameters in a second simulation representing the September

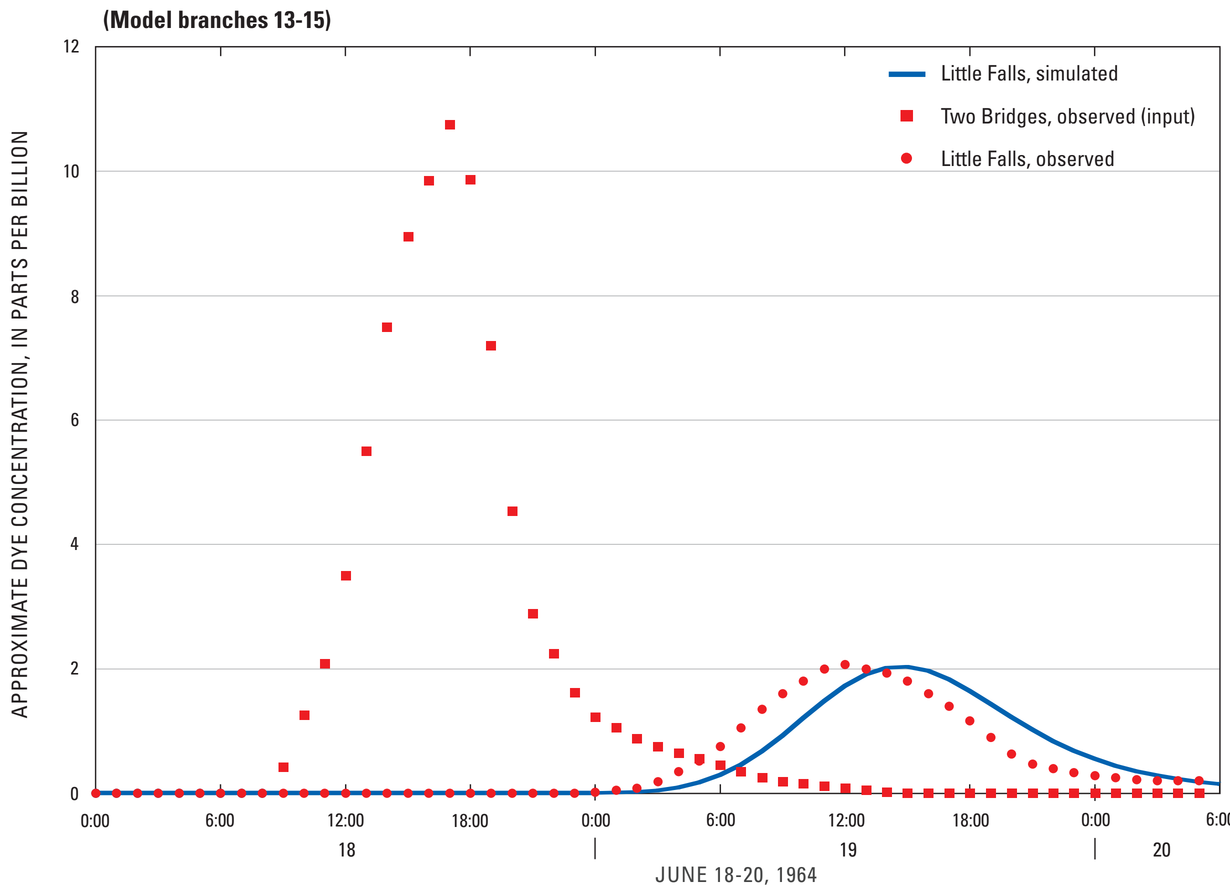


Figure 35. Calibrated dye transport between Two Bridges and Little Falls, New Jersey. (Observed data from Horwitz and Anderson, 1966.)

1964 tracer test. The DAFLOW and BLTM submodels were reconstructed and run. Because only time-of-travel of the peak dye concentration was available from that tracer test, the input pollutograph from the June 1964 tracer test was used. Simulated results indicate a peak time-of-travel of 55.5 hours, whereas the measured data indicate a peak time-of-travel of 58.3 hours. Thus, the transport submodel created indicates that simulated values for parameter A0 are very good in subreaches 13 to 15.

Limitations of the Simulation Analysis

Hydrologic models are only as good as the assumptions used to develop them and the data used as input. One source of error is model error. Limitations of the DAFLOW and BLTM computer programs are discussed in the respective code documentation reports. Calibration is less good at some locations than at others as a result of the effects of spatial and temporal discretization, flat channel slope, the model's weak representation of backwater conditions and off-channel storage, and a low ratio of advection to dispersion. Limitations of the mixing algorithm include simplified assumptions about local flow conditions and estimates for parameter values. For example, reverse flow is not allowed downstream from Two Bridges, represented by branch 13 (fig. 6). Validation can be expected to be worse than calibration in some cases because model parameters are adjusted only during the calibration process and not during validation.

Further, ground-water withdrawals from shallow wells near the river can induce the loss of river water to the well screens. This effect may be offset to some degree by point-source discharges to the river. Withdrawals have their greatest effect at low flow. Individual withdrawals within the study area are documented in Storck and Nawyn (2001). Most of these withdrawals represent within-basin water use. To account for the effect of withdrawals or to include base flows, additional diversions and discharges could be included as model boundary conditions, or a linked ground-water/surface-water computer program such as MODFLOW-DAFLOW (Jobson and Harbaugh, 1999) could be used.

Another source of error is data error, such as errors in rainfall-runoff relations associated with estimates of subbasin flows, which were determined using the drainage-area ratio method. Other data inaccuracies include errors in various gage data, such as the effects of regulation and reservoir releases and the effects of backwater on flow at certain gages during water year 2003, and errors in dye-tracer data, such as the effects of poorly mixed dye. In addition, the discharge and diversion flow data are subject to inaccuracies, particularly in water year 2002.

Despite the limitations described above, model calibration and validation over a range of flow conditions indicate that the model's ability to simulate flow in the Passaic River Basin generally is good. For a regional model with a daily calibration, the shape of a simulated hydrograph is not expected to match exactly the shape of an observed hydrograph. Although the model may not simulate local effects at all locations within the basin, it adequately simulates flow conditions in the basin as a whole. The error at most gaging stations during most water years is within 15 percent, and coefficient of determination (RSQ) is greater than 0.75. Comparisons of flow duration and other properties complement these statistics. These results indicate an acceptable calibration and validation of the flow model.

Summary

The Passaic River Basin, the third largest drainage basin in New Jersey (950 mi^2), is in the heavily urbanized area outside New York City, with a population of 2 million. Mainstem tributaries of the Passaic River include the Pequannock, Wanaque, Ramapo, Pompton, Rockaway, and Whippany Rivers. The Saddle River subbasin is outside the study area. Efforts to develop Total Maximum Daily Loads (TMDLs) in the nontidal part of the basin (805 mi^2) have focused on nutrient loading of the Wanaque Reservoir in the northern part of the basin. One source of nutrient loading is the transfer of water diverted at two downstream intakes back upstream to refill the reservoir. The larger of these diversions is Wanaque South intake, on the lower Pompton River near Two Bridges.

To support TMDL development efforts for nutrients in the basin, the NJDEP and local stakeholders determined that a water-quality model was needed to address the issue. TRC Omni Environmental Corp. developed this watershed water-quality model. An important input to this model was the river hydraulics. The USGS, in cooperation with the NJDEP and NJEC, developed a flow-routing model to provide this input. This report describes the development of the input flow data, construction and calibration of the flow model, and development of an algorithm for the model to simulate hydraulic mixing near the Wanaque South intake upstream from the confluence of the Passaic and Pompton Rivers. Integration issues between the flow model and the water-quality model also are described.

The Diffusion Analogy Flow model (DAFLOW) was used for flow routing and input to the Water Quality Analysis Simulation Program (WASP), which was used to simulate water-quality transport. Approximately 108 miles of the Passaic River and relevant tributaries were simulated. The river was discretized into 17 branches, 18 junctions, and 145 nodes (channel cross sections). The time-step size for the flow model was limited to 3 hours. Boundaries for the flow model consisted of flows at six upstream gaging stations and estimated flows for three smaller tributaries. Ungaged subbasins (111 total with a combined drainage area of 287 mi^2) consisted of tributaries and unchanneled drainage that contribute flow to the mainstem. Flows were estimated using the drainage-area ratio method. Twenty-five major municipal or industrial point-source discharges and five point-source diversions were simulated using flow data collected from facilities or extracted from NJDEP databases.

The model was calibrated for water year 2001 (low flow) and validated for water years 2000 (average flow), 2002 (extreme low flow), and 2003 (high flow). Channel cross-section geometry was calibrated by adjusting simulated area and top width parameters. Several approaches were used for geometry calibration, and simulation data were compared quantitatively to measured data. Flow was calibrated at locations of five mainstem gaging stations and one estimated-flow station. The target calibration range was medium to low flows, as the Wanaque South intake typically does not operate during high flows or very low flows. Simulated flow mass balance, hydrographs, flow-duration curves, and velocity and depth data were calibrated against observed data. Mass balance (total volume) was calibrated quantitatively by adjusting the choice of index gages and (or) coefficients in the drainage-area ratio equations by trial and error. Hydrograph fit (flood-wave speed, wave attenuation, and spread) was calibrated visually and by using quantitative error measures. Simulated results generally were within the accuracy of the observed data. Flow calibration and validation results for 19 of 20 comparisons indicated average mass-balance and model-fit errors of 6.6 and 15.7 percent, respectively. Calibration results for gage 01389500, Passaic River at Little Falls, were less accurate during water year 2002. The model reasonably represents the time variation of streamflow in the nontidal Passaic River Basin.

An algorithm (subroutine) was developed for DAFLOW to simulate hydraulic mixing that occurs near the Wanaque South intake upstream from the confluence of the Pompton and Passaic Rivers. Flow entrained by the intake, depending on local flow conditions, can be derived from multiple sources, including effluent from a nearby wastewater facility. The three sources contain different phosphorus loads. The algorithm determines the proportion of flow from each source, but operates within a narrow flow range when mixing occurs. Advection occurs outside this flow range. The equations used in the algorithm are based on the theory of diffusion and lateral mixing in rivers. The algorithm is based on a flow mass balance and consists of five equations and five input parameters. Parameters used in the equations were estimated from limited available local flow and water-quality data (for example, phosphorus loads). Model results over the 4 water years indicated the variation in distribution of source water to the intake; these results compared favorably with limited available reported data. As expected, the main source of water was the Pompton River. During certain short periods of low flow and high diversion, however--particularly in water year 2002, when flow was extremely low--wastewater effluent and flow from the Passaic River made up for the insufficient flow in the Pompton River.

As additional verification of the simulated hydraulics for use in water-quality modeling, the Branched Lagrangian Transport Model (BLTM) was used to simulate dye transport in the 4-mile subreach between Two Bridges and Little Falls, the only subreach for which published dye-concentration data were available. Rhodamine B dye tracer was used in two injection tests. Flow and transport submodels of branches 13 to 15 of the existing flow model were created using 1-hour time steps and reconstructed flow and concentration boundary conditions. Dye decay and longitudinal dispersion were calibrated to a tracer test done in June 1964. The submodel was roughly validated to a tracer test done in September 1964. Concentration mass, time-of-travel of the peak dye, and peak attenuation and spread of the dye cloud were reproduced. These results provide additional support regarding the accuracy of the DAFLOW model, particularly channel storage area.

The flow model indicated that flow routing was not as sensitive to hydraulic geometry parameters as was cross-sectional area, depth, and flow velocity. Model results were not sensitive to channel slope, but were sensitive to time step sizes less than 3 hours. A formal sensitivity analysis also was done to evaluate mixing algorithm parameter values. Limitations of the simulation analysis include model error (for example from calibration) and data error (for example gage flows). The flow and transport models are considered accurate given the indicated limitations.

Acknowledgments

The author thanks Harvey Jobson, formerly of the USGS Office of Surface Water, for his invaluable technical advice during the course of this study. He is the author of the computer programs used in this study and developed the mixing algorithm discussed in this report. The author also thanks the staff at TRC Omni (particularly Marcelo Cerucci), developer of the TMDL water-quality model, for a thorough technical review of the draft version of this report. Their comments were used to supplement existing report text. They also contributed to the development and calibration of the flow model. Officials of the major point-source discharge and diversion facilities in the study area are acknowledged for providing the requested flow and water-quality data. Finally, NJDEP Division of Watershed Management personnel are thanked for their technical review of the draft report.

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Spitz, F.J.,—**Simulation of Surface-Water Conditions in the Nontidal Passaic River Basin, New Jersey**—Scientific Investigations Report 2007-5052

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