science for a changing world

Prepared in cooperation with the Onondaga Lake Partnership

Hydrologic and Water-Quality Characterization and Modeling of the Onondaga Lake Basin, Onondaga County, New York

Scientific Investigations Report 2008–5013

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

Cover. Photographs showing aerial view of downtown Syracuse, N.Y., by William Hecht, and view of strip farming by Brian Hall, Onondaga County Soil and Water Conservation District.

Hydrologic and Water-Quality Characterization and Modeling of the Onondaga Lake Basin, Onondaga County, New York

By William F. Coon and James E. Reddy

Prepared in cooperation with the Onondaga Lake Partnership

Scientific Investigations Report 2008–5013

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

U.S. Department of the Interior
DIRK KEMPTHORNE, Secretary

U.S. Geological Survey
Mark D. Myers, Director

U.S. Geological Survey, Reston, Virginia: 2008

For product and ordering information:
World Wide Web: http://www.usgs.gov/pubprod
Telephone: 1-888-ASK-USGS

For more information on the USGS--the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment:
World Wide Web: http://www.usgs.gov
Telephone: 1-888-ASK-USGS

Suggested citation:
Coon, W.F., and Reddy, J.E., 2008, Hydrologic and water-quality characterization and modeling of the Onondaga Lake basin, Onondaga County, New York: U.S. Geological Survey Scientific Investigations Report 2008–5013, 85 p.

Contents

Figures

Tables

Conversion Factors and Datum

Inch-Pound to International System (SI) Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton, short (2,000 lb)	0.9072	megagram (Mg)
	Application rate	
pounds per acre per year [(lb/acre)/yr]	1.121	kilograms per hectare per year [(kg/ha)/yr]

Time: h, hour; min, minute; s, second

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

$$°C = (°F-32)/1.8$$

Vertical coordinate information is referenced to National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

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

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

List of Abbreviations and Acronyms

AD	Atmospheric deposition
AMP	Ambient monitoring program
BMP	Best-management practices
CGAP	Channel geometry analysis program
CSO	Combined-sewer overflows
DEM	Digital elevation models
DLG	Digital line graphs
FEMA	Federal Emergency Management Agency
FIS	Flood-insurance studies
GIS	Geographical Information System
HRU	Hydrologic response units
HSPF	Hydrological Simulation Program–FORTRAN
HSG	Hydrologic soil group
IMPLNDs	Impervious land segments
ME	Mean error
METRO	Metropolitan
NLCD	National land cover data
NWS	National Weather Service
NPS	Nonpoint-source
OCWA	Onondaga County Water Authority
OLP	Onondaga Lake Partnership
PERLNDs	Pervious land segments
RCHRES	Reaches or reservoirs
UCI	User-control input
TMDL	Total maximum daily loads
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
USLE	Universal soil-loss equation
WWTP	Wastewater-treatment plant
WDM	Watershed data management

Chemical Abbreviations

BOD	Biochemical oxygen demand
DO	Dissolved oxygen
NH_3	Ammonia nitrogen
NO_2	Nitrite nitrogen
NO_3	Nitrate nitrogen
NO_x	Nitrate-plus-nitrite nitrogen
OP	Orthophosphate
OrgN	Organic nitrogen
OrgP	Organic phosphorus
SRP	Soluble reactive phosphorus
TDP	Total dissolved phosphorus
TKN	Ammonia-plus-organic nitrogen (total Kjeldahl nitrogen)
TP	Total phosphorus
TSS	Total suspended solids

This page has been left blank intentionally.

Hydrologic and Water-Quality Characterization and Modeling of the Onondaga Lake Basin, Onondaga County, New York

By William F. Coon and James E. Reddy

Abstract

Onondaga Lake in Onondaga County, New York, has been identified as one of the Nation's most contaminated lakes as a result of industrial and sanitary-sewer discharges and stormwater nonpoint sources, and has received priority cleanup status under the national Water Resources Development Act of 1990. A basin-scale precipitation-runoff model of the Onondaga Lake basin was identified as a desirable water-resources management tool to better understand the processes responsible for the generation of loads of sediment and nutrients that are transported to Onondaga Lake. During 2003–07, the U.S. Geological Survey (USGS) developed a model based on the computer program, Hydrological Simulation Program–FORTRAN (HSPF), which simulated overland flow to, and streamflow in, the major tributaries of Onondaga Lake, and loads of sediment, phosphorus, and nitrogen transported to the lake. The simulation period extends from October 1997 through September 2003.

The Onondaga Lake basin was divided into 107 subbasins and within these subbasins, the land area was apportioned among 19 pervious and impervious land types on the basis of land use and land cover, hydrologic soil group (HSG), and aspect. Precipitation data were available from three sources as input to the model. The model simulated streamflow, water temperature, concentrations of dissolved oxygen, and concentrations and loads of sediment, orthophosphate, total phosphorus, nitrate, ammonia, and organic nitrogen in the four major tributaries to Onondaga Lake–Onondaga Creek, Harbor Brook, Ley Creek, and Ninemile Creek. Simulated flows were calibrated to data from nine USGS streamflow-monitoring sites; simulated nutrient concentrations and loads were calibrated to data collected at six of the nine streamflow-monitoring sites. Water-quality samples were collected, processed, and analyzed by personnel from the Onondaga County Department of Water Environment Protection. Several time series of flow, and sediment and nutrient loads were generated for known sources of these constituents, including the Tully Valley mudboils (flow and sediment), Otisco Lake (flow and nutrients), the Marcellus wastewater-treatment plant (flow and nutrients), and springs from carbonate bedrock (flow). Runoff from the impervious sewered areas of the City of Syracuse was adjusted for the quantity that was treatable at the county wastewater-treatment plant; the excess flows were routed to nearby streams through combined sanitary-and-storm-sewer overflows. The mitigative effects that the Onondaga Reservoir and Otisco Lake were presumed to have on loads of sediment and particulate constituents were simulated by adjustment of parameter values that controlled sediment settling rates, deposition, and scour in the reservoir and lake.

Graphical representations of observed and simulated data, and relevant statistics, were compared to assess model performance. Simulated daily and monthly streamflows were rated "very good" (within 10 percent of observed flows) at all calibration sites, except Onondaga Creek at Cardiff, which was rated "fair" (10–15 percent difference). Simulations of monthly average water temperatures were rated "very good" (within 7 percent of observed temperatures) at all sites. No observed data were available by which to directly assess the model's simulation of suspended sediment loads. Available measured total-suspended-solids data provided an indirect means of comparison but, not surprisingly, yielded only "fair" to "poor" ratings (greater than 30 percent difference) for simulated monthly sediment loads at half the water-quality calibration sites. Simulations of monthly orthophosphate loads ranged from "very good" (within 15 percent of measured loads) at three sites to "poor" (greater than 35 percent difference) at one site; simulations of ammonia nitrogen loads ranged from "very good" at one site to "fair" (25–35 percent difference) at two sites. Simulations of monthly total phosphorus, nitrate, and organic nitrogen loads were generally rated "very good" at all calibration sites.

Sources of uncertainty in model results were identified, including (1) errors in precipitation data, (2) limitations in model structure, (3) nonuniqueness of values for highly sensitive parameters, (4) errors or bias in data used to calibrate the different components of the model, (5) misclassification of land-use and land-cover data, (6) changes in land use during the simulation period, (7) unidentified sources or sinks of

chemical loads and water-quality processes that varied over time, and (8) differences in scale between large calibrated subbasins and small subbasins to which calibrated parameter values were transferred. Uncertainty in simulations of water-quality constituents was compounded by uncertainty in the processes on which the water-quality simulations were based. Therefore, sediment simulations were affected by uncertainty in the simulation of hydrology, and nutrient simulations were affected by uncertainty in both the hydrologic and sediment processes, as well as in simulations of water temperature and dissolved oxygen concentrations.

The calibrated model can be used to simulate scenarios that represent planned or hypothetical development and implementation of best-management practices in the Onondaga Lake basin and to assess the effects that these changes and practices are likely to have on rural and urban nonpoint sources of pollution to Onondaga Lake. Model results also can be used as input to a hydrodynamic model of Onondaga Lake that is being developed by Onondaga County and to prioritize areas of the basin where mitigative measures to decrease sediment and nutrient loads could provide the greatest benefits to Onondaga Lake.

Introduction

Onondaga Lake, which covers 4.5 mi^2, lies near the center of Onondaga County in central New York (fig. 1); its basin extends southward and encompasses 285 mi^2 of mixed land uses. Onondaga Lake has been identified as one of the Nation's most contaminated lakes owing to industrial and wastewater-treatment discharges, combined storm-and-sanitary-sewer overflows, and rural and urban nonpoint sources of pollution (Onondaga Lake Partnership, 2006; Effler and Hennigan, 1996). As a consequence, the lake has received priority cleanup status under the national Water Resources Development Act of 1990 (U.S. Congress, 1990). Local remediation goals for the lake established by the Onondaga Lake Citizens Advisory Committee include (1) improvement of water quality to allow consumption of fish and allow human contact with lake waters from the mouth of Onondaga Creek to Onondaga Lake outlet, (2) restoration of the wildlife habitat to sustain the ecosystem in the lake proper and the lower reaches of its tributaries, and (3) enhancement of the aesthetic quality of the surface water and shoreline (Effler, 1996).

Since the 1970s, Onondaga County has been proactive in decreasing the deleterious effects of combined-sewer overflows (CSOs), which discharge to three of Onondaga Lake's main tributaries—Onondaga and Ley Creeks and Harbor Brook—within the city boundaries of Syracuse, by mitigating the effects of active CSOs and by closing others. As of 2007, only 49 of the original 90 overflow points remain (Onondaga County Department of Water Environment Protection, 2007). Numerous industries in Syracuse and in the townships mostly east and south of the lake have discharged wastewater either directly to the lake or to its tributaries. The number of these discharges and their chemical loads have been greatly controlled during recent decades (Effler, 1996), but they are still a source of contamination to the lake. Discharges from the Syracuse Metropolitan wastewater-treatment plant (METRO) at the south end of the lake also contribute nutrient loads to Onondaga Lake. Recent improvements to the plant have substantially decreased phosphate and ammonia loads, and additional upgrades are planned (Onondaga County Department of Water Environment Protection, 2006).

The major nonpoint sources of pollution are in urban and agricultural areas. Urbanization, which is characterized by an increase in impervious surfaces and an improvement in the hydraulic efficiency by which water moves from land surfaces to a drainage system, causes changes in a basin's response to precipitation by reducing infiltration and decreasing storm-runoff travel time, which in turn increases runoff and peak flows (Natural Resources Conservation Service, 1986). Urbanization also increases the quantity of chemicals that can be deposited on (airborne contaminants from industries and motor vehicles) or applied to (fertilizers, pesticides, and herbicides) land surfaces, which often are connected directly to natural (stream channels) or manmade (ditches and culverts) drainage systems. This combination of factors results in increases in post-development chemical loads carried by storm runoff.

Agricultural areas can contribute large loads of nutrients, pesticides, and sediment to nearby streams. Best-management practices (BMPs) that focus on erosion control and nutrient management have been implemented on many farms in the basin and presumably have a beneficial effect on water quality, but this effect has not been quantified in the Onondaga Lake basin. Farmsteads, where livestock, primarily dairy cows, are raised in confined areas, can be point sources of pollution, as well as nonpoint sources when manure spreading on nearby fields is used as a waste-disposal practice.

The various sources of pollution create a complex water-resources challenge for Federal, State, and local agencies, which have been charged with improving the lake's water quality (Onondaga County, 1998). An assessment of the magnitude of the contributions from these sources and an evaluation of possible mitigative measures to decrease loads from any one source, along with the associated costs, will enable the development of a strategy by which total chemical loads to the lake can be decreased. Development of this strategy is complicated by the natural variability of hydrologic and water-quality processes, the complexity of nutrient runoff and transport relations, and the spatial and temporal variability of these relations among the subbasins within the Onondaga Lake basin. Many steps have been taken to mitigate chemical loads in the basin on a site-specific basis, that is, at a particular farm or an urban neighborhood. Coordinated efforts to address this problem have seldom been undertaken basinwide, and problems downstream infrequently can be solved without the cooperation of those who live in the upstream areas of the basin.

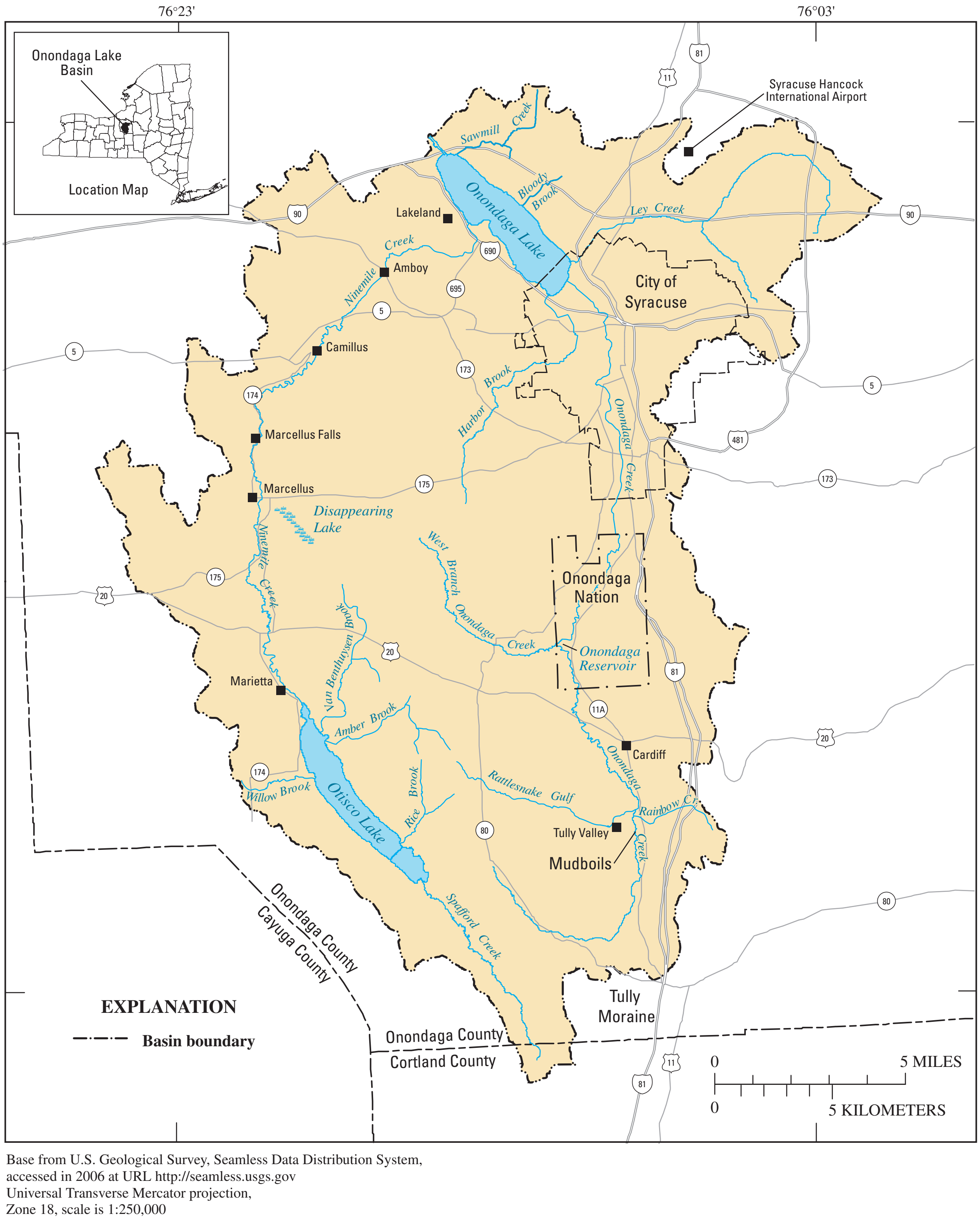

Figure 1. Location of the Onondaga Lake basin, Onondaga County, N.Y., including major streams, selected municipalities, and geographic features in and near the basin.

Onondaga Lake drains to the Seneca River, a tributary of the Oswego River. A model of the river system from Cross Lake on the Seneca River (west of Onondaga Lake) to the dam on the Oswego River at Phoenix, N.Y., (northeast of Onondaga Lake) has been developed (Quantitative Environmental Analysis, LLC, 2005). Work to develop a hydrodynamic model of Onondaga Lake is ongoing and will enable the simulation of flows and chemical transport through the lake and into Seneca River (Joseph Mastriano, Onondaga County Department of Water Environment Protection, written commun., 2007). What was lacking in this modeling program was a comprehensive precipitation-runoff model of the Onondaga Lake basin, which could simulate runoff from the basin and provide time series of flows and associated chemical loads for input to the lake model.

A basin-scale computer model was envisioned as a tool for water-resources managers to (1) better understand the relation of land use to hydrologic and water-quality processes that occur within the basin, (2) identify areas of the basin that generate disproportionately large nutrient loads, (3) predict the probable effects of future development on peak flows and chemical loads and guide decision-makers on the extent and location of land-use changes within the basin, (4) assess the requirement for and location of BMPs to reduce the expected adverse effects of present or future land uses, and (5) provide a mechanism for coordinating a basinwide strategy to address water-resources issues. In 2003, the U.S. Geological Survey (USGS), in cooperation with the Onondaga Lake Partnership (OLP), a consortium representing Federal, State, and local interests, began a 5-year project to develop a precipitation-runoff model to achieve these objectives.

Previous Modeling Studies

The USGS developed a precipitation-runoff model of a 42-mi^2 area of the Ninemile Creek basin between Marietta and Camillus (fig. 1) using the computer program, Hydrological Simulation Program—FORTRAN (HSPF; Bicknell and others, 2001) to assess the probable hydrologic effects of future suburban development and the mitigative effects of stormwater detention (Zarriello, 1999). The basin segmentation from this model was incorporated into the present model. Other components of the model, such as the hydrologic response units (HRUs)—the basic building blocks of the model—and their associated parameter values, were not used in the present model. Instead, HRUs and parameter values that were more widely applicable to the Onondaga Lake basin were used.

Coyle (2002) used a Geographic Information System in developing a model to estimate concentrations of three nonpoint-source (NPS) constituents—total phosphorus, ammonia-plus-organic nitrogen, and total suspended solids—in water at eight sites on three tributaries to Onondaga Lake during three storms. Basin characteristics that were deemed influential in generating NPS loads include land-cover type, soil type, land-surface slope, and stream proximity. Estimated mean concentrations, derived from a national database by the U.S. Environmental Protection Agency (Terrene Institute, 1996), were assigned by land use to the applicable areas of the basin.

The combined storm-and-sanitary-sewer system of the City of Syracuse has been simulated with the computer model Storm Water Management Model (SWMM; Huber and Dickinson, 1988) to assess the system's response to rainfall and to actual and proposed combined sewer-overflow abatement measures (D.P. Davis and Chris Somerlot, Brown and Caldwell Consultants, written commun., 2005). Coupling of this model with the present model was considered but abandoned owing to the difference in the level of detail between the SWMM model, which simulated flow through pipes in the City of Syracuse in great detail, and the proposed precipitation-runoff model, which simulated the runoff and water-quality processes from a much larger area and in a more generalized manner.

Other Pertinent Studies

Paschal and Sherwood (1987) provide estimates of sediment and nutrient loads from the five main tributaries of Otisco Lake during 1982–83 and relate sediment and nutrient loads to land use, geology, and soil type. The unusually large sediment and nutrient loads from Spafford Creek compared to those generated in other subbasins are documented. Callinan (2001) presents temperature and water-quality data for Otisco Lake during 1996-99, discusses trends in water-quality characteristics, and reports a high sediment accumulation rate—0.29 in/yr—for the lake.

Several studies of the upper Onondaga Creek basin have been conducted by the USGS. Some of these studies have dealt with the surficial geology and ground-water resources of the basin (Kappel and Miller, 2003 and 2005); others have documented the activities of mudboils—volcano-like cones of fine sand and silt created by the upwelling of sediment-laden ground water along Onondaga Creek in the vicinity of Otisco Road—and their large contributions of sediment to Onondaga Creek (Kappel and others, 1996; Kappel and McPherson, 1998).

Sullivan and Moonen (1994) conducted a survey of the Onondaga Lake basin, inventoried sites of roadbank and streambank erosion, and estimated the total gross sediment load from these sources, as well as the net sediment load delivered to Onondaga Lake. Blatchley (2000) repeated the inventory but only for the Onondaga Creek basin.

Effler and others (1992) conducted a study of concentrations and loads of suspended solids in Onondaga Creek and found that most of the suspended solids load transported during storm runoff was resuspended stream sediment and eroded bank material, and, on the basis of microscopy-based analyses of individual particles, determined that the ultimate source of most of this material was the mudboils near the southern end of the basin. The Upstate

Freshwater Institute (2004) conducted a 1-year (2002–03) water-quality study of the Onondaga Creek basin. Surface grab samples from eight sampling sites were analyzed for total phosphorus, total dissolved phosphorus, soluble reactive phosphorus (orthophosphate), nitrate-plus-nitrite nitrogen, total ammonia, total suspended solids, and other constituents. Samples were collected during just one storm, which happened to fall within the biweekly sampling schedule of the study; all other samples were collected during low-flow periods.

Parsons Consultants (2004) conducted a preliminary literature review to identify and compile ranges of total phosphorus loading rates per unit area, which are based on the land covers and land uses that are present in the Onondaga Lake basin. This document has not been finalized as of May 2007, but a draft version of the report is on file in the Ithaca, N.Y., office of the USGS.

Purpose and Scope

This report presents information on the development, calibration, and performance of a precipitation-runoff model of the Onondaga Lake basin. The Hydrological Simulation Program—FORTRAN (HSPF) (Bicknell and others, 2001) was used to simulate (1) overland flow to, and streamflow in, the major tributaries of Onondaga Lake, and (2) loads of phosphorus and nitrogen that are washed from the land surfaces and transported to Onondaga Lake by the major tributaries. Streamflow, water-quality, and meteorological data collected during October 1997 through September 2003, and land-use and land-cover data collected during 1991–93, which were input to the model or used for model calibration, are described in the report. Model performance is assessed using graphical and statistical methods. Uncertainty in the model results is discussed, and an example of the model's application to assess land-use changes is provided.

Study Area

Onondaga Lake in Onondaga County, N.Y., covers 4.5 mi^2 and receives runoff from 285 mi^2. Almost 40 percent of the basin is forested, 30 percent is agricultural land use, and 21 percent, including the City of Syracuse, comprises residential, commercial, industrial, and transportation land uses (U.S. Geological Survey, 1999). The remaining 9 percent comprises wetlands and water bodies, including Otisco and Onondaga Lakes. Current chemical loads are generated from forested, agricultural, and urban nonpoint sources; industrial waste beds; combined-sewer overflows; wastewater-treatment-plant effluent; and industrial point sources.

Streamflows and chemical loads are monitored in the four major tributaries to Onondaga Lake (fig. 2)—Onondaga Creek, Ninemile Creek, Ley Creek, Harbor Brook. Two small tributaries, Bloody Brook and Sawmill Creek, along the northern shore of Onondaga Lake, the outfall from the Syracuse Metropolitan (METRO) wastewater-treatment plant (WWTP) at the southeastern end of the lake, and outflows from two industrial areas—Crucible Specialty Metals, a steel manufacturing facility, and the former Allied-Signal Chemical Corporation—both along the southwestern shore of the lake, also are monitored. Onondaga and Ninemile Creek subbasins cover almost 80 percent of the Onondaga Lake drainage area but account for only about 66 percent of the lake's surface-water inflow (table 1). The discrepancy is accounted for by the discharges from the METRO plant, the water being derived mainly from sources outside of the Onondaga Lake drainage basin, that is, Skaneateles Lake and Lake Ontario. The METRO discharges also contribute the largest load of total phosphorus on an annual basis (table 1).

Climate

Average annual precipitation in the Syracuse, N.Y., area is about 39 in., including that from an average snowfall of about 115 in., as recorded by the National Weather Service station at the Syracuse Hancock International Airport (Northeast Regional Climate Center, 2005). On average the area receives measurable precipitation on 171 days per year; precipitation is derived mainly from storms that pass across the interior of the country northeastward toward the St. Lawrence valley. Thunderstorms are common during the summer months; they occur an average of 30 days per year and can generate short-lived, but intense, downpours (National Weather Service, 2007). Lake Ontario influences the distribution and quantity of rain and snowfall because prevailing winds generally move eastward across the lake, which does not freeze during the winter, and pick up and transport moisture landward. Precipitation shows a seasonal pattern with greater precipitation falling during the summer than during the winter. The average monthly precipitation for June through September is 3.72 in., whereas that for January through March is 2.42 in. Spatial variation in precipitation across the study area can be substantial; annual totals differ by an average of 3 to 7 in. and by as much as 13 in. among three precipitation-recording stations in the study area (fig. 2). On average, during 1997 to 2003, annual precipitation was greater in the Otisco Lake basin and less in the south-central Onondaga Creek basin than elsewhere in the basin. The annual mean temperature is 47.4°F. Monthly mean temperatures range from 22.4°F in January to 70.4°F in July; the lowest and highest percentages of possible sunshine are recorded during the same months—33 and 63 percent, respectively (Northeast Regional Climate Center, 2005).

Geology

The Onondaga Lake basin is underlain by layers of sedimentary bedrock that strike east-west and dip gently to the south at 40 to 50 ft per mile. Silurian bedrock underlies the lowlands north of Syracuse, whereas younger Devonian

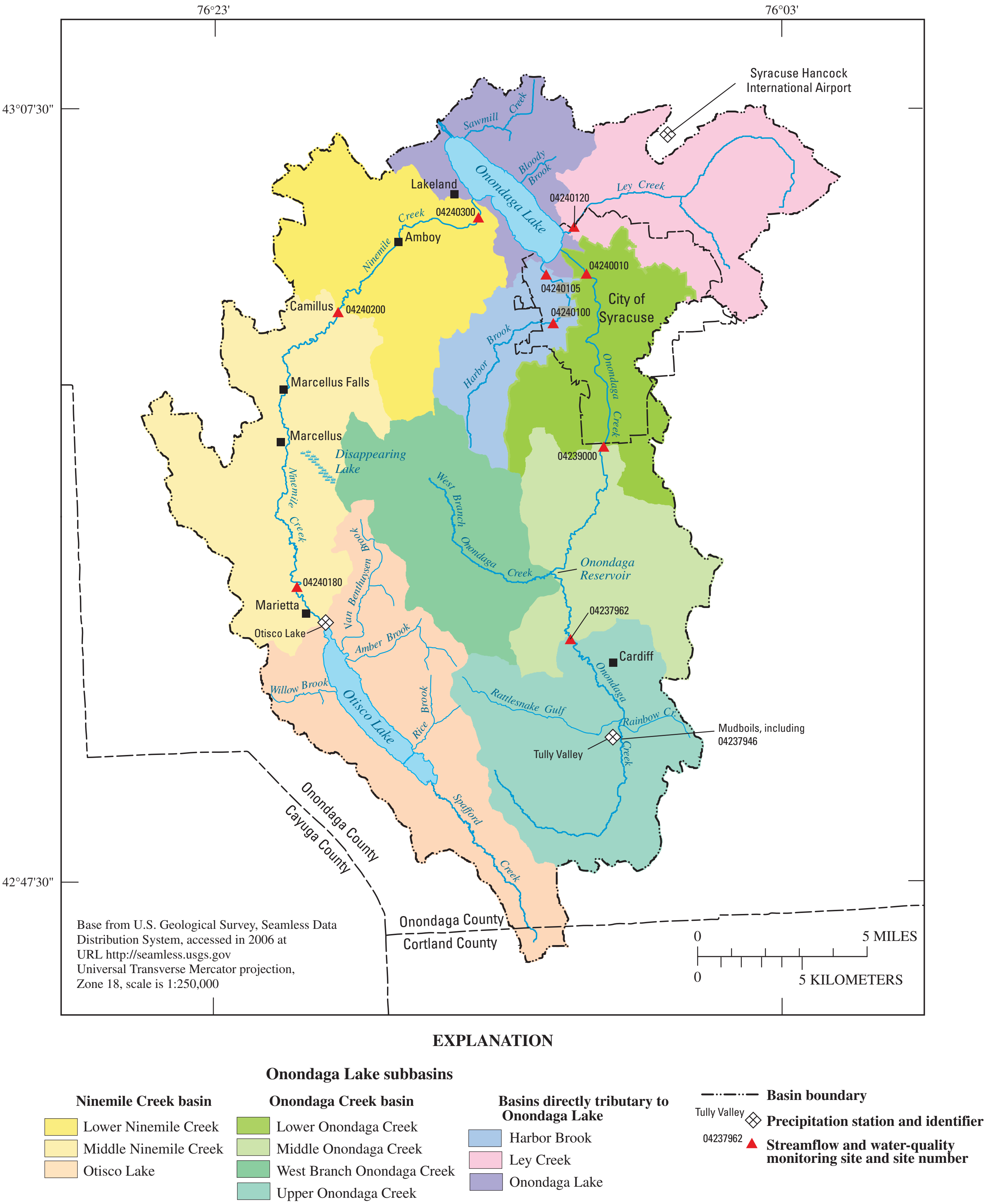

Figure 2. Locations of precipitation, streamflow, and water-quality monitoring sites in the Onondaga Lake basin, Onondaga County, N.Y.

Table 1. Contributions of surface-water inflow and selected constituent loads from major inflow sources to Onondaga Lake, Onondaga County, N.Y.

[Values are percentages of total measured inflows or input loads to Onondaga Lake. na, not applicable]

Lake inflow source	Drainage area	Surface-water inflow[1]	Load of total phosphorus[2]	Load of total suspended solids[2]
Onondaga Creek	38.9	35.1	18.6	50.1
Ninemile Creek	40.4	30.8	13.5	27.9
Ley Creek	10.5	8.7	6.6	8.8
Harbor Brook	4.2	2.1	1.3	2.5
Syracuse Metropolitan (METRO) wastewater treatment plant (sum of main and bypass outfalls)	na	22.5	59.2	10.4
Other sources[3]	na	na	0.8	0.3

[1] Based on 1997–2003 flow data from U.S. Geological Survey (Hornlein and others, 1999 through 2004) or Onondaga County Department of Water Environment Protection (Antonio Deskins, written commun., 2004).

[2] Based on 1997–2003 data from Onondaga County Department of Water Environment Protection (Antonio Deskins, written commun., 2004).

[3] Includes outflow from Crucible Specialty Metals and from former Allied-Signal Chemical Corporation industrial complex.

units form the hills in the southern part of Onondaga County (Kappel and Miller, 2005). The sedimentary bedrock is commonly overlain by glaciated drift including till, kame, lacustrine, and outwash deposits. The bedrock surface in the Onondaga Creek valley slopes downward from the Tully Moraine area (fig. 1) at the southern end of Onondaga County to its lowest point just south of Onondaga Lake, then rises gradually to the north under Onondaga Lake. Along the thalweg (deepest part) of the bedrock trough, the thickness of unconsolidated valley-fill deposits averages 420 ft and exceeds 800 ft near the Tully moraine (Kappel and Miller, 2003). The thickness of unconsolidated deposits averages less than 10 ft on hill tops and varies considerably on the hillsides (W.M. Kappel, U.S. Geological Survey, oral commun., 2005).

Carbonate bedrock can transmit large volumes of ground water through fractures, bedding planes, and solution openings. In the Onondaga Lake basin where carbonate bedrock crops out, mainly along the topographically prominent Onondaga Escarpment, spring discharges dominate the base flows in the receiving surface channels—Onondaga Creek, Harbor Brook, and Ninemile Creek.

Till is the dominant glacial deposit in the basin and overlies 56 percent of the bedrock in the basin, especially in the upland areas in the central and southern parts of the basin (fig. 3). A valley-heads moraine, the Tully Moraine (fig. 1), fills the deep Onondaga Creek valley at its southern end. Proglacial lacustrine silt-and-clay deposits, which cover 19 percent of the basin, are present across the northern part of the basin and in the valley bottoms of the southern part of the Onondaga Creek basin and of the Ninemile Creek and Spafford Creek subbasins, north and south, respectively, of Otisco Lake. These deposits, when cut through by high-gradient streams, such as Rattlesnake Gulf in the southern part of the Onondaga Creek valley (fig. 2), can be large sources of sediment. Outwash and deltaic and alluvial sand and gravel deposits, which cover 5 percent of the basin, generally overlie proglacial fine-grained deposits.

Soils

Soils in Onondaga County generally are derived from glacial deposits—mainly till, but also outwash and lacustrine silt and clay—or underlying sedimentary rocks—shale, limestone, and dolostone. For the most part the resulting soils are more than 40 in. deep, gently sloping to moderately sloping, and medium textured, that is dominated by very-fine-sand- to silt-sized particles. Soils are mainly well drained or moderately well drained, which means when infrequently saturated, they do not remain so for long periods (Hutton and Rice, 1977). Till and lacustrine silt and clay are the parent materials of 75 percent of the soils in the Onondaga Lake basin, and generally produce soils with low permeability and high runoff potential. Most of Onondaga Lake basin soils are expected to have moderate to slow infiltration rates when thoroughly wetted and moderate to slow rates of water transmission within the soil profile.

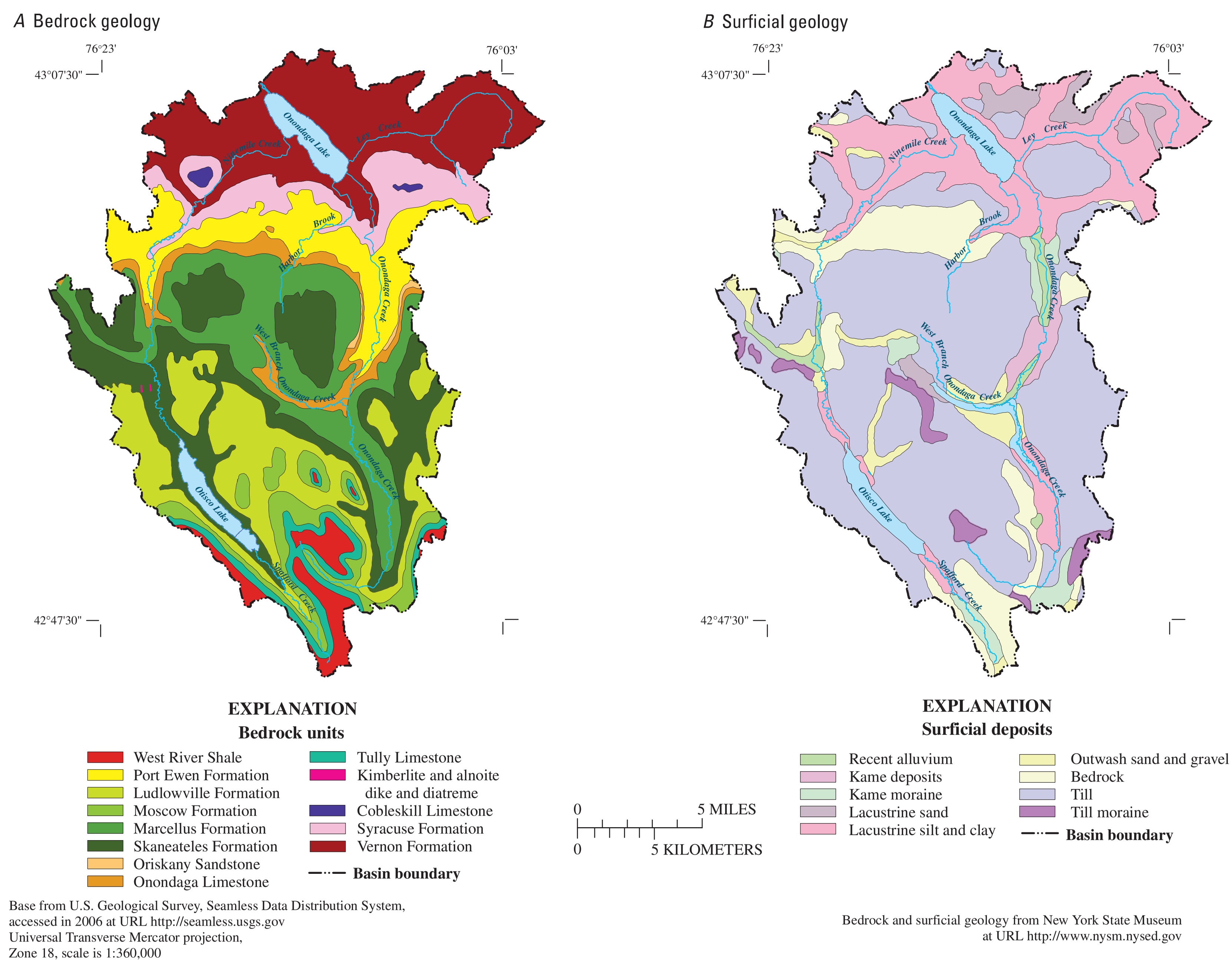

Figure 3. Generalized geologic maps of the Onondaga Lake basin, Onondaga County, N.Y., showing *(A)* bedrock and *(B)* surficial geology.

Land Use and Land Cover

Based on National Land Cover Data (NLCD) derived from satellite imagery during 1991-93 (fig. 4; U.S. Geological Survey, 1999), almost 40 percent of the Onondaga Lake basin is forested, and 24 percent is covered in pasture or hay. About 6 percent of the basin is used for row crops or livestock operations. Almost 18 percent of the basin is classified as developed, including low- and high-intensity residential uses (13.5 percent), and commercial, industrial, and transportation uses (4.5 percent). An additional 3 percent is urban or recreational grass, and 6.4 percent is covered by wetlands, ponds, and small lakes. Wetlands in the basin are mainly riparian, but they also cover large expanses in the headwaters of Ley Creek and are common in the low-gradient areas along the drainage divides of many subbasins, especially between the Otisco Lake—Ninemile Creek and West Branch Onondaga Creek basins (fig. 2).

The southern half of the basin retains a rural nature with a mix of forest, pasture, and agricultural uses (fig. 4). Forests cover nearly 60 percent of the headwater areas of the Onondaga Creek basin, and agricultural operations cover more than 40 percent of the land in the West Branch Onondaga Creek, Otisco Lake, and middle Ninemile Creek subbasins (fig. 2; table 2). These percentages decrease with an increase in urban development to the north around Onondaga Lake, especially from the City of Syracuse at the southeastern end of the lake. Developed land uses cover more than 40 percent of the Harbor Brook basin and more than 50 percent of the lower Onondaga Creek subbasin and Ley Creek basin (fig. 2; table 2).

Surface Water

Onondaga Creek is about 27 mi long and descends more than 1,000 ft from its headwaters near the Onondaga-Cortland Counties border at the southern end of the basin to its mouth at Onondaga Lake (fig. 2). The creek drains 111 mi^2, including 26.8 mi^2 from its main tributary, West Branch Onondaga Creek. Midway through the basin, the Onondaga Reservoir (fig. 2), which is located within the Onondaga Nation, controls storm runoff from 67.7 mi^2 and, to an unknown degree, causes the deposition of stormwater nutrients and sediment. Built in 1949, the reservoir's dam is a flow-through structure that detains stormflows but has no mechanism for long-term impoundment of water. From the northern boundary of the Onondaga Nation to Onondaga Lake, Onondaga Creek has been channelized to control flooding in the urbanized areas of the basin. At the southern end of Syracuse, flows in the creek are augmented from springs that discharge from the Onondaga Escarpment. In addition to increasing base flows, these discharges raise winter and lower summer water temperatures in the creek. The effect of these discharges on the water quality of Onondaga Creek is unknown.

Ninemile Creek basin, which drains 115 mi^2, encompasses Spafford Creek, Otisco Lake, and Ninemile Creek (fig. 2). With a total length of about 34 mi, the stream network drops more than 800 ft from the headwaters of Spafford Creek to its mouth at Onondaga Lake. Otisco Lake has a surface area of 2,300 acres (3.6 mi^2) and receives runoff from 42.2 mi^2, including 12 mi^2 drained by Spafford Creek, its main tributary. Otisco Lake has a substantial effect on streamflows and water-quality loads; storm runoff is detained and sediment and particulate constituents are retained by the lake. Otisco Lake is also a source of public water; on average 16 to 18 Mgal/d (26.0 ft^3/s) are withdrawn from the lake by Onondaga County Water Authority to meet the water needs of suburban areas of Onondaga County (Nicholas Kochan, Onondaga County Water Authority, oral commun., 2003). This withdrawal might partly or wholly explain the fact that the Ninemile Creek subbasin, the largest of the Onondaga Lake subbasins, contributes less flow to Onondaga Lake on a mean annual basis than Onondaga Creek with a slightly smaller drainage area (Nicholas Kochan, Onondaga County Water Authority, oral commun., 2003).

Spring discharges augment flows in Ninemile Creek from Marcellus Falls—north of the Village of Marcellus—to Camillus. As occurs in Onondaga Creek, these discharges raise winter and lower summer water temperatures and have an unknown effect on water quality.

Ley Creek is a low-gradient stream—it drops less than 50 ft in its 10-mi length—and drains 30.0 mi^2 of land to the north and east of Syracuse (fig. 2). More than 11 percent of its area is covered by wetlands, which cause a slow runoff response in the headwater areas of the basin. Harbor Brook, which drains 12.1 mi^2, is about 7.5 mi long and drops more than 620 ft from its headwaters to Onondaga Lake. An instream detention basin just upstream from the USGS streamflow-monitoring station (number 04240100; fig. 2) detains stormflows and has an unknown effect on water quality.

Streamflows in these channels are measured at nine USGS monitoring stations, which account for surface drainage from 94 percent of the basin. Additionally two small ungaged subbasins (Sawmill Creek, 2.34 mi^2, and Bloody Brook, 3.88 mi^2, both on the northeastern side of the lake), the METRO wastewater-treatment plant, and two minor point sources (Tributary 5A and an outfall from the former Allied-Signal Corporation, both on the southwestern side of the lake) discharge to the lake.

Large percentages of impervious areas in the urbanized subbasins of the Onondaga Lake basin can produce rapid increases in streamflows, which appear as spikes in local hydrographs. These spikes, which are short in duration and recede shortly after the cessation of precipitation, are followed by slower-rising and longer-lasting peaks caused by runoff from the rural areas of a subbasin. These succeeding peaks might exceed the initial runoff spike depending on a storm's pattern, duration, and intensity. Within the City of Syracuse, storm runoff also is affected by a combined storm-

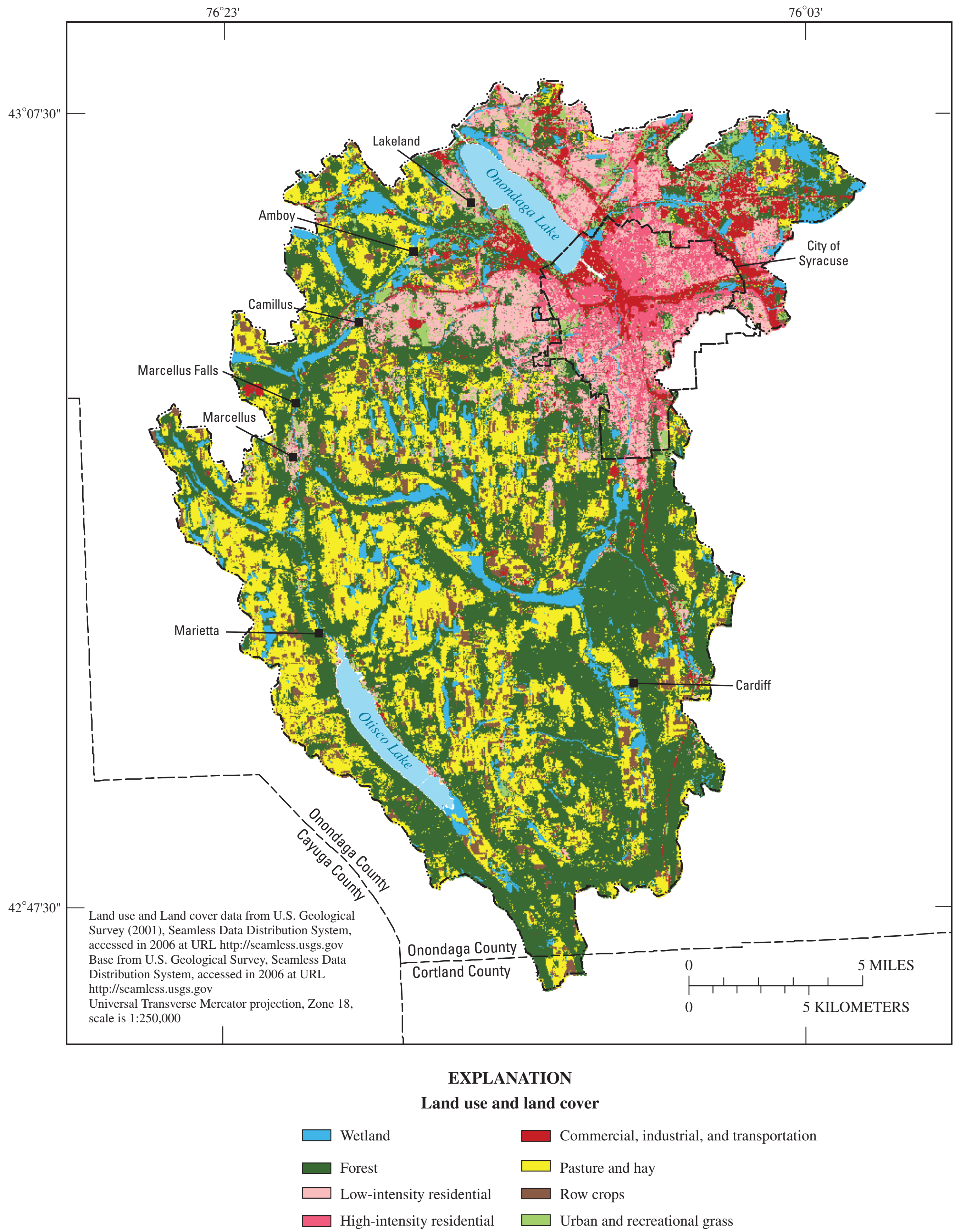

Figure 4. Land use and land cover in the Onondaga Lake basin, Onondaga County, N.Y.

Table 2. Land use and land cover in subbasins of the Onondaga Lake basin, Onondaga County, N.Y.

[Data from National Land Cover Data (U.S. Geological Survey, 1999). Values are percentages. Column totals that do not add to 100.0 are due to rounding. Geographical divisions are shown in figure 2.]

Land use or land cover	Onondaga Creek basin				Harbor Brook basin	Ley Creek basin	Ninemile Creek basin		
	Upper	West Branch	Middle	Lower			Otisco Lake basin	Middle	Lower
Forest	58.8	42.0	63.3	28.2	28.6	17.9	45.9	40.5	35.9
Pasture-hay	27.6	37.7	20.4	7.2	18.3	5.3	32.9	39.1	23.5
Row crops	7.9	10.3	5.5	1.8	2.9	2.5	7.5	8.7	5.0
Wetland-water	4.5	8.1	5.6	2.2	3.4	11.3	12.7	7.0	10.3
Urban or recreational grass	0.4	0.6	0.8	3.3	5.6	9.1	0.3	1.2	5.8
Low-intensity residential	.3	.7	2.2	22.7	25.4	20.5	.6	2.4	12.9
High-intensity residential	.0	.0	.3	24.7	13.1	14.1	.0	0.3	2.1
Commercial, industrial, and transportation	.4	.7	1.8	10.0	2.7	19.2	.2	.8	4.5

and-sanitary-sewer system, which routes storm runoff to the METRO wastewater-treatment plant, where it is treated along with sanitary sewage before discharge to Onondaga Lake. A few small subbasins have stormwater storage capabilities that can detain runoff for post-storm treatment. The flows from the other combined sewers are subject to METRO's maximum treatment rate of 240 Mgal/d, which can be exceeded when precipitation rates are greater than about 0.10 in/hr (D.P. Davis, Brown and Caldwell Consultants, oral commun., 2005). When this occurs, the combined sewers overflow and their loads of nutrients and sediment are discharged to surface channels, which carry the loads to Onondaga Lake.

Ground Water

Ground-water discharge to surface channels accounts for most of the streamflow in the Onondaga Lake basin—ranging from 56 percent of streamflow in Ley Creek to 80 percent in Ninemile Creek. Recharge to the ground-water flow system is likely through (1) permeable sediments overlying and adjacent to the buried valley walls, and (2) near-surface bedrock that is highly fractured and jointed. Springs are common (1) along the sides of the Tully Moraine (fig. 1) at the southern end of the Onondaga Creek valley (Kappel and Miller, 2003); (2) at outcrops of carbonate bedrock along Onondaga Creek north of the southern boundary of the City of Syracuse, Ninemile Creek between Marcellus and Camillus, and the headwaters of Harbor Brook; and (3) in the channel bottom along the main stem of Onondaga Creek near its mouth. Water that becomes ground water eventually is discharged to a surface-water body within the Onondaga Lake basin (Kappel, 2000). Base flows are sustained and water temperatures are lowered during the summer and raised during the winter as a result of spring discharges.

Ground water in the southern part of the Onondaga Creek valley is under confined conditions with hydraulic heads (water levels) tens of feet above land surface (Kappel and Miller, 2005). A thick layer of lacustrine silt and clay most likely overlies a basal valley-fill sand-and-gravel aquifer in the bedrock trough of this valley, resulting in confined conditions and limiting the flow of ground water northward into the northern part of the aquifer (Kappel and Miller, 2005). This fine-grained confining layer also hinders the vertical movement of water to and from the basal aquifer. Water in this aquifer has become enriched with minerals through dissolution of halite, calcite, and gypsum, and is distinctly different from ground water in an overlying unconfined aquifer, which has a much lower dissolved-solids content (Kappel, 2000). The chemical properties of water in the basal aquifer also differ greatly from south to north. Ground water from deep wells near the northern base of the Tully Moraine at the southern end of the Onondaga Creek valley is potable (Kappel and Miller, 2003), but that from wells in the northern end of the aquifer near Onondaga Lake is a highly concentrated brine and has been measured to be up to six times as salty as sea water (Kappel, 2000). Highly concentrated brine also is present in the lower section of the Ninemile Creek valley (Kappel and Miller, 2005).

Surface runoff from a 3.44-mi^2 subbasin in the Ninemile Creek basin east and southeast of the Village of Marcellus drains to a natural depression that is underlain by Onondaga Limestone. Water that collects in this depression, called Disappearing Lake, has no surface outlet and drains through bedrock fractures at rates that vary with the depth of the water in the depression (Proett, 1978). The most probable discharge points for this water are springs along a shale-limestone interface downstream from Marcellus Falls and about 2 mi downstream from Disappearing Lake.

Precipitation-Runoff Model

The temporal and spatial variability of hydrologic and water-quality conditions and the complexity of nutrient runoff and transport processes necessitated the use of a tool that allowed a system-wide analysis of these processes. Such a tool is a precipitation-runoff model, which was developed for the Onondaga Lake basin and was calibrated with data from nine USGS streamflow-monitoring sites and six co-located water-quality-monitoring sites operated by the Onondaga County Department of Water Environment Protection (WEP).

Data from three precipitation stations (fig. 2) were used as input to the model along with other meteorological data obtained from the National Weather Service station at the Syracuse Hancock International Airport. Geographical Information System (GIS) coverages of hydrology, geology, soils, and land use and land cover were evaluated to assess the hydrologic and water-quality characteristics of the basin and were consolidated for input to the model. The basin was divided into 107 subbasins and, within subbasins, into 19 different land types, each of which was assumed to exhibit consistent hydrologic and water-quality responses to precipitation and other meteorological inputs. Model performance was assessed by graphical and statistical methods, and parameter sensitivity and model uncertainty were evaluated.

Model Selection

The model selected for simulation of runoff and chemical loads in response to precipitation is the Hydrological Simulation Program—FORTRAN (HSPF, version 12; Bicknell and others, 2001). HSPF, which was developed jointly by the U.S. Environmental Protection Agency and the USGS, is a mathematical model designed to simulate hydrologic and water-quality processes in natural and manmade water systems and is considered a comprehensive and flexible model for these purposes (Donigian and Huber, 1991).

HSPF has been used extensively to simulate basin hydrology (Dinicola, 1990, 1997, and 2001; Flippo and Madden, 1994; Berris, 1995; Duncker and others, 1995; Mastin, 1996; Raines, 1996; Jacomino and Fields, 1997; Srinivasan and others, 1998; Duncker and Melching, 1998; and Zarriello, 1999) and nonpoint-source water-quality processes (Reddy and others, 1999; Bergman and Donnangelo, 2000; Martin and others, 2001; Wicklein and Schiffer, 2002; and Senior and Koerkle, 2003). HSPF also has been used to (1) simulate sediment transport (Fontaine and Jacomino, 1997) and atrazine transport (Laroche and others, 1996; DeGloria and others, 1999; Bergman and others, 2002); (2) estimate total maximum daily loads (TMDL) (Yagow and others, 2001); (3) evaluate the probable effects of hypothetical land-use changes (Bohman and others, 1995; Lohani and others, 2001; Wicklein and Schiffer, 2002; Coon and Johnson, 2005) or instream detention basins (Donigian and others 1997; Coon and Johnson, 2005) on flooding and water-quality conditions; (4) analyze surface-water and ground-water interactions (Zarriello and Reis, 2000); (5) evaluate the effects of BMPs on agricultural and urban nonpoint-sources of pollution (Donigian and Love, 2002), and the effects of wetland restoration on runoff (Jones and Winterstein, 2000); and (6) provide flow data for input to a hydraulic model and the subsequent generation of flood-hazard maps (Soong and others, 2005).

HSPF was selected for this study on the basis of its widespread and varied use by the scientific community, and for its ability to simulate (1) snowmelt processes, (2) all streamflow components (surface runoff, interflow, and base flow) and their chemical contributions, (3) individual storms at a less-than-daily time step, (4) concentrations and loads of sediment, nitrogen, and phosphorus, and (5) the effects of proposed or hypothetical changes in the basin, such as additional BMPs, elimination of some or all CSOs or WWTP discharges, land-use changes, and detention basins. The results of these simulations based on hypothetical changes can be compared with those based on existing conditions. Along with pre- and post-processing software that have been developed to provide interactive capabilities for model input development and manipulation, data storage and data analysis, and model output analysis (Flynn and others, 1995; Kittle and others, 1998; Lumb and others, 1994), an HSPF model provides a basinwide management tool that county and State personnel can use to make informed water-resource decisions regarding the potential benefits of proposed mitigative measures to decrease constituent loads and to meet TMDL goals for Onondaga Lake.

Model Description

HSPF is a lumped-parameter, semi-distributed, continuous-simulation, conceptual precipitation-runoff model (Duncker and Melching, 1998; Zarriello and Ries, 2000; Martin and others, 2001). Many model parameters are not physically measurable, and their respective values must be obtained through calibration. HSPF is constructed in a modular format; each module controls the simulation of specific processes within the model.

In HSPF, the land surface is divided into hydrologic response units (HRUs), and the surface-water bodies (streams and lakes) are divided into reaches or reservoirs (RCHRESs). HRUs are assumed to exhibit consistent hydrologic and water-quality responses to precipitation, potential evapotranspiration, and other meteorological factors on the basis of their land use, soil characteristics, subsurface geology, and any other factors that might control the hydrologic and water-quality processes in the basin. HRUs are categorized as either pervious land segments (PERLNDs) or impervious land segments (IMPLNDs). HSPF can simulate all components of streamflow, including surface or overland flow, interflow, and base flow. Base flow is ground-water discharge to streams, and interflow is shallow, subsurface flow, which represents a flow component that has a faster response than ground-water flow, but a slower response than surface runoff.

Overland flows, subsurface flows, and chemical loads from PERLNDs, and overland flows and chemical loads from IMPLNDs, are routed to RCHRESs (or to other PERLNDs) by means of linkages defined in the NETWORK module or jointly in the SCHEMATIC and MASS-LINK modules. Hydraulic and water-quality processes within a RCHRES are simulated by the RCHRES module; flows and chemical loads are routed downstream from reach to reach by storage-routing (kinematic-wave) methods (Bicknell and others, 2001). For each RCHRES, a relation between water depth, surface area, storage volume, and outflow (discharge) is defined in a user-supplied function table (FTABLE).

HSPF permits input of precipitation and meteorological data from many sources, depending on the availability of data. It also allows application of atmospheric deposition to selected HRUs and routing of flow diversions and point-source chemical loads to appropriate RCHRESs. Hourly or daily time series data required by HSPF are stored in a Watershed Data Management (WDM) file and input to the model through the EXTERNALSOURCES module. Output type and storage locations in the WDM are identified through the EXTERNALTARGETS module. Time series data can be input directly to a WDM through IOWDM, a computer program designed for this purpose (U.S. Geological Survey, 1998), or ANNIE, a computer program for interactive management of data in a WDM (Flynn and others, 1995). Other time series data can be computed and automatically stored in a WDM through ANNIE or WDMUtil, a data-management utility program (U.S. Environmental Protection Agency, 1999). GenScn (Kittle and others, 1998), an interactive computer program that has many of the features of ANNIE and WDMUtil, also can be used to generate and analyze model scenarios and compare model results. WDMUtil or GenScn also can be used to check for and correct missing or erroneous data.

Model Input and Calibration Data

Simulation of streamflow by HSPF requires hourly or daily records of precipitation and potential evapotranspiration; simulation of snowmelt processes requires additional records of air and dewpoint temperatures, wind speed, and solar radiation. Diversions into and out of a basin should be identified, and their estimated flows and chemical loads input to the model. Some of the instream water-quality processes simulated by HSPF also require water-temperature data, which can be input from a recorded time series or generated by HSPF. HSPF can simulate the accumulation of sediment and chemical constituents on the land surface through either estimation of accumulation rates or input of atmospheric-deposition data, if available. Observed streamflows, water temperatures, and chemical concentrations and loads are used to calibrate the model. All model-input data must be entered at the same time step as the model-simulation run (hourly), either directly from a data file or by a conversion factor stipulated in the user-control input (UCI) file. (See appendix 1 for a summary of the sources of the data used in model development.)

Meteorological Data

Meteorological data for the model were obtained from three sources—a National Weather Service (NWS) station at the Syracuse Hancock International Airport, a USGS station near Tully Valley, and an Onondaga County Water Authority (OCWA) station at Otisco Lake (fig. 2; table 3). The NWS station at the Hancock Airport is just northeast of the study area and provides hourly and daily data on precipitation, air temperature, dewpoint temperature, wind speed, and percentage of cloud cover. Comparison of the hourly and daily precipitation records indicated errors in the hourly data, which represent original uncorrected values that were stored directly from the precipitation recording device. A second device measured daily total precipitation, which was considered reliable (Kathryn Vreeland, Northeast Regional Climate Center, oral commun., 2004). Therefore, despite the errors in the hourly record, which presumably affected the magnitude more than the timing of the hourly values, the erroneous hourly record was used to disaggregate the daily record to an hourly time step by a program contained in WDMUtil (U.S. Environmental Protection Agency, 1999). The USGS station is in the southern part of the Onondaga Creek basin near the Tully mudboils (fig. 2) and provides an hourly record of precipitation. The OCWA station at the northern end of Otisco Lake on the western side of the study area provides a daily record of precipitation; the readings were made at 7 a.m. This record was disaggregated to an hourly time step on the basis of the hourly time series from the other two stations, again by methods contained in WDMUtil, which adjusts the disaggregated record for a 24-hr time step that begins at 7 a.m.

Regardless of the precipitation-record source, all other meteorological data that were input to the model—air temperature, dewpoint temperature, wind speed, percentage of cloud cover, solar radiation, and potential evapotranspiration—were obtained directly from, or derived from data collected at, the Hancock Airport weather station. Estimates of solar radiation and potential evapotranspiration were calculated by methods based on Hamon and others (1954) and Hamon (1961), respectively, which are contained in WDMUtil (U.S. Environmental Protection Agency, 1999). Two additional time series were available—a daily record of snowfall water equivalents from the Otisco Lake area was supplied by OCWA, and measurements of snowpack depth were provided by the Hancock Airport station. These data were used to

Table 3. Data-collection sites and data used in development of precipitation-runoff model, Onondaga Lake basin, Onondaga County, N.Y.

[Site locations are shown in figure 2. mi², square miles; na, not applicable]

Site	Site identifier	Drainage area (mi^2)	Data type	Period of record used in model
Meteorological data-collection sites and data input to the model				
National Weather Service at Syracuse Hancock International Airport	Syracuse Hancock International Airport	na	Precipitation, air and dew-point temperatures, wind speed, cloud cover, snowfall, and snow-pack depth	1997–2003
U.S. Geological Survey at Tully Valley	Tully Valley	na	Precipitation	1997–2003
Onondaga County Water Authority at Otisco Lake	Otisco Lake	na	Precipitation, snowfall, and snow-water equivalent	1997–2004
Streamflow, water-quality, and water temperature data-collection sites and data used for model calibration [1]				
Onondaga Creek near Cardiff	04237962	33.9	Streamflow and water temperature	10/01–9/03
Onondaga Creek at Dorwin Avenue	04239000	88.5	Streamflow and water quality	10/97–9/03
Onondaga Creek at Spencer Street	04240010	110	Streamflow and water quality	10/97–9/03
Harbor Brook at Holden Street	04240100	10.0	Streamflow and water quality	10/97–9/03
Harbor Brook at Hiawatha Boulevard	04240105	12.1	Streamflow and water quality	10/97–9/03
Ley Creek at Park Street	04240120	29.9	Streamflow and water quality	10/97–9/03
Ninemile Creek near Marietta	04240180	45.1	Streamflow	10/97–9/03
Ninemile Creek at Camillus	04240200	84.3	Streamflow	10/97–9/03
Ninemile Creek at Lakeland	04240300	115	Streamflow and water quality Water temperature	10/97–9/03 11/99–9/03
Other data-collection sites and data input to the model				
USGS Onondaga Creek Tributary No. 6 below main mudboil depression area at Tully	04237946	0.32	Streamflow and suspended sediment	10/97–9/03
Onondaga County Water Authority at Otisco Lake	Otisco Lake	42.3	Lake levels and releases, and water-supply withdrawals	10/97–9/03
Otisco Lake [2]	Otisco Lake	42.3	Water quality	1996–1999
Marcellus wastewater-treatment plant	Marcellus	na	Discharge and water quality	10/97–9/03
Onondaga Lake [3]	Onondaga Lake	285	Lake elevations	10/97–9/03

[1] Streamflow and water-temperature data from U.S. Geological Survey; water-quality data from Onondaga County Department of Water Environment Protection. Water-quality data include concentrations and loads of soluble reactive phosphorus (orthophosphate), total phosphorus, ammonia, ammonia-plus-organic nitrogen, nitrate, nitrite, and total suspended solids.

[2] Data from New York State Department of Environmental Conservation (Callinan, 2001).

[3] U.S. Geological Survey station, Onondaga Lake at Liverpool, N.Y. (04240495).

calibrate the snow-accumulation and snowmelt processes in the basin.

A major potential source of error in a precipitation-runoff model is the undocumented spatial variability in precipitation quantity within a basin (Chaubey and others, 1999; Straub and Bednar, 2000; Troutman, 1983). Data from the three precipitation stations that were used in the model showed large differences in monthly and annual quantities (fig. 5). Annual precipitation totals from the Hancock Airport record differed from the totals in the Tully Valley and Otisco Lake records by an average of 4.0 and 3.2 in/yr, respectively, whereas totals from the two southern stations—Tully Valley and Otisco Lake—differed by more than 7 in/yr. Except for errors that arose from equipment malfunction or improper field-measurement techniques, which were subsequently corrected, there is no basis on which to assess the accuracy of these records. Therefore, the records were assumed to provide reasonably accurate estimates of precipitation that are representative of quantities that fell some distance from the measurement site.

Surface-Water Data

Streamflow records were obtained from nine USGS streamflow-monitoring stations (fig. 2; table 3) and were used to calibrate the hydrologic component of the model. These datasets were reviewed, and any missing or erroneous hourly values, such as those recorded during days of ice-affected or estimated daily discharges, were identified and corrected through WDMUtil (U.S. Environmental Protection Agency, 1999) or GenScn (Kittle and others, 1998). Daily mean flows were used at three stations—Harbor Brook at Holden Street, Ninemile Creek near Marietta, and Ninemile Creek at Lakeland—where estimated values made up a large percentage of each station's record. Eight of the nine stations were in operation during the entire calibration period, October 1997 to September 2003; streamflow monitoring began during October 2001 at Onondaga Creek near Cardiff. Published records for Ninemile Creek at Camillus end during September 1998; unpublished records for the remainder of the calibration period were available from the Ithaca, N.Y., office of the USGS.

Measured inflow from the mudboils at Tully Valley and the Marcellus wastewater-treatment plant (monthly average discharges) were available. Data on the daily outflows from Otisco Lake to Ninemile Creek and withdrawals by the water-treatment plant near Marcellus were provided by the OCWA.

Otisco Lake Data

Data for Otisco Lake were provided by the Onondaga County Water Authority (M.J. Murphy, Onondaga County Water Authority, written commun., 2004). Personnel from the OCWA water-treatment plant near Marcellus make once-daily (7 a.m.) measurements of precipitation, including snowfall water equivalency, at the north end (outlet) of the lake. Lake levels and gate openings at the dam at the outlet of the lake are recorded, and flow through the gates (either as weir or orifice flow) and flow over the dam are computed from rating curves that were produced at the time of the dam's construction. The combined lake outflows were reasonably close to discharges measured at the USGS streamflow-monitoring station on Ninemile Creek near Marietta, about 1.8 mi downstream from

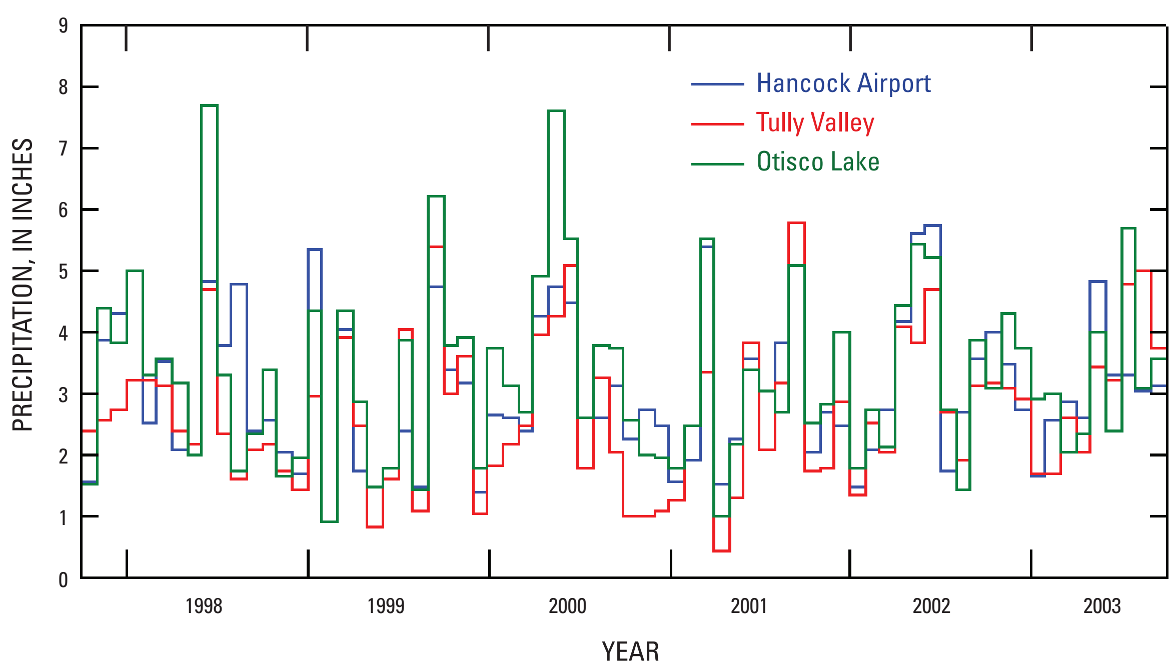

Figure 5. Monthly precipitation data used in precipitation-runoff model of the Onondaga Lake basin, Onondaga County, N.Y.

the lake (fig. 6), except when creek flows dropped below about 13 ft^3/s. During these periods, the computed gate releases were erroneously high; these flows were adjusted to better approximate the creek flows. (See section on "Simulation Complexities.") OCWA also records the withdrawals of water from the lake for water supply to suburban areas in and outside the Onondaga Lake basin. Both time series of lake outflows were input to the model to accurately simulate water removal from the lake. Cross-sectional data from a bathymetric map of Otisco Lake (Schaffner and Oglesby, 1978) were used to compute a relational table of lake water-surface elevation, surface area, and storage volume for the model. The relation between lake stage (measured in reference to the top of the dam at an elevation of 786.60 ft NGVD 29) and storage volume was defined as

$$V = 186.6 * S + 76{,}885 \ , \tag{1}$$

where

V is storage volume, in acre-feet,

and

S is stage, in inches.

The coefficient of determination for this equation is 0.9975. From this relation and the daily recorded lake levels (stages), a time series of lake-storage volume was generated; this time series was used to calibrate the inflows to the lake.

Onondaga Lake Data

Onondaga Lake water-surface elevations are recorded hourly at a USGS monitoring station near Liverpool, N.Y. (station 04240495). Cross-sectional data from a bathymetric map of Onondaga Lake (Water on the Web, 2004) were used to compute a relational table of water-surface elevation, surface area, and storage volume for the model. Although this relation was not required to run the model and no water-quality processes were simulated for the lake, this relational table was developed to permit realistic simulation of changes in the lake's storage. The relation between lake elevation and storage volume was defined as

$$V = 3{,}018.8 * E - 991{,}221 \ , \tag{2}$$

where

V is storage volume, in acre-feet,

and

E is water-surface elevation, in feet.

The coefficient of determination for this equation is 0.9992. From this relation and the recorded lake elevations, a time series of lake-storage volume was generated. Unlike Otisco Lake, whose water-surface elevation is controlled by the dam and gate openings at its outlet, Onondaga Lake has no such outlet structures. Its elevations are primarily controlled by operation of the dam and hydroelectric plant at

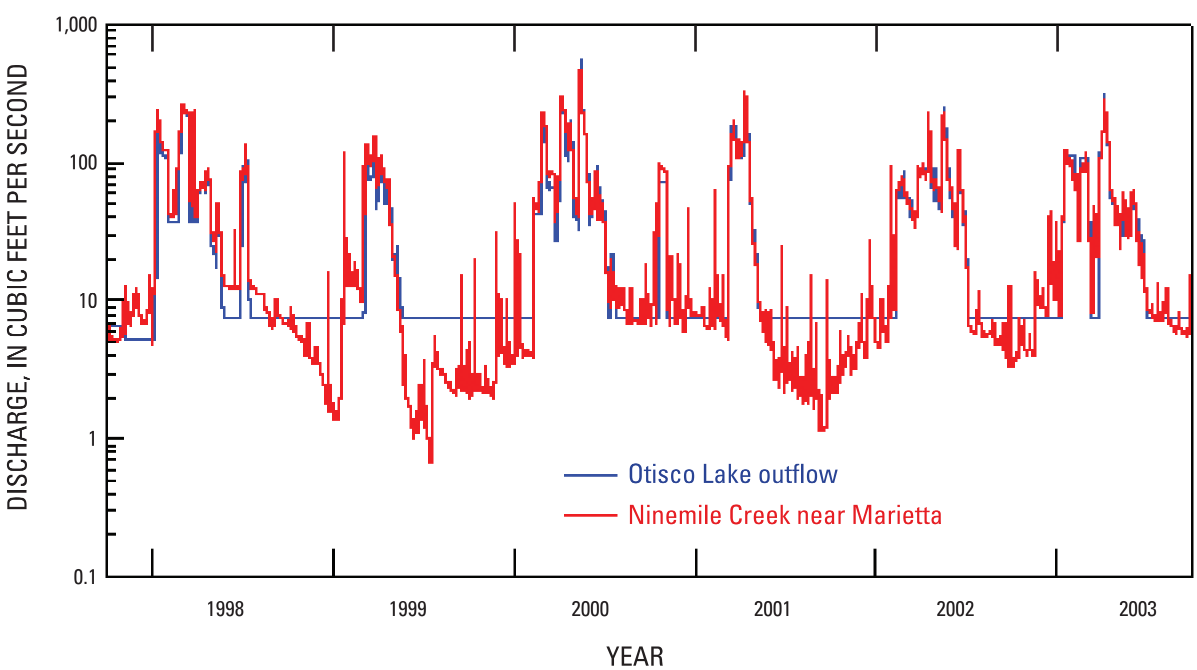

Figure 6. Daily mean discharge from Otisco Lake and in Ninemile Creek near Marietta, Onondaga Lake basin, Onondaga County, N.Y., 1997–2003.

Phoenix, N.Y., about 8 mi north of Onondaga Lake and can be affected by inflows from the Seneca River and possibly by wind-generated seiche. Because of these complicating factors, definition of a relation between lake inflows and lake-volume changes was not possible. To maintain storage volume within a reasonable range of computed values, lake outflows were estimated as the adjusted measured inflows to the lake lagged by one day. In the short term, this approximation was imprecise, but on an annual basis, it represented lake outflows, such that simulated lake volumes were reasonably close to estimated volumes.

Sediment Data

A literature search was conducted to identify sediment-related studies that had been conducted in the Onondaga Lake basin and to compile sediment loading rates that could be used to estimate loading rates for the basin. Computed sediment-load data from a study conducted in the Otisco Lake basin during 1982–83 (Paschal and Sherwood, 1987) were used to simulate the sediment concentrations and loads in the Otisco Lake basin; parameter values used in these simulations were then transferred and used elsewhere in the Onondaga Lake basin.

Estimated Sediment Loading Rates

Sediment erosion rates and export coefficients are often sought to estimate sediment loads derived from a basin; however, these terms are not synonymous. An erosion rate is the gross amount of sediment that is removed from a land surface; it is usually estimated using an equation, such as the Universal Soil-Loss Equation (USLE; Wischmeier and Smith, 1978), and does not account for storage of sediment between the eroded area and a downgradient point at which loads might be measured. As such, an erosion rate would be considered an edge-of-field estimate of sediment yield. An export coefficient is an estimate of that portion of a constituent mass that has been removed from the land surface, carried to and transported in a receiving waterway, and measured at some point downstream. It is a measure of the net amount of sediment that has been removed from a land surface and, in many cases, can be considered an end-of-basin estimate of sediment yield. If not measured from flow and concentration data, an export coefficient can be estimated as the gross amount of sediment adjusted by a sediment delivery ratio, which accounts for sediment that has been retained in depressions or by vegetation on the land surface or by deposition in the stream channel. The sediment delivery ratio has an inverse relation with drainage area; hence, the farther from the originating eroded surface, the lower the delivery ratio and the export coefficient. The average drainage area of the subbasins used in the HSPF model of the Onondaga Lake basin was about 2.5 mi^2, and 85 percent of the subbasins were from 1 to 5 mi^2 in size. The estimated sediment delivery ratios for basins in this size range are 0.29 to 0.21 (U.S. Army Corps of Engineers, 1977).

A literature search was conducted to compile export coefficients that were applicable to the land covers and land uses found in the Onondaga Lake basin (table 4). Reported values were mostly end-of-basin estimates (associated drainage-area sizes were not always reported, however), and although they were associated with a single dominant land use in the basin, they often reflected loading rates from multiple land uses. As a result, export coefficients can vary widely for a particular land cover or land use. Average values were selected for initial calibration of the sediment-related parameters of the Onondaga Lake basin model (table 4).

The only known study in the Onondaga Lake basin that reported land-use-specific erosion rates and end-of-basin export coefficients was conducted by Paschal and Sherwood (1987), who used the Universal Soil-Loss Equation (Wischmeier and Smith, 1978) to estimate sediment loads carried by the major tributaries to Otisco Lake during 1982–83. The annual erosion rates attributed to forest and pasture land were about 1 ton/acre; the upper quarter of the Spafford Creek subbasin, which has less agricultural land than the rest of the subbasin had an estimated erosion rate of 0.25 tons/acre. Erosion rates for cropland varied—about 1.5 tons/acre for about 47 percent of the cropland with conservation practices (including diversions, grassed waterways, strip cropping, subsurface drains, and conservation tillage) and 3 to 30 tons/acre for cropland with inadequate conservation practices. Sheet and rill erosion were identified as the major forms of soil erosion; streambank erosion was identified as a probable substantial source of sediment in some streams. The lower part of Spafford Creek flows through lacustrine silt and clay deposits, which are easily eroded and are the source of disproportionately large sediment loads to Otisco Lake. End-of-basin calculations of annual sediment loading rates to Otisco Lake ranged from 0.52 tons/acre for Spafford Creek to 0.05 tons/acre for VanBenthuysen Brook (table 5). Paschal and Sherwood (1987) noted that only about 15 percent of the USLE-estimated soil losses from the land surfaces were actually delivered to Otisco Lake. This sediment delivery ratio was less than the 25 percent that would be expected for subbasins with drainage areas between 1 and 5 mi^2 (U.S. Army Corps of Engineers, 1977).

Streambank and Roadbank Erosion

The Onondaga County Soil and Water Conservation District periodically conducts inventories of roadbank and streambank erosion. A comprehensive survey of roadbank erosion was conducted throughout the Onondaga Lake basin during 1992; randomly selected sites of streambank erosion were inventoried during 1994 (Sullivan and Moonen, 1994). Both roadbank and streambank erosion were reassessed during 2000 but only in the Onondaga Creek basin (Blatchley, 2000). The volume of eroded soil was computed from an estimated bank recession rate, or the rate at which an eroding bank recedes on an annual basis (U.S. Department of Agriculture, 1993). In the case of streambank erosion, this rate is based on

Table 4. Target and simulated sediment export coefficients for pervious and impervious land-segment types in precipitation-runoff model, Onondaga Lake basin, Onondaga County, N.Y.

[Values are in tons per acre per year. —, no data]

Land-segment type	Target value[1]	Simulated value	
		Initial	Final[2]
Pervious land segment			
Forest with high-runoff potential	0.10	0.10	0.21
Forest with low-runoff potential	—	.05	.05
Pasture-hay with high-runoff potential	.76	.75	.68
Pasture-hay with low-runoff potential	—	.44	.15
Row crops	2.36	2.36	1.27
Row crops in lacustrine silt-clay soils	12	10.1	15.2
Farmstead (livestock and dairy)	3.00	2.99	2.79
Wetland	.001	.001	.001
Urban[3]	.37	.37	.36
Low-intensity residential	.28	.28	.30
Commercial, industrial, transportation	.54	.54	.54
Impervious land segment			
Low-intensity residential	.30	.30	.30
Commercial, industrial, transportation	.35	.36	.36

[1] Average value from those found in scientific literature (Lietman and others, 1983; Kappel and others, 1986; Sherwood, 1984; Helsel, 1985, and various references cited therein; Paschal and Sherwood, 1987; Thomann and Mueller, 1987; Crawford and Lenat, 1989; Donigian and others, 1997; Frick and Buell, 1999; Donigian and Love, 2003; and Coulter and others, 2004).

[2] After calibration to annual end-of-basin loads measured in Otisco Lake tributaries, 1982-83 (Paschal and Sherwood, 1987).

[3] Average of pervious and impervious high-intensity residential land types.

Table 5. Target and simulated sediment loads for Otisco Lake tributaries in precipitation-runoff model, Onondaga Lake basin, Onondaga County, N.Y.

[Values are in tons per acre per year.]

Otisco Lake tributary	Target value, 1982–83 data [1]	Simulated value	
		Initial [2]	Final [3]
Spafford Creek	0.52	0.26	0.38
Rice Brook	.10	.21	.11
Willow Brook	.12	.26	.13
Amber Brook	.10	.12	.07
VanBenthuysen Brook	.05	.12	.06

[1] Data from Paschal and Sherwood, 1987.

[2] Sediment loads based on calibration to unit-area loading rates for pervious and impervious land-segment types from literature values (table 4).

[3] Sediment loads based on calibration to annual end-of-basin loads measured in Otisco Lake tributaries, 1982-83 (computed from data in Paschal and Sherwood, 1987).

soil texture, stream alignment and gradient, the presence or absence of vegetation, and the slopes of the eroding bank and of any depositional bar. For calculation of roadbank recession rates, soil texture, bank vegetation and slope, and drainage to the bank slope and at the base of the slope are assessed. These rates are larger at road cuts and at sites of ditch-maintenance operations performed by local highway departments.

Sullivan and Moonen (1994) estimated total annual erosion of 318 and 2,335 tons of sediment from roadbanks and streambanks, respectively, in the Onondaga Lake basin. Of the streambank load, 69 and 31 percent were attributed to the Onondaga Creek and Ninemile Creek basins, respectively. Of the total load, only 89 tons were estimated as being delivered to Onondaga Lake. Blatchley (2000) estimated that the combined tonnage of sediment eroded from streambanks and roadbanks in the Onondaga Creek basin alone was 2,025 tons, and of this quantity, about 70 tons were transported to Onondaga Lake.

The main reason for the large decrease in loads carried to Onondaga Lake was the sediment-trapping capability of the Onondaga Reservoir and Otisco Lake. The sediment retention rate of the Onondaga Reservoir (RCHRES 121) was estimated to be 75 percent (Sullivan and Moonen, 1994) from a relation between capacity-inflow ratios and reservoir trap efficiencies that was developed for reservoirs with permanent pools (D.S. Sullivan, Onondaga County Soil and Water Conservation District, retired, written commun., 2005). Technical guidance related to this methodology (U.S. Department of Agriculture, 2006) suggests that the selected value should be lowered by 10 percent if the reservoir is a dry reservoir, and an additional 10 percent if the inflow load is dominated by fine-textured sediment (silt and clay). Both of these factors apply to the Onondaga Reservoir, but it is unclear whether they were taken into consideration in the 75-percent estimate.

The U.S. Army Corps of Engineers (USACE), which constructed the Onondaga Dam on Onondaga Creek in 1949, anticipated the need to monitor sedimentation rates in the reservoir by establishing 21 valley transects (or ranges) in 1951 to be used to measure sediment accumulation over time (U.S. Army Corps of Engineers, 1955). By 1987 no sedimentation surveys had been performed owing to “the absence of significant runoff events and associated sediment accumulation” (U.S. Army Corps of Engineers, 1987), although this period included the April 1960 period-of-record high-water event that raised the water in the reservoir by 29 ft (Hornlein and others, 1999). No sedimentation survey had been conducted as of 2005. Contrary to the implied conclusion of the USACE, the sediment-removal capability of the reservoir is believed to be substantial, but possibly not as large as the 75-percent value estimated by Sullivan and Moonen (1994).

In the Ninemile Creek basin, a similar, albeit larger, retention rate of 90 percent was estimated for sediment loads carried into Otisco Lake (RCHRES 409; Sullivan and Moonen, 1994). Recent (2006–07) results of water-quality analyses of samples from Otisco Lake tributary inflows and from the lake outflow (unpublished data in the files of the Ithaca, N.Y., office of the USGS) appear to support this magnitude of the mitigative effects of Otisco Lake. The arithmetic mean concentration of selected constituents in periodically collected stormflow and base-flow samples from four tributaries were averaged and compared with similar values from the Otisco Lake outflow. The constituent concentrations in the lake outflow are typically much lower than concentrations in the inflow (table 6); removal efficiencies have not been computed, however.

Sediment Contribution from Mudboil Area in Upper Onondaga Creek Basin

The mudboils are a unique hydrologic and sedimentological phenomenon near Tully Valley in the upper Onondaga Creek basin (location shown in fig. 2). Mudboils are volcano-like cones of fine sand and silt that range from several inches to several feet in height and from several inches to more than 30 ft in diameter (Kappel and McPherson, 1998). Ground water under confined conditions moves upward through a dense layer of silt and clay and deposits its sediment load on

Table 6. Concentrations of selected constituents in Otisco Lake outflow and tributary inflow, Onondaga County, N.Y., 2006–07.

[Unpublished data on file in the Ithaca, N.Y., office of the U.S. Geological Survey. Concentrations are in milligrams per liter. E, estimated]

Constituent	Average concentration in four Otisco Lake tributaries[1]	Concentration in Otisco Lake outflow	Ratio of lake outflow to average concentration in tributary inflow
Orthophosphate	0.07	E 0.004	0.06
Total phosphorus	.49	.017	.04
Ammonia nitrogen	.14	.034	.24
Nitrate-plus-nitrite nitrogen	2.18	.33	.15
Ammonia-plus-organic nitrogen	2.03	.34	.17
Suspended sediment	680	11.8	.02

[1] Spafford Creek, Rice Brook, Willow Brook, and tributary at Williams Grove.

the land surface near the mudboil's vent or carries the fine particles to Onondaga Creek. Mudboils are a large source of sediment to the creek; in 1992, the average daily sediment load from the mudboils was 30 tons. Remediation efforts, including surface-water diversion, installation of depressurizing wells, and an impoundment dam, have decreased loads to an average daily load of less than 2 tons (Kappel and McPherson, 1998).

Data on daily sediment loads from the mudboils (Hornlein and others, 1999, 2000, 2001, 2002, 2003, 2004) were input to the Onondaga Lake basin model as a point source to Onondaga Creek (RCHRES 106). HSPF requires that the sediment load be apportioned among three size classes: sand, silt, and clay. The proportions were estimated from periodic particle-size analyses that were available from 1991 through 2005 (Hornlein and others, 1993 through 2004; Szabo and others, 2006). Prior to July 1993 when an impoundment dam caused substantial decreases in sediment loads and altered the composition of the sediment load, fine-grained sand, silt, and clay represented about 8, 43, and 49 percent of the sediment load on an annual basis, respectively. Since 1993, these percentages shifted to 2, 31, and 67 percent, respectively. These latter values were used to apportion sediment loads from the mudboils to the three particle-size classes during the calibration period 1997 to 2003.

Bed-Material Particle-Size Data

HSPF requires information on the composition of the bed material in the RCHRESs to simulate sediment transport in the basin. Particle-size analyses of bed material in the channels of the Onondaga Lake basin were not performed for this study. Instead, each reach within the basin was inspected to identify the dominant bed material in the channel. On the basis of this inspection and a relation between channel slope and median bed-material particle size that was developed from detailed bed-material analyses performed on sediment samples collected in another New York State basin (Coon and Johnson, 2005), the percentages of sand, silt, and clay in each RCHRES were estimated. For steep reaches that were dominated by gravel or larger particle sizes, the sand fraction was assumed to be the major component of the sand-silt-clay material; therefore, sand was estimated as 85 percent, silt as 10 percent, and clay as 5 percent of the fine-grained bed material that filled the spaces between the larger particles of the bed. For low-gradient reaches that were dominated by fine-grained particles, the percentages of silt and clay were expected to increase in relation to the sand fraction. Therefore, the percentages of sand, silt, and clay in these channels were estimated as 70, 20, and 10, respectively. Bed-material porosity, another required HSPF parameter, was estimated from average values given in Davis and DeWiest (1966), Freeze and Cherry (1979), and Fetter (1980); 40 percent was assigned to each RCHRES.

To simulate the processes of within-stream scour and sediment deposition, the RCHRESs were grouped on the basis of channel slope, presence of riverine wetlands, and observations of dominant bed-material sizes. Reaches, which had bed slopes less than 0.005, and (or) were classified as riverine wetlands by NLCD (U.S. Geological Survey, 1999), and (or) were dominated by silt and clay bed materials, were classified as low-gradient reaches. Deposition and scour of fine-grained sediments were simulated in these reaches. Of these reaches, Otisco and Onondaga Lakes and Onondaga Reservoir were uniquely simulated. The remaining reaches, that is, those with bed slopes greater than 0.005 and dominated by gravel, cobble, and boulder bed materials, were classified as high-gradient reaches. These latter reaches were simulated as "flow-through" reaches in regard to fine-grained sediment processes; that is, sand, silt, and clay particles were not permitted to aggrade nor degrade within the reach.

Surface-Water-Quality Data

Contributions of selected constituents from the land surface were initially estimated from values in the literature on the basis of land cover or land use, then adjusted during calibration to improve the fit between observed and simulated data. Simulated concentrations and loads in streamflow were calibrated to measured concentrations and computed loads at six water-quality-monitoring sites (table 3). Data from long-term and regular sampling programs, such as the Onondaga County WEP ambient monitoring program (EcoLogic, LLC, 2001), were used preferentially during the model-calibration process over datasets that contained only a few periodic measurements during the simulation period.

Estimated Nutrient Loading Rates

Calibration of the water-quality components of the model required measured or estimated loading rates of nonpoint-source constituents, as well as the concentrations of these constituents in streamflow. Nutrient loading rates are highly variable and depend on local physiographic and climatic characteristics, including land use, land-use intensity, soil texture, soil type (mineral or organic), soil chemistry, surficial geology, slope, distance of overland flow, drainage density, precipitation (quantity, duration, and intensity), frequency of storms, and runoff rate (Beaulac and Reckhow, 1982; Sonzogni and others, 1980). Loading rates often refer to field-scale (edge-of-field) estimates of constituent loads that are generated from a unit area of a specific land use or land cover. These loads often are adjusted to account for the decrease in constituent loads resulting from depositional processes along the overland-flow path. The resultant edge-of-stream load is that mass of a constituent that presumably enters a stream channel and is then subject to within-channel processes of deposition, transformation, uptake, and resuspension. The loading rates that are measured at the downstream end of a basin reflect the integration of multiple input sources and within-stream processes; nonetheless, they are often referred to as land-use-specific loading rates or export coefficients and are associated with the dominant land use in the basin. For lack of edge-of-field and edge-of-stream loading-rate data that are directly applicable to the Onondaga Lake basin, representative loading rates for phosphorus constituents (table 7) and nitrogen constituents (table 8) were estimated from values published in scientific literature and, in this report, are referred to as end-of-basin export coefficients.

Few water-quality studies that could provide guidance on the selection of nutrient loading rates directly applicable to the Onondaga Lake basin have been conducted. Several studies have focused on the water-quality effects of farm-related activities and the efficacy of BMPs that were implemented to mitigate those effects (Hyde and others, 1999; Hyde, 2005; Moffa and Associates, 2002; and Brown and Caldwell, 2005), but in most cases, the published data could not be incorporated into the model-calibration process because of poor project design, failure to follow accepted sample-processing procedures, or inability or failure to present study results in the desired units of mass per unit area. The one exception was the study conducted by Hyde and others (1999), which assessed the effects of the closure of a 120-cow dairy farm on nutrient concentrations in a nearby stream and found that annual total phosphorus (TP) loads dropped from a pre-closure level of 1.4 lb/ac to 0.6 and 0.2 lb/ac during the two subsequent years. Parsons (2004), after assuming an arbitrary farm size of 2 acres, summarizes data from Moffa and Associates (2002) and reports a range of TP loading rates from 400 to 850 lb/ac/yr or an average of 625 lb/ac/yr. The two orders of magnitude difference between the values reported in these studies raised doubts about identifying a TP export coefficient that might be representative of average conditions in the Onondaga Lake basin. Paschal and Sherwood (1987) computed loads of nitrogen [ammonia-plus-organic nitrogen (TKN), ammonia nitrogen (NH_3), organic nitrogen (OrgN), and nitrate-plus-nitrite nitrogen (NO_x)] and phosphorus [TP, total inorganic phosphorus, total dissolved phosphorus (TDP),

Table 7. Target and simulated orthophosphate and total phosphorus export coefficients for pervious and impervious land-segment types in precipitation-runoff model, Onondaga Lake basin, Onondaga County, N.Y.

[Values are in pounds per acre per year. –, no data]

Land-segment type	Orthophosphate			Total phosphorus		
	Range [1]	Target value [1]	Simulated value	Range [2]	Target value[2]	Simulated value
Pervious land segment						
Forest	0.01–0.09	0.05	0.02	0.02–0.60	0.13	0.09
Pasture-hay	.02–.24	.13	.02	.045–.93	.45	.25
Row crops	.04–.36	.19	.04	.002–4.10	.77	2.11
Farmstead (livestock and dairy)	–	–	.24	1.4–625	[3]–	15.0
Wetland	–	–	.04	.02–.66	.34	.04
Urban	.04–.36	.12	.10	.27–4.28	1.11	.77
Impervious land segment						
Low-intensity residential	.06–.18	.12	.09	.36–1.96	.92	.48
Commercial, industrial, transportation	.02–.27	.14	.10	.09–6.78	2.32	1.03
Combined storm-and-sanitary-sewer overflow area						
Harbor Brook	–	–	–	–	.51–65	1.00
Ley Creek	–	–	–	–	.81–1.03	1.53
Onondaga Creek	–	–	–	–	1.39–1.76	1.72

[1]Average value cited in scientific literature (Clesceri and others, 1986; Frick and Buell, 1999; and Coulter and others, 2004).

[2]Average value cited in scientific literature (Omernik, 1977; Reckhow and others, 1980; Sonzogni and others, 1980; Lietman and others, 1983; Sherwood, 1984; Clesceri and others, 1986; Kappel and others, 1986; Paschal and Sherwood, 1987; Thomann and Mueller, 1987; Frink, 1991; Panuska and Lillie, 1995; Frick and Buell, 1999; McFarland and Hauck, 2001; Moffa and Associates, 2002; Endreny and Wood, 2003; Coulter and others, 2004; Parsons Consultants, 2004; and the following three references cited in Lin, 2004: Rast and Lee, 1978; Loehr and others, 1989; and Dodd and others, 1992).

[3]Indeterminate due to wide range in reported values. Hyde and others (1999) report a value as low as 1.4 lb/ac/yr, whereas Parsons Consultants (2004) summarize data from Moffa and Associates (2002) and report a range of 400 to 850 lb/ac/yr or an average of 625 lb/ac/yr.

Table 8. Target and simulated nitrate and organic nitrogen export coefficients for pervious and impervious land-segment types in precipitation-runoff model, Onondaga Lake basin, Onondaga County, N.Y.

[Values are in pounds per acre per year. –, no data; e, estimated value]

Land-segment type	Nitrate			Organic nitrogen		
	Range[1]	Target value[1]	Simulated value	Range[2]	Target value[2]	Simulated value
Pervious land segment						
Forest	0.53–0.91	0.68	3.3	0.09–2.8	1.7	1.6
Pasture-hay	–	1.0 e	5.8	.66–2.35	1.5	1.9
Row crops	4.1–18.2	10.3	11.1	1.54–9.7	4.3	3.1
Farmstead (livestock and dairy)	–	8.8	13.6	1.1–17.1	10.2	8.8
Wetland	–	–	0.3	–	–	0.6
Urban	3.09–5.33	4.3	1.6	1.2–11.2	4.8	2.1
Impervious land segment						
Low-intensity residential	2.69–.44	3.0	1.1	1.0–7.1	3.9	2.1
Commercial, industrial, transportation	–	5.0 e	1.6	4.92–21.2	13.1	4.4

[1]Average value cited in scientific literature (Omernik, 1977; Lietman and others, 1983; Sherwood, 1984; Clesceri and others, 1986; Paschal and Sherwood, 1987; Frick and Buell, 1999; and Coulter and others, 2004).

[2]Average value cited in scientific literature (Omernik, 1977; Lietman and others, 1983; Clesceri and others, 1986; Kappel and others, 1986; Paschal and Sherwood, 1987; and Frick and Buell, 1999).

dissolved orthophosphate, and dissolved organic phosphorus] that were delivered to Otisco Lake by its tributaries during 1982–83. End-of-basin total loads and basinwide unit area values are presented in the report, but no attempt was made to assign export coefficients that were land-use specific.

The nutrient components of the Onondaga Lake basin model were initially calibrated to land-use-specific estimates of loadings that were selected from values in the literature —the target values listed in table 7 for orthophosphate and total phosphorus and table 8 for nitrate and organic nitrogen. Adjustments to pertinent parameter values in the model were made to improve the fit between observed and simulated concentrations and between computed and simulated loads. The final simulated values also are listed in tables 7 and 8 and highlight the potential inaccuracies that might result from the use of loading rates derived from literature values rather than from basin-specific data.

Onondaga County Department of Water Environment Protection Data

Water-quality data were obtained from six of the nine USGS sites at which streamflow was monitored during the simulation period (fig. 2; table 3; Antonio Deskins, Onondaga County Department of Water Environment Protection, written commun., 2004). A limited dataset consisting of concentrations of orthophosphate (OP), TP, TKN, and total suspended solids (TSS) was available for a seventh site—Onondaga Creek near Cardiff.

Beginning in August 1998, biweekly and selected storm sampling was conducted by WEP as part of the Ambient Monitoring Program (AMP). Biweekly sample-collection protocols were established for each site at this time. Width- and depth-integrated samples were collected under low-flow conditions with an isokinetic sampler on Onondaga Creek at Dorwin Avenue (station 04239000) and at Kirkpatrick Street (which is the second bridge downstream from the USGS streamflow-monitoring site at Spencer Street, station 04240010), Harbor Brook at Velasko Road (which is the first bridge upstream from the USGS streamflow-monitoring site at Holden Street, station 04240100), and Ninemile Creek at State Highway 48 at Lakeland (station 04240300; EcoLogic, LLC, 2001; fig. 2). With an isokinetic sampler, water approaching the intake nozzle undergoes no change in speed or direction as it enters the orifice (Edwards and Glysson, 1988). Near-surface grab samples were collected during stormflows at these sites using a 2-gallon stainless-steel bucket (Antonio Deskins, Onondaga County Department of Water Environment Protection, oral commun., 2007). At low-velocity sites—Harbor Brook at Hiawatha Boulevard (station 04240105) and Ley Creek at Park Street (station 04240120)—samples were collected with a Kemmerer sampler and composited from three points across the stream. Samples were collected and processed according to procedures described by U.S. Environmental Protection Agency (1982). Samples were analyzed for soluble reactive phosphorus (SRP or orthophosphate), TDP, TP, NH_3, OrgN, TKN, nitrate (NO_3), nitrite (NO_2), and TSS.

Storm runoff was sampled frequently over a period of several days at the biweekly sampling sites plus additional sites—two on Onondaga Creek and one on Ley Creek. Stormflow samples were collected by dip sampling at mid-channel with a stainless steel bucket. Sample bottles were filled directly from the bucket and were filtered and preserved when appropriate (EcoLogic, LLC, 2001). Samples were analyzed for SRP, TDP, TP, TKN, and TSS. Analyses were performed by the WEP laboratory following the procedures described in U.S. Environmental Protection Agency (2003; EcoLogic, LLC, 2001).

Prior to the implementation of the AMP in August 1998, all samples were collected in a stainless steel bucket by a single mid-channel grab-sampling method. To assess the effect that the change in sampling protocol might have on the dataset, paired samples—one collected by the mid-channel grab method and a second collected by the depth-integrated method—were collected during base flow and stormflow on Onondaga Creek at Dorwin Avenue and Ninemile Creek at Lakeland from August 1998 to December 2000. All samples were analyzed for TP and TSS; stormflow samples also were analyzed for SRP, TDP, and TKN, and the resulting concentrations were compared. Although variance in the concentrations of paired samples increased as concentrations approached their respective analytical limits of detection, no consistent identifiable difference between the concentrations of the paired samples was noted (EcoLogic, LLC, 2001). Therefore, the change in sampling protocol apparently did not introduce a systematic bias into the datasets, and the entire water-quality record was deemed useable for model calibration purposes.

The WEP water-quality data were the primary source of data used for model calibration of in-stream constituent concentrations. Where necessary, parameter values that controlled nutrient loading rates from the land segments were adjusted to approximate the timing, range, and seasonal patterns of concentrations measured at the water-quality monitoring sites. WEP computed monthly loads of the measured constituents on the basis of these concentrations and on flows measured at the USGS streamflow-monitoring sites, which are co-located with the WEP water-quality sites. Loads at Onondaga Creek near Cardiff were not computed. Loads were computed with a program, FLUX (Walker, 1999), which provides a suite of load-calculation methods that can be selected on the basis of the relation between concentration and flow. The method used to compute the Onondaga Lake tributary loads is a multiple-regression model that represents concentration variations associated with flow, season, and year (trend) for a given time period and generates a daily time series of predicted concentrations (EcoLogic, LLC, 2003). A second daily time series is generated by interpolating residuals, that is, observed-minus-predicted concentrations, between adjacent sampling dates. The two time series were merged to create a daily concentration series, which along with daily streamflows was used to compute loads (EcoLogic, LLC, 2003). Because of the increased uncertainty associated with loads computed at short time steps, daily loads were summed and monthly loads were made available for model calibration. (Antonio Deskins, Onondaga County Department of Water Environment Protection, written commun., 2004).

Project Watershed Data

Water-quality data from miscellaneous sites throughout the Onondaga Lake basin were obtained through the efforts of Project Watershed, a multi-organizational program developed to monitor the water quality of streams in central New York and to facilitate water-resources education (Project Watershed, 2005). Samples were collected quarterly or less frequently by trained adult volunteers or by students in high-school science classes. Analyses of NO_3, OP, dissolved oxygen (DO), and biochemical oxygen demand (BOD) were performed in the field. Water temperatures also were measured. These data were used in a limited way, that is, when necessary or likely to improve the relation between observed and simulated values at sites where longer records and more frequent sampling were unavailable from WEP.

Otisco Lake Data

New York State Department of Environmental Conservation conducted a study of the Finger Lakes during 1996–99, which included collection of epilimnion and hypolimnion water samples (Callinan, 2001; C.W. Callinan, New York State Department of Environmental Conservation, written commun., 2005). These samples were analyzed for SRP, TDP, TP, NH_3, TKN, NO_3, NO_2, and TSS. Daily constituent loads were computed from average constituent concentrations in the epilimnion and daily lake outflow data that were provided by Onondaga County Water Authority (M.J. Murphy, Onondaga County Water Authority, written commun., 2004); loads were input to the model as point sources by way of the EXTERNAL SOURCES module.

Marcellus Wastewater-Treatment Plant Data

Personnel at the Marcellus WWTP collected samples of the plant's effluent once monthly; samples were analyzed for NH_3, TKN, TP, and TSS by commercial laboratories (John Hopkins, Marcellus WWTP, written commun., 2005). Loads of NH_3, TKN, and TP were computed from once-monthly instantaneous flows and constituent concentrations that were assumed to be representative of flows and concentrations for an entire month; TSS loads were not computed because of the large number of censored concentrations (concentrations below the analytical detection limit). Loads of OrgN were computed as the difference between TKN and NH_3. Nitrite and nitrate nitrogen concentrations were estimated on the basis of the relation between TKN and these constituents, as measured at the METRO WWTP. Similarly, OP concentrations were estimated as a percentage of TP concentrations, as measured at the METRO WWTP. These concentrations of NO_2, NO_3, and OP were then used to compute their respective loads. Organic phosphorus (OrgP) loads were computed as the difference between TP and TDP. All computed loads were input to the model as point sources by way of the EXTERNAL SOURCES module. Ninemile Creek water was sampled above and below the plant's outfall; samples were analyzed for NH_3, TKN, total dissolved solids, and DO.

Water-Temperature Data

Water temperatures were measured hourly at two USGS monitoring stations—Onondaga Creek near Cardiff (04237962) and Ninemile Creek at Lakeland (04240300) (fig. 2). Temperatures were measured by sensors in acoustic Doppler streamflow-velocity meters (which require water temperature to adjust measurements of the speed of sound) and were not field checked. These temperature records covered only part of the calibration period; the Lakeland record began during November 1999, and the Cardiff record began during October 2001.

Measurements of water temperature also were made by WEP personnel at the six water-quality-monitoring stations, which include Ninemile Creek at Lakeland (fig. 2; table 3) and by participants of the Project Watershed (2005) program at miscellaneous sites throughout the Onondaga Lake. Water temperatures were measured in conjunction with collection of water-quality samples. These continuous records and periodic measurements of water temperatures were used to calibrate the water temperatures simulated by the Onondaga Lake basin model; records that covered longer periods were used preferentially in the calibration process.

Model Structure

A basin, whose hydrologic and water-quality processes are simulated by HSPF, is divided into subbasins, each with an associated stream channel. HRUs, which make up the land surface of each subbasin, receive precipitation and other meteorological inputs and generate flows and chemical loads that are routed to the stream channel and passed downstream from reach to reach. The hydrologic and water-quality processes that occur in the pervious and impervious HRUs are simulated by the HSPF modules, PERLND and IMPLND, respectively (table 9). Different sections of these modules deal with overland and subsurface flows, snowmelt, water temperature, and sediment and nutrient generation and transport. Routing of flows and loads through the stream network is performed by the RCHRES module. Parameter values that control these processes can be changed within a simulation period through the SPEC-ACTIONS module. Natural or man-induced changes in the basin, such as application of fertilizer in agricultural areas or street sweeping in urban areas, can be simulated by this module. The effects of BMPs can be simulated by the BMPRAC module, which permits the assignment of removal fractions to constituent loads. Guidance on a strategy for modeling the Onondaga Lake basin, including model set-up, development, and calibration of all components of the model was obtained from Donigian and others (1984).

Basin Representation

Primary segmentation of the Onondaga Lake basin, that is, delineation of subbasins, was based on the spatial distribution of precipitation; three areas were approximately defined by Thiessen (1911) polygons generated for the three precipitation stations—Tully Valley, Otisco Lake, and Hancock Airport (fig. 7). This segmentation placed the southern half of the Onondaga Creek basin into the Tully Valley precipitation area; most of the West Branch Onondaga Creek and about two-thirds of the Ninemile Creek basin into the Otisco Lake precipitation area; and the remaining areas—the northern ends of Onondaga and Ninemile Creek basins, all of Harbor Brook and Ley Creek basins, and small subbasins that drain directly to Onondaga Lake—into the Hancock Airport precipitation area.

Further segmentation of the basin was based on six factors: (1) the confluences of major tributaries, (2) an estimate of reach length, such that flow time through an average RCHRES under mean flow conditions would approximate the simulation time step of one hour, (3) an arbitrary size limit that subbasins not exceed 3 percent of the total basin area, (4) the locations of large changes in channel slope and bed-material type that would affect the storage-to-discharge relation and sediment-transport processes in a RCHRES, (5) the locations of monitoring sites, and (6) the locations at which simulated discharge or chemical-load data might be desired. Subbasin boundaries that previously had been defined for an HSPF model of Ninemile Creek between Marietta and Camillus (fig. 2; Zarriello, 1999) were, for the most part, retained for the present model. This segmentation of the Onondaga Lake basin resulted in 107 subbasins (fig. 7), each of which represents less than 2.5 percent of the total basin area or less than about 4,530 acres, except for the area that drains directly to Otisco Lake, which contains about 7,060 acres or 3.8 percent of the total Onondaga Lake basin. The average drainage area of the subbasins used in the Onondaga Lake basin model is about 2.5 mi^2, and 85 percent of the subbasins are from 1 to 5 mi^2 in size.

Hydrologic Response Units (HRUs)

The HRUs into which the Onondaga Lake basin was divided were assumed to show homogeneous hydrologic and water-quality responses to precipitation, potential evapotranspiration, and other meteorological factors. Each HRU was designated as pervious land (PERLND) or impervious land (IMPLND).

Table 9. Structure of Hydrological Simulation Program—FORTRAN (HSPF) model for simulation of hydrologic and water-quality processes.

Model section	Process simulated by HSPF
PERLND Module for simulating processes of a pervious land segment	
PWATER	Water budget (overland and subsurface flows)
SNOW	Accumulation and melting of snow and ice
SEDMNT	Production and removal of sediment
PSTEMP	Soil temperatures
PWTGAS	Water temperature and dissolved-gas concentrations
PQUAL	Generation of chemical constituents
IMPLND Module for simulating processes of an impervious land segment	
IWATER	Water budget (overland flow)
SNOW	Accumulation and melting of snow and ice
SOLIDS	Accumulation and removal of solids
IWTGAS	Water temperature and dissolved-gas concentrations
IQUAL	Generation of chemical constituents
RCHRES Module for simulating processes of a reach or reservoir	
HYDR	Hydraulic behavior
HTRCH	Heat exchange with atmosphere and bed, and water temperature.
SEDTRN	Behavior of inorganic sediment
RQUAL	Constituents involved in biochemical transformations
OXRX	Dissolved oxygen and biochemical oxygen demand
NUTRX	Inorganic nitrogen and phosphorus balances
PLANK	Plankton populations (organic nitrogen, phosphorus, and carbon)
Modules for simulating unique or variable conditions	
BMPRAC	Change in chemical-load resulting from best-management practice
SPEC-ACTIONS	Changes in simulated processes due to natural or man-induced changes in the basin

Pervious Land Segments

The basin characteristics that were expected to affect the hydrologic and water-quality responses of the pervious land segments are land use and land cover, hydrologic soil group, and aspect, as described below.

Land Use and Land Cover

The land-use and land-cover classification was selected as a basis for defining the HRUs because land use and land cover strongly affect evapotranspiration rates, and runoff and water-quality processes. The primary source of land-use and land-cover data was National Land Cover Data (NLCD) (fig. 4; U.S. Geological Survey, 1999); data were collected about 1992. The NLCD is considered to be an acceptable general land-cover-classification product for large regions, although some small-scale inaccuracies can be expected. Inaccuracies were identified, and two revisions to the NLCD were made to improve the land-use and land-cover data for the Onondaga Lake basin model. (1) The NLCD may misclassify emergent wetlands as row-crop land (Coon and Johnson, 2005). Therefore, a separate wetland GIS coverage was generated that included all wetlands identified in the National Wetland Inventory (U.S. Fish and Wildlife Service, 2000) and freshwater wetlands regulated by the New York State Department of Environmental Conservation (1999). This new wetland coverage was digitally incorporated into the NLCD coverage. (2) NLCD grid cells that were classified as row crops in areas that were obviously “developed,” such as downtown Syracuse, were reclassified as urban grass.

Data in a second and more current NLCD dataset (U.S. Geological Survey, 2005) were collected during 2001, but the dataset had not been finalized by 2005. The 2001 NLCD dataset was used as the basis for the Coastal Change Analysis Program (C-CAP) of the National Oceanic and Atmospheric Administration (2004). This dataset focused

EXPLANATION

Precipitation areas

- Tully Valley
- Hancock Airport
- Otisco Lake

Basin boundary

402 **Subbasin boundary and number**

Streams

Tully Valley **Precipitation station and identifier**

04237962 **Streamflow and water-quality monitoring site and site number**

Figure 7. Subbasins and precipitation areas used in precipitation-runoff model of the Onondaga Lake basin, Onondaga County, N.Y.

on classification of coastal wetland areas and had not been reviewed for the non-coastal land covers and land uses as of 2005. Despite the lack of ground-truthing of the 2001 NLCD, the two datasets were compared and the following discrepancies were noted. (1) The 2001 NLCD incorporated the data from the National Wetland Inventory (U.S. Fish and Wildlife Service, 2000); therefore, more areas in the 2001 dataset were classified as wetlands without the additional processing that was required to achieve the same results for the 1992 NLCD. (2) The acreages classified as row crops and as pasture-hay in the 1992 NLCD were different than in the 2001 NLCD, but the sum of these acreages was generally about the same and indicated the use of the conservation practice of rotating field uses from one year to the next. (3) The 2001 dataset indicated a loss of about 200 acres of forested land and an increase of less than 0.6 mi^2 of developed land. Given the relatively small differences between the two datasets and the intermediate state of finality of the 2001 NLCD, the 1992 dataset was used for the Onondaga Lake basin model.

Hydrologic Soil Group (HSG)

HSG is a classification of soils based on the soil properties that affect runoff potential. These properties influence the minimum rate of infiltration for a bare soil after prolonged wetting and when not frozen, and include (1) depth to a seasonally high water table, (2) saturated hydraulic conductivity after prolonged wetting, and (3) depth to a layer with a very slow water transmission rate. The infiltration rate is the rate at which water enters the soil at the surface and is controlled by surface conditions. The transmission rate is the rate at which water moves within the soil profile and is controlled by soil properties. The influence of ground cover is treated independently (U.S. Department of Agriculture, 2003).

Soils are classified into four HSGs; each group of soils has similar runoff potential under similar storm and cover conditions. These groups are defined by Natural Resources Conservation Service soil scientists as follows (U.S. Department of Agriculture, 2001):

A. Soils with low runoff potential. They chiefly consist of deep, well-drained to excessively drained sands or gravels. They have a high infiltration rate even when thoroughly wetted and a high rate of water transmission (greater than 0.30 in/hr).

B. Soils that chiefly consist of moderately deep to deep, moderately well-drained to well-drained soils that have moderately fine to moderately coarse textures. They have a moderate infiltration rate when thoroughly wetted and a moderate rate of water transmission (0.15 to 0.30 in/hr).

C. Soils that chiefly have a layer that impedes downward movement of water or have moderately fine to fine texture. They have a slow infiltration rate when thoroughly wetted and a slow rate of water transmission (0.05 to 0.15 in/hr).

D. Soils with high runoff potential. They chiefly consist of clay soils that have a high swelling potential, soils that have a permanently high water table, soils that have a claypan or clay layer at or near the surface, and shallow soils over nearly impervious material. They have a very slow infiltration rate when thoroughly wetted and a very slow rate of water transmission (0.0 to 0.05 in/hr).

Till and lacustrine silt and clay are the parent materials of 75 percent of the soils in the Onondaga Lake basin (fig. 3) and generally produce soils with low permeability and high runoff potential. Classification of the soils by HSG, however, indicates that 58 percent of the soils are HSG-B soils and 18 percent are HSG-C soils. Therefore, most of Onondaga Lake basin soils are expected to have moderate to slow infiltration rates when thoroughly wetted and moderate to slow rates of water transmission within the soil profile. The soils for forest and pasture-hay land types, which together account for almost 64 percent of the Onondaga Lake basin land types, were grouped into two categories: HSG types A and B soils were combined and treated as soils with low runoff potential, and HSG types C and D soils were combined and treated as soils with high runoff potential. The soils for the other land types—row crops, farmsteads, wetland, and developed land uses—which individually did not exceed 9 percent of the basin area, were not similarly subdivided on the basis of HSGs.

Aspect

The aspect of the hill slopes was considered an important hydrologic characteristic because of its effect on the timing and magnitude of snowmelt. North-facing slopes would receive less solar radiation than south-facing slopes during the winter with the result that snow on north-facing slopes would melt more slowly than snow on south-facing slopes. As with the HSG data, forest and pasture-hay land types were divided into south- and north-facing areas. This distinction permitted adjustment of key snow-related parameters in the model (SHADE, TSNOW) so that snowmelt processes could be more accurately simulated.

Impervious Land Segments

The impervious areas of the basin were divided into categories similar to those used for the developed pervious HRUs, that is, by low- and high-intensity residential, and commercial-industrial-transportation land uses. The percentages of effective impervious area, that is, the impervious area that is directly connected to the surface drainage system and does not drain to adjacent pervious areas, were estimated during the calibration of summer peak flows in developed areas. Runoff from impervious areas produces a spike in streamflow that precedes a second peak generated by runoff from the rest of the basin. The parameter values that affect runoff for impervious areas were adjusted to match the timing and magnitude of the initial spikes. Once the percentages of effective impervious area for the three developed land types were determined, the complements of the effective-impervious values were used as the percentages of the pervious areas for these land types (table 10).

Table 10. Estimated percentages of effective-impervious and pervious areas for the developed land-use categories in the precipitation-runoff model of the Onondaga Lake basin, Onondaga County, N.Y.

[Values are in percent]

Developed land-use category	Estimated effective impervious area	Estimated pervious area
Low-intensity residential	5	95
High-intensity residential	40	60
Commercial, industrial, and transportation	66	34

The actual acreages of the developed pervious and impervious areas of each subbasin could have been manually computed and input in the SCHEMATIC block of the model. To facilitate any possible changes to these percentages that might be deemed necessary during the calibration process, however, this step was not performed. Rather the total developed acreage that applied to a given land type was input to the SCHEMATIC block for both the PERLND and IMPLND associated with that land type. Then in the appropriate MASS-LINK blocks, the percentages listed in table 10 were incorporated into the multiplication factors, and the correct acreages for each land type were computed during each model run. For example, if 100 acres had been classified as low-intensity residential in a given subbasin, then 100 acres was assigned to both the pervious and impervious portions of this land type in the SCHEMATIC block. Then, in the MASS-LINK block, the appropriate multiplication factors—0.05 for the IMPLND and its complement, 0.95, for the PERLND—were used to compute the correct acreages, 5 and 95 acres, respectively, for each land type.

Impervious areas within the CSO areas of the basin were not computed from the basinwide percentages listed in table 10; rather they were estimated from documentation for a hydraulic model of the Syracuse area (D.P. Davis, Brown and Caldwell Consultants, written commun., 2003). A weighted percentage of impervious area was computed from the percent imperviousness and the drainage area of the CSOs that were found in each simulated subbasin. This percentage was applied to the total areas of each of the three developed land-use types—low-intensity residential, high-intensity residential, and commercial-industrial-transportation, and the result was entered into the model as the effective impervious area. The difference between total and impervious areas was assigned to the pervious portion of that land use. Therefore, the impervious area estimated for the CSO areas was assumed to be a more precise estimate than would have resulted if the basinwide percentages—5, 40, and 66 (table 10)—had been used.

Summary of Hydrologic Response Units

The NLCD land-use and land-cover categories were grouped into nine PERLND HRUs as follows:

1. **Forest**—About 40 percent of the basin is covered with deciduous, evergreen, and mixed forests and orchards. Of this, evergreen trees were estimated to cover only 17 percent of the forested areas.

2. **Pasture-hay**—Twenty-four percent of the basin is classified as pasture or hay fields, which include nonforested rural areas and abandoned agricultural fields.

3. **Row crops**—Almost 6 percent of the basin is estimated to be in active agricultural use. After hay crops, which are included in the previous NLCD category, corn and alfalfa are the major row crops grown in the basin; small grains and soybeans also are grown (Brian Hall, Onondaga County Soil and Water Conservation District, written commun., 2007).

4. **Farmstead**—This is not a category that is classified by NLCD. It refers to livestock and dairy farms, most of which are small family-run operations found in the southern part of the Onondaga Lake basin. The Onondaga County Soil and Water Conservation District identified 20 farmsteads in the Onondaga Creek basin and 31 in the Ninemile Creek basin, of which 17 are located in the Otisco Lake basin (Jeffrey Carmichael and Brian Hall, Onondaga County Soil and Water Conservation District, written commun., 2004 and 2006). An arbitrary average size of 3 acres was estimated for a farmstead. For a given subbasin, this acreage times the number of farmsteads was input to the model, and the acreage originally assigned to pasture-hay land use was decreased by an equal amount.

5. **Urban or recreational grass**—Three percent of the basin is covered with golf courses, public parks, and large expanses of residential lawns.

6. **Wetlands and water bodies (lakes and ponds)**—Wetlands and water bodies cover 9.2 percent of the basin; Onondaga and Otisco Lakes account for almost 3 percent of this total. Wetlands include riverine, lacustrine, palustrine, open-water, emergent, scrub-shrub, and forested wetlands as classified by the National Wetland Inventory (U.S. Fish and Wildlife Service, 2000), and regulatory freshwater wetlands as classified by New York State Department of Environmental Conservation (1999).

7. **Low-intensity residential**—This land use covers 8.7 percent of the basin and includes single family housing where constructed materials (primarily buildings

and pavement) account for 30 to 80 percent of the total area.

8. **High-intensity residential**—This land use covers 4.8 percent of the basin and includes heavily built-up urban centers in which people reside; vegetation covers less than 20 percent of the total area, and constructed materials cover 80 to 100 percent of the area.

9. **Commercial**—This land use covers 4.5 percent of the basin and includes industrial and transportation uses, and is defined as all highly developed lands not classified as high-intensity residential.

Forest and pasture-hay land types were further divided on the basis of low- and high-runoff-potential soils, as well as south- and north-facing slopes. Also, a unique PERLND, a subset of row crops, was created in order to simulate the large sediment loads derived from lacustrine silt-and-clay soils that are planted in row crops. This erosional process was documented in the Spafford Creek basin by Paschal and Sherwood (1987) and was assumed to exist in the Onondaga Lake basin wherever similar characteristics were found. Finally, the impervious areas of the basin were divided into similar categories, as were the developed pervious HRUs, that is, by low- and high-intensity residential, and commercial-industrial-transportation land uses. This segmentation of the basin produced a set of 19 HRUs: 16 PERLNDs (2 land types—forest and pasture-hay—that were subdivided by 2 HSG classes and 2 aspect classes plus 8 land types that were not further subdivided) and 3 IMPLNDs (table 11).

Distinctions Among Hydrologic-Response-Unit Groups

The above categorization of PERLNDs and IMPLNDs resulted in a set of 19 HRUs (table 11), which was replicated for each of the three areas that were delineated by the Thiessen (1911) lines defined by the precipitation-record sites (fig. 7). The HRUs in the Tully Valley precipitation area include

Table 11. Description of hydrologic-response units used in the precipitation-runoff model of the Onondaga Lake basin, Onondaga County, N.Y.

[Dash indicates that the hydrologic response unit was not divided according to this basin characteristic]

Number	Land use or land cover	Hydrologic soil group runoff potential	Aspect
Undeveloped Pervious Land Segments (PERLNDs)			
1	Forest	Low	South-facing
2	Forest	High	South-facing
3	Forest	Low	North-facing
4	Forest	High	North-facing
5	Pasture-hay	Low	South-facing
6	Pasture-hay	High	South-facing
7	Pasture-hay	Low	North-facing
8	Pasture-hay	High	North-facing
9	Row crops	–	–
10	Farmstead (livestock and dairy)	–	–
11	Urban or recreational grass	–	–
12	Wetland-water	–	–
16	Row crops in lacustrine silt-and-clay soils	–	–
Developed Pervious Land Segments (PERLNDs)			
13	Low-intensity residential	–	–
14	High-intensity residential	–	–
15	Commercial, industrial, and transportation	–	–
Impervious Land Segments (IMPLNDs)			
1	Low-intensity residential	–	–
2	High-intensity residential	–	–
3	Commercial, industrial, and transportation	–	–

PERLNDs 1–16 and IMPLNDS 1–3; those in the Hancock Airport precipitation area include PERLNDs 101–116 and IMPLNDS 101–103; and those in the Otisco Lake precipitation area include PERLNDs 301–316 and IMPLNDS 201–203. The CSO impervious areas, as described in the section "Impervious Land Segments," are located within the boundaries of the Hancock Airport precipitation area but were uniquely simulated and assigned IMPLND numbers 111–113. Two other areas of the Onondaga Lake basin—the Harbor Brook basin and the Otisco Lake basin—were deemed to have distinct hydrologic characteristics that could not be calibrated with the same parameter values that were used elsewhere in their respective precipitation areas and thus required separate sets of HRUs.

The Harbor Brook basin exhibited hydrologic characteristics that presumably were present elsewhere in the Onondaga Lake basin, but because of the small size of the Harbor Brook basin, 12.1 mi^2, these characteristics had a greater effect on the subbasin's hydrology than similar characteristics in a large subbasin. This effect of scale was most evident with the simulation of base flows. The headwaters of Harbor Brook cut through the Onondaga Escarpment from which large quantities of ground water can be discharged. A hydrograph-separation analysis performed by HYSEP (Sloto and Crouse, 1996) indicated that 76 percent of the total flow in Harbor Brook at Holden Street (04240100), with a drainage area of 10.0 mi^2, was base flow. The next smallest measured subbasin was Ley Creek with a drainage area of almost 30 mi^2 but a base-flow component of only 56 percent; Ley Creek does not cut across the Onondaga Escarpment, however. The streamflow-monitoring site downstream from the Onondaga Escarpment in the Onondaga Creek basin is Onondaga Creek at Spencer Street (04240010), which has a drainage area of 110 mi^2 and a base-flow component of about 70 percent. The flows in Harbor Brook could not be calibrated with the same parameter values that were used for Onondaga, Ley, or Ninemile Creeks; therefore, a unique set of PERLNDs, numbered 121–135, was created for this basin.

Difficulties that arose during the calibration of Otisco Lake inflows and storage volumes necessitated the creation of a unique set of PERLNDs for this basin. Otisco Lake tributaries exhibited a quicker runoff response than was found downstream from the lake. This response was documented during a 1982–83 USGS study (Paschal and Sherwood, 1987), and parameter values in the model were adjusted to mimic the pattern of seasonal flows that was identified at that time. HSPF parameter values that controlled infiltration, ground-water storage, and ground-water and interflow rates were decreased for the Otisco Lake PERLNDs, 201-216, compared to those values assigned to the PERLNDs (numbered 301-316) in the middle Ninemile Creek subbasin (fig. 2).

Stream Reaches

Basin hydrography was obtained from digital line graphs (DLGs) of the stream network; this GIS coverage was a reproduction of the "blue-line" hydrography shown on USGS topographic maps of the basin (on file in the Troy, N.Y., office of the USGS). Stream reaches (RCHRESs) were delineated as part of the basin-segmentation process, and their lengths and changes in elevation from upstream to downstream ends were calculated. RCHRES lengths were either extracted from the hydraulic data used for Federal Emergency Management Agency (FEMA) flood-insurance studies (Federal Emergency Management Agency, 1978, 1980, 1981a, 1981b, 1981c, 1981d, 1982a, 1982b, 1983, 1984, 1986) or measured with an ArcView (Environmental Systems Research Institute, 1992) graphic tool. The change in channel elevation was computed from FEMA flood-insurance cross-sectional data, digital elevation models (DEMs), or contour elevations on USGS topographic maps.

Each RCHRES required a function table (Ftable) that defines the relations among channel-storage volume and water depth, stream-surface area, and discharge. The depth-to-discharge relation was usually defined by the hydraulic properties at the downstream end of the reach, whereas the relation among surface area, volume, and discharge was a function of the hydraulic properties of the entire reach. Surface area and storage were calculated from cross-sectional data that were either collected for FEMA flood-insurance studies (FIS) or extracted from DEMs and modified by field measurements of channel top widths and depths. Relations among stage and top width, cross-sectional area, and discharge were calculated by the Channel Geometry Analysis Program (CGAP; Regan and Schaffranek, 1985). Energy gradients, which were required for the calculation of discharge, were estimated from water-surface slopes of 100-year flows given in the FIS or from channel slopes measured from topographic maps or computed from the DEM data. Roughness coefficients were taken from FIS or estimated during site visits. CGAP discharges were calibrated to the high flows given in the FIS and to stage-to-discharge relations developed at USGS streamflow-monitoring stations. Calibration entailed adjusting the energy gradients, roughness coefficients, or both, which were assumed to change with flow depth and with the number of flow-constricting bridges and culverts in the reach. Ftables that could be input directly to the model were generated by GENFTBL (R.S. Regan, U.S. Geological Survey, written commun., 1992), a utility program of CGAP that uses the top widths and cross-sectional areas computed by CGAP to compute water-surface area and channel-storage volume for each RCHRES.

Generally the number of RCHRESs and subbasins in a model are equal. In the present model, however, there is one less RCHRES (a total of 106), because the Onondaga Creek and West Branch Onondaga Creek branches of the Onondaga Reservoir were combined into one RCHRES. Elevation-storage data for the Onondaga Reservoir were furnished by the USACE from a capacity table dated 1953, which had been published in USGS annual data reports (for example, Hornlein and others, 1999). The elevation-discharge data were furnished by the USACE using a formula and graph dated 1945 (U.S. Army Corps of Engineers, 1947). These data permitted development of an Ftable for the entire impoundment area of the reservoir, including the subbasin along Onondaga Creek directly upstream from the Onondaga Dam (subbasin 121; fig. 7) and the most downstream subbasin of West Branch Onondaga Creek (subbasin 120). Runoff from both of these subbasins was routed to a single RCHRES, number 121.

RCHRES 409 and 503 are the simulated reaches for Otisco and Onondaga Lakes, respectively. Depth-volume relations were computed from bathymetry maps and were included in each RCHRES' Ftable, but because the outflow from these lakes is affected by regulation and withdrawals, no attempt was made to directly simulate discharges on the basis of volume. Instead time series of outflows were created from available data. In the case of Otisco Lake, daily records of flows over the dam and through the gates, and withdrawals by OCWA, were used to simulate removal of water from the lake. For Onondaga Lake, adjusted daily inflows from the gaged tributaries were used as estimates of outflows from the lake. Although imprecise, this estimate of outflows permitted simulation of lake volumes that were reasonably close to computed volumes.

Simulation Complexities

Unique hydrologic features of the Onondaga Lake basin required special coding of the model. These features include ground-water discharges from springs, channel losses to bedrock fractures, a tunnel through which Harbor Brook flows, storm runoff in the combined storm-and-sanitary-sewer areas of Syracuse, and adjustment of the Otisco Lake outflows that were furnished by the OCWA. The incorporation of these features resulted in a more complex model than otherwise might have been required.

Springs in Onondaga Creek Valley

Springs are present and substantial ground-water discharges have been documented where carbonate bedrock crops out along the valley walls in both the Onondaga and Ninemile Creek valleys (fig. 3). In the Onondaga Creek valley, discharges from some of the many springs in the area have been measured and show a seasonal pattern; spring-time flows can be as much as seven times greater than fall flows (unpublished data on file in the Ithaca, N.Y., office of the USGS). The combined measured flow of only three springs found north of Syracuse's southern municipal boundary was as great as 3.72 ft^3/s during May 2002; a comparable combined flow from three springs south of the city was measured during May 2004. The flows from these six springs represented only a fraction of the total potential flow from all springs in the area. An estimated time series of spring inflows, which reflects the seasonal pattern documented by discharge measurements, was input to the model to correct a discrepancy between flows simulated in Onondaga Creek at Dorwin Avenue (04239000) and at Spencer Street (o4240010); an area of the basin where spring flows are conveyed directly to Onondaga Creek through stormwater culvert systems. In areas where culverts are absent, upstream from Dorwin Avenue, the parameter values that control ground-water storage and discharge in the model simulated flows reasonably well without the need for inflow additions.

Harbor Brook

Similar to Onondaga Creek, Harbor Brook is the recipient of discharges from springs along the Onondaga Escarpment. A time series of estimated spring flows was input to the model in the EXTERNAL SOURCES module.

Low-flow discharge measurements and comparison of low-flow records from Harbor Brook at Holden Street (04240100) with those at Hiawatha Boulevard (04240105) (2.1 mi downstream) indicated that some losses in flow, ranging from 0.2 to 1 ft^3/s, occurred before the stream entered a tunnel about 1 mi downstream from Holden Street (unpublished data on file in the Ithaca, N.Y., office of the USGS). Model parameter values simulated these losses adequately without the need for additional manipulation of the model.

The tunnel, which is part of RCHRES 206 (fig. 7), prevents meteorological inputs—precipitation, solar radiation, and wind—from reaching or affecting about 50 percent of this RCHRES. To decrease these inputs to levels that were deemed appropriate for this RCHRES, the multiplication factors associated with each of these meteorological time series in the EXTERNAL SOURCES module of the model was set to 0.50.

Disappearing Lake and Springs in Ninemile Creek Valley

Disappearing Lake (fig. 2) is a seasonal lake in the Ninemile Creek basin where runoff from subbasin 422 (fig. 7) is retained in a channel depression that has no surface outlet but drains through fractures in the underlying limestone bedrock. Presumably this water resurfaces from springs below Marcellus Falls (about 2 mi downstream; fig. 2) and enters Ninemile Creek at that point. Proett (1978) studied Disappearing Lake and developed a relation between the lake's stage and subsurface discharge, which was computed on the basis of the change in the lake's volume after taking into account precipitation, surface and estimated ground-water inflows, and evaporation losses. This stage-discharge relation was used to create an Ftable for RCHRES 422; the discharge was targeted to the Marcellus Falls reach, RCHRES 424.

In the Ninemile Creek valley, large ground-water inflows to the creek have been noted north of the village of

Marcellus, near Marcellus Falls, where the creek cuts through the Onondaga Escarpment. These spring inflows, much of which presumably originates from Disappearing Lake, as discussed above, have not been measured. This ground-water discharge has a substantial effect on Ninemile Creek's water temperatures; summer temperatures decrease from the mid-70s above the falls to the 50- to 60-degree range below the falls. The creek, which is transformed from a warm-water stream to a high-quality trout stream (Kelly, 1998), remains cold as far north as the Amboy area—about 6.5 mi downstream—where the temperature influence of the springs is diminished. Discharges from springs, in addition to those simulated as coming from Disappearing Lake, were estimated at a constant rate and were input to the model in the EXTERNAL SOURCES module.

Storm Runoff in Combined-Sewer-Overflow Areas of Syracuse

Storm runoff, in the areas of Syracuse that have a combined storm-and-sanitary-sewer system, required special treatment in the model. Storm runoff is captured by the sewer system and routed to the METRO WWTP for treatment prior to being discharged directly into Onondaga Lake. METRO provides full treatment to flows up to 126 Mgal/d; flows ranging from 126 to 240 Mgal/d receive primary treatment and disinfection, and bypass the plant through a second outfall (EcoLogic, LLC, 2006). When flow rates exceed 240 Mgal/d, water that has backed up in the sewer system is discharged to nearby streams through CSOs. Output from a computer model of the city's sewer system has indicated that the METRO plant can handle storm runoff that is generally delivered at a rate of about 0.10 to 0.15 in/hr (D.P. Davis, Brown and Caldwell Consultants, written commun., 2005). Any runoff in excess of this flow rate will be discharged to nearby streams through the CSOs. On the basis of this information, the surface runoff from the impervious CSO areas of Syracuse were simulated by a series of GENER commands such that 0.10 in/hr of runoff was removed from the overland-flow volume, and the remainder of the runoff was routed to each subbasin's respective RCHRES.

Discrepancy in Otisco Lake Gate Flows

Otisco Lake obscures the hydrologic response between inflow from its tributaries and outflow to Ninemile Creek. An outflow time series was generated for Otisco Lake from data provided by Onondaga County Water Authority (M.J. Murphy, Onondaga County Water Authority, written commun., 2004); these data include computed flows through the gates and over the dam at the northern end of Otisco Lake. Use of this computed record for the Otisco Lake outflow made simulation easier, reduced any error that might have resulted from an alternative method of simulating outflows, and permitted more precise calibration of Otisco Lake storage volumes than would have been possible otherwise.

Reported gate releases from Otisco Lake during low-flow periods were erroneously high when compared with observed flows at the USGS streamflow-monitoring station on Ninemile Creek near Marietta (04240180), 1.8 mi downstream. The discrepancy, which was noted on flow-duration plots at the point where Marietta flows dropped below 13 ft^3/s, was greatest when Marietta flows fell to 1 to 2 ft^3/s, but Otisco Lake gate releases were computed at 7.4 ft^3/s (or 4.3 Mgal/d for a gate opening of 1 in.). There was no plausible reason for a decrease in low flows in the intervening area between the lake and the streamflow-monitoring station. A regression equation was developed to correct the gate releases during these periods:

$$Q_{adj} = 0.582 * MarQ - 7.5656 , \qquad (3)$$

where

Q_{adj} is the adjustment to the Otisco Lake gate releases,

and

$MarQ$ is the observed daily flow at Ninemile Creek near Marietta, both in cubic feet per second.

This adjustment was input to the model as a time series of negative or zero values during those periods when Marietta flows were less than or greater than 13 ft^3/s, respectively. During periods when Marietta flows exceeded 13 ft^3/s, lake discharges (or the combined through-gate and over-the-dam flows) were used as furnished by OCWA.

Channel Losses to Bedrock Fractures

Channel losses to bedrock fractures were reported for the headwater subbasins along the valley sides of the upper Onondaga Creek valley (W.M. Kappel, U.S. Geological Survey, oral commun., 2006). These fractures presumably were a result of subsidence that resulted from brine mining operations in the area. The streamflow losses were small enough that they were undetected in the observed streamflow record for the most upstream calibration point along Onondaga Creek at State Highway 20 near Cardiff (04237962); therefore, these losses were not simulated in the model.

Model Calibration and Performance

The Onondaga Lake basin precipitation-runoff model was calibrated in a step-wise manner. First, the hydrologic component of the model was calibrated to streamflow data recorded at the nine streamflow-monitoring stations. After reasonable fits between observed and simulated flow data were obtained, the model was calibrated, in turn, to available sediment, water-temperature, and nutrient data.

Calibration of the model was based on the assumptions that (1) no other local factors would exert an influence great enough to interfere with the presumed homogenous responses of the HRUs; (2) precipitation quantities and timing were reasonably represented by the three precipitation records used in the model; (3) all other meteorological factors—air and dewpoint temperatures, solar radiation, potential evapotranspiration, wind speed, and cloud cover—were identical to those measured or computed from data recorded at the NWS station at Hancock Airport just outside the northeastern boundary of the basin; and (4) conditions in the basin, including land uses, drainage patterns, imperviousness, and sediment and nutrient loading rates, would remain fairly constant during the calibration period. In reality, none of these assumptions were valid, and uncertainty in the simulated results was expected.

As described in the section, “Hydrologic Response Units (HRUs),” and based on the assumption that each HRU would exhibit homogeneous hydrologic and water-quality responses to precipitation and other meteorological factors, the same parameter values were initially assigned to each HRU category, regardless of its location in the basin. For example, each south-facing forested HRU with low-runoff potential was assigned the same parameter values regardless of its PERLND number or the subbasin in which it is located. Strict adherence to this plan limited the precision of calibration that could be achieved at any given streamflow-monitoring site in the basin, and meant that minimization of the differences between observed and simulated values at any one calibration point would be sacrificed for parameter-value consistency. Researchers have noted that values for some key parameters can vary from one basin to another, even in the same geographical area (Donigian and others, 1983; Laroche and others, 1996; Carrubba, 2000) and that these variations can simply be a matter of difference in scale, that is, the size of a particular basin in relation to its calibration point. Therefore, in spite of the initial plan to maintain parameter-value consistency throughout the basin, experience and necessity required that some initial parameter values be adjusted to improve the fit between observed and simulated data. In most cases, plausible explanations for the noted discrepancies in the data were identifiable, and adjustments were deemed reasonable and appropriate. Unavoidably, some of these discrepancies could not be explained, and parameter-value adjustments likely resulted, not only from real differences in the hydrology or water chemistry of a particular subbasin, but also from errors in the input or calibration data.

The objective of simulating basin hydrology and water-quality processes using a precipitation-runoff model is to select parameter values that reliably and accurately reproduce the physical processes that the model is intended to mimic. It is widely accepted that a computer model can be calibrated, or appear to be calibrated, by any number of different sets of parameter values (Doherty and Johnston, 2003). This nonuniqueness of parameter-value sets, which results from manual, subjective calibration of a model, introduces uncertainty in the model results but can be controlled by use of an automated parameter-estimation program that offers a reproducible, objective method of selecting parameter values that will calibrate a model. Such a program is PEST (Doherty, 2002 and 2003), which can select the combination of parameter values that minimizes the differences between field observations and model outputs, as well as evaluate model predictive uncertainty. PEST was used to estimate initial values for some of the primary or most sensitive parameters in the hydrologic component of the Onondaga Lake basin model (table 12). These parameters—AGWRC, DEEPFR, INFILT, INTFW, IRC, KVARY, LZETP, LZSN, and UZSN—can have a large effect on model results. Although PEST was used extensively during the initial calibration attempts, it failed to produce acceptable results when multiple-site calibrations were programmed, and many of the PEST-estimated values were revised during subsequent manual calibration steps.

The issue of parameter-value nonuniqueness became less important owing to simultaneous calibration of several datasets. Whereas calibration to a single dataset could yield a wide range of results in calibrated parameter-value sets, the introduction of a second or a third calibration dataset narrowed the range of parameter values that would generate the best fit between observed and simulated data at all sites. In the case of the Onondaga Lake basin model, calibration included two to three datasets for a given major subbasin and seven to nine datasets overall. Although no claim is made that the final parameter-value set is unique, the departure from the best parameter-value set has been decreased by the method of multiple-site calibration.

Model performance during the calibration period was assessed on the basis of the weight-of-evidence approach (Donigian, 2002), which incorporates qualitative and quantitative measures of evaluation and includes graphical comparisons and statistical tests. Graphical comparisons included time-series plots of observed and simulated values. Daily and monthly mean flows and water temperatures, monthly total sediment and nutrient loads, residual plots (simulated minus computed values over time) of water-quality data, and periodically measured concentrations of water-quality constituents were evaluated. Statistical tests included error statistics (percentages of mean error and mean absolute error) and correlation tests (linear-correlation coefficient and coefficient of model-fit efficiency).

Mean error (ME), or bias, indicates whether the model is overestimating or underestimating a given constituent. ME is the average of the differences between simulated and observed values, accounts for the positive or negative sign of the difference, and equals

$$\sum (S - O) / N \quad , \tag{4}$$

where

S = simulated value,

O = observed value,

and

N = number of values in the sample.

Table 12. Primary and sensitive parameters used in the hydrologic and snowmelt components of Hydrological Simulation Program–FORTRAN (HSPF).

Parameter	Definition
	Hydrologic processes
AGWRC	Active ground-water recession coefficient, controls the rate at which ground water discharges to streams.
DEEPFR	Fraction of ground water lost to deep aquifers.
INFILT	Index of soil-infiltration capacity.
INTFW	Interflow parameter, controls the amount of infiltrated water that becomes shallow subsurface flow.
IRC	Interflow-recession coefficient, an index for the rate of shallow subsurface flow.
KVARY	Active-ground-water outflow modifier, represents the variable influence that ground-water inflow has on ground-water outflow.
LZETP	Lower-zone evapotranspiration parameter, represents the density of deep-rooted vegetation that conveys water from the unsaturated zone upward to the atmosphere.
LZSN	Lower-zone nominal storage, an index to the soil-moisture holding capacity of the unsaturated zone.
UZSN	Upper-zone nominal storage, an index to the amount of storage capacity in depressions and the surface-soil layer.
	Snowmelt processes
CCFACT	Factor to adjust heat transfer from atmosphere to snowpack.
SHADE	Fraction of land segment shaded from solar radiation.
SNOWCF	Correction factor for poor snow-catch efficiency

The percentage of mean error (ME%) is the average of the differences between simulated and observed values expressed as a percentage of the observed value, and equals

$$100 \times 1/N \sum (S - O)/O \ . \tag{5}$$

For HSPF simulations, the agreement between annual and monthly simulated and observed flows can be characterized as “very good” when the mean error is less than 10 percent, “good” when the error is 10 to 15 percent, and “fair” when the error is 15 to 25 percent (table 13; Donigian, 2002). Similar criteria for evaluating the agreement between simulated and observed mean water temperatures and monthly and annual sediment and nutrient loads are given in table 13.

Mean absolute error (MAE) is the average of the absolute values of the differences between simulated and observed values, and equals

$$\sum |S - O| / N \ . \tag{6}$$

The percentage of mean absolute error (MAE%) is the average of the absolute values of the differences between simulated and observed values, expressed as a percentage of the observed values, and equals

$$100 \times 1/N \sum \left(|S - O| / O \right) \ . \tag{7}$$

The correlation coefficient, *R*, (Duncker and Melching, 1998) is a measure of the strength of association between two continuous variables and equals

$$\frac{\sum (x_o - \bar{x}_o) \times (x_s - \bar{x}_s)}{\sqrt{\sum (x_o - \bar{x}_o)^2 \times \sum (x_s - \bar{x}_s)^2}} \ , \tag{8}$$

where

x_o = observed value for given time step,
$\bar{x}_o$ = average observed value for given time step,
x_s = simulated value for given time step,

and

$\bar{x}_s$ = average simulated value for given time step.

Ranges of correlation coefficients and their respective qualifications for agreement between simulated and observed streamflows are presented in table 13. A summary of published HSPF model-performance results (Coon and Johnson, 2005) shows that *R* values for daily mean flows simulated at 23 calibration points in 6 models range from 0.66 to 0.98, and those for monthly mean flows simulated at 23 calibration points in 9 models range from 0.80 to 0.99. The *R* values computed for monthly flows always exceeded those computed for daily flows for a given model. *R* values used to describe the agreement between simulated and observed water-quality data are uncommon in scientific literature.

The coefficient of model-fit efficiency, *E*, (Nash and Sutcliffe, 1970; Duncker and Melching, 1998; Zarriello and Reis, 2000) is defined as

$$\frac{\sum (x_o - \bar{x}_o)^2 - \sum (x_o - x_s)^2}{\sum (x_o - \bar{x}_o)^2} \ , \tag{9}$$

where the variables are defined as in equation 8 above.

Table 13. Selected criteria for evaluating Hydrological Simulation Program—FORTRAN (HSPF) model performance.

[Data from Donigian, 2002. <, less than; >, greater than.]

	Percentage difference between simulated and observed monthly or annual values			
	Very good	**Good**	**Fair**	**Poor**
Streamflow	< 10	10–15	15–25	> 25
Sediment loads	< 20	20–30	30–45	> 45
Water temperature	< 7	8–12	13–18	> 18
Nutrient loads	< 15	15–25	25–35	> 35
	Correlation coefficient (*R*)			
Daily streamflow	0.89–0.95	0.84–0.89	0.77–0.84	< 0.77
Monthly streamflow	.92–.97	.87–.92	.81–.87	< .81

The coefficient of model-fit efficiency is a direct measure of the fraction of the variance of the original data series explained by the model (Duncker and Melching, 1998) and provides a more rigorous evaluation of fit quality than the correlation coefficient. *R* indicates only that the series being compared have similar patterns of exceeding and being less than their respective mean values, whereas *E* takes into account the magnitude of differences between the observed and simulated values. Published *E* values for HSPF models range from 0.42 to 0.98 for daily mean flows simulated at 16 calibration points in 5 models, and from 0.72 to 0.96 for monthly mean flows simulated at 18 calibration points in 7 models (Coon and Johnson, 2005). The *E* values computed for monthly flows either equaled or exceeded those computed for daily flows for a given model. Like correlation coefficients, *E* values used to describe the agreement between simulated and observed water-quality data are uncommon in scientific literature.

Hydrology

The hydrology of the basin was calibrated to records from nine streamflow-monitoring sites and to the storage volume of Otisco Lake. Guidance on initial and typical ranges of parameter values was obtained from a technical note published by the U.S. Environmental Protection Agency (U.S. Environmental Protection Agency, 2000). Daily flow data were used at all calibration sites for the 6-year calibration period (1997–2003), except for Onondaga Creek near Cardiff, whose record extended from October 1, 2001, to September 30, 2003.

Streamflows at Nine Monitoring Sites

The hydrologic components of the model were calibrated in a two-step process. First, snow-related parameter values were estimated. Snowfall quantities from the Otisco Lake area, snow-pack depths recorded by the NWS at the Hancock Airport, and snowmelt hydrographs from eight streamflow-monitoring sites were used in this step. Following acceptable calibration results for the snowmelt periods, values for other parameters that strongly affect hydrologic responses in the various parts of the basin were estimated. Calibration took into account daily flows, base flows, stormflows, monthly and storm volumes, and flow-duration times at the eight streamflow-monitoring sites, as well as monthly average volumes of Otisco Lake. The streamflow record for Ninemile Creek near Marietta, just downstream from Otisco Lake, was used to correct gate releases from Otisco Lake that were furnished by OCWA.

Peak stormflows were subsequently calibrated to hourly observed flows at all sites with hourly records, but the fit between observed and simulated daily flows was considered more important for the purposes of the model than that between observed and simulated hourly flows. As part of this calibration step, the percentage of effective impervious area was adjusted to improve the fit between observed and simulated summer peak flows in developed areas. The final percentages that were applied to each land type—low-intensity and high-intensity residential, and commercial-industrial-transportation—were 5, 40, and 66 percent, respectively (table 10).

Graphical comparisons of observed and simulated daily and monthly flows (figs. 8–12) indicated that simulated flows were neither consistently low nor high in relation to observed flows at the monitoring sites. Graphs of flow-duration curves, or plots of the percentage of time that flows were exceeded, show close agreement between the ranges and durations of daily observed and simulated flows at a given monitoring site during the simulation period.

The correlation coefficients (*R*) for simulated-to-observed flows range from 0.73 to 0.98 for daily flows and 0.86 to 0.99 for monthly flows at the nine streamflow-monitoring sites (table 14). The coefficients of model-fit efficiency (*E*) range from 0.47 to 0.96 for daily flows and 0.69 to 0.99 for monthly flows. The lowest values of *R* and *E* related to daily flows were associated with Onondaga Creek near Cardiff (04237962), which had only 2 years of record for calibration,

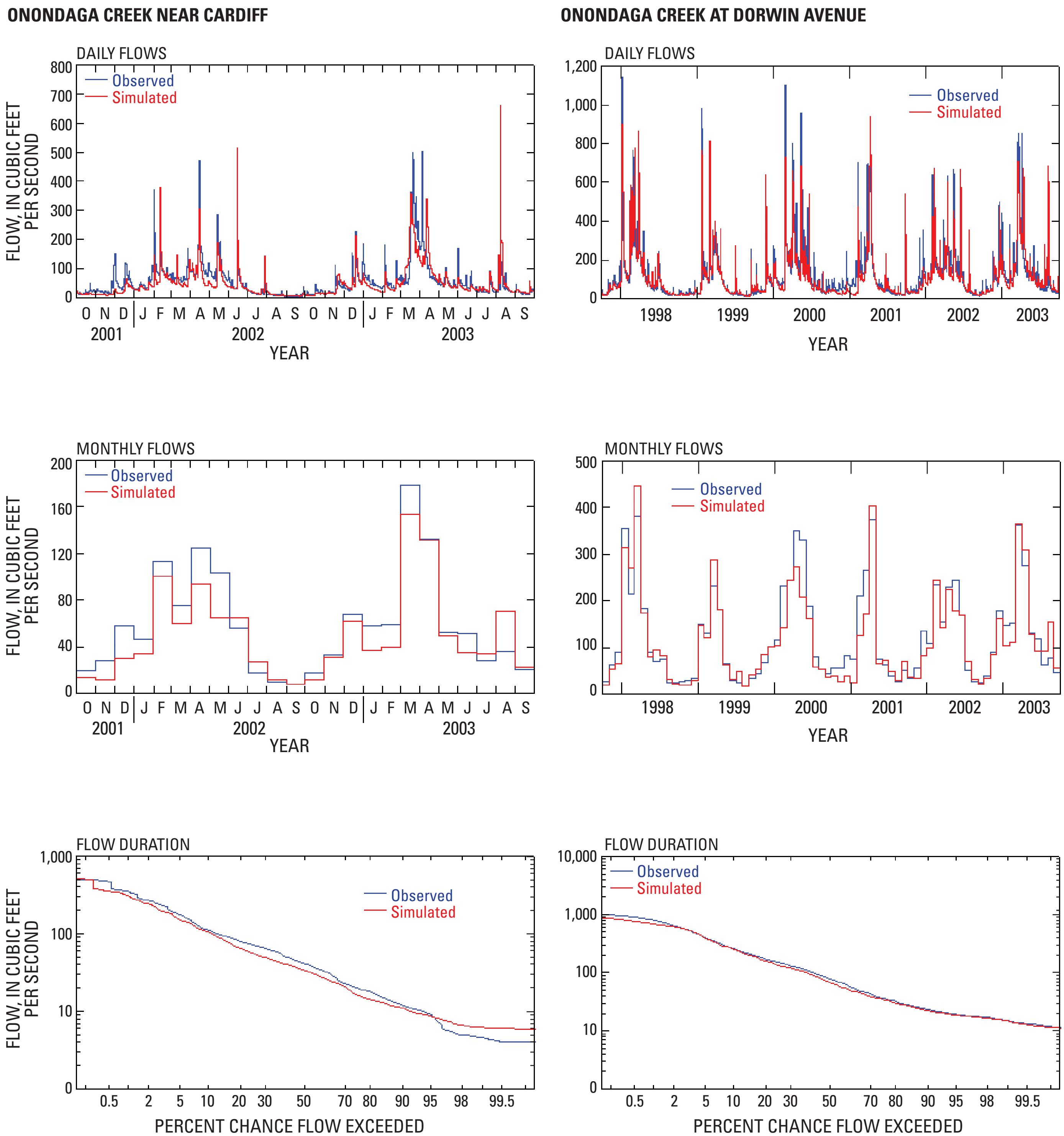

Figure 8. Daily and monthly observed and simulated streamflows, and observed and simulated flow-duration curves, at Onondaga Creek near Cardiff, 2001–03, and Onondaga Creek at Dorwin Avenue, 1997–2003, in the Onondaga Lake basin, Onondaga County, N.Y.,

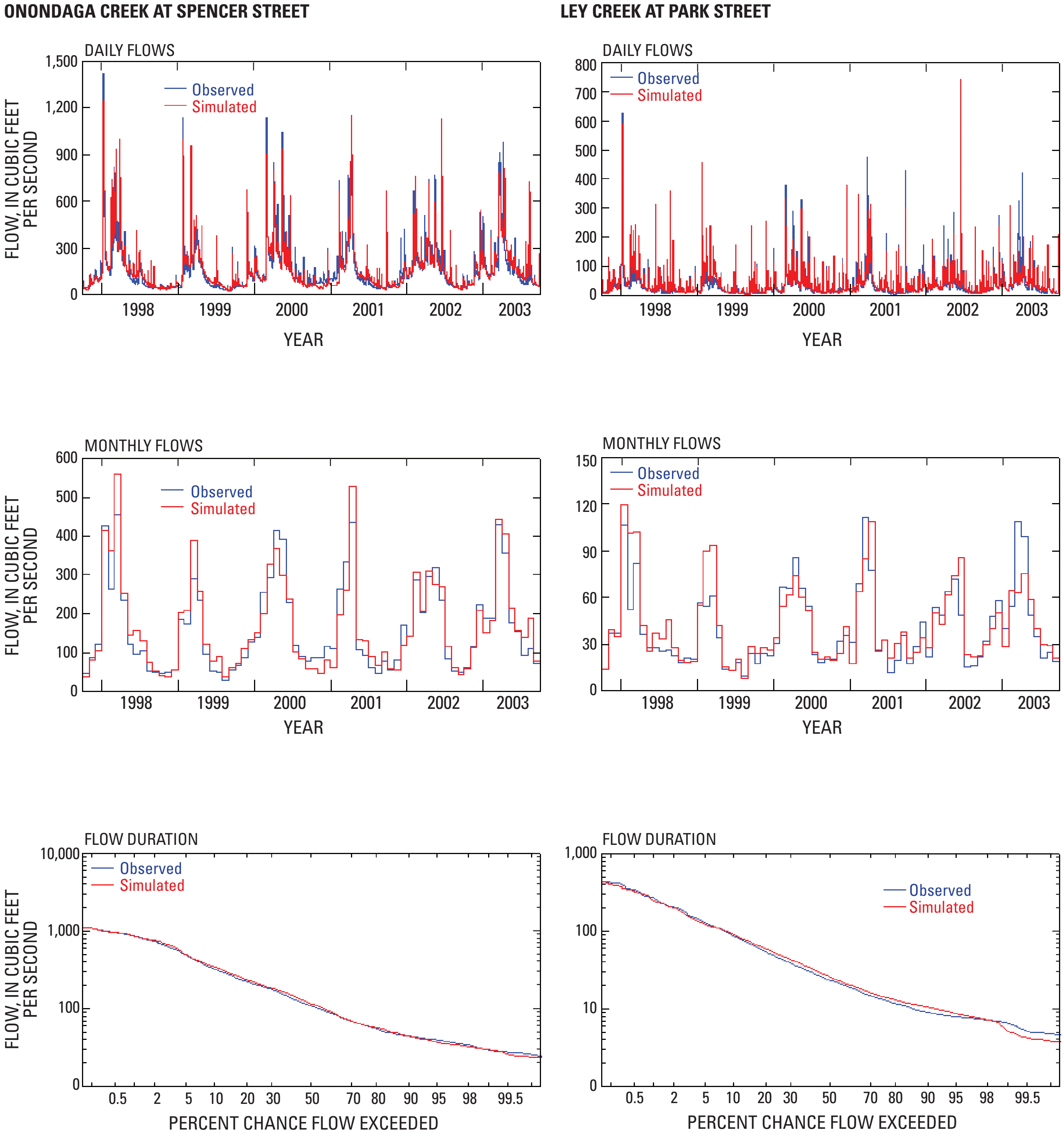

Figure 9. Daily and monthly observed and simulated streamflows, and observed and simulated flow-duration curves, at Onondaga Creek at Spencer Street and Ley Creek at Park Street in the Onondaga Lake basin, Onondaga County, N.Y., 1997–2003.

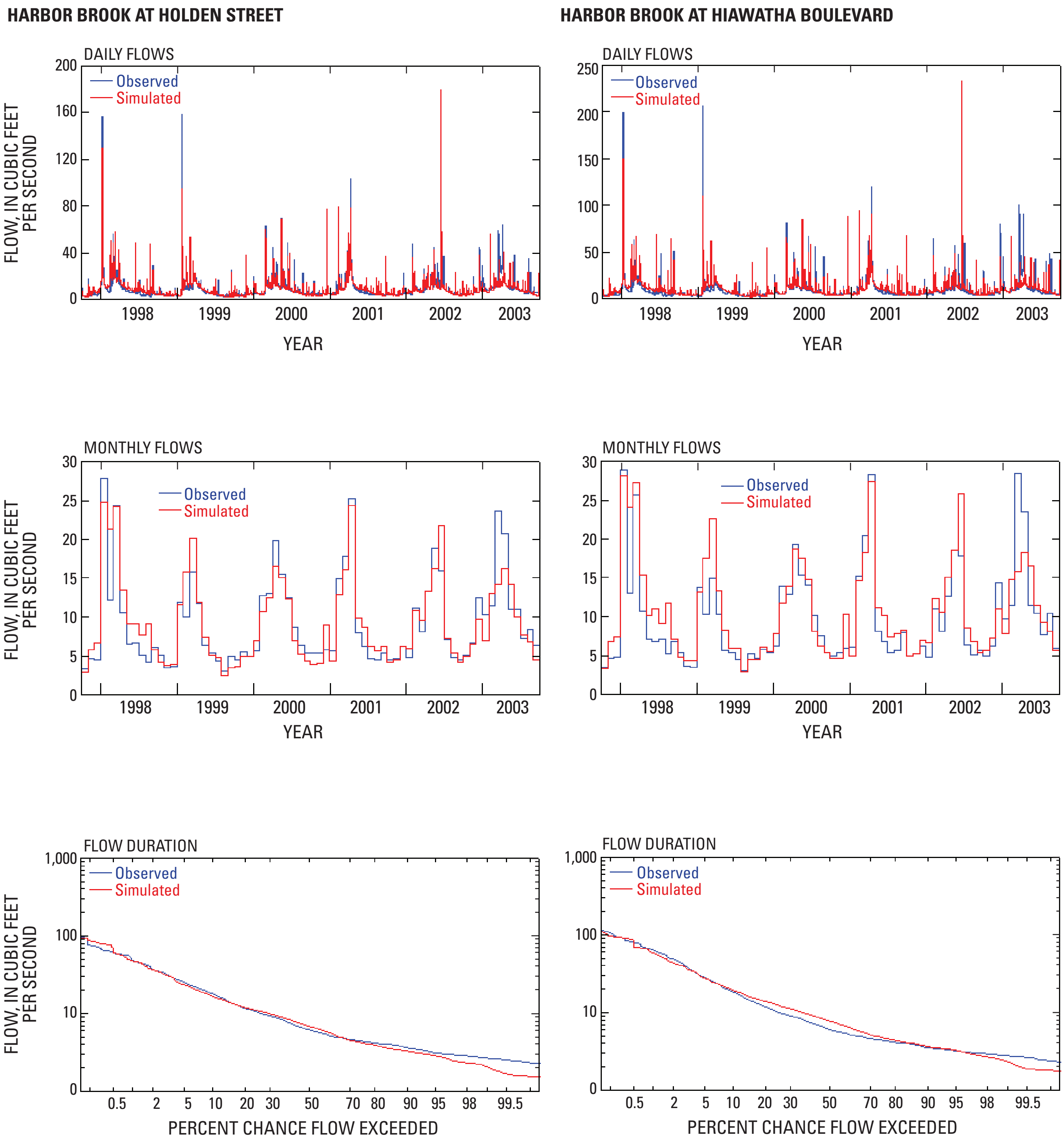

Figure 10. Daily and monthly observed and simulated streamflows, and observed and simulated flow-duration curves, at Harbor Brook at Holden Street and Harbor Brook at Hiawatha Boulevard in the Onondaga Lake basin, Onondaga County, N.Y., 1997–2003.

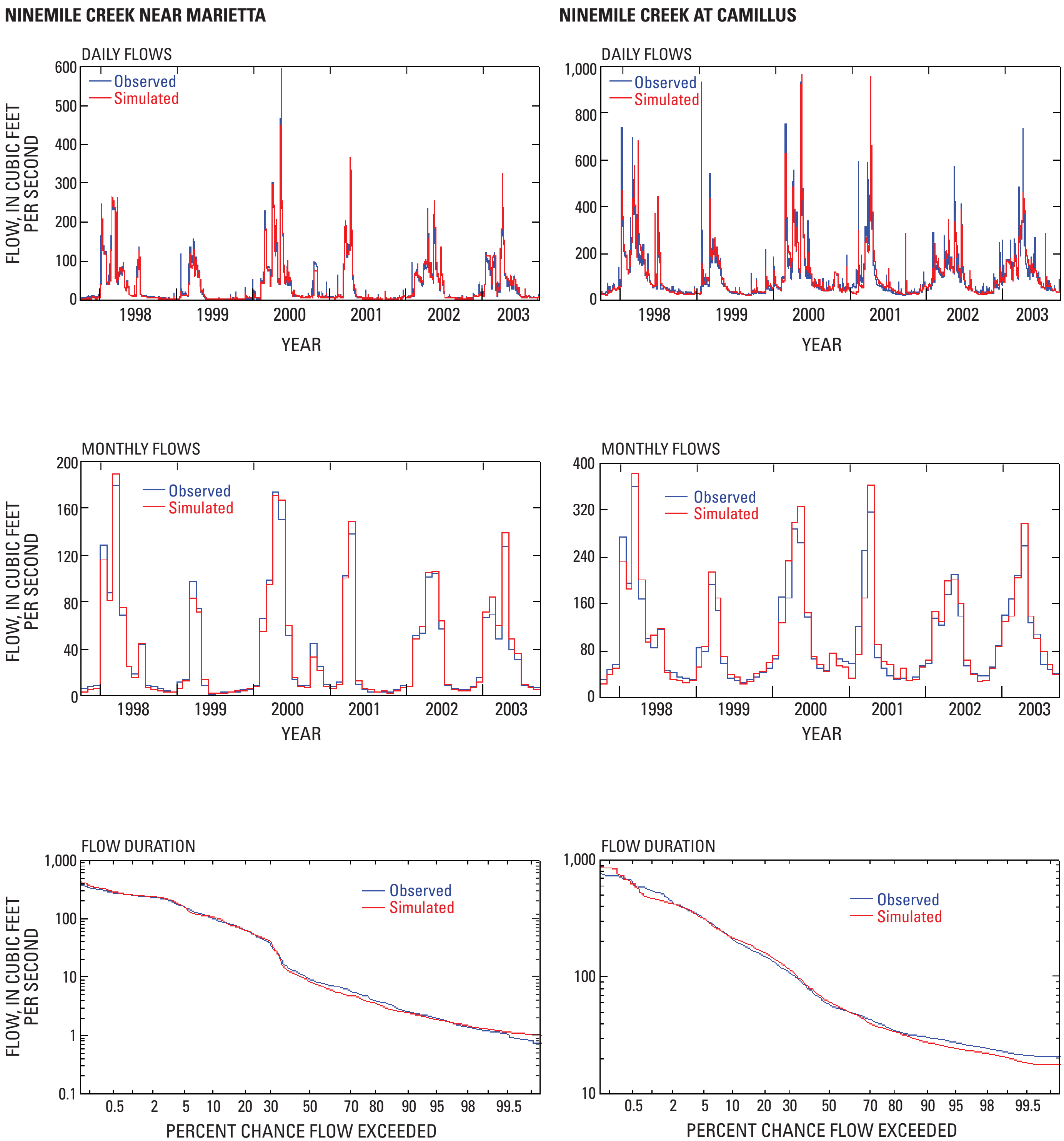

Figure 11. Daily and monthly observed and simulated streamflows, and observed and simulated flow-duration curves, at Ninemile Creek at Marietta and Ninemile Creek at Camillus in the Onondaga Lake basin, Onondaga County, N.Y., 1997–2003.

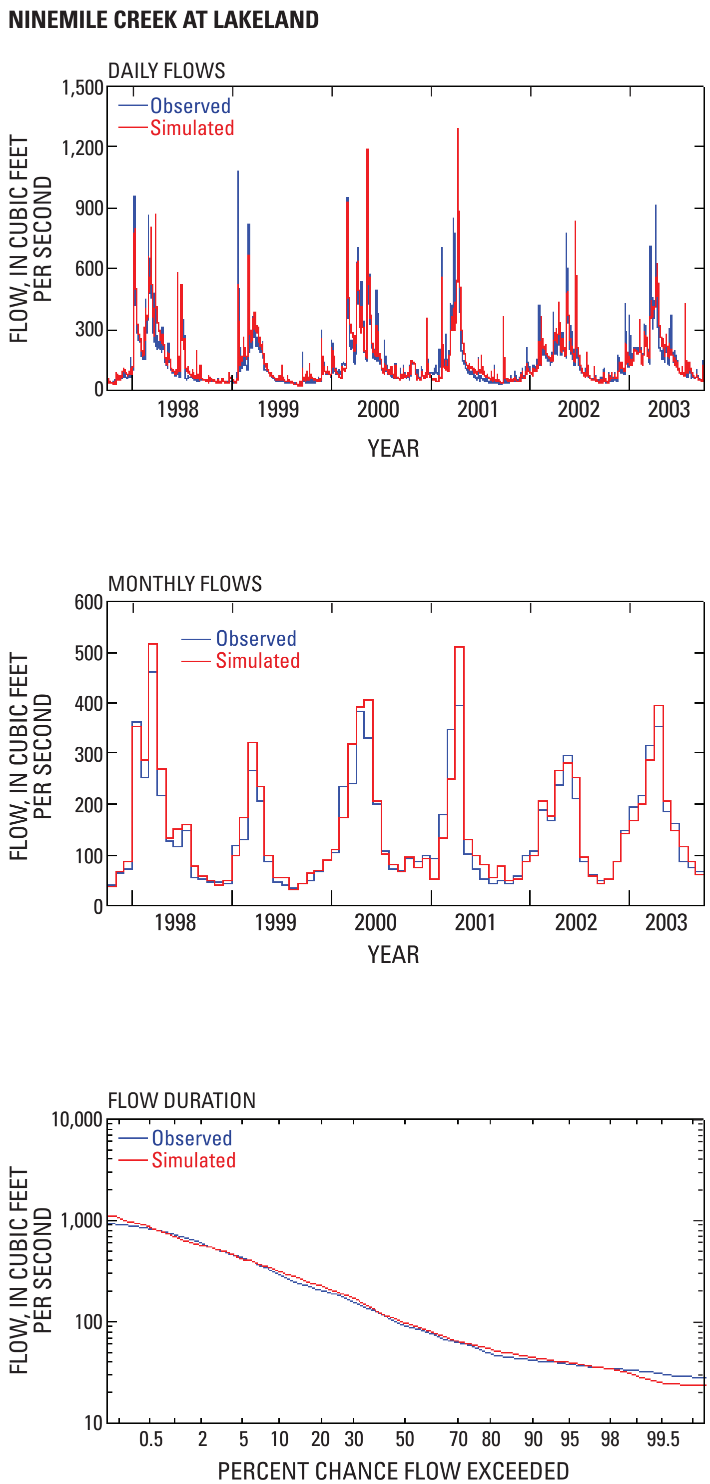

Figure 12. Daily and monthly observed and simulated streamflows, and observed and simulated flow-duration curves, at Ninemile Creek at Lakeland in the Onondaga Lake basin, Onondaga County, N.Y., 1997–2003.

Table 14. Model-performance statistics for simulated streamflow at nine monitoring sites in the Onondaga Lake basin, Onondaga County, N.Y.

[Locations of monitoring sites are shown in figure 2. Periods of record for observed data are listed in table 3. ft^3/s, cubic feet per second]

Monitoring site	Mean observed flow (ft^3/s)	Mean simulated flow (ft^3/s)	Correlation coefficient	Mean error (bias) (ft^3/s)	Mean error (percent)	Mean absolute error (ft^3/s)	Mean absolute error (percent)	Coefficient of model-fit efficiency
Daily mean streamflow								
Onondaga Creek near Cardiff	57.82	49.59	0.73	-8.23	-16.59	21.51	43.37	0.47
Onondaga Creek at Dorwin Avenue	123.37	114.97	.87	-8.40	-7.30	36.00	31.32	.76
Onondaga Creek at Spencer Street	160.93	168.25	.89	7.32	4.35	41.39	24.60	.78
Harbor Brook at Holden Street	9.19	9.33	.82	0.14	1.47	2.56	27.42	.64
Harbor Brook at Hiawatha Blvd.	9.72	10.75	.80	1.03	9.55	3.33	30.98	.60
Ley Creek at Park Street	39.74	42.10	.82	2.36	5.60	14.39	34.19	.63
Ninemile Creek near Marietta	36.23	36.46	.98	.23	0.63	5.42	14.87	.96
Ninemile Creek at Camillus	101.01	102.86	.90	1.85	1.80	21.96	21.35	.79
Ninemile Creek at Lakeland	141.06	149.55	.91	8.49	5.68	29.80	19.92	.81
Monthly mean streamflow								
Onondaga Creek near Cardiff	58.04	49.75	0.94	-8.28	-16.65	13.35	26.83	0.84
Onondaga Creek at Dorwin Avenue	123.84	115.38	.94	-8.46	-7.33	23.12	20.04	.88
Onondaga Creek at Spencer Street	161.46	168.82	.95	7.36	4.36	28.96	17.16	.89
Harbor Brook at Holden Street	9.21	9.36	.90	0.15	1.61	1.71	18.21	.81
Harbor Brook at Hiawatha Blvd.	9.74	10.79	.88	1.05	9.70	2.18	20.23	.72
Ley Creek at Park Street	39.87	42.31	.86	2.45	5.78	8.72	20.62	.69
Ninemile Creek near Marietta	36.36	36.59	.99	.23	0.62	3.77	10.29	.99
Ninemile Creek at Camillus	101.33	103.10	.97	1.77	1.72	14.94	14.49	.92
Ninemile Creek at Lakeland	141.47	149.97	.97	8.50	5.67	21.16	14.11	.91

whereas the other sites had 6 years of record. The highest values of *R* and *E* for both daily and monthly flows were associated with Ninemile Creek near Marietta (04240180), whose record reflected the computed discharges from Otisco Lake that were directly input to the model. Except for the low values computed for the Cardiff flows, the values in table 14 generally fall within the range of published values for other HSPF models (Coon and Johnson, 2005). These model-performance criteria (table 14) indicate that simulated daily and monthly flows would be rated “very good” at all monitoring sites, except Onondaga Creek at Cardiff, which would be rated “fair.”

Otisco Lake Storage Volume

Calibration of Otisco Lake storage volume was aided by the availability of flow records from 1982–83 for the five major tributaries to Otisco Lake. During 1982–83, the USGS conducted a sediment- and nutrient-load study of the Otisco Lake basin (Paschal and Sherwood, 1987). As part of that study, streamflows for the five main tributaries to Otisco Lake—Spafford Creek, Rice Brook, Willow Brook, Amber Brook, and VanBenthuysen Brook—were monitored. Understandably, these 1980s flows could not be used for direct calibration of flows during the model-calibration period; however, the monthly average flows provided a target range of flows that could be approximated to ensure that simulated flows during 1997–2003 were reasonable on the basis of the measured historical flows. The success of these approximations can be seen for the monthly flows presented in figure 13. One noticeable discrepancy between the observed and simulated monthly flows was the slightly higher simulated flows during the summer months on most tributaries. Attempts to simulate near-zero flows at these sites were unsuccessful. A plausible explanation for the discrepancies is that the 1982–83 streamflow-monitoring sites were located near the mouth of each stream, which were subject to sediment aggradation, and some of the streamflow likely followed a subsurface path to the lake. The simulated flows would not reflect this alternate path and would be greater than the measured surface flows. Regardless of these low-flow discrepancies, this step improved the calibration of Otisco Lake storage volumes (fig. 14).

Water Temperature

In HSPF water temperature in a reach is simulated as the combined effects of heat entering a RCHRES from overland flow, interflow, and ground-water flow, and from the heat-exchange processes across a RCHRES’ boundaries, both the air-water and water-sediment interfaces (Bicknell and others, 2001). The temperature of each inflow component is considered to be equal to the soil temperature of the layer from which the flow originates. Therefore the temperature of overland flow is equal to the surface-layer soil temperature, that of interflow is equal to the upper-layer soil temperature, and that of ground water is equal to the lower-layer soil temperature. Soil temperatures are adjustments of observed air temperatures, and are estimated using regression equations. RCHRES heat-exchange processes across the air-water interface are simulated as functions of solar radiation, air temperature, dewpoint temperature, wind speed, and percentage of cloud cover. Heat movement between the water and bed sediment is computed on the basis of monthly equilibrium ground temperatures (input values) and the difference between water and sediment temperatures.

Simulated water temperatures were calibrated to observed values on the basis of hourly records at two sites, periodic measurements at the WEP water-quality monitoring sites, and infrequent measurements elsewhere in the basin. The simulated temperatures at the two hourly sites—Onondaga Creek near Cardiff (04237962) and Ninemile Creek at Lakeland (04240300) (periods of record are given in table 3)—closely match the observed values; daily mean temperatures at these sites are presented in figure 15. The mean errors and absolute mean errors of the daily mean temperatures were less than 2 and 6 percent, respectively, at both sites; the coefficients of model-fit efficiency were greater than 0.90 and 0.96 for daily and monthly mean temperatures, respectively (table 15). Comparisons of simulated water temperatures with those periodically measured at the remaining five WEP water-quality monitoring sites (fig. 16) also showed close agreement. Mean errors and absolute mean errors between observed and simulated values were less than 4 and 9 percent, respectively, at these sites; the coefficients of model-fit efficiency range from 0.84 to 0.90 (table 15). Overall, these graphs and statistics indicate that water-temperature simulations by the model would be rated “very good” on the basis of model-performance criteria as defined by Donigian (2002; table 13).

Discrepancies between the simulated and observed water temperatures at Onondaga Creek at Spencer Street, Harbor Brook at Hiawatha Blvd, and Ley Creek at Park Street were noted and attributed to the proximity of these sites to highly urbanized areas of the basin. These areas have high percentages of imperviousness and elaborate storm-sewer systems that efficiently route water from impervious areas to nearby streams. At these sites, simulated temperatures would frequently spike upwards at the onset of runoff, plummet during the second hour of runoff, and then gradually rise to pre-storm temperatures over the following 5 to 6 hours. This pattern, which is often generated by the model for simulated constituent concentrations as well, is a result of how HSPF simulates water temperatures and constituent concentrations in short reaches and under flashy runoff conditions. High slopes or large areas of impervious surfaces will produce a sudden increase in local inflow to a reach without a corresponding increase in inflow from upstream reach segments. This results in a much larger volume of outflow than the volume in the reach at the start of the hourly time step and produces a spike and subsequent drop in water temperature or constituent concentration. Even though these simulated discrepancies can

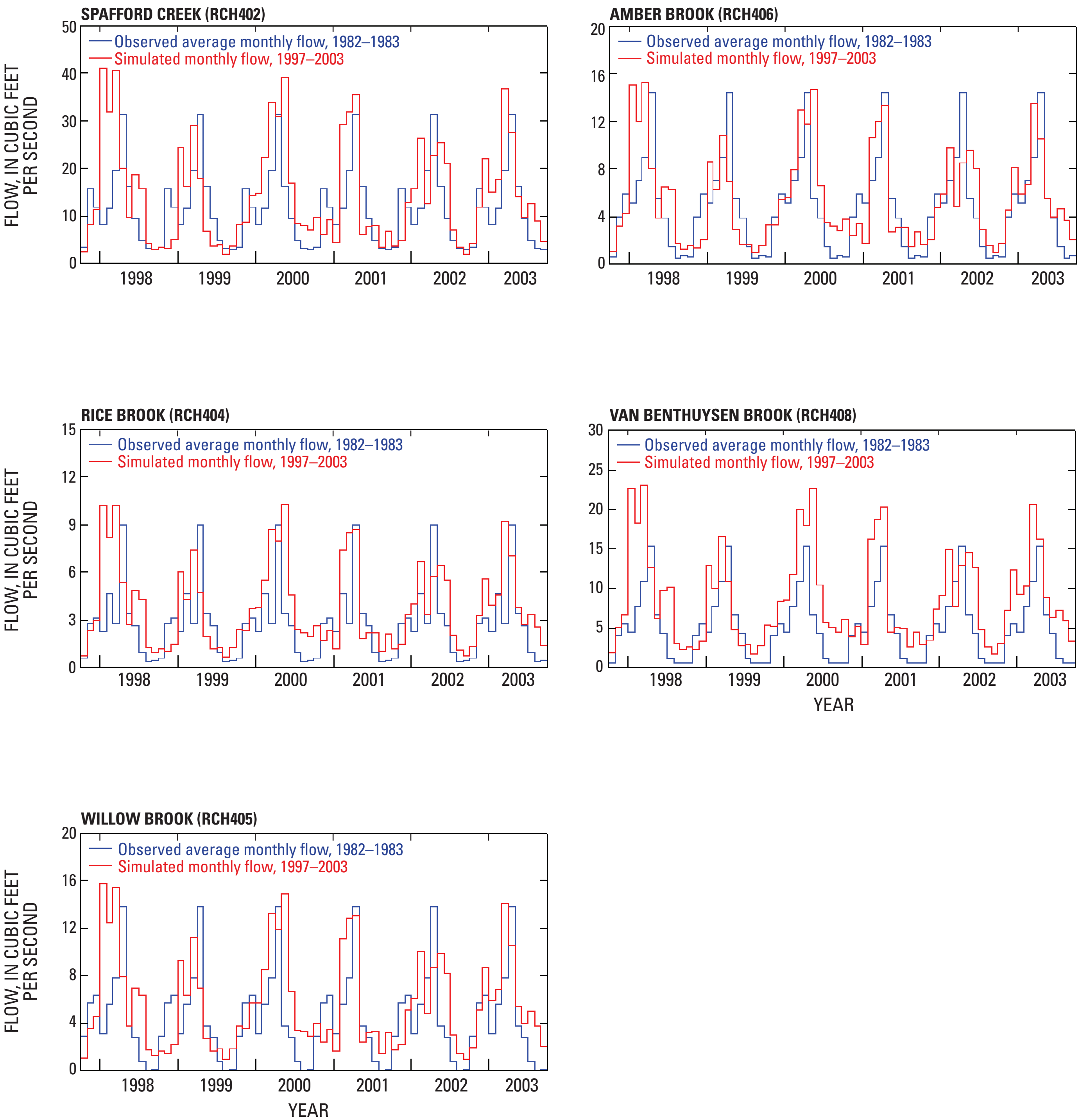

Figure 13. Observed 1982–83 average, and simulated 1997–2003, monthly flows for five tributaries to Otisco Lake, Onondaga County, N.Y.

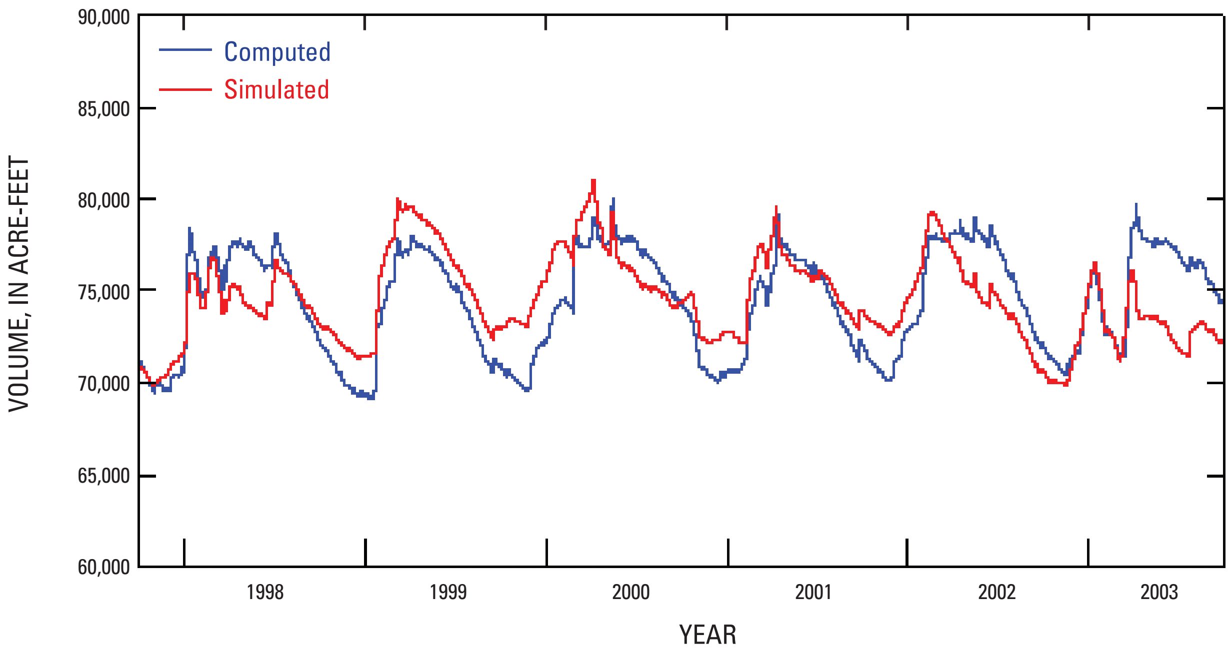

Figure 14. Computed and simulated storage volumes at Otisco Lake, Onondaga Lake basin, Onondaga County, N.Y., 1997–2003.

be found in the hourly record, they seldom appear in the daily record as the extremes average out over several time steps.

Dissolved Oxygen

In HSPF dissolved oxygen concentrations in a reach are the net values that result from the simulation of many processes. DO concentrations in overland flow are assumed to be at saturation levels and are computed as functions of water temperature. The concentrations of DO in interflow and ground-water flow are provided by the modeler and can vary monthly. The processes that determine the concentration of dissolved oxygen in a RCHRES include longitudinal advection of DO, sinking of BOD material, oxygen demand from materials in or released from the RCHRES' bottom sediments, oxygen reaeration, oxygen depletion resulting from the decay of BOD materials, the effects of nitrification on DO activity by phytoplankton and benthic algae, and respiration by zooplankton (Bicknell and others, 2001). Most of these processes are dependent on or, to some degree, functions of water temperature; the details of water-temperature simulations are presented in the previous section.

Simulated dissolved oxygen concentrations were calibrated to observed values on the basis of periodic measurements at the WEP water-quality monitoring sites and infrequent measurements elsewhere in the basin. The agreement between simulated and observed values (fig. 17) is generally poor, mainly owing to changes in the range of observed DO values during the calibration period. In all cases, the simulated DO values were higher than observed values for the first 3 years of the calibration period, but comparable to observed values during the last 3 years. No plausible explanation can be offered for the apparent change in the ranges of the DO concentrations in the measured records, but HSPF, which is designed to simulate static or average conditions in a basin, could not replicate this changing pattern over time as indicated by these plots.

Suspended Sediment

Calibration of suspended sediment required that several sediment-related issues dealing with sources and sinks of sediment in the basin be addressed first. Then suspended sediment concentrations and loads were calibrated by a three-step procedure that progressed from field-scale to basin-scale processes and then to within-channel processes. Field-scale calibration was performed by simulating soil detachment and sheet and rill erosion from land surfaces and approximating published sediment loading rates for given land types. Basin-scale calibration was performed on computed loads from tributaries of Otisco Lake; calibrated parameter values were then transferred to other subbasins in the Onondaga Lake basin. Within-channel calibration focused on the processes of sediment deposition and transport, and the simulation of relatively stable bed conditions. A final check of the simulated sediment output was conducted at a multi-subbasin scale through comparison of simulated suspended-sediment loads with computed total-suspended-solids loads at the WEP water-quality-monitoring sites.

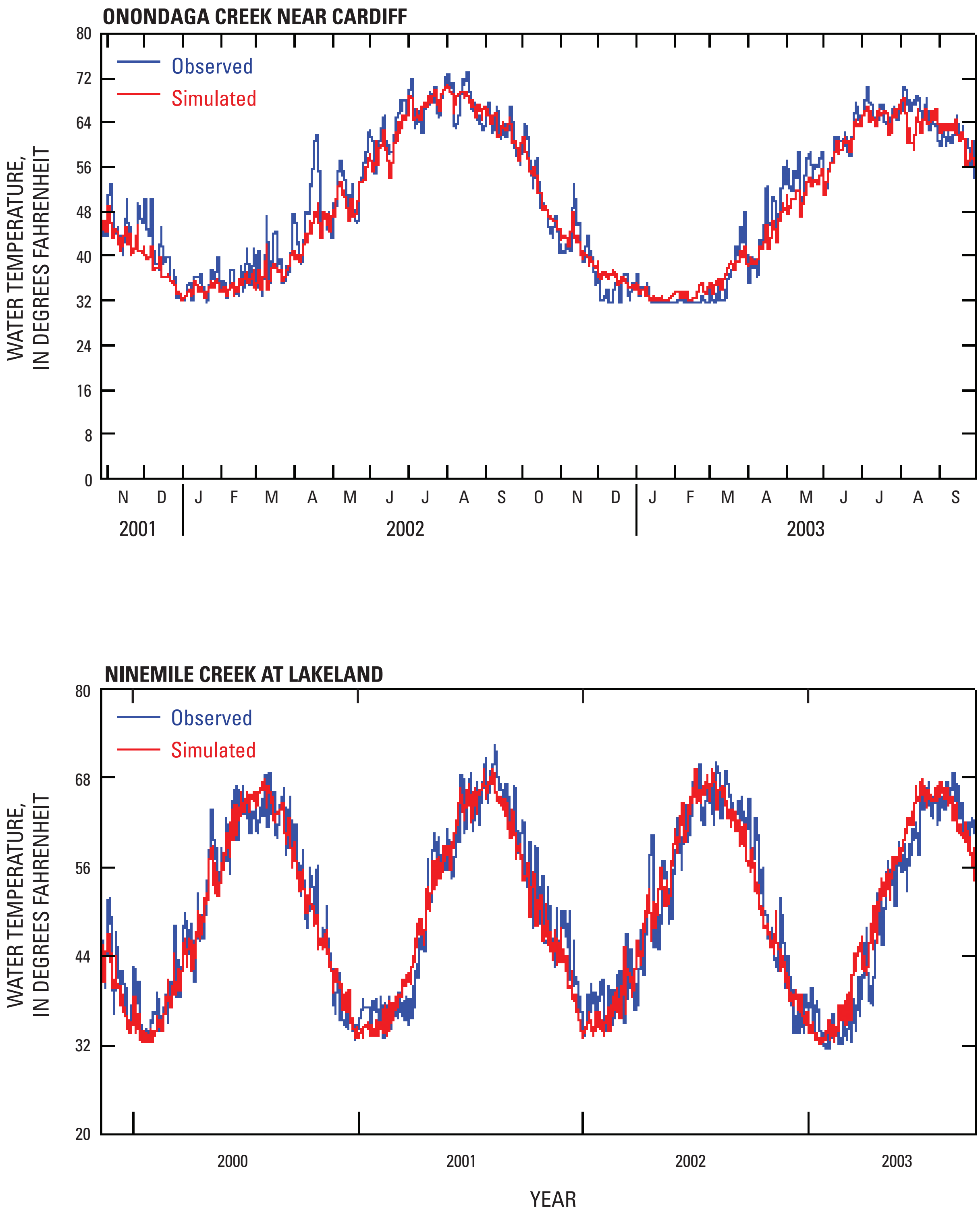

Figure 15. Observed and simulated daily mean water temperatures at Onondaga Creek near Cardiff, 2001–03, and Ninemile Creek at Lakeland, 1997–2003, Onondaga Lake basin, Onondaga County, N.Y.

Table 15. Model-performance statistics for simulated water temperatures at seven monitoring sites in the Onondaga Lake basin, Onondaga County, N.Y.

[Locations of monitoring sites are shown in figure 2. Periods of record for observed data are listed in table 3. °F, degrees Fahrenheit]

Monitoring site	Mean observed value (°F)	Mean simulated value (°F)	Standard deviation observed values (°F)	Standard deviation simulated values (°F)	Correlation coefficient	Mean error (percent)	Mean absolute error (percent)	Coefficient of model-fit efficiency
Monthly mean water temperature at continuous-record monitoring sites								
Onondaga Creek near Cardiff	49.55	49.04	12.64	12.47	0.99	-1.04	2.14	0.99
Ninemile Creek at Lakeland	50.33	50.17	11.39	11.32	.99	-0.31	3.08	.97
Daily mean water temperature at continuous-record monitoring sites								
Onondaga Creek near Cardiff	49.60	49.10	12.88	12.39	.98	-1.03	4.09	.96
Ninemile Creek at Lakeland	50.31	50.15	11.64	11.37	.96	-0.31	5.17	.91
Water temperature at periodically measured sites								
Onondaga Creek at Dorwin Avenue	51.00	50.85	14.03	12.99	.95	.55	6.78	.90
Onondaga Creek at Spencer Street	49.06	51.01	10.92	12.14	.96	3.86	6.62	.87
Harbor Brook at Holden Street	52.67	52.68	9.25	9.45	.93	.22	5.57	.85
Harbor Brook at Hiawatha Blvd.	49.72	48.86	8.54	8.95	.93	-1.70	5.25	.84
Ley Creek at Park Street	50.99	52.28	14.26	13.80	.94	3.42	8.49	.87

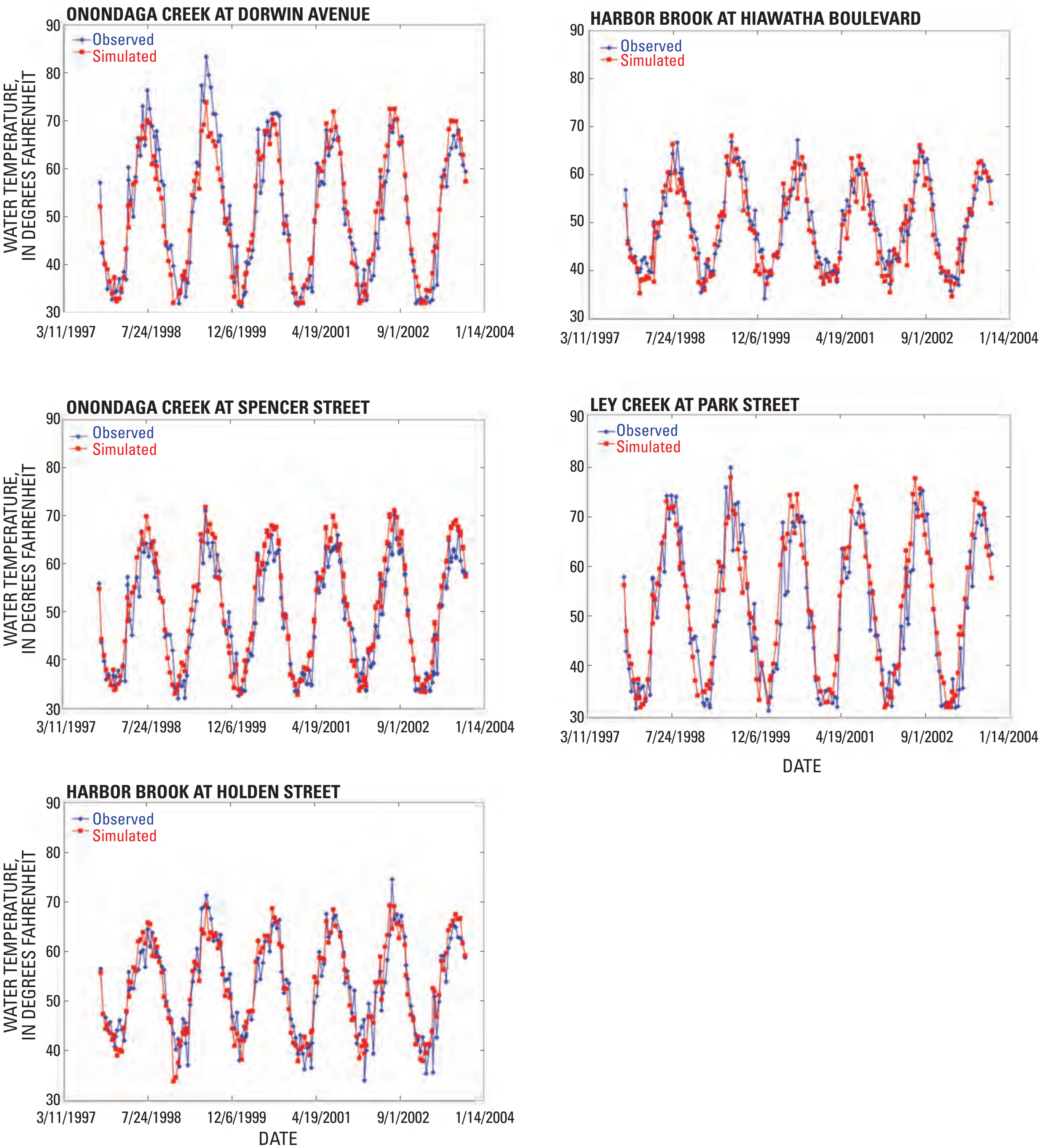

Figure 16. Observed and simulated water temperatures at five monitoring sites in the Onondaga Lake basin, Onondaga County, N.Y., 1997–2003.

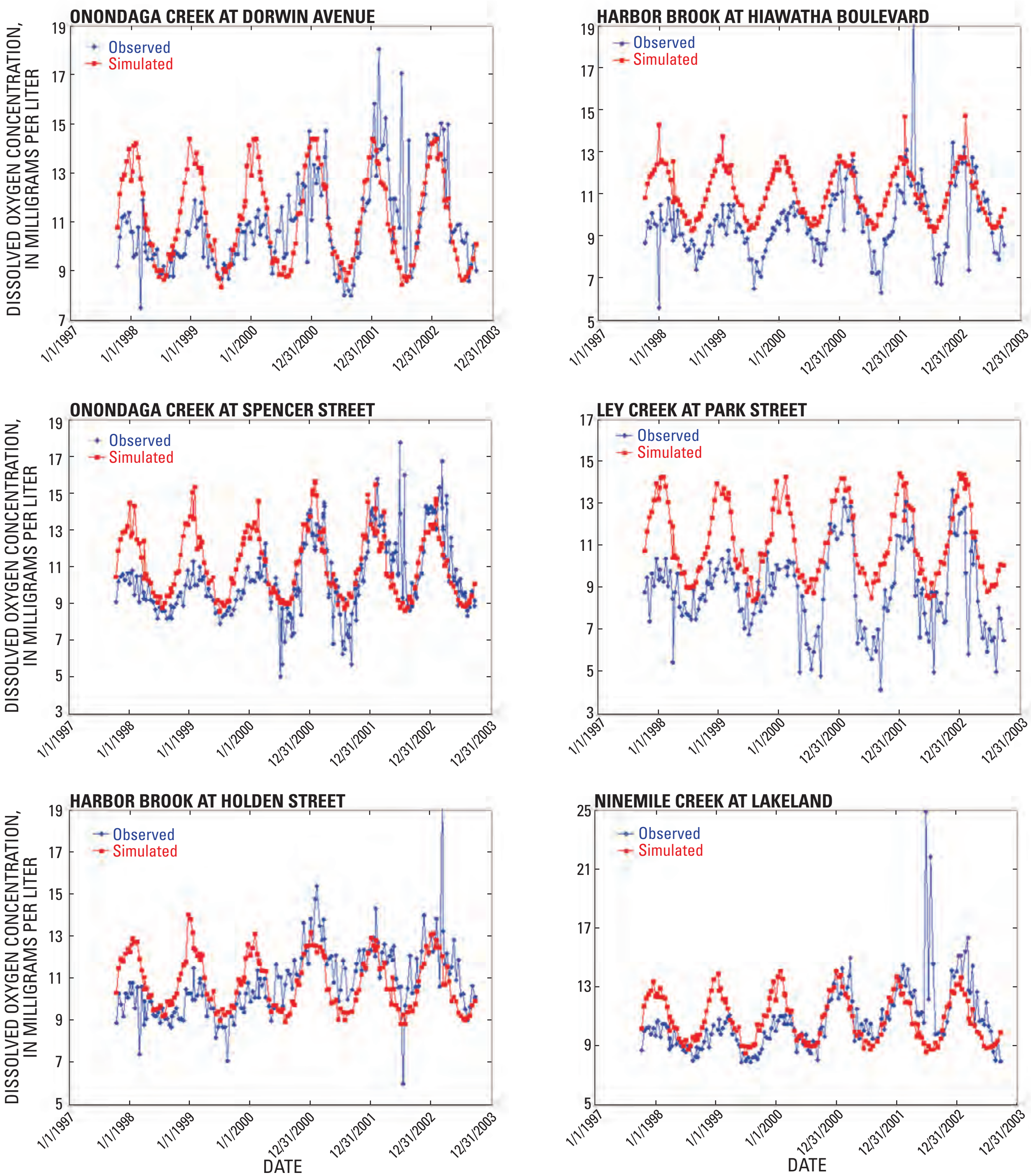

Figure 17. Observed and simulated concentrations of dissolved oxygen at six monitoring sites in the Onondaga Lake basin, Onondaga County, N.Y., 1997–2003.

Sediment-Related Issues

During the sediment calibration process, several unique sediment-related issues needed to be addressed. The Tully Valley mudboils were a constant source of fine-grained sediment in the southern part of the Onondaga Creek basin during the calibration period. The daily sediment loads from this source, which are available for 1991 through the calibration period (Hornlein and others, 1999, 2000, 2001, 2002, 2003, 2004), were input to the model as a point source of sediment.

Other large sediment sources in the same general area are Rattlesnake Gulf and Rainbow Creek, directly opposite each other to the west and east of Onondaga Creek, respectively. Where these streams flow down the steep valley sides, streambank and within-channel materials are eroded and carried to the valley floor or to Onondaga Creek. In Rattlesnake Gulf (RCHRES 109; fig. 7), these loads are derived from mainly lacustrine silt and clay deposits that slump into the stream channel; turbidity is evident near the mouth of this stream year round. In Rainbow Creek (RCHRES 105; fig. 7), the source of sediment is primarily glacial deposits of sand and gravel that have been incised by the stream. Rainbow Creek can be relatively clear during low-flow periods but very turbid during high flows. Although these sediment sources are known, no data were available to quantify their individual or combined contributions to loads in Onondaga Creek. The model parameters that control scour (TAUCS) and the erodibility of the channel bed (M) were adjusted to simulate the aggravated erosion of the streambanks along the high-gradient reaches of these channels.

As discussed previously, large estimated loads of sediment are derived from roadbank and streambank erosion throughout the Onondaga Lake basin (Sullivan and Moonen, 1994; Blatchley, 2000). Although these sediment sources are not land-use specific, they reflect natural processes or human activities that are ubiquitous across the basin. As the data to simulate these sources independently were unavailable, their contributions were assumed to be incorporated into the land-use-specific loading rates that were simulated by the model.

Lacustrine silt-and-clay deposits are particularly prone to erosion, especially when they have been disturbed by agricultural activities, such as the planting of row crops, and are the source of disproportionately large sediment loads in the Onondaga Lake basin, such as in the lower reaches of Spafford Creek, the main tributary to Otisco Lake (Paschal and Sherwood, 1987). These loads were simulated by adjustment of soil-detachment and soil-washoff parameter values associated with this land-segment type.

The Onondaga Reservoir on Onondaga Creek downstream from the confluence with West Branch Onondaga Creek has an unknown mitigative effect on sediment loads. Although this dam is a flow-through structure without gates or any other mechanism to retain storm runoff, by design it does attenuate stormflows and cause temporary detention and, depending on water levels, dispersal of stormwater across the floodplain. These effects suggest that the dam would mitigate sediment loads by causing sedimentation; however, no study has been conducted to document the effectiveness of this process. The presumed sediment-retention capability of the reservoir was simulated by adjusting parameter values to increase deposition, especially of sand and silt-sized particles, and to minimize the occurrence of scour.

Otisco Lake has a substantial effect on the sediment loads that are carried by its tributaries. The removal efficiency of the lake has not been determined, but the clear water that is discharged from the lake to Ninemile Creek, even during storm runoff periods, attests to the lake's high sediment-removal capability. Much of this removal can be attributed to the lake's size—5.4 mi long and an average of 33 ft deep—and to an estimated water-retention time of 1.9 years (Schaffner and Oglesby, 1978), but it is also greatly facilitated by an abandoned causeway that cuts across the southern part of the lake. This causeway, constructed in 1899–1900 to permit east-west passage across the lake at a point that marked the southern end of the lake prior to construction of a dam at the lake's outlet in 1868–69, traps much of the sediment load brought into the lake by Spafford Creek (Paschal and Sherwood, 1987). The high sediment-removal rate of Otisco Lake was simulated by adjustment of parameter values that control sediment settling rates, deposition, and scour.

Calibration of Suspended Sediment

Guidance on initial and typical ranges of sediment-related parameter values were obtained from a technical note published by the U.S. Environmental Protection Agency (2006). HSPF simulates sediment buildup on and washoff from pervious and impervious land segments in units of mass per unit area (tons/acre). Rates of erosion for the various land segments in the model were estimated from published values in the scientific literature; the targeted and initially calibrated loading rates were very close (table 4). The simulated sediment-loading rates were then compared with the computed annual loads measured in the five main tributaries to Otisco Lake during 1982–83 (Paschal and Sherwood, 1987). These data might not be directly applicable to subbasin conditions during 1997–2003 because of the implementation of soil-management practices on many of the farms in the basin between 1983 and 1998 (Brian Hall, Onondaga County Soil and Water Conservation District, written commun., 2006). However, the presumed benefits of these practices, which might be inconsistently adhered to over time, have not been documented. Therefore, in the absence of any other estimates of sediment loading rates that were available from within the Onondaga Lake basin, the 1982–83 annual loads were used as target values for further calibration of the model. This step improved the match between simulated and computed loading rates for the Otisco Lake tributaries (table 5) but also resulted in changes to the unit-area loading rates that were used in the previous step (table 4). Comparison of the initially calibrated and final values presented in table 4 points out the potential inaccuracy that could arise from using loading rates estimated from literature values rather than those measured in the basin being simulated. Loading rates for forest land types were increased, and those for pasture-hay, row-crops, and farmstead land types were decreased. The parameter values for row crops in lacustrine silt-and-clay soils required unusually large increases to approximate the measured annual loads in Spafford Creek, Otisco Lake's main tributary.

The calibrated parameter values for the Otisco Lake subbasins that pertained to the processes of sediment accumulation and removal from the land surface for a particular land type were transferred to, and used for simulation of these processes in, the other subbasins of the Onondaga Lake basin. At the edge of field, the simulated loads from land segments were apportioned among sand, silt, and clay fractions prior to input to the appropriate RCHRES. The percentages of these fractions—10 percent sand, 55 percent silt, and 35 percent clay—were based on particle-size analyses of stormflow sediment loads in tributaries to Otisco Lake during 1982–83 (Paschal and Sherwood, 1987).

Parameter values that control within-channel sediment deposition and scour processes were adjusted to maintain relatively stable bed conditions in each of the RCHRESs through the calibration period. Apparent errors in the rate of aggradation or erosion of streambed segments were identified from plots of sediment storage of sand-, silt-, and clay-sized particles during the calibration period for each of the RCHRESs in the model. The coefficient of the sand-transport algorithm and the fall velocity of sand particles were adjusted to simulate deposition and scour of sand-sized particles. Threshold shear-stress values based on the range of shear-stress values that were computed by HSPF for a given RCHRES were input to the model to control deposition and scour of silt- and clay-sized particles.

A final check of the simulated sediment output was performed through comparison of simulated suspended-sediment concentrations and computed total-suspended-solids concentrations at the USGS and WEP water-quality monitoring sites. Gray and others (2000) point out the potential negative bias that occurs when concentrations of suspended solids are used as a surrogate for concentrations of suspended sediment. This bias can arise as a result of differences in the analytical methods used to measure each constituent, especially for concentrations measured in stormflow samples that might comprise a large percentage of sand-sized material. (See appendix 2 for further discussion of this issue.) Nonetheless, a final check of the simulated suspended sediment data was conducted to ensure that these concentrations and loads were comparable to, if not greater than, the observed suspended-solids concentrations and loads (fig. 18). Model performance statistics for monthly loads of simulated suspended sediment and computed total suspended solids not surprisingly showed poor agreement between these two constituents (table 16). On the basis of the percentage mean error criteria of Donigian (2002), the sediment simulations for three monitoring sites—Onondaga Creek at Spencer Street, Harbor Brook at Holden Street, and Ninemile Creek at Lakeland—are rated "good"; those for Onondaga Creek at Dorwin Avenue are rated "fair"; and those for Harbor Brook at Hiawatha Boulevard and Ley Creek at Park Street are rated "poor" (with mean errors greater than 35 percent).

Nutrients

Loads of orthophosphate, total phosphorus, nitrate nitrogen, and organic nitrogen were simulated for the modeled land segments. These constituents, rather than others, were selected for simulation because loading rates for these constituents are available in scientific reports (see tables 7 and 8), and concentrations and loads of these constituents could be directly output by HSPF. Each of these constituents (QUAL) could be simulated by one or a combination of four methods that are available in HSPF; a QUAL can be associated with ground water (QUALGW), interflow (QUALIF), overland flow (QUALOF), and (or) sediment (QUALSD). A QUALSD can be associated with sediment that is washed off a land surface, scoured from the soil matrix, or both. The flow components of a simulated QUAL are linked to the PWATER and IWATER sections of the PERLND and IMPLND modules, respectively, whereas the sediment components are linked to the SEDMNT and SOLIDS sections of these modules (table 9). The calibration of each QUAL generally followed the following steps. First, the trend of nutrient concentrations in base flows was mimicked by adjusting annual or monthly QUALGW parameter values, which controlled the nutrient contributions in ground-water outflow. Second, nutrient concentrations in storm runoff were simulated by adjusting parameter values associated with one or a combination of the three pathways by which a constituent might be transported in storm runoff: (1) annual or monthly IOQC values, which controlled the constituent contributions in interflow outflow; (2) buildup and washoff of a constituent from a land surface; and (or) (3) as a fraction of sediment washoff or scour. All of these options for simulating constituent concentrations were applicable to PERLNDs; only those options associated with overland flow and sediment processes were applicable to IMPLNDs. Adjustments to parameter values associated with impervious land segments were made after parameter values for pervious land segments were finalized and to further decrease any error that persisted between observed and simulated concentrations of nutrients in storm runoff. Finally, unresolved discrepancies were addressed by adjustment of parameter values that controlled within-stream processes simulated by the OXRX, NUTRX, and PLANK sections of the RCHRES module (table 9). These parameters include the BOD decay rate (KBOD20), the generation of OP and NH_3 by benthic organisms (BRPO4 and BRTAM, respectively), and nitrogen-species transformation rates for ammonia, nitrite, and nitrate (KTAM20, KNO220, and KNO320, respectively).

Of the four nutrients that were simulated for the land segments—OP, TP, NO_3, and OrgN—concentrations of OP and OrgN were simulated by a combination of all four processes

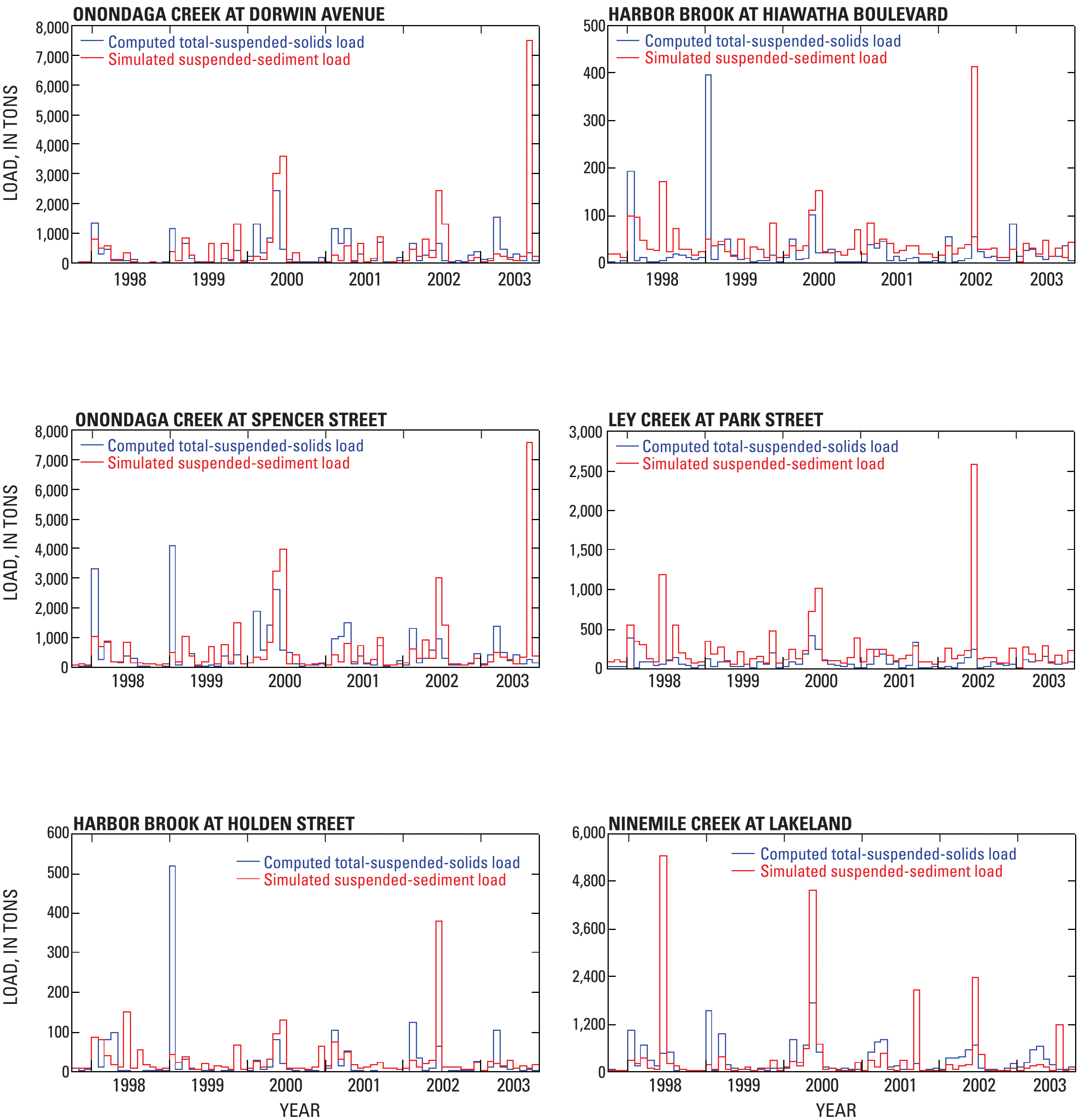

Figure 18. Monthly computed loads of total suspended solids and simulated loads of suspended sediment at six monitoring sites in the Onondaga Lake basin, Onondaga County, N.Y., 1997–2003.

Table 16. Model-performance statistics for monthly simulated sediment and constituent loads at six monitoring sites in the Onondaga Lake basin, Onondaga County, N.Y.

[Locations of monitoring sites are shown in figure 2. Periods of record for observed data are listed in table 3]

Monitoring site	Mean computed value (tons)	Mean simulated value (tons)	Standard deviation computed values (tons)	Standard deviation simulated values (tons)	Correlation coefficient	Mean error (percent)	Mean absolute error (percent)	Coefficient of model-fit efficiency
Computed total-suspended-solids and simulated suspended-sediment loads								
Onondaga Creek at Dorwin Avenue	309.77	445.20	445.15	1,056.93	0.31	30.42	85.98	-4.24
Onondaga Creek at Spencer Street	479.14	571.94	741.33	1,087.95	.22	16.23	86.57	-1.51
Harbor Brook at Holden Street	23.38	29.56	66.19	50.74	.18	20.91	101.32	-0.31
Harbor Brook at Hiawatha Blvd.	24.02	42.21	52.59	53.80	.19	43.10	82.46	-.79
Ley Creek at Park Street	84.64	237.61	85.30	343.04	.48	64.38	66.49	-15.58
Ninemile Creek at Lakeland	266.83	337.55	344.13	890.51	.44	20.95	95.00	-4.44
Orthophosphate loads								
Onondaga Creek at Dorwin Avenue	0.05	0.07	0.08	0.09	.59	36.95	59.67	.00
Onondaga Creek at Spencer Street	.09	.11	.08	.10	.59	11.49	52.50	-.13
Harbor Brook at Holden Street	.01	.01	.01	.01	.60	27.63	54.09	-.38
Harbor Brook at Hiawatha Blvd.	.02	.02	.02	.01	.50	-13.43	57.04	.19
Ley Creek at Park Street	.05	.05	.03	.03	.61	-7.08	40.93	.17
Ninemile Creek at Lakeland	.08	.10	.09	.08	.59	21.12	51.38	.22
Total phosphorus loads								
Onondaga Creek at Dorwin Avenue	.60	.61	.81	.78	.62	1.15	59.50	.25
Onondaga Creek at Spencer Street	.93	.84	1.06	.86	.76	-11.18	47.84	.57
Harbor Brook at Holden Street	.03	.04	.05	.03	.72	12.03	54.01	.51
Harbor Brook at Hiawatha Blvd.	.07	.07	.07	.05	.77	8.63	44.39	.58
Ley Creek at Park Street	.33	.32	.23	.18	.74	-2.44	31.47	.54
Ninemile Creek at Lakeland	.68	.72	.70	.71	.83	5.65	36.15	.65

Table 16. Model-performance statistics for monthly simulated sediment and constituent loads at six monitoring sites in the Onondaga Lake basin, Onondaga County, N.Y. —Continued

[Locations of monitoring sites are shown in figure 2. Periods of record for observed data are listed in table 3]

Monitoring site	Mean computed value (tons)	Mean simulated value (tons)	Standard deviation computed values (tons)	Standard deviation simulated values (tons)	Correlation coefficient	Mean error (percent)	Mean absolute error (percent)	Coefficient of model-fit efficiency
Nitrate nitrogen loads								
Onondaga Creek at Dorwin Avenue	1.60	1.62	11.80	11.67	0.94	0.12	24.54	0.87
Onondaga Creek at Spencer Street	13.54	12.19	12.86	12.99	.94	-11.08	25.05	.86
Harbor Brook at Holden Street	1.28	1.22	0.85	0.76	.89	-4.97	22.34	.79
Harbor Brook at Hiawatha Blvd.	1.22	1.41	.99	.87	.85	13.67	28.05	.68
Ley Creek at Park Street	1.56	1.84	1.32	1.63	.82	15.27	34.56	.44
Ninemile Creek at Lakeland	11.83	12.44	11.02	1.20	.91	4.90	25.24	.82
Ammonia nitrogen loads								
Onondaga Creek at Dorwin Avenue	0.78	0.63	.68	.58	.78	-23.61	52.85	.55
Onondaga Creek at Spencer Street	1.58	1.2	.92	.77	.58	-32.08	54.44	.09
Harbor Brook at Holden Street	.06	.07	.04	.06	.66	16.46	48.92	-.06
Harbor Brook at Hiawatha Blvd.	.11	.09	.1	.06	.52	-26.26	65.36	.2
Ley Creek at Park Street	1.27	1.16	.82	.64	.71	-10.19	38.38	.47
Ninemile Creek at Lakeland	3.68	3.01	2.1	1.62	.8	-22.05	28.28	.54
Organic nitrogen loads								
Onondaga Creek at Dorwin Avenue	3.57	3.69	3.67	3.75	.76	3.12	41.95	.50
Onondaga Creek at Spencer Street	5.29	4.77	4.96	4.26	.76	-10.91	42.51	.55
Harbor Brook at Holden Street	.25	.26	.34	.24	.63	3.72	52.37	.40
Harbor Brook at Hiawatha Blvd.	.32	.34	.36	.28	.73	5.54	41.57	.52
Ley Creek at Park Street	1.88	1.78	1.34	.96	.76	-5.27	33.81	.57
Ninemile Creek at Lakeland	4.41	3.68	4.29	3.05	.84	-19.85	38.96	.66

(table 17). Monthly parameter values were input to simulate OP concentrations in ground water and interflow; annual values were used for parameters associated with overland flow and sediment. Concentrations of TP were simulated using monthly parameter values for the overland-flow and sediment-associated processes; TP concentrations were not simulated as a QUALGW or QUALIF. Concentrations of nitrate were strongly associated with ground water, and to a lesser degree with interflow and overland flow.

HSPF permits the simulation of constituent inputs to the land segments in the model by two methods—atmospheric deposition (AD) and accumulation on the land surface by means of the parameter ACQOP. Wetfall concentrations of nitrate and ammonia were available from a National Atmospheric Deposition station in Aurora, N.Y. (National Atmospheric Deposition Program, 2005). This station is 30 mi west of the Onondaga Lake basin and the uncertainties associated with the precipitation quantities measured at this location, the anticipated discrepancies with precipitation quantities measured in the Onondaga Lake basin, and the transference of these data to the Onondaga Lake basin were likely to impede the calibration of these components of the model. Therefore, in the absence of wetfall or dryfall constituent concentration data collected in the Onondaga Lake basin, atmospheric deposition was estimated and input selectively as an alternative or addition to ACQOP whenever doing so improved the simulation of nutrient concentrations. AD was used instead of ACQOP to simulate OP concentrations, and along with ACQOP, to simulate TP concentrations. Only ACQOP inputs were used to simulate NO_3 and OrgN concentrations.

Within HSPF, the simulated loads of OP, OrgN, and NO_3 that are generated for the HRUs can be passed directly to the appropriate receiving RCHRES in the model, whereas TP loads must be apportioned between two of its three components—orthophosphate and organic phosphorus. The loads of the third component of TP, acid-hydrolyzable phosphorus, were considered negligible for modeling purposes. OrgP loads, which were not simulated owing to the paucity of loading-rate data in scientific literature, were estimated as 84 percent of TP loads on the basis of median concentrations and loads of OP and TP at the six WEP water-quality-monitoring sites. Similarly ammonia (NH_3) loads for the HRUs were estimated as 43 percent of OrgN loads on the basis of median concentrations and loads of TKN, OrgN, and NH_3 at the WEP monitoring sites. Organic carbon input loads were estimated as five times the OrgN loads. Although a direct relation between the mass of a constituent entering a stream and the median concentration of that constituent at a downstream monitoring point has not been established, this procedure provided a means to estimate the required input loads for the processes simulated by the RCHRES module. These quantities were targeted to the RCHRESs in the model by means of the multiplication factors in the MASS-LINK blocks.

Daily loads of OP, OrgP, NH_3, NO_3, and OrgN that were exported from Otisco Lake to Ninemile Creek were estimated using daily lake outflow data and average concentrations in summertime samples collected once monthly from the epilimnion in Otisco Lake during 1996–97 and 1999 by Callinan (2001). Monthly loads of OP, OrgP, NH_3, NO_3, NO_2, and OrgN in effluent discharged from the Marcellus WWTP to Ninemile Creek were estimated using once-monthly instantaneous flow values and concentrations measured in the plant’s effluent. In both cases, these estimated time series of monthly loads were imprecise estimates of point sources of nutrients that were based on the assumption that the available data were representative of flows and constituent concentrations throughout the period for which they were used. All estimated time series of load data were input to the model using an hourly time step through the EXTERNAL SOURCES module.

Simulated nutrient data were calibrated using a three-step process. First, nutrient loads from PERLNDs and IMPLNDs were calibrated to unit-area loading rates estimated from literature values for the various land types represented in the model (tables 7 and 8). Second, simulated concentrations of nutrients in streamflow were calibrated to periodic measurements of concentrations in water samples collected at the six WEP water-quality-monitoring sites (Antonio Deskins, Onondaga County Department of Water Environment Protection, written commun., 2004). Third, simulated loads were compared with those computed by WEP for each constituent at each monitoring site using regression equations

Table 17. Components used to simulate concentrations of four selected nutrients by the precipitation-runoff model of Onondaga Lake basin, Onondaga County, N.Y.

[A, annual parameter values used; M, monthly parameter values used; –, constituent not associated with indicated component of nutrient simulation]

Component of nutrient simulation nutrient is associated with:	Ortho-phosphate	Total phosphorus	Nitrate	Organic nitrogen
Ground water	M	–	M	A
Interflow	M	–	M	A
Overland flow	A	M	A	A
Sediment	A	M	–	A

(EcoLogic, LLC, 2003). The latter two steps generally required adjustments to parameter values that controlled the unit-area loading rates, such that final unit-area loading rates departed from the initial values. (See tables 7 and 8.) Simultaneous calibration to both nutrient concentrations and WEP-computed loads sometimes required conflicting changes in unit-area loading rates. When this occurred, the fit between simulated and measured concentrations, rather than simulated and computed loads, was emphasized. Concentration data were not subject to the assumptions and potential sources of uncertainty that were inherent in the different methods used to compute loads. Departures from the target unit-area loading rates (tables 7 and 8) for each constituent were inevitable, and although every effort was made to have final unit-area loading rates fall within the range of values found in the scientific literature, this was not always possible. Simulated OP loading rates generally were smaller than literature values, whereas simulated NO_3 loading rates were generally greater (tables 7 and 8). These discrepancies point out the potential difficulties in transferring unit-area loading rates from one basin to another and the need for measured loading rates that are directly applicable to the Onondaga Lake basin.

The parameter values for the water-quality components of the model were adjusted to provide the best fit for each constituent at all six water-quality-monitoring sites. Some imprecision in the simulation results were expected because the best combination of parameter values at one calibration point might not have been the best at another; therefore, the values that collectively gave the best results, that is minimized the differences between observed and simulated values on a basinwide basis, were selected as the final values in the model.

Orthophosphate

Orthophosphate is a major dissolved form of phosphorus that is biologically available for uptake by biota in aquatic systems. OP concentrations generally did not exhibit a seasonal pattern, but increased with storm runoff. Simulated concentrations displayed a greater frequency in fluctuations that was not evident in the observed data, but the ranges of the two datasets were comparable at all the water-quality-monitoring sites, except Ninemile Creek at Lakeland, where simulated concentrations failed to match the low measured concentrations (fig. 19). Computed and simulated monthly loads of orthophosphate and their differences (residuals) at the six monitoring sites are shown in figure 20. On the basis of model performance statistics, OP load simulations ranged from “very good” at Onondaga Creek at Spencer Street, Harbor Brook at Hiawatha Boulevard, and Ley Creek at Park Street to “poor” at Onondaga Creek at Dorwin Avenue (mean error of 37 percent; table 16).

Total Phosphorus

Total phosphorus concentrations and loads were strongly correlated with “disturbed” land uses and those that are subject to surface application of nutrients, such as manure and fertilizer; these land uses include agricultural and developed uses. TP concentrations and loads also were strongly correlated with storm runoff and sediment loads. The ranges of simulated and observed concentrations were comparable at all the water-quality monitoring sites (fig. 21). Computed and simulated monthly loads of total phosphorus and their differences (residuals) at the six monitoring sites are shown in figure 22. On the basis of model performance statistics, TP load simulations were “very good” at all monitoring sites (table 16). The largest mean error was 12 percent for simulations at Harbor Brook at Hiawatha Boulevard.

Nitrate Nitrogen

Nitrate is highly soluble and strongly related to ground-water inputs. The smallest contributions of NO_3 typically come from forested areas, which actually can mitigate loads generated from nearby agricultural areas. Agricultural contributions from inorganic fertilizer and animal manure; urban contributions from lawn fertilizers, septic systems, and domestic animals; and atmospheric deposition from industry and automobiles usually are the largest sources of NO_3 (Nolan and others, 1998). NO_3 concentrations exhibited a strong seasonal pattern with highs occurring during winter and lows during late summer to early fall (fig. 23). The frequency of the fluctuations in NO_3 concentrations was greater at the monitoring sites of small drainage areas with large percentages of developed land—the two Harbor Brook sites and Ley Creek—than at those sites with large and more rural drainage areas. Computed and simulated monthly loads of nitrate nitrogen and their differences (residuals) at the six water-quality-monitoring sites are shown in figure 24. On the basis of model performance statistics, NO_3 load simulations were “very good” at all monitoring sites (table 16). The largest mean error was 15 percent for simulations at Ley Creek at Park Street.

Organic Nitrogen

The ranges of simulated and observed concentrations of organic nitrogen were comparable at all the water-quality monitoring sites (fig. 25). Computed and simulated monthly loads of organic nitrogen and their differences (residuals) at the six monitoring sites are shown in figure 26. On the basis of model performance statistics, OrgN load simulations were “very good” at all monitoring sites, except Ninemile Creek at Lakeland, which were “good” (mean error of -20 percent; table 16).

Ammonia Nitrogen

Ammonia is a preferred form of nitrogen for assimilation by aquatic plants and is found in fertilizers and waste products from farmsteads and wastewater-treatment plants. An effort similar to that expended for other constituents was not expended for the calibration of ammonia nitrogen concentrations and loads. Parameter values that affected

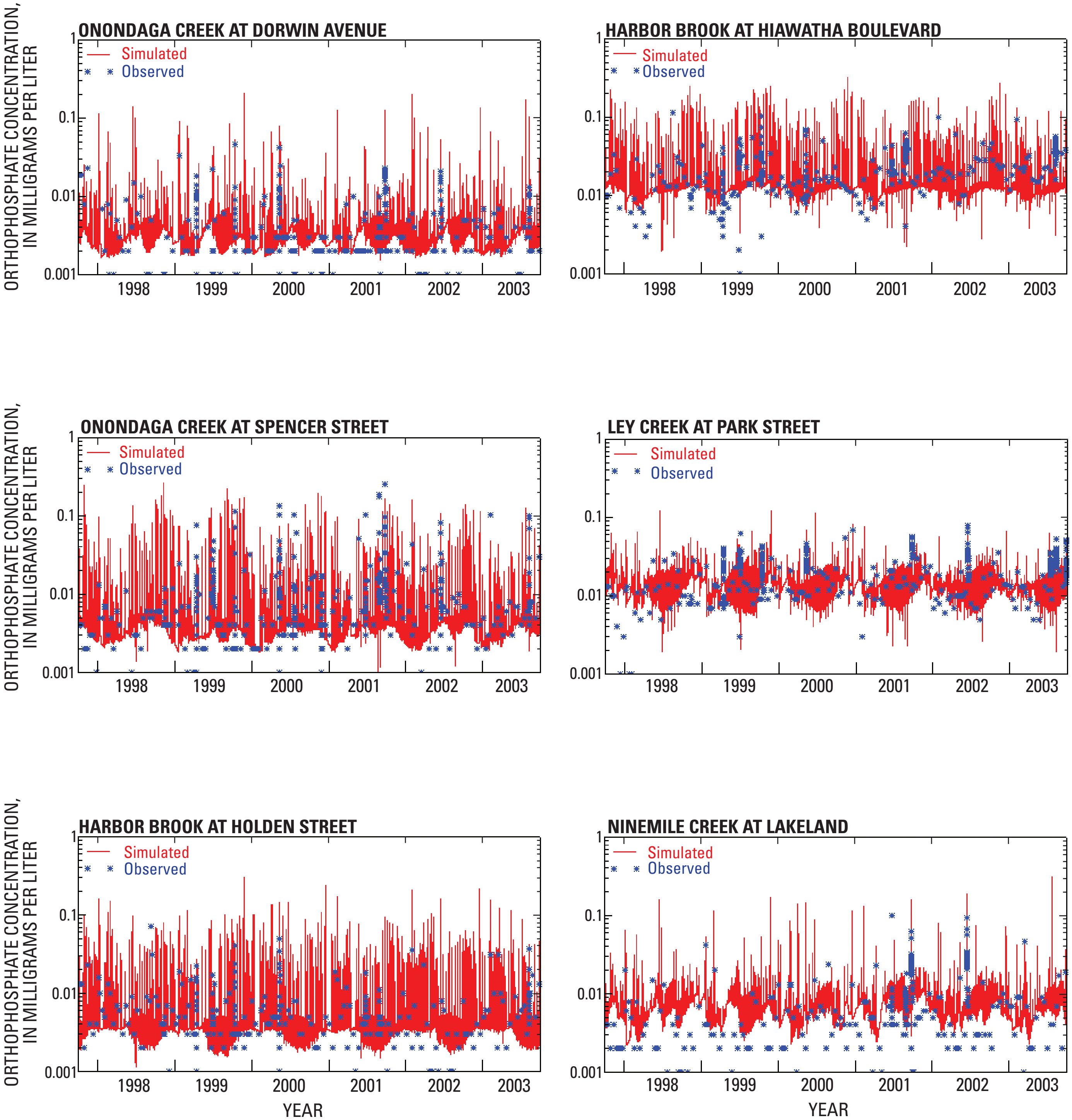

Figure 19. Observed and simulated concentrations of orthophosphate at six monitoring sites in the Onondaga Lake basin, Onondaga County, N.Y., 1997–2003.

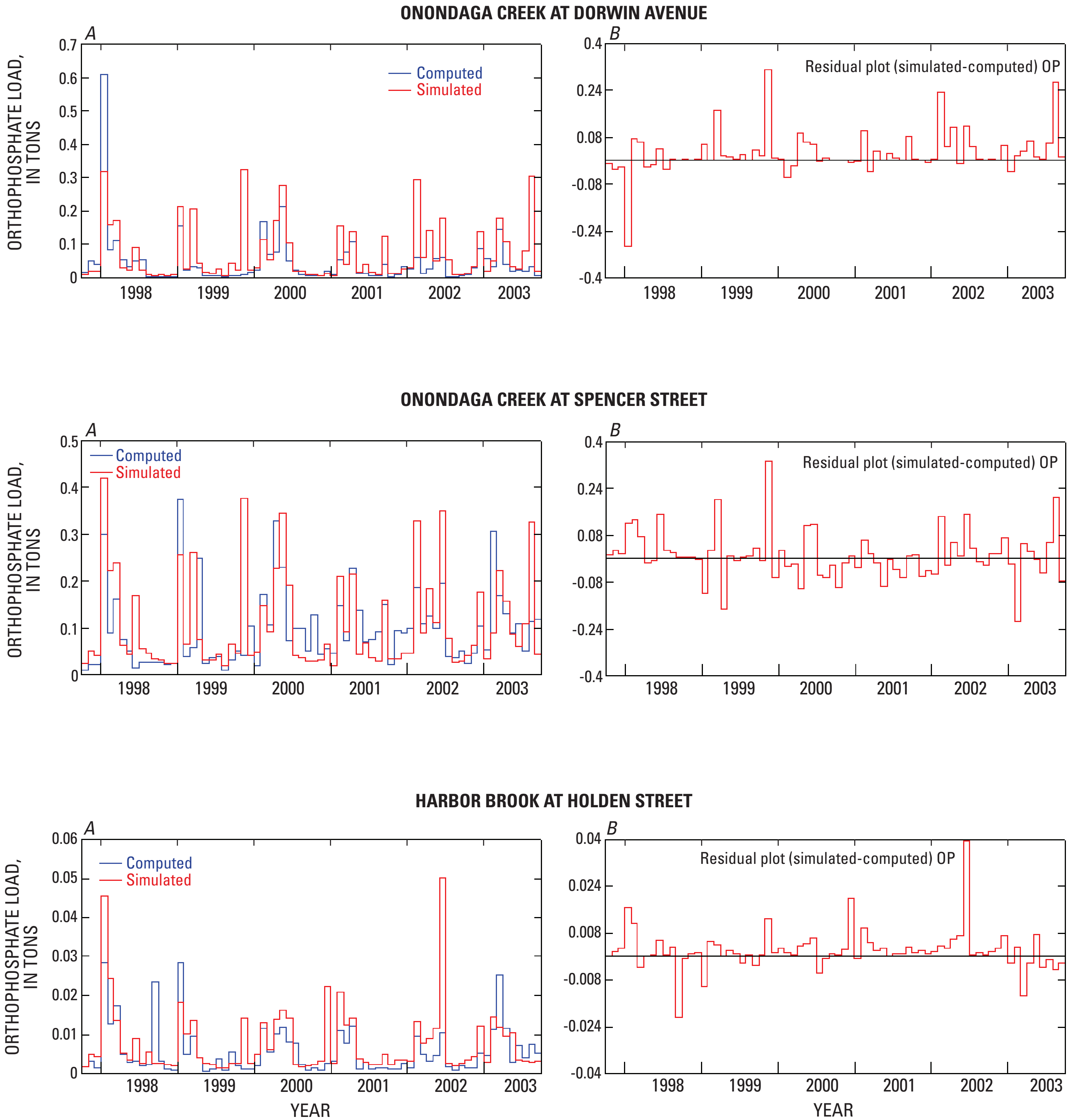

Figure 20. Monthly computed and simulated orthophosphate *(A)* loads and *(B)* residuals at six monitoring sites in the Onondaga Lake basin, Onondaga County, N.Y., 1997–2003.

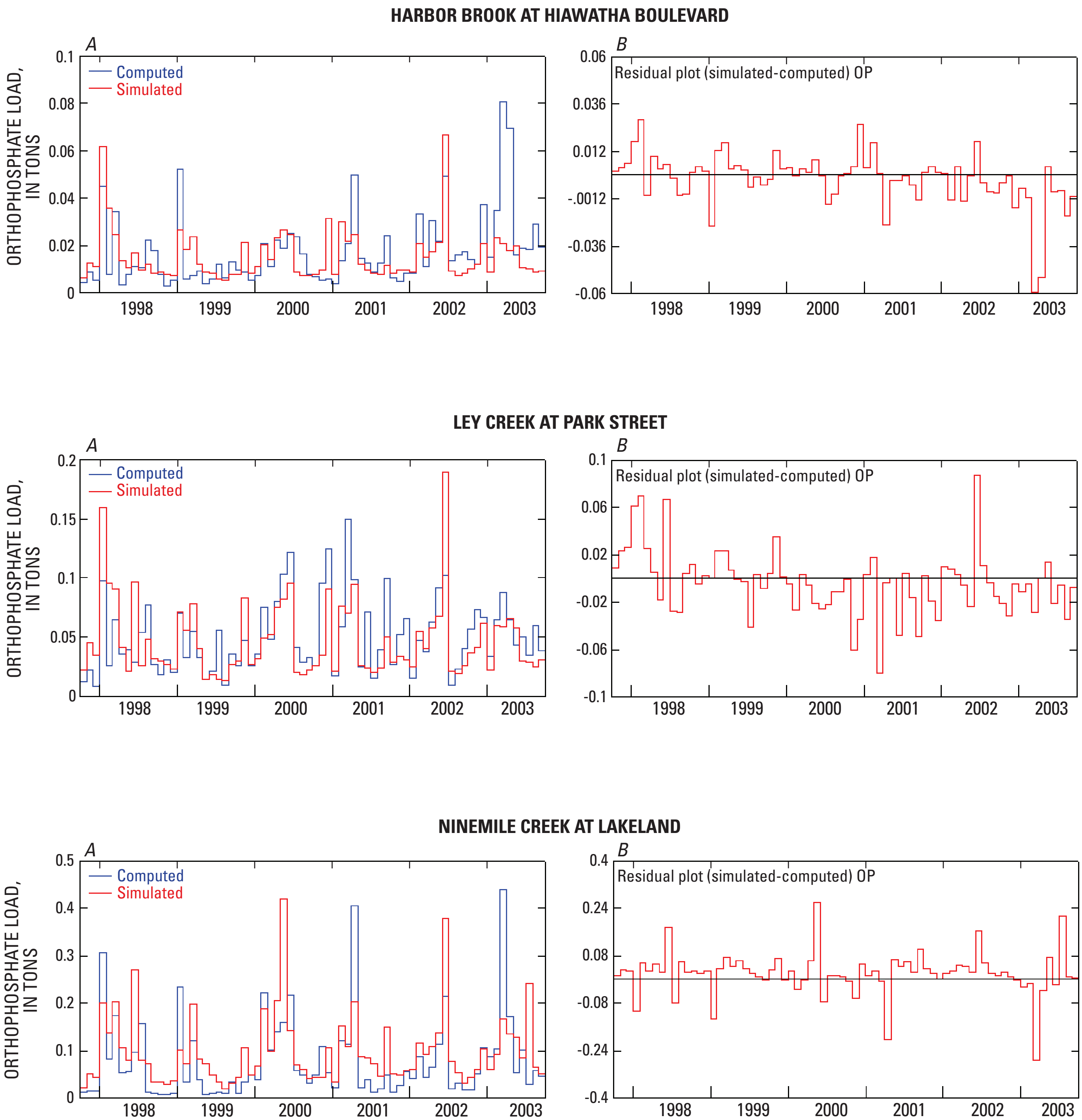

Figure 20. Monthly computed and simulated orthophosphate *(A)* loads and *(B)* residuals at six monitoring sites in the Onondaga Lake basin, Onondaga County, N.Y., 1997–2003.—Continued

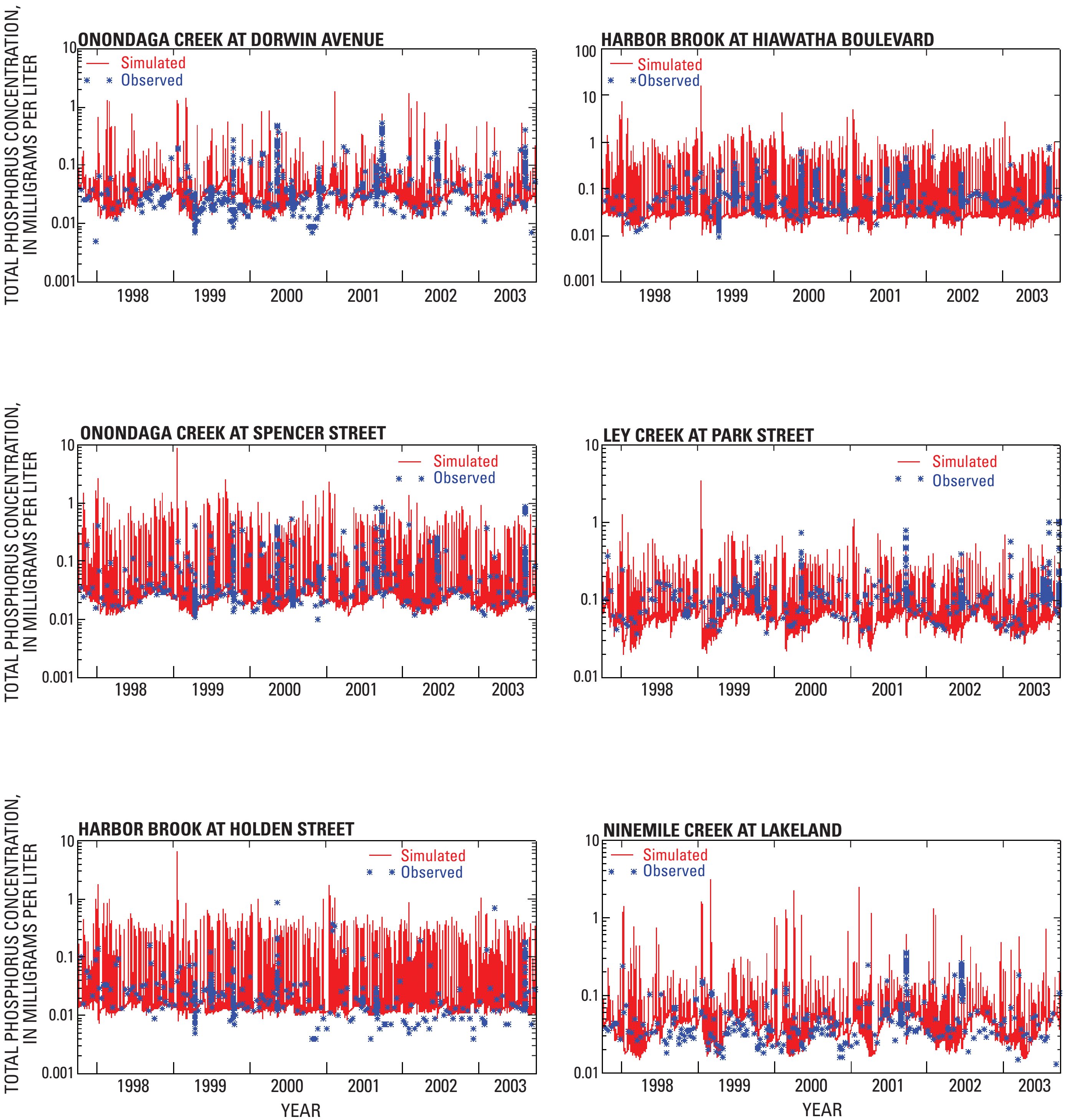

Figure 21. Observed and simulated concentrations of total phosphorus at six monitoring sites in the Onondaga Lake basin, Onondaga County, N.Y., 1997–2003.

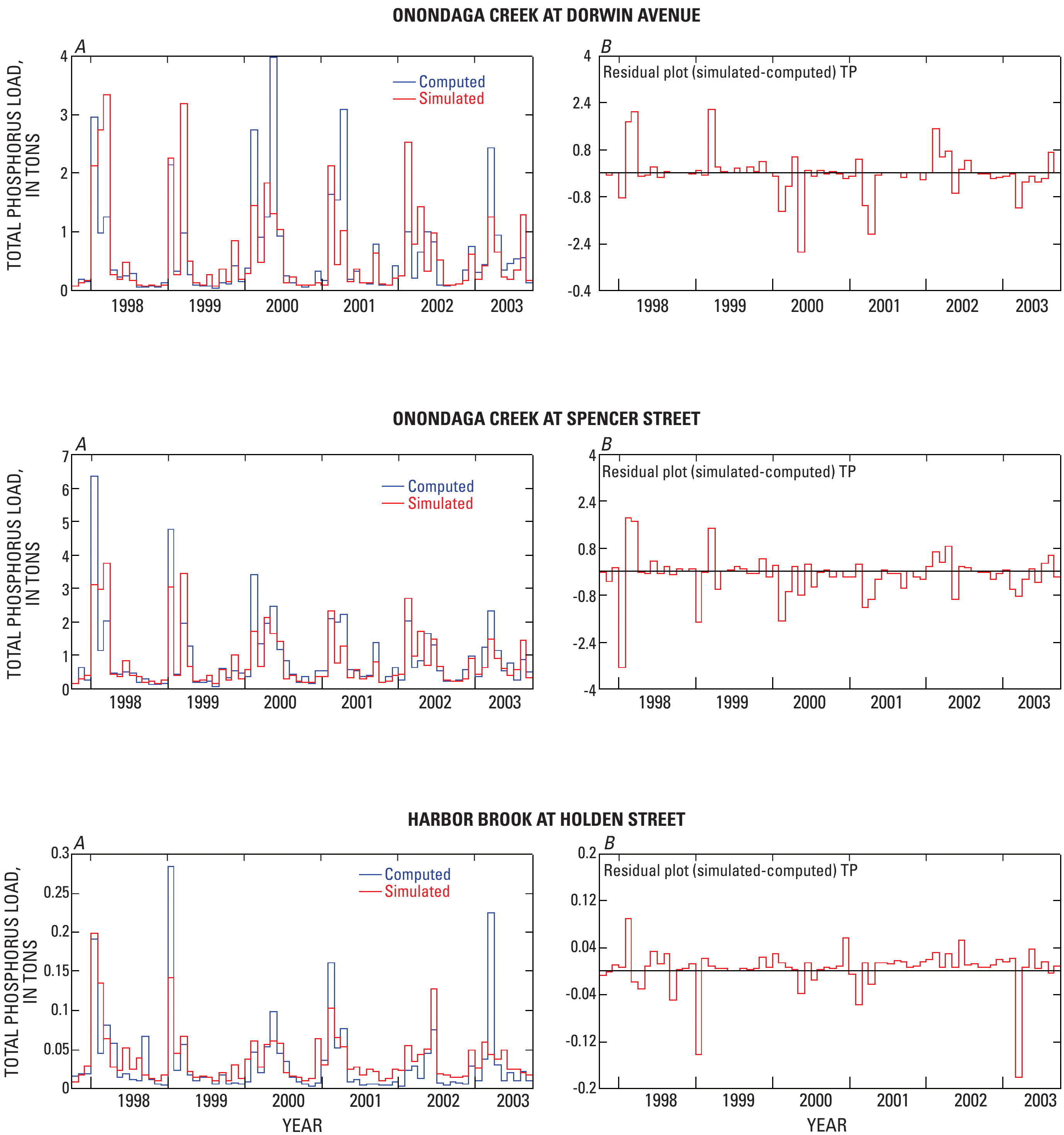

Figure 22. Monthly computed and simulated total phosphorus *(A)* loads and *(B)* residuals at six monitoring sites in the Onondaga Lake basin, Onondaga County, N.Y., 1997–2003.

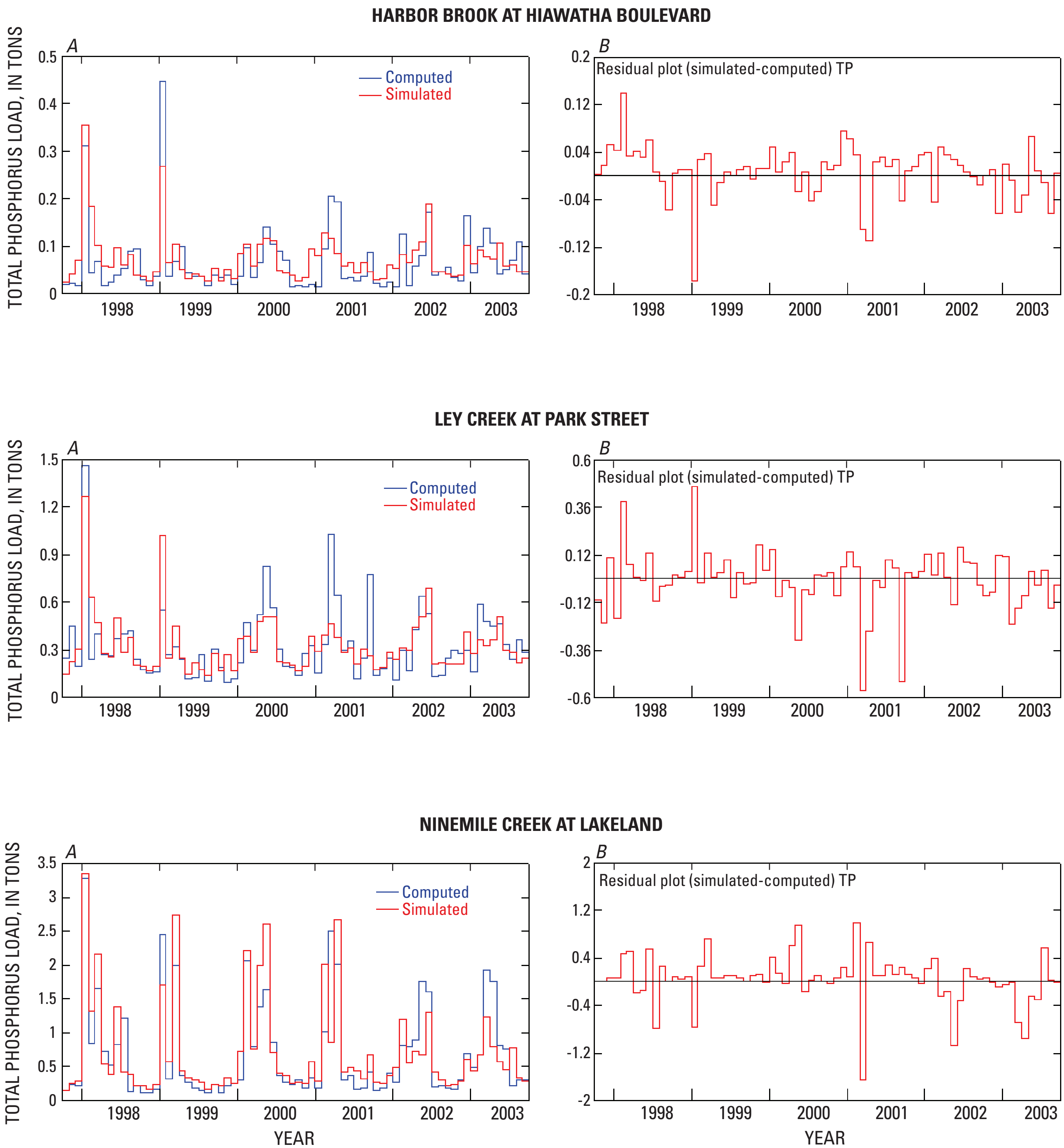

Figure 22. Monthly computed and simulated total phosphorus *(A)* loads and *(B)* residuals at six monitoring sites in the Onondaga Lake basin, Onondaga County, N.Y., 1997–2003.—Continued

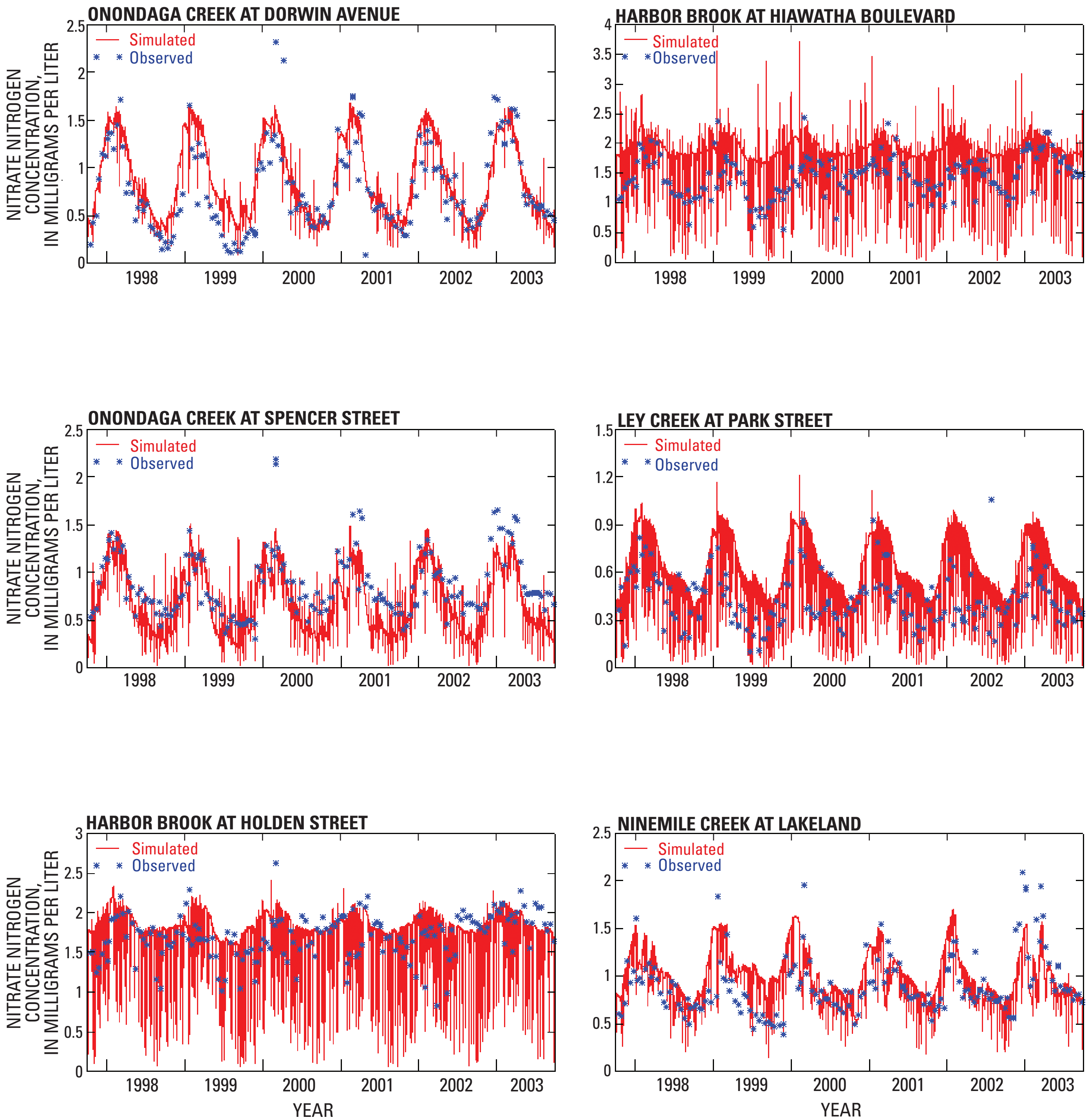

Figure 23. Observed and simulated concentrations of nitrate nitrogen at six monitoring sites in the Onondaga Lake basin, Onondaga County, N.Y., 1997–2003.

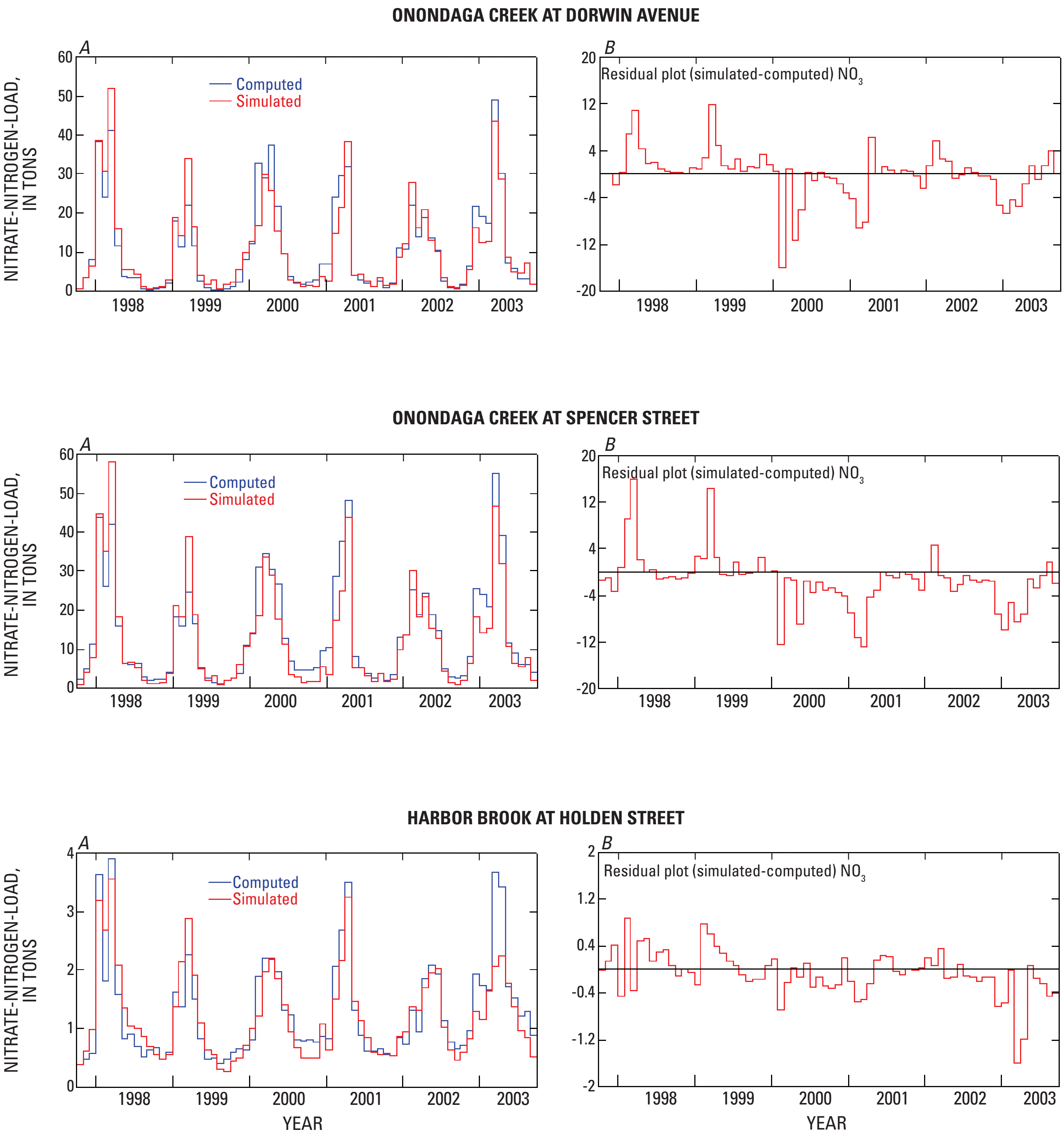

Figure 24. Monthly computed and simulated nitrate nitrogen *(A)* loads and *(B)* residuals at six monitoring sites in the Onondaga Lake basin, Onondaga County, N.Y., 1997–2003.

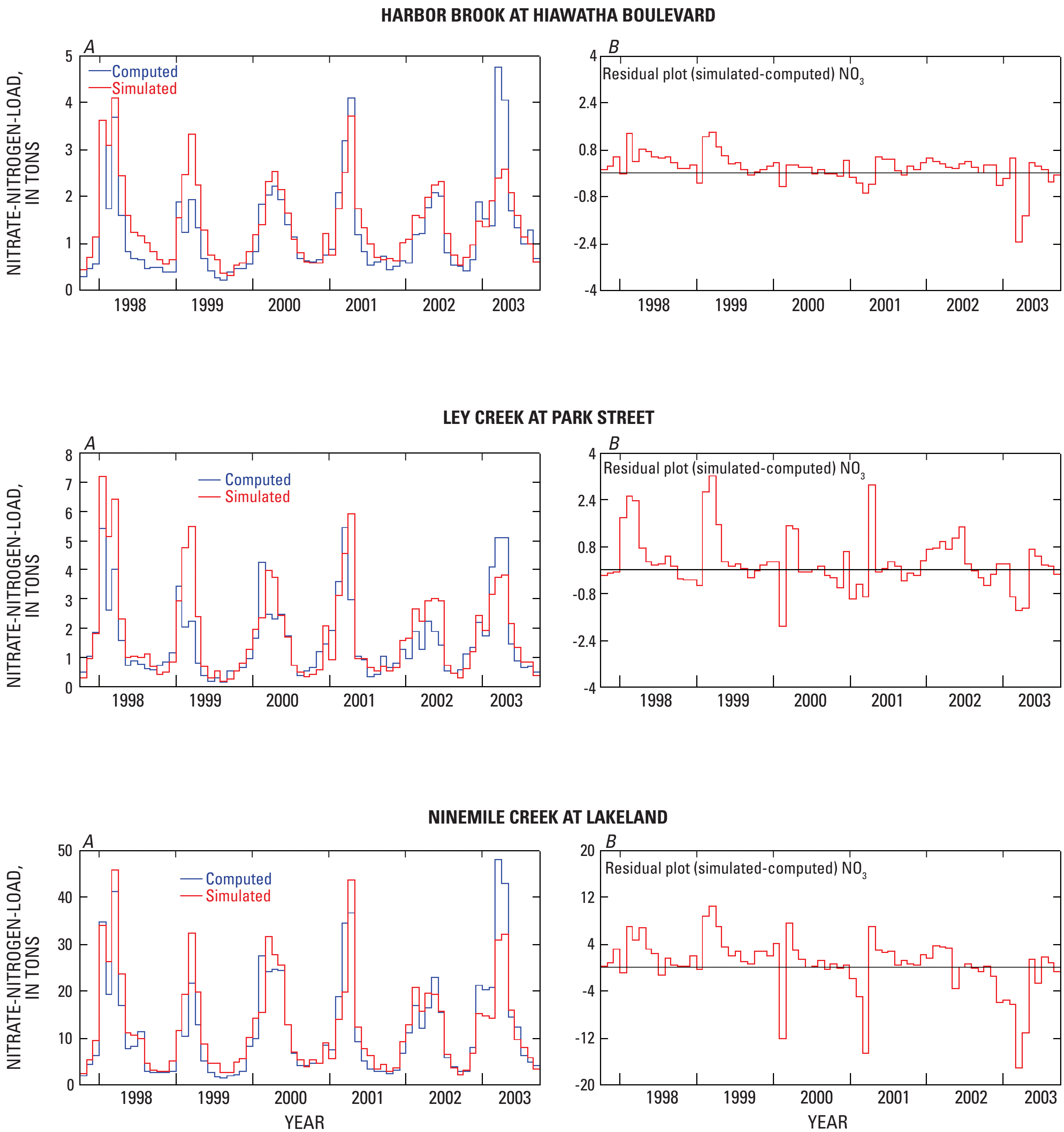

Figure 24. Monthly computed and simulated nitrate nitrogen *(A)* loads and *(B)* residuals at six monitoring sites in the Onondaga Lake basin, Onondaga County, N.Y., 1997–2003.—Continued

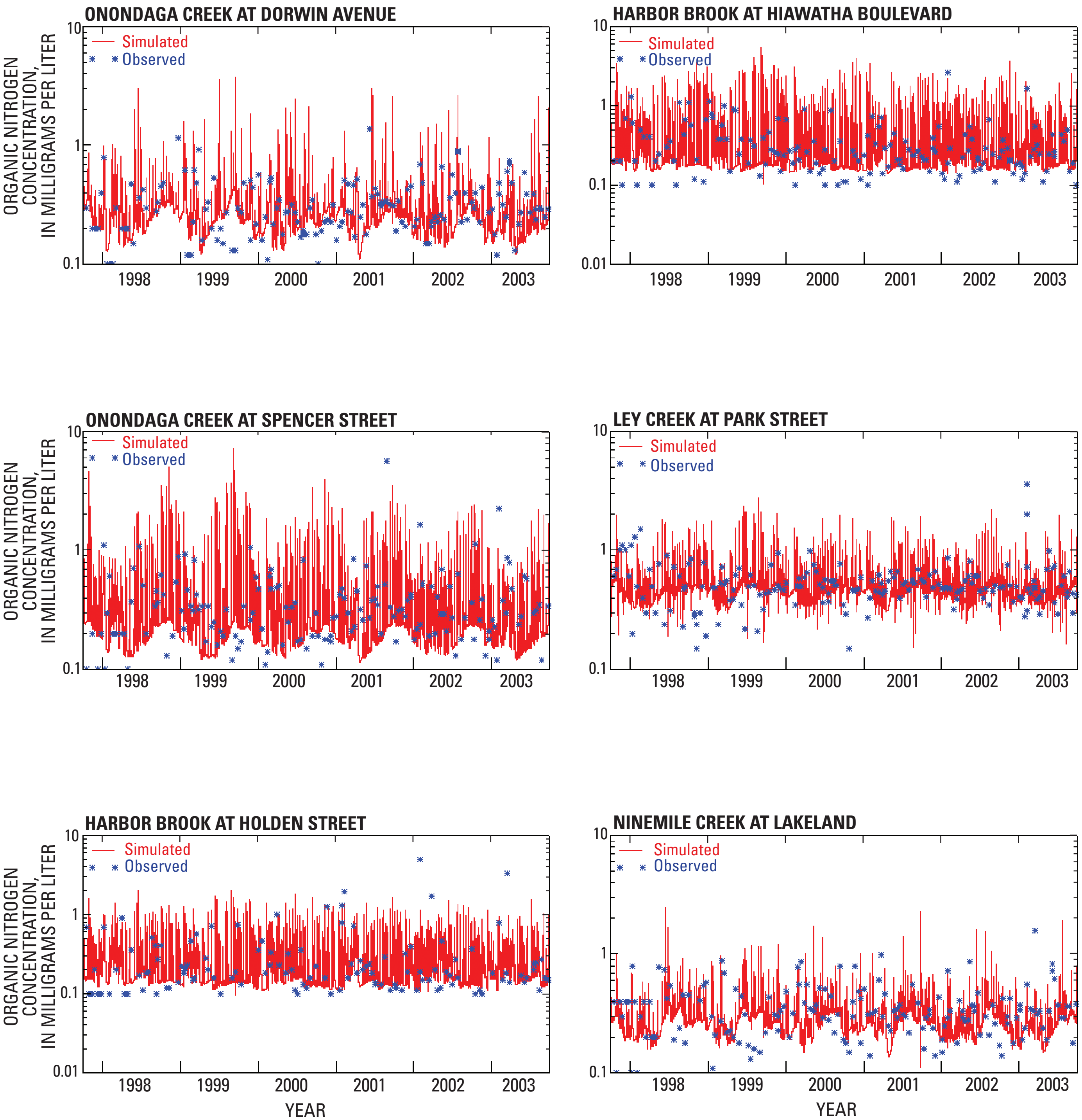

Figure 25. Observed and simulated concentrations of organic nitrogen at six monitoring sites in the Onondaga Lake basin, Onondaga County, N.Y., 1997–2003.

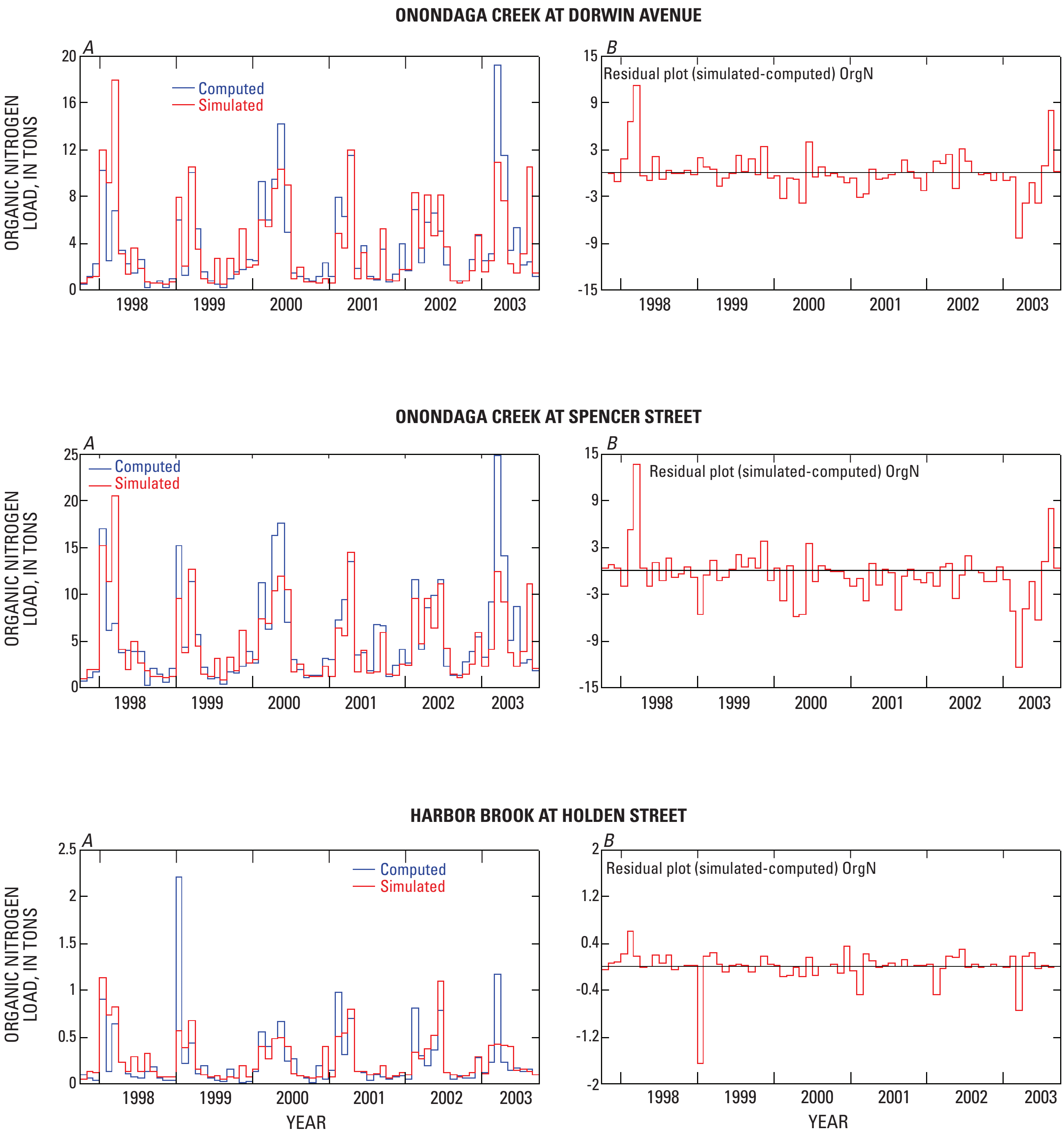

Figure 26. Monthly computed and simulated organic nitrogen *(A)* loads and *(B)* residuals at six monitoring sites in the Onondaga Lake basin, Onondaga County, N.Y., 1997–2003.

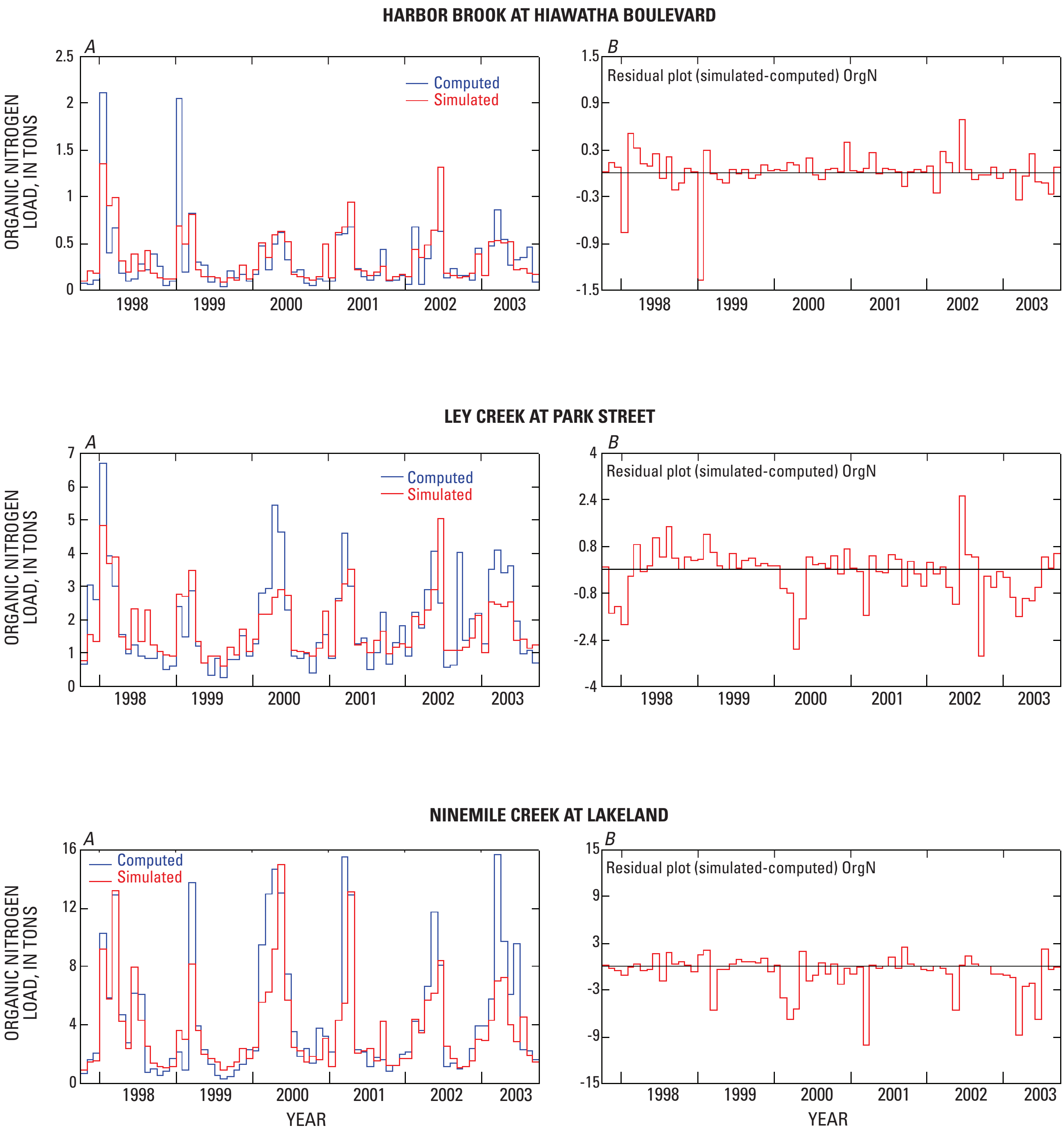

Figure 26. Monthly computed and simulated organic nitrogen *(A)* loads and *(B)* residuals at six monitoring sites in the Onondaga Lake basin, Onondaga County, N.Y., 1997–2003.—Continued

this constituent were adjusted to approximate measured concentrations and to yield loads that were of the same order of magnitude as computed loads (fig. 27). As a result, some residuals are large but are considered to be within acceptable magnitudes, except for January 1998 at Ninemile Creek at Lakeland (fig. 27). On the basis of model performance statistics, NH_3 load simulations ranged from "very good" at Ley Creek at Park Street to "fair" at Harbor Brook at Hiawatha Boulevard and Onondaga Creek at Spencer Street (mean error of -32 percent; table 16). Simulations of NH_3 loads at the other three calibration sites were rated "good".

Model Uncertainty

During development of the Onondaga Lake basin model, many assumptions were necessary to make a complex system manageable within a model structure and to enable use of limited or missing input and calibration data. For example, the driving mechanisms for both hydrologic and water-quality processes were assumed to be adequately described and controlled by the basin characteristics–land use and land cover, hydrologic soil group, and aspect. Precipitation data measured at a specific point in the basin were assumed to be error free, as well as representative of precipitation quantities throughout a large area. The measured constituent concentration data and computed constituent loads that were used for calibration of the water-quality components of the model were assumed to be error free. None of these assumptions, nor others not mentioned, are entirely valid; therefore, uncertainty in the model outputs is to be expected.

Sources of model uncertainty include (1) errors in precipitation data due to measurement error or an insufficient number of precipitation-monitoring sites to adequately represent the precipitation patterns over the basin, (2) limitations in model structure, (3) nonuniqueness of values for highly sensitive parameters, (4) errors or bias in data used to calibrate the different components of the model, (5) misclassification of land-use and land-cover data, (6) changes in land use during the simulation period, (7) unidentified sources or sinks of constituent loads and water-quality processes that varied over time, and (8) differences in scale between the large calibrated subbasins and the small subbasins to which calibrated parameter values were transferred. Some of these sources of uncertainty have been identified by researchers (Troutman, 1982, 1983; Chaubey and others, 1999; Carrubba, 2000; Wood and others, 1988, 1990; Doherty and Johnston, 2003) and can be minimized through attention to their respective causes, but are largely considered unavoidable in many models. Each of these sources of uncertainty is discussed below.

1. **Errors in precipitation data:** A precipitation-runoff model is driven primarily by the precipitation records, which are not only subject to measurement error but, due to a sparse network of measurement sites, can fail to adequately represent nonuniform precipitation patterns across the basin, especially during local summer thunderstorms. This inadequacy, in turn, can produce uncertainty in the model results (Troutman, 1982, 1983; Chaubey and others, 1999; Straub and Bednar, 2000). The three precipitation-monitoring sites that were available for model calibration were insufficient to capture the precipitation patterns across the basin. Comparison of the annual totals from the three sites indicated large differences in precipitation quantities—as much as 7 in/yr. Precipitation variability during summer thunderstorm periods might account for much of these discrepancies. A localized downpour either recorded or not recorded at a precipitation site will generate or fail to generate, respectively, the actual runoff that was produced by the storm some distance from the measurement site. Whether these differences were real or reflect measurement error, using one rather than all three available records to simulate precipitation across the entire basin likely would have introduced large errors and necessitated unwarranted adjustments to parameter values to improve the fit between observed and simulated data. Such adjustments of parameter values will unavoidably play this role in any model given that the error in input data is unknown.
2. **Limitations in model structure:** Land use and land cover, hydrologic soil group, and aspect were identified as the primary basin characteristics that controlled runoff processes and the generation of chemical loads. Other characteristics, such as surficial geology and slope, were considered, but their effects on the simulated processes were assumed to be included in the selected characteristics. The level of detail that was incorporated into the model by development of the HRUs and basin segmentation (as described in the section "Basin Representation") and by simulation of OP, TP, NO_3, and OrgN loads from the HRUs, rather than other constituents (as discussed in the section "Nutrients" under "Model Calibration and Performance"), was deemed appropriate and manageable. Different basin characteristics for development of the HRUs and different criteria for basin segmentation could have been used, and different water-quality constituents could have been simulated in model development, however.
3. **Nonuniqueness of values for highly sensitive parameters:** Many researchers have discussed the potential problems that could arise in modeling owing to the nonuniqueness of a calibrated parameter set (Doherty and Johnston, 2003); in other words, different sets of values assigned to sensitive parameters could yield a calibrated model, but not really simulate the actual hydrologic and water-quality processes occurring in the basin. Misspecification of parameter values is difficult to identify, especially when calibration datasets are limited. As more calibration sets are introduced and if calibration is performed on several datasets simultaneously, then the errors associated with misspecification of parameter

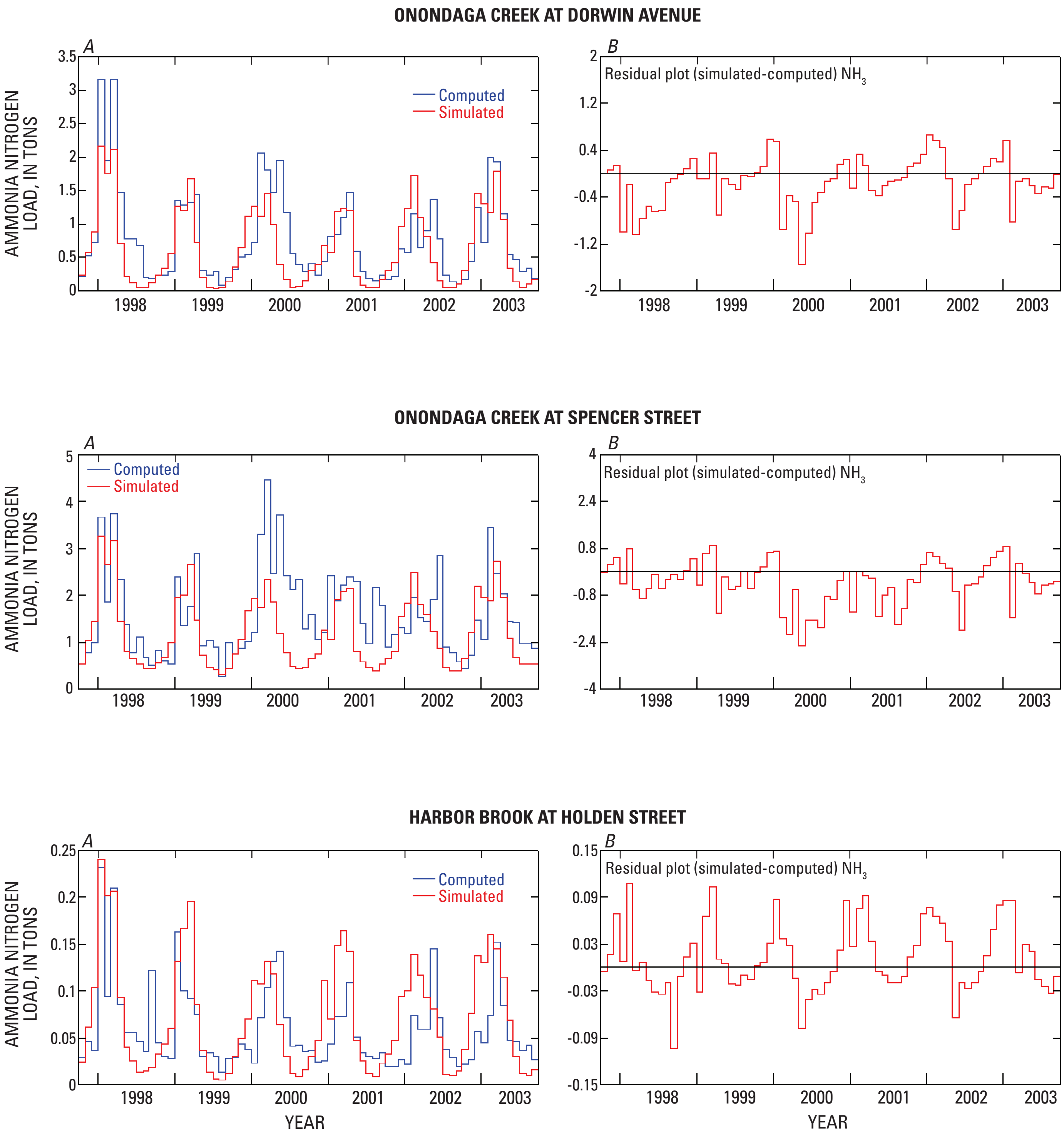

Figure 27. Monthly computed and simulated ammonia nitrogen *(A)* loads and *(B)* residuals at six monitoring sites in the Onondaga Lake basin, Onondaga County, N.Y., 1997–2003.

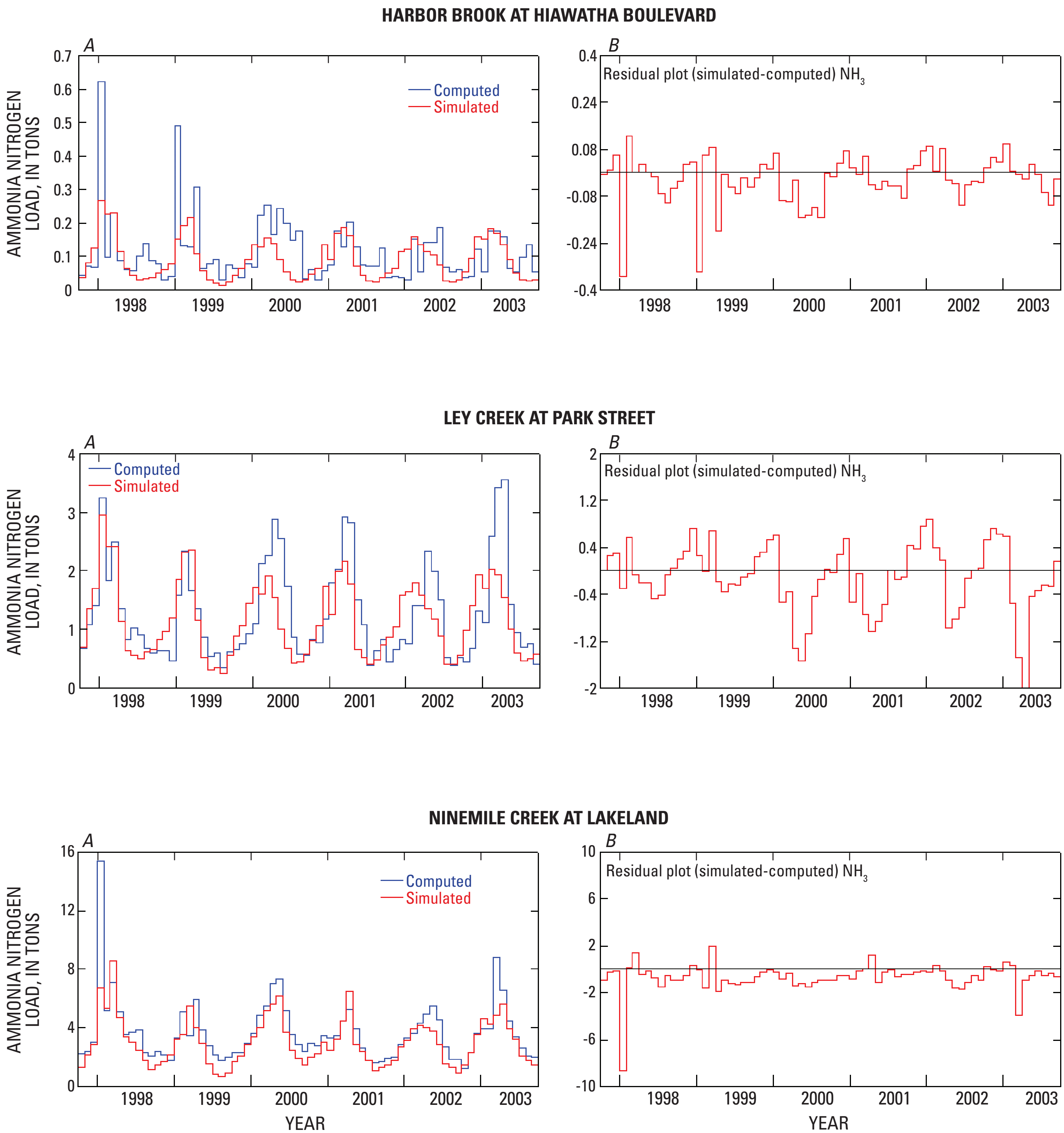

Figure 27. Monthly computed and simulated ammonia nitrogen *(A)* loads and *(B)* residuals at six monitoring sites in the Onondaga Lake basin, Onondaga County, N.Y., 1997–2003.—Continued

values should decrease. In the case of the Onondaga Lake basin model, at least two monitoring sites were located in each major subdivision of the basin and in most instances calibration spanned these subdivisions, such that the same parameter-value sets were used throughout the basin where possible. The only exceptions to this were the Harbor Brook and Otisco Lake subbasins, which exhibited hydrologic characteristics that required unique parameter-value sets to reasonably calibrate the flows in Harbor Brook and the storage volume of Otisco Lake.

4. **Errors or bias in calibration data:** Flow data used to calibrate runoff from the land surface and flows at the nine streamflow-monitoring sites could have contained errors, especially during any periods of missing or ice-affected data. Constituent-concentration data used for calibration could contain errors or a bias caused by improper collection, processing, or analysis of samples. In both cases, parameter values used to simulate flows and the generation and transformation of constituents will unavoidably reflect attempts to minimize the effects of these errors or biases in the model's output.

5. **Misclassification of land-use and land-cover data:** Land-use and land-cover data collected by satellite imagery are subject to error. A general field check of the data was conducted, but a thorough assessment of the accuracy of the data across the entire basin was impractical. Revisions to the NLCD dataset were made as described in the section "Hydrologic Response Units (HRUs)" under "Model Structure." Errors in land-use or land-cover classification affect the acreage values assigned to HRUs and, thus, affect the values of parameters assigned to simulate the hydrologic and water-quality processes within these HRUs.

6. **Changes in land use:** Changes in land use and land cover during the simulation period were discussed in the section "Hydrologic Response Units (HRUs)" under "Model Structure." Although land use will inevitably change over time, and its effect on the model was assumed to be negligible, a model user should be aware of future changes and the limitations they impose on the extrapolation of model results beyond the time period for which the model was developed. In other words, the Onondaga Lake basin model was developed using data that were collected during 1991–93 and were assumed to be applicable to basin conditions during 1997–2003. If a user desires to extend the period of simulation, and if land uses are greatly different from those that existed during 1997–2003, then the model should be updated to reflect these changes.

7. **Unidentified or variable water-quality processes:** The probable effects of the Marcellus WWTP effluent on the water quality of Ninemile Creek have been incorporated into the model. Unidentified sources of constituents, such as those associated with springs or industrial discharges, or identified sources with a seasonal or non-constant pattern will interfere with the calibration of concentrations and loads of these constituents. For example, a decrease in measured NO_3 concentrations in Harbor Brook from Holden Street to Hiawatha Boulevard (fig. 23) presumably due to denitrification within the intervening tunnel, was not replicated by the model. Similarly, measured DO concentrations (fig. 17) that showed a noticeable increase during the latter half of the simulation period at all monitoring sites could not be replicated; average conditions were simulated throughout the simulation period.

8. **Effect of subbasin scale:** The development of the HRUs required assumptions and parameter values that represented average conditions over a range of characteristics—land use, land cover, infiltration rate, and runoff potential—that were applicable at a basinwide scale. As subbasin size decreases, the ranges of values for the parameters used to simulate these characteristics—actual slope, overland flow length, upper- and lower-zone nominal storages, and infiltration-capacity and interflow indices—narrow and become increasingly uniform. Thus, the optimal parameter values for a given subbasin might depart from the basinwide averages. The ideal modeling situation, where parameter values remain constant regardless of subbasin size, probably does not occur because certain key parameters are likely to vary from one subbasin to another, even within the same geographic area (Donigian and others, 1983; Wood and others, 1988 and 1990; Laroche and others, 1996; Carrubba, 2000). Consequently, parameter values selected to minimize errors at a basinwide scale cannot be expected to yield satisfactory results at a local scale, where the subbasin characteristics can differ substantially from the basinwide averages.

The uncertainty associated with simulation of the hydrologic component of the model will unavoidably be passed along and contribute to the uncertainty in the simulated sediment loads. This is especially true for errors in the precipitation input. Because sediment loads are directly related to detachment of soil particles resulting from rainfall impact, washoff of sediment from pervious and impervious land types, and transport of sediment to and in stream channels, any errors in precipitation will affect simulated sediment loads. This error can be seen in the plots of measured total-suspended-solids and simulated suspended-sediment loads (fig. 18). Many of the monthly spikes in suspended-sediment loads resulted from spatial variability in precipitation as discussed in "Errors in precipitation data" above.

In a similar manner, the accurate simulation of water-quality data was dependent on the successful calibration of the hydrologic and sediment processes in the basin. Unlike the simulation of sediment, which was wholly a function of surface runoff, the simulations of nutrient loads were complicated by their possible associations with any of three flow paths—overland, interflow, and ground water. If the dominant flow component changed from subbasin to subbasin, then the dominant removal and transport mechanisms could change as well. The simulations of nutrient loads also were subject to (1) errors in the simulated processes of accumulation and removal of sediment from land surfaces and in the transport of that sediment from one reach to another, which controls the volume and transport of constituents associated with sediment, and (2) errors in simulated water temperature and dissolved oxygen concentrations, which strongly affect within-channel microbial activity and the transformations of nutrients.

Uses of the Model

The calibrated precipitation-runoff model of the Onondaga Lake basin has many potential uses. With the aid of a text editor and GenScn (Kittle and others, 1998), different scenarios can be simulated, and new datasets of nutrient loads can be generated for before-and-after comparisons within the time frame of the calibrated model. Possible scenarios could include simulation of (1) proposed land-use changes, (2) agricultural BMPs, (3) storm-runoff detention basins, and (4) additional closures and abatement of combined-sewer overflows in the City of Syracuse. A primary use of the model would be to generate time series of nutrient loads from scenarios such as these, and eventually provide these data as input to a hydrodynamic model of Onondaga Lake, which is currently (2007) being developed (Joseph Mastriano, Onondaga County Department of Water Environment Protection, written commun., 2007). The effects of the changes simulated by the scenarios could be assessed within and at the outlet of the lake. Model output also could be used to (1) prioritize areas of the basin in which mitigative measures to decrease sediment and nutrient loads could have the greatest beneficial effect on Onondaga Lake, and (2) estimate total maximum daily loads (TMDLs) for the lake. (See appendix 3 for information on how to obtain GenScn and HSPF, and identification of the pertinent files that are required to run the Onondaga Lake basin model.)

Model-Use Example as a Means to Assess Model Sensitivity

To assess the sensitivity of the model to the above-listed scenarios, an example of a land-use change has been created and simulated. In this test scenario, a 320-acre (0.5-mi^2) residential-commercial development is proposed for subbasin 103, which covers 1,536 acres and drains to RCHRES 103, a tributary of Onondaga Creek. (NOTE: This scenario is completely hypothetical; there are no current or future plans by any private or public entity to develop this subbasin for residential or commercial uses.) About 67 and 28 percent of the subbasin is forested and in pasture-hay, respectively. Assume that the proposed development will be constructed in an area that is presently classified as forest with a mix of north- and south-facing slopes and soils with both high and low runoff potentials (PERLNDs 1–4, from table 11). Assume also that 160 and 120 acres will be converted to low- and high-density residential uses, respectively, and the remaining 40 acres will be converted to commercial, transportation, or industrial uses. The probable effects of this development on flows and water quality at the downstream end of RCHRES 103 are shown in figure 28. Note that with an increase in impervious area, peak flows and total runoff from the subbasin are greater, as are loads of sediment and most chemical constituents. Loads of nitrate nitrogen decrease, however.

Summary

During 2003–07, the U.S. Geological Survey developed a precipitation-runoff model of the Onondaga Lake basin. This model is based on the computer program, Hydrological Simulation Program–FORTRAN (HSPF), and simulated (1) overland flow to, and streamflow in, the major tributaries of Onondaga Lake, and (2) loads of sediment, phosphorus, and nitrogen that were washed from the land surfaces and transported to Onondaga Lake by the major tributaries. The simulation period extends from October 1997 through September 2003.

The Onondaga Lake basin was divided into 107 subbasins primarily on the basis of drainage area, geomorphic changes along the main channels of the basin, and streamflow travel time through the reach associated with a given subbasin. The average drainage area of the subbasins used in the model is about 2.5 mi^2. Within these subbasins, the land area was apportioned among 19 pervious and impervious land types, or hydrologic response units (HRUs), on the basis of land use and land cover, hydrologic soil group (HSG), and aspect. Each HRU was assumed to show consistent hydrologic and water-quality responses to precipitation and other meteorological inputs. Land type and HSG were assumed to adequately represent the runoff potential of each HRU; aspect was included to improve simulation of snowmelt processes in the basin. Forest and pasture-hay land types dominate the southern part of the basin. Developed land types increase northward and dominate the area around Onondaga Lake

Precipitation data from three sites—Hancock Airport, Tully Valley, and Otisco Lake—were used as input to the model. The basin was divided into three areas approximately defined by Thiessen polygons, and one precipitation record was assigned to each of these areas. Other required meteorological time series were obtained directly from, or derived from data collected at, the Hancock Airport weather station.

The Onondaga Lake basin model simulated streamflow, water temperature, concentrations of dissolved oxygen, and concentrations and loads of sediment, orthophosphate, total phosphorus, nitrate, ammonia, and organic nitrogen in the

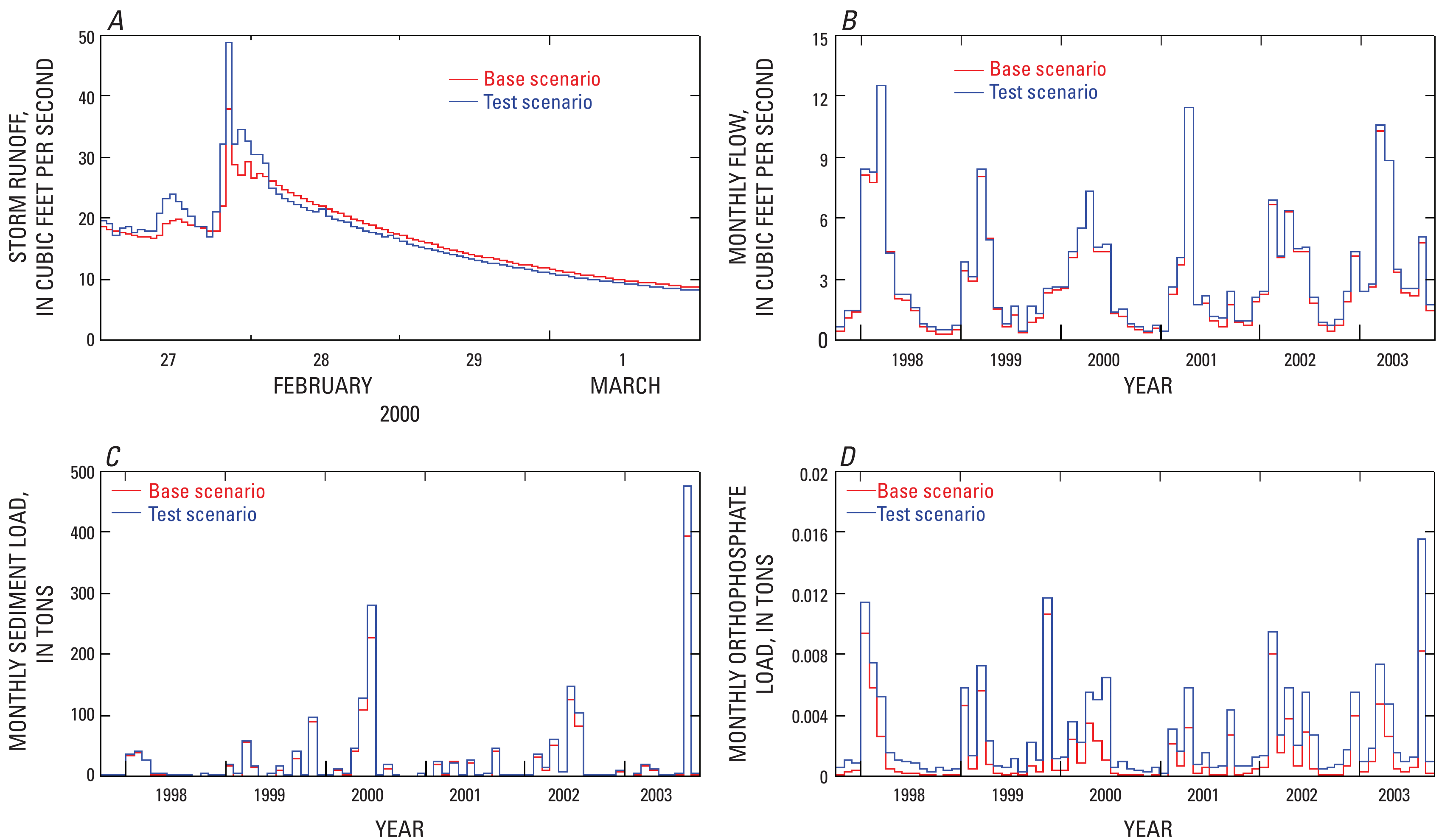

Figure 28. Probable effects of hypothetical land-use changes on *(A)* storm runoff, *(B)* monthly flows, *(C)* monthly loads of sediment, *(D)* monthly loads of orthophosphate, *(E)* monthly loads of total phosphorus, *(F)* monthly loads of nitrate nitrogen, and *(G)* monthly loads of organic nitrogen from an Onondaga Creek subbasin, Onondaga Lake basin, Onondaga County, N.Y.

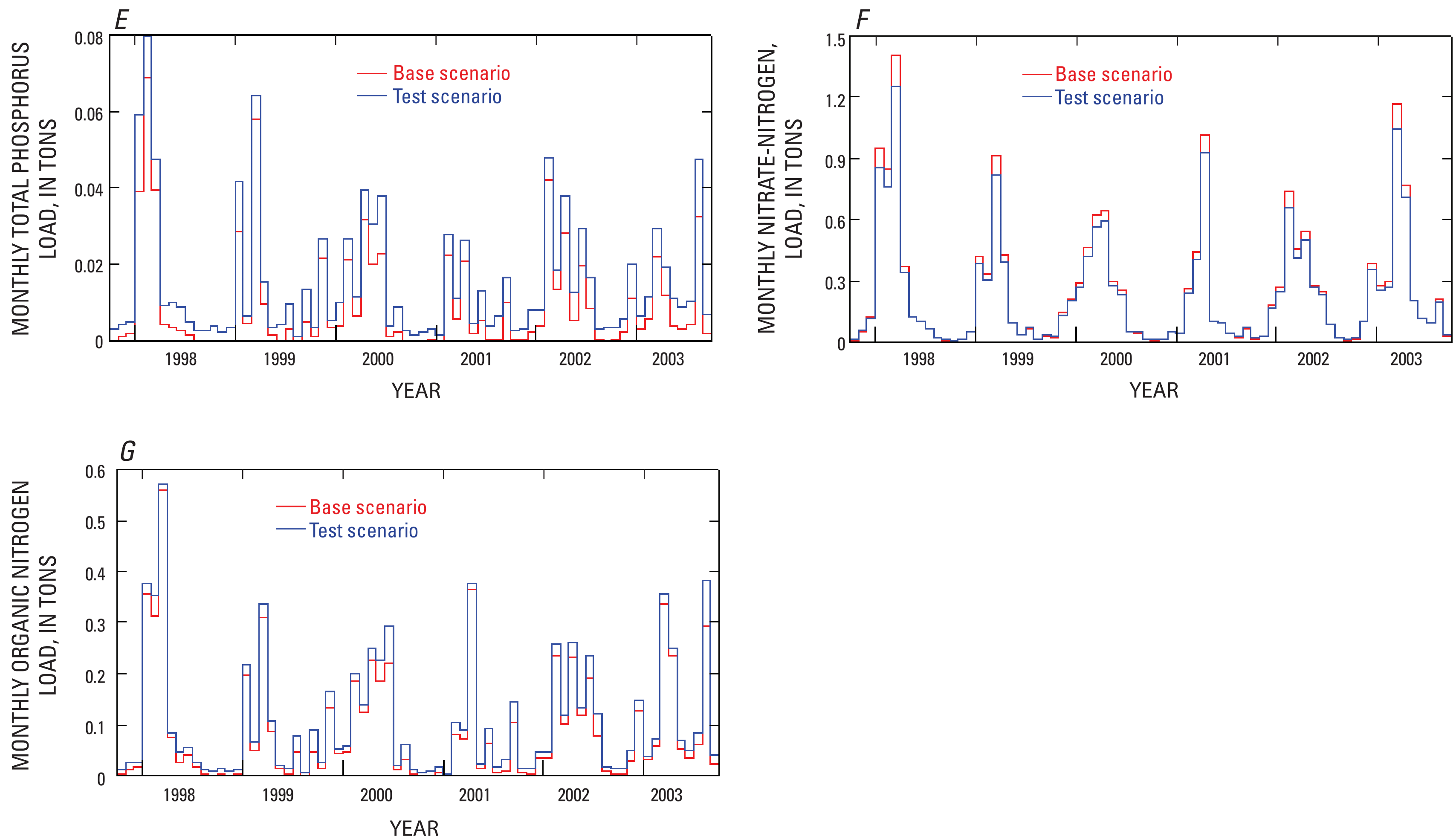

Figure 28. Probable effects of hypothetical land-use changes on *(A)* storm runoff, *(B)* monthly flows, *(C)* monthly loads of sediment, *(D)* monthly loads of orthophosphate, *(E)* monthly loads of total phosphorus, *(F)* monthly loads of nitrate nitrogen, and *(G)* monthly loads of organic nitrogen from an Onondaga Creek subbasin, Onondaga Lake basin, Onondaga County, N.Y.—Continued

four major tributaries to Onondaga Lake—Onondaga Creek, Harbor Brook, Ley Creek, and Ninemile Creek. Simulated flows were calibrated to data from nine USGS streamflow-monitoring sites; simulated nutrient concentrations and loads were calibrated to data collected at six of the nine streamflow sites by personnel from the Onondaga County Department of Water Environment Protection. Measured inflows and sediment loads from the Tully Valley mudboils were input to Onondaga Creek. Estimated nutrient loads from Otisco Lake and the Marcellus wastewater-treatment plant (WWTP) were input to Ninemile Creek. Spring discharges were estimated and input to Onondaga Creek, Harbor Brook, and Ninemile Creek. The surface losses from Disappearing Lake were routed to Ninemile Creek downstream from Marcellus Falls. Surface runoff from the impervious combined sanitary-and-storm-sewer areas of Syracuse was decreased by an estimated volume to simulate flow that was carried through storm sewers to the Syracuse Metropolitan (METRO) WWTP. The remainder of the runoff, which was in excess of the 240 Mgal/d maximum flow rate of the WWTP, was routed, along with its associated chemical loads, to nearby streams. Onondaga Reservoir and Otisco Lake have great mitigative effects on loads of sediment and particulate constituents being transported by Onondaga and Ninemile Creeks, respectively. These effects were simulated by adjustment of the parameter values that controlled sediment settling rates, deposition, and scour.

Graphical comparisons of observed and simulated data and relevant statistics were used to assess model performance. Simulated daily and monthly flows were rated “very good” (within 10 percent of observed flows) at all monitoring sites except Onondaga Creek at Cardiff, which was rated “fair” (15–25 percent difference). Simulations of monthly average water temperatures were rated “very good” (within 7 percent of observed temperatures) at all sites. No observed data were available by which to directly assess the model’s simulation of suspended-sediment loads. Available data on measured loads of total suspended solids provided an indirect means of comparison but, not surprisingly, yielded “fair” to “poor” ratings (greater than 30 percent difference) for simulated monthly sediment loads at half the water-quality monitoring sites. Simulations of monthly orthophosphate loads ranged from “very good” (within 15 percent of measured loads) at three sites to “poor” (greater than 35 percent difference) at one site; those of ammonia nitrogen loads ranged from “very good” at one site to “fair” (between 25–35 percent difference) at two sites. Simulations of monthly total phosphorus, nitrate, and organic nitrogen loads were generally rated “very good” at all monitoring sites.

Uncertainty in model results could arise from (1) errors in precipitation data, (2) limitations in model structure, (3) nonuniqueness of values for highly sensitive parameters, (4) errors or bias in data used to calibrate the different components of the model, (5) misclassification of land-use and land-cover data, (6) changes in land use during the simulation period, (7) unidentified sources or sinks of chemical loads and water-quality processes that varied over time, and (8) differences in scale between large calibrated subbasins and small subbasins to which calibrated parameter values were transferred. Uncertainty in simulations of water-quality constituents was compounded by uncertainty in the model results on which the water-quality processes were based. Therefore, sediment simulations would be affected by uncertainty in the simulation of hydrology, and nutrient simulations would be affected by uncertainty in both the hydrologic and sediment processes, as well as, in simulations of water temperature and concentrations of dissolved oxygen.

The calibrated model can be used to simulate scenarios that represent planned or hypothetical development and implementation of BMPs in the Onondaga Lake basin, and to assess the effects that these changes and practices are likely to have on rural and urban nonpoint sources of pollution to Onondaga Lake. Model results also can be used as input to a hydrodynamic model of Onondaga Lake that is being developed by Onondaga County and to prioritize areas of the basin where mitigative measures to decrease sediment and nutrient loads could provide the greatest benefits to Onondaga Lake.

Acknowledgments

Numerous agencies and people assisted in the compilation of data that were required to calibrate the model. The personnel of the Onondaga County Department of Water Environment Protection, in particular Joseph Mastriano, Jeanne Powers, Antonio Deskins, Janaki Suryadevara, Nicholas Capozza, and Christopher Dietman, provided water-quality data from sites in WEP’s Ambient Monitoring Program, and flow and water-quality data for the Syracuse Metropolitan wastewater-treatment plant. Mark Murphy, manager of the Onondaga County Water Authority water-treatment plant near Marcellus, provided data on Otisco Lake water levels and withdrawals, as well as precipitation data. John Hopkins, operator of the Marcellus wastewater-treatment plant, provided water-quality data for Ninemile Creek near the plant. Clifford Callinan, New York State Department of Environmental Conservation, provided water-quality data for Otisco Lake.

Jeffrey Carmichael, Director, and Brian Hall of the Onondaga County Soil and Water Conservation District provided data on farming and dairy operations in the Onondaga Lake basin. Daniel Davis and Christopher Somerlot of Brown and Caldwell Consultants provided maps and a computer model of the Syracuse combined storm-and-sanitary-sewer systems, and answered many questions regarding that system’s operation. Dr. Angelica L. Gutierrez-Magness, USGS, Baltimore, Md., and Dr. John Doherty, Watermark Numerical Computing, Brisbane, Australia, provided assistance in the use of PEST for calibration of the Onondaga Lake basin model.

References Cited

Beaulac, M.N., and Reckhow, K.H., 1982, An examination of land use-nutrient export relationships: Water Resources Bulletin, v. 18, no. 6, p. 1013–1024.

Bergman, M.J., and Donnangelo, L.J., 2000, Simulation of freshwater discharges from ungaged areas to the Sebastian River, Florida: Journal of the American Water Resources Association, v. 36, no. 5, p. 1121–1132.

Bergman, M.J., Green, W., and Donnangelo, L.J., 2002, Calibration of storm loads in the South Prong watershed, Florida: Journal of the American Water Resources Association, v. 38, no. 5, p. 1423–1436.

Berris, S.N., 1995, Conceptualization and simulation of runoff generation from rainfall for three basins in Thurston County, Washington: U.S. Geological Survey Water-Resources Investigations Report 94–4038, 149 p.

Bicknell, B.R., Imhoff, J.C., Kittle, J.L., Jr., Jobes, T.H., and Donigian, A.S., Jr., 2001, Hydrological Simulation Program—Fortran, user's manual for version 12: Athens, Ga., U.S. Environmental Protection Agency, 873 p., accessed April 15, 2005, at http://www.epa.gov/docs/ostwater/BASINS/bsnsdocs.html#hspf

Blatchley, T.C., 2000, A streambank and roadbank erosion inventory of the Onondaga Creek watershed, Onondaga County, New York: Lafayette, N.Y., Onondaga County Soil and Water Conservation District, 35 p.

Bohman, L.R., Berris, S.N., and Hess, G.W., 1995, Interactive computer program to simulate and analyze streamflow, Truckee and Carson Rivers basins, Nevada and California: U.S. Geological Survey Fact Sheet 165–95, 5 p.

Brown and Caldwell, 2005, Onondaga Lake watershed nonpoint source environmental benefits project (EBP), Round II, Onondaga County, N.Y.: Syracuse, N.Y., Central New York Regional Planning and Development Board, paginated by section.

Callinan, C.W., 2001, Water quality study of the Finger Lakes: New York State Department of Environmental Conservation, 152 p., accessed February 2005, at http://www.dec.state.ny.us/website/dow/fingerlakes/

Carrubba, Lee, 2000, Hydrologic modeling at the watershed scale using NPSM: Journal of the American Water Resources Association, v. 36, no. 6, p. 1237–1246.

Chaubey, I., Haan, C.T., Salisbury, J.M., and Gruwald, S., 1999, Quantifying model output uncertainty due to spatial variability of rainfall: Journal of the American Water Resources Association, v. 35, no. 5, p. 1113–1123.

Clesceri, N.L., Curran, S.J., and Sedlak, R.I., 1986, Nutrient loads to Wisconsin lakes—Part I. Nitrogen and phosphorus export coefficients: Water Resources Bulletin, v. 22, no. 6, p. 983–990.

Coon, W.F., and Johnson, M.S., 2005, Effects of land-use changes and stormflow-detention basins on flooding and nonpoint-source pollution, in Irondequoit Creek Basin, Monroe and Ontario Counties, New York—Application of a precipitation-runoff model: U.S. Geological Survey Scientific Investigations Report 2005–5070, 67 p.

Coulter, C.B., Kolka, R.K., and Thompson, J.A., 2004, Water quality in agricultural, urban, and mixed land use watersheds: Journal of the American Water Resources Association, v. 40, no. 6, p. 1593–1601.

Coyle, E.E., 2002, A GIS non-point source pollution model of the Onondaga Lake watershed: Syracuse, N.Y., State University of New York, College of Environmental Science and Forestry, Department of Environmental and Resource Engineering, Master of Science thesis, 156 p.

Crawford, J.K., and Lenat, D.R., 1989, Effects of land use on the water quality and biota of three streams in the Piedmont province of North Carolina: U.S. Geological Survey Water-Resources Investigations Report 89–4007, 67 p.

Davis, S.N., and DeWiest, R.J.M., 1966, Hydrogeology: New York, N.Y., John Wiley & Sons, 463 p.

DeGloria, S.D., Pacenka, S., Porter, M.J., Anderson, G., Smith, W.G., Weingart, D., Bladon, R., and Baveye, P., 1999, Applicability of a simulation model to determine the environmental fate of atrazine in the Canajoharie Creek watershed, New York: New York State Water Resources Institute, Cornell University, Ithaca, N.Y., accessed September 2000, at http://www.cfe.cornell.edu/wri/projects/pesticides/canajoharie/fr/canafinal0.html

Dinicola, R.S., 1990, Characterization and simulation of rainfall-runoff relations for headwater basins in western King and Snohomish Counties, Washington: U.S. Geological Survey Water-Resources Investigations Report 89–4052, 52 p.

Dinicola, R.S., 1997, Estimates of recharge from runoff at the Hanford site, Washington: U.S. Geological Survey Water-Resources Investigations Report 97–4038, 172 p.

Dinicola, R.S., 2001, Validation of a numerical modeling method for simulating rainfall-runoff relations for headwater basins in western King and Snohomish Counties, Washington: U.S. Geological Survey Water-Supply Paper 2495, 162 p.

Dodd, R.C., McMahon, G., and Stichter, S., 1992, Watershed planning in the Albemarle-Pamlico estuarine system, Report 1—Annual average nutrient budgets: Raleigh, N.C., U.S. Environmental Protection Agency, Center for Environmental Analysis, Report 92–10.

Doherty, John, 2002, PEST—model-independent parameter estimation (4th ed.): Brisbane, Australia, Watermark Numerical Computing, pagination by section.

Doherty, John, 2003, PEST surface water utilities: Brisbane, Australia, Watermark Numerical Computing and University of Idaho, 81 p., plus appendices.

Doherty, John, and Johnston, J.M., 2003, Methodologies for calibration and predictive analysis of a watershed model: Journal of the American Water Resources Association, v. 39, no. 2, p. 251–265.

Donigian, A.S., Jr., 2002, Watershed model calibration and validation—the HSPF experience: Water Environment Federation National TMDL Science and Policy 2002, Phoenix, Ariz., November 13–16, 2002, Specialty Conference Proceedings, 30 p., accessed September 2003, at http://www.aquaterra.com/TMDL.Nov02.Donigian.Paper.doc

Donigian, A.S., Jr., Chinnaswamy, R.V., and Jobes, T.H., 1997, Conceptual design of multipurpose detention facilities for flood protection and nonpoint source pollution control: Mountain View, Calif., Aqua Terra Consultants, 151 p.

Donigian, A.S., Jr., and Huber, W.C., 1991, Modeling of nonpoint source water quality in urban and non-urban areas: Athens, Ga., U.S. Environmental Protection Agency, EPA-600/3–91–039, 78 p.

Donigian, A.S., Jr., Imhoff, J.C., and Bicknell, B.R., 1983, Predicting water quality resulting from agricultural nonpoint source pollution via simulation—HSPF, *in* Schaller, F.W., and Bailey, G.W., eds., Agricultural Management and Water Quality: Ames, Iowa, Iowa State University Press, p. 200–249.

Donigian, A.S., Jr., Imhoff, J.C., Bicknell, B.R., and Kittle, J.L., Jr., 1984, Application guide for Hydrological Simulation Program—FORTRAN (HSPF): U.S. Environmental Protection Agency, EPA-600/3–84–065, 177 p.

Donigian, A.S., Jr., and Love, J.T., 2002, The Connecticut watershed model—a tool for BMP impact assessment in Connecticut: Water Environment Federation-Watershed 2002, Fort Lauderdale, Fla., February 23–27, 2002, Proceedings, 20 p.

Donigian, A.S., Jr., and Love, J.T., 2003, Sediment calibration procedures and guidelines for watershed modeling: Water Environment Federation TMDL 2003, Chicago, Ill., November 16–19, 2003, Specialty Conference Proceedings, 20 p., accessed May 2004, at http://www.aquaterra.com/publications.html

Duncker, J.J., and Melching, C.S., 1998, Regional rainfall-runoff relations for simulation of streamflow for watersheds in DuPage County, Illinois: U.S. Geological Survey Water-Resources Investigations Report 98–4035, 80 p.

Duncker, J.J., Vail, T.J., and Melching, C.S., 1995, Regional rainfall-runoff relations for simulation of streamflow for watersheds in Lake County, Illinois: U.S. Geological Survey Water-Resources Investigations Report 95–4023, 71 p.

EcoLogic, LLC., 2001, Onondaga Lake ambient monitoring program—2000 annual report: Cazenovia, N.Y., paginated by section.

EcoLogic, LLC., 2003, Onondaga Lake ambient monitoring program—2001 annual report, Appendix 4, Mass-balance modeling: Cazenovia, N.Y., 26 p., accessed July 2003, at http://www.ongov.net/WEP/wepdf/we152001AMPApxFinal.pdf

EcoLogic, LLC., 2006, Onondaga Lake ambient monitoring program—2005 annual report: Cazenovia, N.Y., paginated by section.

Edwards, T.K., and Glysson, G.D., 1988, Field methods for measurement of fluvial sediment: U.S. Geological Survey Open-File Report 86–531, 118 p.

Effler, S.W., ed., 1996, Limnological and engineering analysis of a polluted urban lake—prelude to environmental management of Onondaga Lake, New York: New York, Springer-Verlag, Inc., 832 p.

Effler, S.W., and Hennigan, R.D., 1996, Onondaga Lake, New York—Legacy of pollution: Lake and Reservoir Management, v. 12, no. 1, p. 1–13.

Effler, S.W., Johnson, D.L., Jiao, J.F., and Perkins, M.G., 1992, Optical impacts and sources of suspended solids in Onondaga Creek, U.S.A.: Water Resources Bulletin, v. 28, no. 2, p. 251–262.

Endreny, T.A., and Wood, E.F., 2003, Watershed weighting of export coefficients to map artificial phosphorus loading rates: Journal of the American Water Resources Association, v. 39, no. 1, p. 165–181.

Environmental Systems Research Institute, 1992, ArcView, version 3.2: Redlands, Calif., Environmental Systems Research Institute.

Federal Emergency Management Agency, 1978, Flood Insurance Study, Town of Dewitt, Onondaga County, New York: Washington, D.C., U.S. Federal Emergency Management Agency, 37 p. plus maps.

Federal Emergency Management Agency, 1980, Flood Insurance Study, Town of Camillus, Onondaga County, New York: Washington, D.C., U.S. Federal Emergency Management Agency, 40 p. plus maps.

Federal Emergency Management Agency, 1981a, Flood Insurance Study, Town of Geddes, Onondaga County, New York: Washington, D.C., U.S. Federal Emergency Management Agency, 32 p. plus maps.

Federal Emergency Management Agency, 1981b, Flood Insurance Study, Village of Camillus, Onondaga County, New York: Washington, D.C., U.S. Federal Emergency Management Agency, 21 p. plus maps.

Federal Emergency Management Agency, 1981c, Flood Insurance Study, Village of East Syracuse, Onondaga County, New York: Washington, D.C., U.S. Federal Emergency Management Agency, 23 p. plus maps.

Federal Emergency Management Agency, 1981d, Flood Insurance Study, Village of Marcellus, Onondaga County, New York: Washington, D.C., U.S. Federal Emergency Management Agency, 15 p. plus maps.

Federal Emergency Management Agency, 1982a, Flood Insurance Study, Town of Marcellus, Onondaga County, New York: Washington, D.C., U.S. Federal Emergency Management Agency, 20 p. plus maps.

Federal Emergency Management Agency, 1982b, Flood Insurance Study, Town of Salina, Onondaga County, New York: Washington, D.C., U.S. Federal Emergency Management Agency, 34 p. plus maps.

Federal Emergency Management Agency, 1983, Flood Insurance Study, Town of Onondaga, Onondaga County, New York: Washington, D.C., U.S. Federal Emergency Management Agency, 19 p. plus maps.

Federal Emergency Management Agency, 1984, Flood Insurance Study, Town of Lafayette, Onondaga County, New York: Washington, D.C., U.S. Federal Emergency Management Agency, 36 p. plus maps.

Federal Emergency Management Agency, 1986, Flood Insurance Study, City of Syracuse, Onondaga County, New York: Washington, D.C., U.S. Federal Emergency Management Agency 35 p. plus maps.

Fetter, C.W., Jr., 1980, Applied hydrogeology: Columbus, Ohio, Merrill Publishing, 488 p.

Flippo, H.N., Jr., and Madden, T.M., Jr., 1994, Calibration of a streamflow-routing model for the Delaware River and its principal tributaries in New York, New Jersey, and Pennsylvania: U.S. Geological Survey Water-Resources Investigations Report 93–4160, 31 p.

Flynn, K.M., Hummel, P.R., Lumb, A.M., and Kittle, J.L., Jr., 1995, User's manual for ANNIE, Version 2, a computer program for interactive hydrologic data management: U.S. Geological Survey Water-Resources Investigations Report 95–4085, 211 p.

Fontaine, T.A., and Jacomino, V.M.F., 1997, Sensitivity analysis of simulated contaminated sediment transport: Journal of the American Water Resources Association, v. 33, no. 2, p. 313–326.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, N.J., Prentice-Hall, 604 p.

Frick, E.A., and Buell, G.R., 1999, Relation of land use to nutrient and suspended-sediment concentrations, loads, and yields, in the Upper Chattahoochee River Basin, Georgia, 1993–98: 1999 Georgia Water Resources Conference, University of Georgia, Athens, Ga., Proceedings, accessed April 12, 2006, at http//ga.water.usgs.gov/nawqa/1999fricknbuell.pdf

Frink, C.R., 1991, Estimating nutrient exports to estuaries: Journal of Environmental Quality, v. 20, no. 4, p. 717–724.

Gray, J.R., Glysson, G.D., Turcios, L.M., and Schwarz, G.E., 2000, Comparability of suspended-sediment concentration and total suspended solids data: U.S. Geological Survey Water-Resources Investigations Report 00–4191, 14 p.

Hamon, R.W., 1961, Estimating potential evapotranspiration: Proceedings of the American Society of Civil Engineers, Journal of the Hydraulic Division, v. 87, no. HY3, p. 107–120.

Hamon, R.W., Weiss, L.L., and Wilson, W.T., 1954, Insolation as an empirical function of daily sunshine duration: Monthly Weather Review, v. 82, no. 6, p. 141–146.

Helsel, D.R., 1985, Contributions of suspended sediment from highway construction and other land uses to the Olentangy River, Columbus, Ohio: U.S. Geological Survey Water-Resources Investigations Report 84–4336, 31 p.

Hornlein, J.F., Szabo, C.O., Zajd, H.J., Jr., and Deloff, D.D., 1993, Water-resources data—New York, water year 1992, volume 3, western New York: U.S. Geological Survey Water-Data Report NY-92–3, 303 p.

Hornlein, J.F., Szabo, C.O., Zajd, H.J., Jr., and Deloff, D.D., 1994, Water-resources data—New York, water year 1993, volume 3, western New York: U.S. Geological Survey Water-Data Report NY-93-3, 289 p.

Hornlein, J.F., Szabo, C.O., and Zajd, H.J., Jr., 1995, Water-resources data—New York, water year 1994, volume 3, western New York: U.S. Geological Survey Water-Data Report NY-94-3, 341 p.

Hornlein, J.F., Szabo, C.O., Zajd, H.J., Jr., and Mulks, R.L., 1996, Water-resources data—New York, water year 1995, volume 3, western New York: U.S. Geological Survey Water-Data Report NY-95-3, 339 p.

Hornlein, J.F., Szabo, C.O., Zajd, H.J., Jr., and Mulks, R.L., 1997, Water-resources data—New York, water year 1996, volume 3, western New York: U.S. Geological Survey Water-Data Report NY-96-3, 300 p.

Hornlein, J.F., Szabo, C.O., Zajd, H.J., Jr., and Mulks, R.L., 1998, Water-resources data—New York, water year 1997, volume 3, western New York: U.S. Geological Survey Water-Data Report NY-97-3, 346 p.

Hornlein, J.F., Szabo, C.O., Zajd, H.J., Jr., and Mulks, R.L., 1999, Water-resources data—New York, water year 1998, volume 3, western New York: U.S. Geological Survey Water-Data Report NY-98-3, 383 p.

Hornlein, J.F., Szabo, C.O., Zajd, H.J., Jr., and Mulks, R.L., 2000, Water-resources data—New York, water year 1999, volume 3, western New York: U.S. Geological Survey Water-Data Report NY-99-3, 372 p.

Hornlein, J.F., Szabo, C.O., Zajd, H.J., Jr., and Mulks, R.L., 2001, Water-resources data—New York, water year 2000, volume 3, western New York: U.S. Geological Survey Water-Data Report NY-00-3, 404 p.

Hornlein, J.F., Szabo, C.O., Sherwood, D.A., and McInnes, S.K., 2002, Water-resources data—New York, water year 2001, volume 3, western New York: U.S. Geological Survey Water-Data Report NY-01-3, 376 p.

Hornlein, J.F., Szabo, C.O., Sherwood, D.A., and McInnes, S.K., 2003, Water-resources data—New York, water year 2002, volume 3, western New York: U.S. Geological Survey Water-Data Report NY-02-3, 336 p.

Hornlein, J.F., Szabo, C.O., and Sherwood, D.A., 2004, Water-resources data—New York, water year 2003, volume 3, western New York: U.S. Geological Survey Water-Data Report NY-03-3, 376 p.

Huber, W.C., and Dickinson, R.E., 1988, Storm water management model, version 4: U.S. Environmental Protection Agency, EPA 600/3-88/001, 569 p.

Hutton, F.Z., Jr., and Rice, C.E., 1977 Soil survey of Onondaga County, New York: Washington, D.C., U.S. Department of Agriculture, Soil Conservation Service, 235 p. plus 67 soil maps.

Hyde, J.B., 2005, Final report—Water quality improvements following implementation of dairy BMPs in the Otisco Lake watershed: Troy, N.Y., New York State Department of Health, Bureau of Water Supply Protection, 12 p.

Hyde, J.B., Sklenar, K.S., and Neuhauser, W.G., 1999, Impact of dairy operation closure on nutrient loading to Grout Brook (Cortland County, New York): Troy, N.Y., New York State Department of Health and Onondaga County Soil and Water Conservation District, 10 p.

Jacomino, V.M.F., and Fields, D.E., 1997, A critical approach to the calibration of a watershed model: Journal of the American Water Resources Association, v. 33, no. 1, p. 143–154.

Jones, P.M., and Winterstein, T.A., 2000, Characterization of rainfall-runoff response and estimation of the effect of wetland restoration on runoff, Heron Lake basin, southwestern Minnesota, 1991–97: U.S. Geological Survey Water-Resources Investigations Report 00–4095, 48 p.

Kappel, W.M., 2000, Salt production in Syracuse, New York (“The Salt City”) and the hydrogeology of the Onondaga Creek valley: U.S. Geological Survey Fact Sheet 139–00, 8 p.

Kappel, W.M., and McPherson, W.S., 1998, Remediation of mudboil discharges in the Tully valley of central New York: U.S. Geological Survey Fact Sheet 143–97, 4 p.

Kappel, W.M., and Miller, T.S., 2003, Hydrogeology of the Tully trough, southern Onondaga County and northern Cortland County, New York: U.S. Geological Survey Water-Resources Investigations Report 03–4112, 16 p.

Kappel, W.M., and Miller, T.S., 2005, Hydrogeology of the valley-fill aquifer in the Onondaga trough, Onondaga County, New York: U.S. Geological Survey Scientific Investigations Report 2005–5007, 13 p.

Kappel, W.M., Sherwood, D.A., and Johnston, W.H., 1996, Hydrogeology of the Tully valley and characterization of mudboil activity, Onondaga County, New York: U.S. Geological Survey Water-Resources Investigations Report 96–4043, 71 p.

Kappel, W.M., Yager, R.M., and Zarriello, P.J., 1986, Quantity and quality of urban storm runoff in the Irondequoit Creek Basin near Rochester, New York—Part 2. Quality of storm runoff and atmospheric deposition, rainfall-runoff-quality modeling, and potential of wetlands for sediment and nutrient retention: U.S. Geological Survey Water-Resources Investigations Report 85–4113, 93 p.

Kelly, J.M., 1998, An angling history of Nine Mile Creek: Marcellus, N.Y., Marcellus Historical Society News, v. 3, issue 4, p. 1–2.

Kittle, J.L., Jr., Lumb, A.M., Hummel, P.R., Duda, P.B., and Gray, M.H., 1998, A tool for the generation and analysis of model simulation scenarios for watersheds (GenScn): U.S. Geological Survey Water-Resources Investigations Report 98–4134, 152 p. [Online at http://water.usgs.gov/software/genscn.html]

Laroche, Anne-Marie, Gallichand, J., Lagacé, R., and Pesant, A., 1996, Simulating atrazine transport with HSPF in an agricultural watershed: Journal of Environmental Engineering, v. 122, no. 7, p. 622–630.

Lietman, P.L., Ward, J.R., and Behrendt, T.E., 1983, Effects of specific land uses on nonpoint sources of suspended sediment, nutrients, and herbicides—Pequea Creek Basin, Pennsylvania 1979–80: U.S. Geological Survey Water-Resources Investigations Report 83–4113, 88 p.

Lin, J.P., 2004, Review of published export coefficients and event mean concentration (EMC) data: U.S. Army Engineer Research and Development Center, Wetlands Regulatory Assistance Program, Technical Notes Collection ERDC TN-WRAP-04–3, 15 p. [Online at www.wes.army.mil/el/wrap]

Loehr, R.C., Ryding, S.O., and Sonzogni, W.C., 1989, Estimating the nutrient load to a water body, *in* Ryding, S.O., and Rast, W., eds., The control of eutrophication of lakes and reservoirs, Man and the Biosphere series, v. 1: Paris, United Nations Educational, Scientific, and Cultural Organization (UNESCO), Parthenon Publishing Group, p. 115–146.

Lohani, V.K., Chanat, J., and Kibler, D., 2001, Use of HSPF model in land use management in urbanizing watersheds: Blacksburg, Va., Virginia Polytechnic Institute, accessed April 17, 2001, at http://landscapes.ce.vt.edu/publications/minnesota.pdf

Lumb, A.M., McCammon, R.B., and Kittle, J.L., Jr., 1994, Users manual for the expert system (HSPEXP) for calibration of the Hydrological Simulation Program-Fortran: U.S. Geological Survey Water-Resources Investigations Report 94–4168, 102 p.

Martin, G.R., Zarriello, P.J., and Shipp, A.A., 2001, Hydrologic and water-quality characterization and modeling of the Chenoweth Run basin, Jefferson County, Kentucky: U.S. Geological Survey Water-Resources Investigations Report 00–4239, 197 p.

Mastin, M.C., 1996, Surface-water hydrology and runoff simulations for three basins in Pierce County, Washington: U.S. Geological Survey Water-Resources Investigations Report 95–4068, 148 p.

McFarland, A.M.S., and Hauck, L.M., 2001, Determining nutrient export coefficients and source loading uncertainty using in stream monitoring data: Journal of the American Water Resources Association, v. 37, no. 1, p. 223–236.

Moffa and Associates, 2002, Onondaga Lake nonpoint source environmental benefit project: Syracuse, N.Y., Central New York Regional Planning and Development Board, paginated by section.

Nash, J.E., and Sutcliffe, J.V., 1970, River flow forecasting through conceptual models, Part-I, A discussion of principles: Journal of Hydrology, v. 10, p. 282–290.

National Atmospheric Deposition Program, 2005, National Atmospheric Deposition Program: accessed November 2007, at http://nadp.sws.uiuc.edu/

National Oceanic and Atmospheric Administration, 2004, NOAA Coastal Change Analysis Program: National Oceanic and Atmospheric Administration, accessed August 2004 at http://www.csc.noaa.gov/crs/lca/ccap.html

National Weather Service, 2007, Climatological narrative for Syracuse, New York: National Weather Service Binghamton, N.Y., accessed May 2007, at www.erh.noaa.gov/bgm/climate/syr/syrclim.txt

Natural Resources Conservation Service, 1986, Urban hydrology for small watersheds: Washington, D.C., U.S. Department of Agriculture, Natural Resources Conservation Service Technical Release 55, paginated by section.

New York State Department of Environmental Conservation, 1999, Regulatory Freshwater Wetlands for Onondaga County: New York State Department of Environmental Conservation, accessed July 2003, at Cornell University Geospatial Information Repository (CUGIR) at http://cugir.mannlib.cornell.edu/bucketinfo.jsp?id=470

Nolan, B.T., Ruddy, B.C., Hitt, K.J., and Helsel, D.R., 1998, A national look at nitrate contamination of ground water: Water Conditioning and Purification, v. 39, no. 12, p. 76–79. Online at http://water.usgs.gov/nawqa/wcp/

Northeast Regional Climate Center, 2005, Comparative climatic data for the United States: Northeast Regional Climate Center, accessed April 2005, at http://met-www.cit.cornell.edu/ccd.html

Omernik, J.M., 1977, Nonpoint source-stream nutrient level relationships—A nationwide study: U.S. Environmental Protection Agency Ecological Research Series Report no. EPA600/3-77–105, 151 p.

Onondaga County Department of Water Environment Protection, 1998, Onondaga Lake Improvement Project, Consent judgment—summary: Onondaga County, accessed December 2006, at http://www.lake.onondaga.ny.us/ol14.htm

Onondaga County Department of Water Environment Protection, 2006, Onondaga Lake Improvement Project, Upgrading treatment, accessed December 2006, at http://www.lake.onondaga.ny.us/ol32.htm

Onondaga County Department of Water Environment Protection, 2007, Onondaga Lake Improvement Project, Abating combined sewer overflow: Onondaga County, accessed March 2007, at http://www.lake.onondaga.ny.us/ol31.htm

Onondaga Lake Partnership, 2006, Onondaga Lake pollution: Onondaga Lake Partnership, accessed December 2006, at http://www.onlakepartners.org/p12.html

Panuska, J.C., and Lillie, R.A., 1995, Phosphorus loadings from Wisconsin watersheds—Recommended phosphorus export coefficients for agricultural and forested watersheds: Wisconsin Department of Natural Resources, Research Management Findings, no. 38, 4 p.

Parsons Consultants, 2004, Comprehensive non-point source pollution control plan for the Onondaga Lake watershed, Onondaga County, New York, Draft 3 dated August 16, 2004: U.S. Army Corps of Engineers, Buffalo, N.Y., paginated by section.

Paschal, J.E., Jr., and Sherwood, D.A., 1987, Relation of sediment and nutrient loads to watershed characteristics and land use in the Otisco Lake basin, Onondaga County, New York: U.S. Geological Survey Water-Resources Investigations Report 86–4036, 62 p.

Proett, B.A., 1978, Hydrogeology of Marcellus Disappearing Lake: Syracuse, N.Y., Syracuse University, Department of Geology, Master of Science thesis, 128 p.

Project Watershed, 2005, Protecting central New York H2O: Project Watershed, accessed February 2005, at http://projectwatershed.org. Data stored at http://watershed.syr.edu

Quantitative Environmental Analysis, LLC, 2005, Three Rivers water quality model—Final, phase 2 report: Liverpool, N.Y., accessed April 2007, at http://www.lake.onondaga.ny.us/ol3392.htm

Raines, T.H., 1996, Simulation of storm peaks and storm volumes for selected subbasins in the West Fork Trinity River basin, Texas-water years 1993–94: U.S. Geological Survey Water-Resources Investigations Report 96–4110, 41 p.

Rast, W., and Lee, G.F., 1978, Summary analysis of the North American (U.S. portion) OECD eutrophication project—Nutrient loading—Lake response relationship and trophic status indices: U.S. Environmental Protection Agency Ecological Research Series Report no. EPA 600/3–78–008, 455 p.

Reckhow, K.H., Beaulac, M.N., and Simpson, J.T., 1980, Modeling phosphorus loading and lake response under uncertainty—A manual and compilation of export coefficients: U.S. Environmental Protection Agency, Report no. EPA 440/5–80–011, 214 p.

Reddy, K.R., Kadlec, R.H., Flaig, E., and Gale, P.M., 1999, Phosphorus retention in streams and wetlands—A review: Critical Reviews in Environmental Science and Technology, v. 29, no. 1, p. 83–146.

Regan, R.S., and Schaffranek, R.W., 1985, A computer program for analyzing channel geometry: U.S. Geological Survey Water-Resources Investigations Report 85–4335, 49 p.

Schaffner, W.R., and Oglesby, R.T., 1978, Limnology of eight Finger Lakes—Hemlock, Canadice, Honeoye, Keuka, Seneca, Owasco, Skaneateles, and Otisco, *in* Bloomfield, J.A., (ed.), Lakes of New York State, volume I, Ecology of the Finger Lakes: New York, Academic Press, p. 313–470.

Senior, L.A., and Koerkle, E.H., 2003, Simulation of streamflow and water quality in the Brandywine Creek subbasin of the Christina River basin, Pennsylvania and Delaware, 1994–98: U.S. Geological Survey Water-Resources Investigations Report 02–4279, 207 p.

Sherwood, D.A., 1984, Assessment of nonpoint-source nutrient discharges from the Switzer Creek basin, Steuben County, New York: U.S. Geological Water-Resources Investigations Report 83–4278, 24 p.

Sloto, R.A., and Crouse, M.Y., 1996, HYSEP—A computer program for streamflow hydrograph separation and analysis: U.S. Geological Survey Water-Resources Investigations Report 96–4040, 46 p.

Sonzogni, W.C., Chesters, G., Coote, D.R., Jeffs, D.N., Konrad, J.C., Ostry, R.C., and Robinson, J.B., 1980, Pollution from land runoff: Environmental Science and Technology, v. 14, no. 2, p. 148–153.

Soong, D.T., Straub, T.D., and Murphy, E.A., 2005, Continuous hydrologic simulation and flood-frequency, hydraulic, and flood-hazard analysis of the Blackberry Creek watershed, Kane County, Illinois: U.S. Geological Survey Scientific Investigations Report 2005–5270, 66 p.

Srinivasan, M.S., Hamlett, J.M., Day, R.L., Sams, J.I., and Peterson, G.W., 1998, Hydrologic modeling of two glaciated watersheds in northeast Pennsylvania: Journal of the American Water Resources Association, v. 34, no. 4, p. 963–978.

Straub, T.D., and Bednar, R.J., 2000, Bias in runoff parameter estimation induced by rainfall data: U.S. Geological Survey, Urbana, Ill., accessed September 2000, at http://smig.usgs.gov/SMIG/features_0900/rainfall.html

Sullivan, D.S., and Moonen, H.F., 1994, Onondaga Lake watershed streambank/roadbank erosion inventory: Syracuse, N.Y., U.S. Department of Agriculture, Soil Conservation Service, 28 p.

Szabo, C.O., Grover, J.S., and McInnes, S.K., 2006, Water-resources data—New York, water year 2005, volume 3, western New York: U.S. Geological Survey Water-Data Report NY-05-3, 480 p., accessed June 2007, at http://ny.water.usgs.gov/pubs/wdr/wdrny053/

Terrene Institute, 1996, A watershed approach to urban runoff—Handbook for decision makers: Alexandria, Va., Terrene Institute, 115 p.

Thiessen, A.H., 1911, Precipitation for large areas: Monthly Weather Review, v. 39, no. 7, p. 1082–1084.

Thomann, R.V., and Mueller, J.A., 1987, Principles of surface water quality modeling and control: New York, Harper Collins, 479 p.

Troutman, B.M., 1982, An analysis of input errors in precipitation-runoff models using regression with errors in the independent variables: Water Resources Research, v. 18, no. 4, p. 947–964.

Troutman, B.M., 1983, Runoff prediction errors and bias in parameter estimation induced by spatial variability of precipitation: Water Resources Research, v. 19, no. 3, p. 791–810.

Upstate Freshwater Institute, 2004, Onondaga Nation monitoring program for Onondaga Creek and its tributaries 2002–2003: Syracuse, N.Y., Upstate Freshwater Institute, Inc., 35 p.

U.S. Army Corps of Engineers, 1947, Design data for Onondaga Dam and Reservoir: U.S. Army Corps of Engineers, Buffalo, N.Y., miscellaneous plates on file in the office of the U.S. Geological Survey, Ithaca, N.Y.

U.S. Army Corps of Engineers, 1955, Reservoir regulation manual, Oswego River Basin, Onondaga Creek dam and reservoir, Syracuse, New York: U.S. Army Corps of Engineers, Buffalo, N.Y., 54 p.

U.S. Army Corps of Engineers, 1977, STORM Storage, treatment, overflow runoff model: U.S. Army Corps of Engineers, Institute of Water Resources, Hydrologic Engineering Center, 184 p.

U.S. Army Corps of Engineers, 1987, Reservoir regulation manual, Oswego River Basin, Onondaga Creek dam and reservoir, Syracuse, New York: U.S. Army Corps of Engineers, Buffalo, N.Y., 67 p.

U.S. Congress, 1990, Water Resources Development Act of 1990: 101st Congress, Public Law 101-640, accessed January 2007, at http://www.fws.gov/habitatconservation/Omnibus/WRDA1990.pdf

U.S. Department of Agriculture, 1993, Field office technical guide, Section I, Erosion prediction: New York, U.S. Department of Agriculture, Soil Conservation Service, paginated by section.

U.S. Department of Agriculture, 2001, Hydrology, section 4, National Engineering Handbook: U.S. Department of Agriculture, Natural Resources Conservation Service, accessed April 2005, at ftp://ftp.wcc.nrcs.usda.gov/downloads/hydrology_hydraulics/neh630

U.S. Department of Agriculture, 2003, National soil survey handbook, title 430-VI: U.S. Department of Agriculture, Natural Resources Conservation Service, accessed April 2005, at http://soils.usda.gov/technical/handbook

U.S. Department of Agriculture, 2006, Sedimentation, section 3, National Engineering Handbook: U.S. Department of Agriculture, Natural Resources Conservation Service, accessed June 2006, at http://www.info.usda.gov/CED/ftp/CED/neh-3.htm

U.S. Environmental Protection Agency, 1982, Handbook for sampling and sample preservation of water and wastewater: U.S. Environmental Protection Agency, EPA-600/4-82-029, 402 p.

U.S. Environmental Protection Agency, 1999, WDMUtil—A tool for managing watershed modeling time-series data, version 1.0: U.S. Environmental Protection Agency, EPA-823-C-99–001, 121 p.

U.S. Environmental Protection Agency, 2000, BASINS Technical Note 6—Estimating hydrology and hydraulic parameters for HSPF: U.S. Environmental Protection Agency, EPA-823-R-00-012, 24 p., accessed March 2001, at http://www.epa.gov/waterscience/BASINS/tecnote6.pdf

U.S. Environmental Protection Agency, 2003, Guidelines establishing test procedures for the analysis of pollutants: U.S. Environmental Protection Agency, 40 CFR chap. 1-D — Water Programs, part 136, accessed May 2007, at www.epa.gov/region6/6pd/qa/qadevtools/mod4references/analytical_references/40cfr136_03.pdf

U.S. Environmental Protection Agency, 2005, Better assessment science integrating point and nonpoint sources: U.S. Environmental Protection Agency, accessed November 2005, at www.epa.gov/waterscience/basins/

U.S Environmental Protection Agency, 2006, BASINS Technical Note 8—Sediment parameter and calibration guidance for HSPF: U.S. Environmental Protection Agency, EPA-823-R-00-012, 23 p., accessed March 2007, at http://www.epa.gov/waterscience/BASINS/tecnote8.pdf

U.S. Fish and Wildlife Service, 2000, National Wetlands Inventory: U.S. Fish and Wildlife Service, accessed March 2000, at http://www.nwi.fws.gov/maps

U.S. Geological Survey, 1998, IOWDM-Input and output for a watershed data management (WDM) file, version 2.4: U.S. Geological Survey, software documentation.

U.S. Geological Survey, 1999, National land cover data, New York: U.S. Geological Survey, accessed April 2003, at New York State GIS Clearinghouse at http://www.nysgis.state.ny.us

U.S. Geological Survey, 2005, Multi-resolution Land Characteristics Consortium: U.S. Geological Survey, accessed February 2005, at http://www.mrlc.gov/

Walker, W.W., 1999, Simplified procedures for eutrophication assessment and prediction—user manual: U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, Miss., Instructional Report W-96–2, paginated by section, accessed October 2006, at http://stinet.dtic.mil/cgi-bin/GetTRDoc?AD=ADA286912&Location=U2&doc=GetTRDoc.pdf

Water on the Web, 2004, Lake Onondaga: Water on the Web, accessed August 2004, at http://www.waterontheweb.org/data/onondaga

Wicklein, S.M., and Schiffer, D.M., 2002, Simulation of runoff and water-quality for 1990 and 2008 land-use conditions in the Reedy Creek watershed, east-central Florida: U.S. Geological Survey Water-Resources Investigations Report 02–4018, 74 p.

Wischmeier, W.H., and Smith, D.D., 1978, Predicting rainfall erosion losses—a guide to conservation planning: U.S. Department of Agriculture, Science and Education Administration, Agriculture Handbook 537, 58 p.

Wood, E.F., Sivapalan, M., Beven, K., and Band, L., 1988, Effects of spatial variability and scale with implications to hydrologic modeling: Journal of Hydrology, v. 102, p. 29–47.

Wood, E.F., Sivapalan, M., and Beven, K., 1990, Similarity and scale in catchment storm response: Reviews of Geophysics, v. 28, no. 1, p. 1–18.

Yagow, Gene, Dillaha, Theo, Mostaghimi, Saied, Brannan, Kevin, Heatwole, Conrad, Wolfe, M.L, 2001, TMDL modeling of fecal coliform bacteria with HSPF: St. Joseph, Mich., American Society of Agricultural Engineers Meeting Paper no. 01–2066, 20 p.

Zarriello, P.J., 1999, A precipitation-runoff model for part of the Ninemile Creek watershed near Camillus, Onondaga County, New York: U.S. Geological Survey Water-Resources Investigations Report 98–4201, 60 p.

Zarriello, P.J., and Ries, K.G., III, 2000, A precipitation-runoff model for analysis of the effects of water withdrawals on streamflow, Ipswich River basin, Massachusetts: U.S. Geological Survey Water-Resources Investigations Report 00–4029, 99 p.

Appendix 1. Sources of Data Used in Model Development

The sources of the data that were used in the development of the Onondaga Lake basin model are identified below.

1. *Channel cross-section data* were obtained from town and village Federal Emergency Management Agency (FEMA) Flood Insurance Studies or extracted from digital elevation models (DEMs). Low-water channel geometry was estimated from field measurements.

2. *Climatic data* were obtained from (1) the Environmental Protection Agency at www.epa.gov/OST/ftp/basins/wdm_data/NY_wdm.exe; (2) the National Climatic Data Center, National Oceanic and Atmospheric Administration at www.ncdc.noaa.gov; and (3) the Northeast Regional Climate Center, Cornell University at http://met-www.cit.cornell.edu

3. *Digital (Surface) Elevation Models (DEMs):* DEMs of 10-meter grid size, 0.1-meter elevation resolution DEMs by 7.5 min. USGS quadrangle were obtained from Cornell University Geospatial Information Repository (CUGIR) at http://cugir.mannlib.cornell.edu

4. *Slope data* were derived from DEM data using a GIS utility program, ARCINFO, Environmental Systems Research Institute (1992).

5. *Hydrology and drainage-area delineation:* These GIS layers were produced by and obtained from the Troy, N.Y., office of the U.S. Geological Survey. Hydrology was based on the National Hydrography Dataset that can be obtained at http://nhd.usgs.gov

6. *Wetlands data* were obtained from (1) U.S. Fish and Wildlife Service National Wetlands Inventory at www.nwi.fws.gov/maps; (2) Cornell University Geospatial Information Repository (CUGIR) at http://cugir.mannlib.cornell.edu/Isite/CUGIR_DATA; and (3) New York State Department of Environmental Conservation Freshwater wetlands at http://cugir.mannlib.cornell.edu/bucketinfo.jsp?id=470

7. *Land cover–land use data* were obtained from National Land Cover Data at the New York State GIS Clearinghouse at http://www.nysgis.state.ny.us; and from the National Oceanic and Atmospheric Administration, Coastal Change Analysis at www.csc.noaa.gov/crs/lca/ccap.html

8. *Hydrologic soil groups* were obtained from the Soil Survey Geographic Database (SSURGO) at http://soildatamart.nrcs.usda.gov

9. *Surficial and bedrock geology:* These GIS layers were obtained from the New York State Museum Publications Department at www.nysm.nysed.gov

10. *Statewide digital orthophotography* were obtained from the New York State GIS Clearinghouse at www.nysl.nysed.gov/gis/gateway/inde.html

11. *Streamflow data* were obtained from the National Water Information System of the U.S. Geological Survey at http://waterdata.usgs.gov/nwis/

12. *Water-quality data* collected from monitoring sites co-located with USGS streamflow monitoring sites were obtained from the Onondaga County Department of Water Environment Protection, 650 Hiawatha Blvd West, Syracuse, New York, 13204.

Appendix 2. Suspended Sediment and Total Suspended Solids

The terms suspended sediment and total suspended solids are often used interchangeably in the literature to describe the concentration of solid-phase material suspended in a water-sediment mixture. Water samples analyzed for suspended sediment and suspended solids often are collected and field processed in the same way. The analytical methods used to measure their respective concentrations differ, however, and different results should be expected (Gray and others, 2000). The concentration of suspended sediment is determined by measuring the dry weight of all the sediment from a known volume of a water-sediment mixture, whereas the concentration of suspended solids is determined by measuring the dry weight of sediment from a known volume of a subsample of the original. The differences in the results between the two methods become pronounced when sand-sized material composes a substantial percentage of the sediment in the sample. Stirring, shaking, or otherwise agitating the sample before obtaining a subsample will rarely produce a subsample representative of the suspended material and particle-size distribution of the original sample. In spite of the potential discrepancies between the two types of data, when concentrations or loads for one of these constituents is missing, researchers often will substitute the concentrations or loads of the other; however, suspended-sediment and total-suspended-solids data collected from natural water are not comparable and should not be used interchangeably (Gray and others, 2000).

Appendix 3. Onondaga Lake Basin Model Software and Associated Files

The software program, Generation and Analysis of Model Simulation Scenarios for Watersheds (GenScn), which includes HSPF, is used to run the model and to create and analyze the output from each scenario. GenScn is a component of the software system, BASINS, which stands for Better Assessment Science Integrating Point and Nonpoint Sources. BASINS "is a multipurpose environmental analysis system designed for use by regional, state, and local agencies in performing watershed and water quality-based studies" that has been developed by the U.S. Environmental Protection Agency (2005). BASINS can be downloaded from the world-wide web at www.epa.gov/waterscience/basins/. GenScn version 2.3 was used independently of BASINS version 3.1 for running HSPF and analyzing the output from the Onondaga Lake basin model. HSPF version 12 can be run as a program within GenScn.

The following files identify the Onondaga Lake basin model and any associated files required to run the model.

base.uci—the calibrated version of the user control input (UCI) file for the Onondaga Lake basin model.

onmod.wdm—the watershed data management (WDM) file that contains the time series of data that are required to run the model. These input datasets include meteorological data, flows, and computed loads. The WDM file is also the repository of time series of data that are output during a model run.

onmod.sta—the GenScn project status file, which defines the locations, scenarios, and constituents of the datasets stored in onmod.wdm, identifies the file that contains links to the shapefiles that appear when the Locations/Map option is selected in GenScn, and identifies the database files that contain the discrete water-quality data that have been collected at the water-quality monitoring sites by WEP.

For additional information write to:
New York Water Science Center
U.S. Geological Survey
425 Jordan Road.
Troy, N.Y. 12180

Information requests:
(518) 285-5602
or visit our web site at;
http://ny.water.usgs.gov

Coon and Reddy— Hydrologic and Water-Quality Characterization and Modeling of the Onondaga Lake Basin, Onondaga County, New York—Scientific Investigations Report 2008–5013