In cooperation with the
IRONDEQUOIT CREEK WATERSHED COLLABORATIVE

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

SCIENTIFIC INVESTIGATIONS REPORT 2005-5070

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

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Gale A. Norton, Secretary

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Conversion Factors, Datums, Abbreviations, and Acronyms

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	0.4047	hectare (ha)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
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)
	Mass	
ounce, avoirdupois (oz)	28.35	gram (g)
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton, short (2,000 lb)	0.9072	megagram (Mg)

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

$$°C=(°F-32)/1.8$$

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

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD), a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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

ACRONYMS AND ADDITIONAL ABBREVIATIONS USED IN THIS REPORT:

BMP	Best-management practice
BOD	Biochemical oxygen demand
DO	Dissolved oxygen
ET	Evapotranspiration
GIS	Geographic Information System
HSPF	Hydrologic Simulation Program - Fortran
HSPEXP	Hydrologic Simulation Program - Fortran EXPert system
IMPLND	Impervious land segment
NURP	Nationwide Urban Runoff Program
NYSEBC	New York State Erie (Barge) Canal
PERLND	Pervious land segment
RCHRES	Stream reach or reservoir
UCI	User control input
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey

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

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Abstract

Urbanization of the 150-square-mile Irondequoit Creek basin in Monroe and Ontario Counties, N.Y., continues to spread southward and eastward from the City of Rochester, on the shore of Lake Ontario. Conversion of forested land to other uses over the past 40 years has increased to the extent that more than 50 percent of the basin is now developed. This expansion has increased flooding and impaired stream-water quality in the northern (downstream) half of the basin.

A precipitation-runoff model of the Irondequoit Creek basin was developed with the model code HSPF (Hydrological Simulation Program—FORTRAN) to simulate the effects of land-use changes and stormflow-detention basins on flooding and nonpoint-source pollution on the basin. Model performance was evaluated through a combination of graphical comparisons and statistical tests, and indicated "very good" agreement (mean error less than 10 percent) between observed and simulated daily and monthly streamflows, between observed and simulated monthly water temperatures, and between observed total suspended solids loads and simulated sediment loads. Agreement between monthly observed and simulated nutrient loads was "very good" (mean error less than 15 percent) or "good" (mean error between 15 and 25 percent).

Results of model simulations indicated that peak flows and loads of sediment and total phosphorus would increase in a rural subbasin, where 10 percent of the basin was converted from forest and grassland to pervious and impervious developed areas. Subsequent simulation of a stormflow-detention basin at the mouth of this subbasin indicated that peak flows and constituent loads would decrease below those that were generated by the land-use-change scenario, and, in some cases, below those that were simulated by the original land-use scenario. Other results from model simulations of peak flows over a 30-year period (1970–2000), with and without simulation of 50-percent flow reductions at one existing and nine hypothetical stormflow-detention basins, indicated that stormflow-detention basins would likely decrease peak flows 14 to 17 percent on Allen Creek and 17 to 18 percent on Irondequoit Creek at Blossom Road.

The model is intended as a management tool that water-resource managers can use to guide decisions regarding future development in the basin. The model and associated files are designed to permit (1) creation of scenarios that represent planned or hypothetical development in the basin, and (2) assessment of the flooding and chemical loads that are likely to result. Instream stormflow-detention basins can be simulated in separate scenarios to assess their effect on flooding and chemical loads. This report (1) provides examples of how the model can be applied to address these issues, (2) discusses the model revisions required to simulate land-use changes and detention basins, and (3) describes the analytical steps necessary to evaluate the model results.

Introduction

Urbanization, which is partly characterized by an increase in impervious surfaces, decreases the rate of infiltration through the disturbance of soils (through mixing, removal, or replacement with fill) or through compaction (Natural Resources Conservation Service, 1986) and increases the rate at which stormwater moves from land surfaces to a drainage system. These changes affect the timing of peak flows from different parts of the basin and thereby can change the degree and frequency of local flooding. Urbanization also increases the use of fertilizer, pesticides, and herbicides that can be applied to and the number and quantity of airborne contaminants from industries and automobiles that can accumulate on the land surface and be washed into streams, ditches, and culverts. The net result is a substantial increase in the chemical loads carried by storm runoff to ground water and streams.

The Irondequoit Creek basin (fig. 1) has undergone rapid development during the past 40 years, and recent (1999) property-tax classifications indicate that more than 50 percent of the basin is now residential, commercial, or industrial (B. Houston, Monroe County Department of Planning and Development, written commun., 1999). The U.S. Geological Survey (USGS), in cooperation with Monroe County, has monitored streamflows and stream-water quality

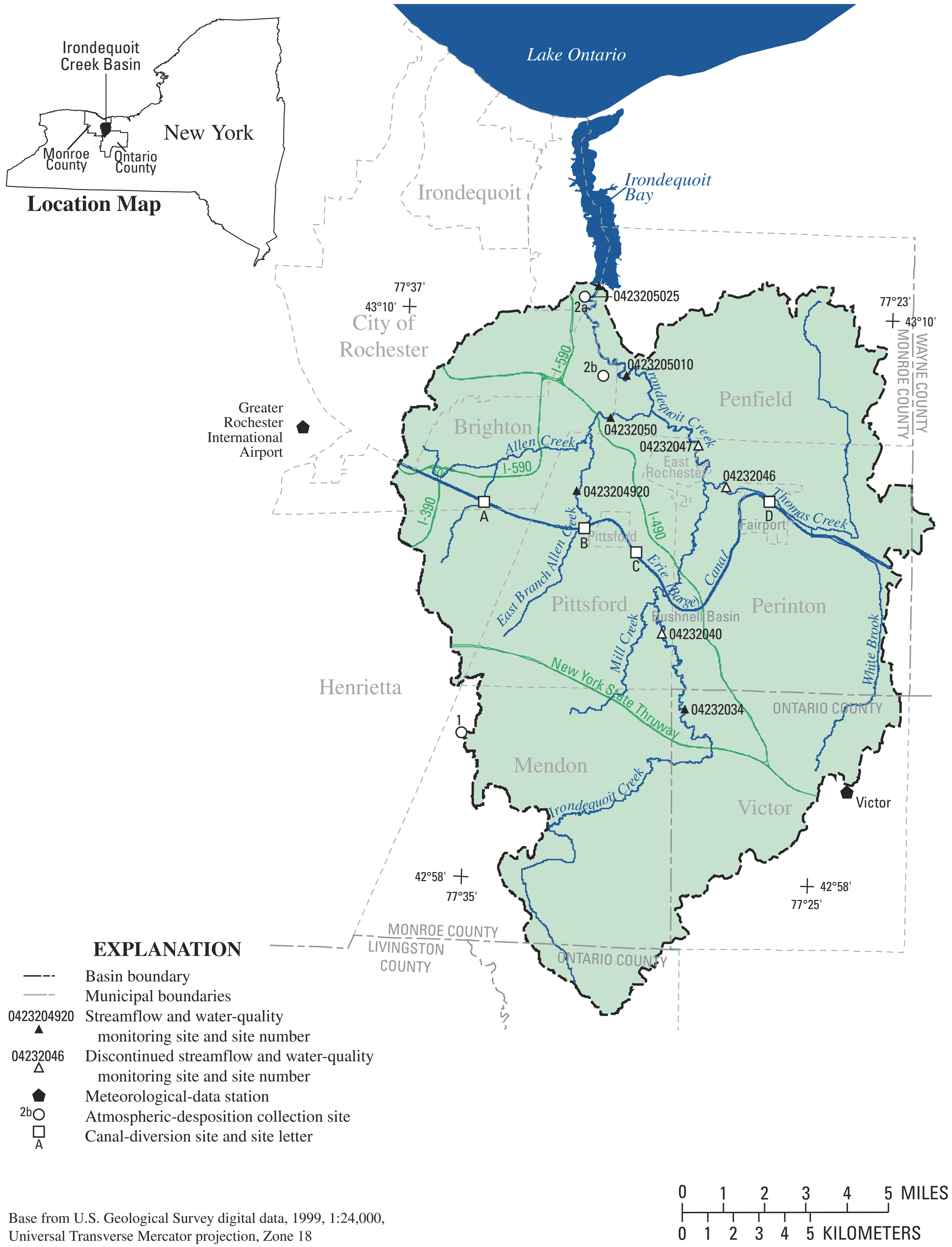


Figure 1. Location of the Irondequoit Creek basin, Monroe and Ontario Counties, N.Y., including towns, major streams, and data-collection sites.

at one site in the Irondequoit Creek basin since 1960, and at many sites since 1980. These data have documented flood discharges and allowed calculation of nutrient loads and assessment of water-quality trends in the basin (Johnston and Sherwood, 1996; Sherwood, 1999, 2001, and 2003; Coon and others, 2000; Coon, 2004). The changes in the hydrology and water quality of Irondequoit Creek and its major tributaries have prompted several measures to mitigate the adverse effects of urbanization. Among these measures are (1) a wastewater-interceptor system, which, since 1978, has diverted effluent from 14 wastewater-treatment facilities out of the basin to a tertiary-treatment plant at the north end of Rochester; (2) a bedrock-tunnel system that, since 1991, permits subsurface storage of stormwater and decreases the frequency of combined-sewer overflows from the City of Rochester into the creek; (3) local zoning and development ordinances, which, along with onsite controls of erosion and storm runoff at new developments, and expanded use of multipurpose stormflow-detention basins, serve to decrease peak streamflows and their associated chemical loads; (4) conversion of dry stormflow-detention basins in older developments to wet basins to promote the removal of nutrients in stormwater through increased biological uptake; and (5) rip-rap reinforcement of erodable banks along Irondequoit Creek and one of its tributaries, Allen Creek, to decrease sediment loads. Additionally, during 1997, Monroe County modified the flow patterns in the Ellison Park wetland at the mouth of Irondequoit Creek, and installed a flow-control structure to increase dispersion and detention of stormflows in the wetland. These measures, along with the diversion of wastewater out of the basin, have decreased the nutrient loads to Irondequoit Bay (Coon and others, 2000; Coon, 2004) and have improved its trophic status (C. Knauf, Monroe County Department of Health, written commun., 2001).

The measure that has been most widely used to decrease peak discharges and their associated chemical loads is the use of stormwater-detention basins because they are relatively inexpensive to construct, can fit a wide variety of sites and outflow requirements, can be incorporated into a proposed development plan, and can be constructed in flood-prone areas that are limited in their development potential. In addition, detention basins have the potential to improve stream-water quality. Any impoundment will do this to a degree by allowing the settling and removal of sediment, particulate constituents, organic matter, and their adherent chemical loads, but a detention basin that is specifically designed for water-quality improvement provides extended detention time, which can further decrease contaminant loads through biological and chemical processes.

Many of the mitigative steps listed above have been done on a site-specific or town-wide basis, but flooding and water-quality issues in downstream areas can rarely be solved without the cooperation of upstream landowners and governmental agencies. Therefore, basinwide coordination of efforts is needed. A basinwide precipitation-runoff model was envisioned as a tool to help water-resource managers to (1) understand the relation between development and the hydrologic and water-quality changes within the basin; (2) predict the probable effects of future development on peak flows and chemical loads; (3) analyze the potential effects of instream stormflow-detention basins to mitigate flooding and contamination; and (4) provide guidance as to the location and design of proposed detention basins.

During 2000–03, the USGS, in cooperation with the Irondequoit Creek Watershed Collaborative (IWC), a consortium representing the counties, towns, and municipalities that lie within the basin, conducted a project to (1) develop a precipitation-runoff model to simulate streamflows and water quality in the Irondequoit Creek basin; (2) use the model to assess the effects of (a) a hypothetical increase in urbanization in the basin, and (b) 10 hypothetical instream detention basins; and (3) instruct representatives of the IWC on the use of the model to create and compare results from a variety of land-use or detention-basin scenarios.

Purpose and Scope

This report (1) documents the development of the precipitation-runoff model and its water-quality component, and (2) presents examples of how the model might be used to assess the effects of future urbanization and instream detention basins on flooding and nonpoint-source pollution loads. Instruction of the IWC on scenario creation and analysis was provided in an earlier report by Coon (2003).

Previous Studies

The water resources of the Rochester area were summarized by Grossman and Yarger (1953). The hydrologic characteristics of the Irondequoit Creek basin were described by Dunn (1965) and studied extensively during 1979–81 as part of the Nationwide Urban Runoff Program (NURP) (U.S. Environmental Protection Agency, 1983; O'Brien and Gere, 1983; Zarriello and others, 1985; Kappel and others, 1986). The NURP study identified the heavily developed areas of the basin as the major sources of chemical loads and noted that snowmelt and spring runoff carried a disproportionate amount of the annual loads. The glacial history and geohydrology of the basin were described by Kappel and Young (1989). Ground-water resources were studied by Yager and others (1985). Also studied were the effects of stormwater-detention basins on the chemical quality of runoff from a small residential development (Zarriello and Sherwood, 1993) and on peak flows and water quality of major streams (Zarriello and Surface, 1989; Zarriello, 1996). The hydrology and water-quality effects of the Ellison Park wetland at the mouth of Irondequoit Creek were documented by Coon (1997; 2004) and Coon and others (2000).

Study Area

The Irondequoit Creek basin encompasses 151 mi^2 in parts of eight townships and two counties, and drains into the southern end of Irondequoit Bay (fig. 1). Most (78 percent) of the basin lies in Monroe County; 22 percent is in Ontario County. The City of Rochester occupies 7 percent of the basin.

Climate

Average annual precipitation (1961–90) in the Rochester area is 31.96 in., including an average snowfall of about 90 in., as recorded by the National Weather Service station at the Greater Rochester International Airport (fig. 1; Northeast Regional Climate Center, 2003). Precipitation is fairly evenly distributed throughout the year; monthly 30-year mean quantities range from 2.08 in. for January to 3.40 in. for August. Spatial variation in precipitation across the study area can be substantial, however. Annual totals vary by an average of 2.7 in. and by as much as 7.2 in. between the Rochester Airport, just northwest of the study area, and a National Weather Service station at Victor, southeast of the study area (fig. 1). Heavy rains fall infrequently in the Rochester area and generally are caused by (1) slowly moving thunderstorms that usually occur from May through September, (2) slowly moving or stalled major low-pressure systems, or (3) hurricanes and tropical storms that move inland (National Climatic Data Center, 1996). On average, the basin receives measurable precipitation on 159 days per year and precipitation in excess of 1 in. on 4 days per year. Lake Ontario affects the distribution and quantity of snowfall, which is substantially greater and more variable along the shore than inland; the lake also modifies air temperatures in the Rochester area and inhibits the extreme temperature fluctuations that are recorded further inland. Daily mean temperature (1961–90) ranges from 23.6 °F in January to 70.2 °F in July; the annual mean temperature is 47.6 °F (Northeast Regional Climate Center, 2003).

Geology and Topography

The basin is underlain by sedimentary rock (limestone, dolostone, sandstone, and shale) that dips gently to the south-southwest (Rickard and Fisher, 1970; Kappel and Young, 1989). The bedrock surface in the central and northern parts of the basin (fig. 2) contains a north-south-trending, V-shaped depression caused by preferential scouring of a preglacial river channel (Irondogenesee River) during one or more ice advances during the last glacial period (Young, 1983). Sand-and-gravel outwash partly fills the buried preglacial Irondogenesee River valley and forms the present-day Irondogenessee aquifer (Olcott, 1995; Kappel and Young, 1989).

The bedrock is overlain by glacial deposits throughout most of the basin. Till is exposed at the land surface in 44 percent of the basin. Thick till and ice-contact deposits are present at glacial-retreat stagnation points across the northern end of the basin and discontinuously across the southern half (fig. 2). Lacustrine deposits (sand, silt, and clay), which are exposed in 32 percent of the basin, are present where proglacial lakes once stood. Alluvium is found along the Irondequoit Creek channel and flood plain from its mouth to just north of the New York State Thruway (fig. 2). Irondequoit Creek incised the glacial deposits in the northern third of the basin; southern migration of channel incision was impeded by a bedrock outcrop just downstream of USGS streamflow-monitoring station 04232047 (fig. 1). Isostatic uplift of the Lake Ontario area, which has progressed at a faster rate at the lake's mouth than elsewhere, caused the lake-surface elevation to rise to its present level, forming embayments at the mouths of Lake Ontario tributaries (Clark and Persoage, 1970; Larsen, 1985; Young, 1998), one of which is Irondequoit Bay and the expansive cattail marsh (Ellison Park wetland) at the mouth of Irondequoit Creek.

The thickness of unconsolidated deposits ranges from 0 to more than 400 ft (fig. 3) and is greatest in the buried Irondogenesee River valley, and in topographically high areas in the southeastern part of the basin near the Monroe-Ontario County boundary and along the southern boundary of the basin in Ontario County. Thickness is least where bedrock is near the surface in the northwestern and northeastern parts of the basin.

Basin topography is the result of glacial scouring and deposition followed by stream erosion of the glacial deposits. Land-surface elevations range from about 250 ft at the northern end of the basin to more than 1,100 ft at the southern end (fig. 3). The high points in the southern half of the basin correspond to thick layers of kame and lacustrine deposits. Relief is greatest in the south, where small headwater valleys contain large elevation differences, and in the north, where incised tributaries to Irondequoit and Allen Creeks have eroded lacustrine sand and silt deposits.

Soils

All soils in the basin are derived from glacial deposits (fig. 2) and can be grouped according to the dominant parent material (Heffner and Goodman, 1973; Pearson and Cline, 1958). Soils that formed on kame deposits and outwash sand and gravel are highly permeable and, except during intense rainfall, generate negligible surface runoff. Soils that formed on lacustrine silt and fine sand have low to moderate permeability; percolation can be impeded by underlying lenses of silt or clay (Waller and Finch, 1982). These soils can be prone to erosion on steep slopes, where the vegetation cover has been removed. In contrast, soils that developed on lacustrine silt and clay deposits have low permeability and are subject to seasonal wetness. Soils that formed on till generally have extremely low permeability (less than 0.6 in/h). Till layers impede downward percolation from overlying deposits, regardless of their origin, and result in saturated soil conditions or shallow interflow along the till surface boundary. Another cause of decreased permeability is land development, which has locally decreased the water-infiltration characteristics of the soil through compaction.

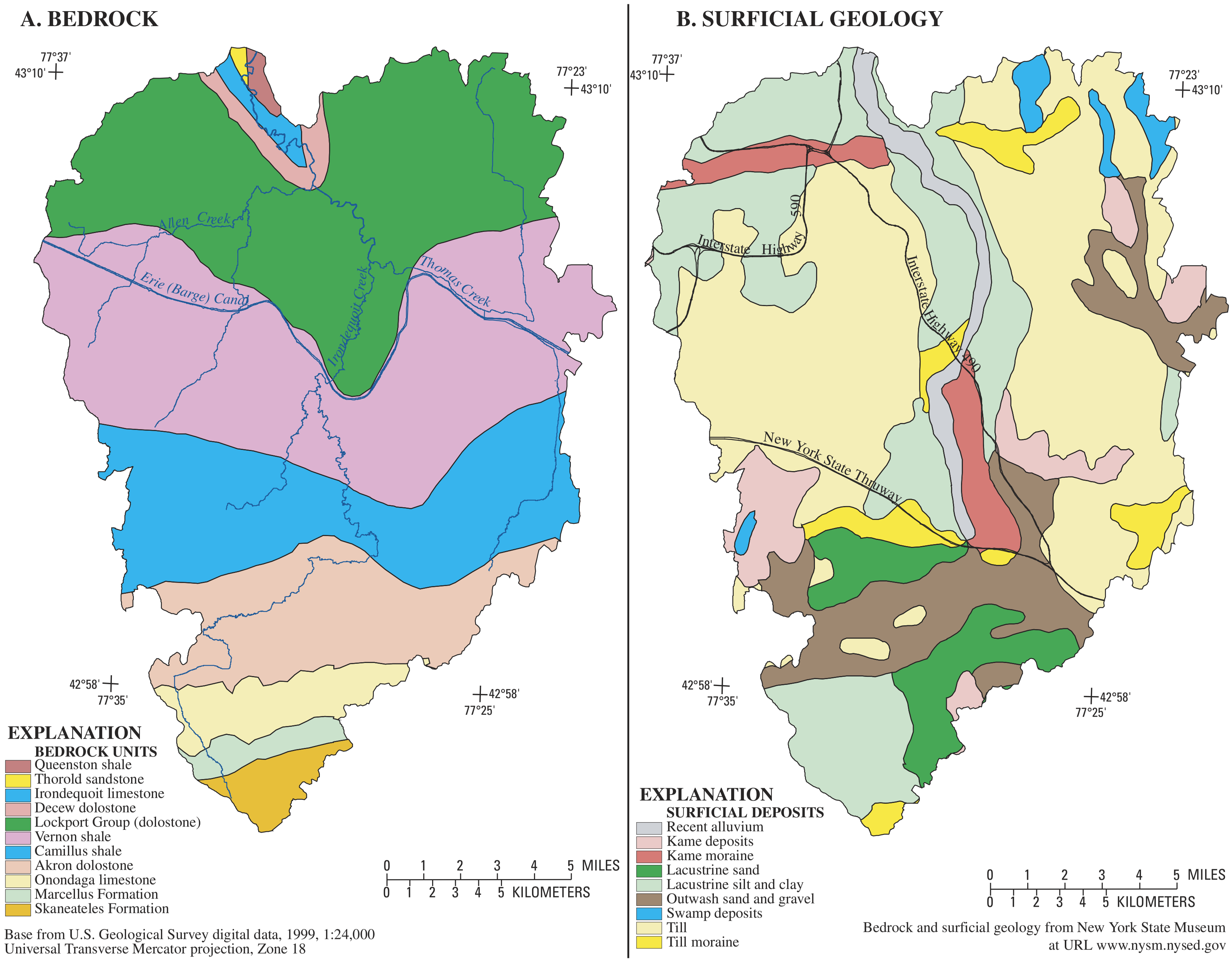


Figure 2. Generalized geologic maps of the Irondequoit Creek basin, Monroe and Ontario Counties, N.Y.: (A.) Bedrock. (B.) Surficial geology.

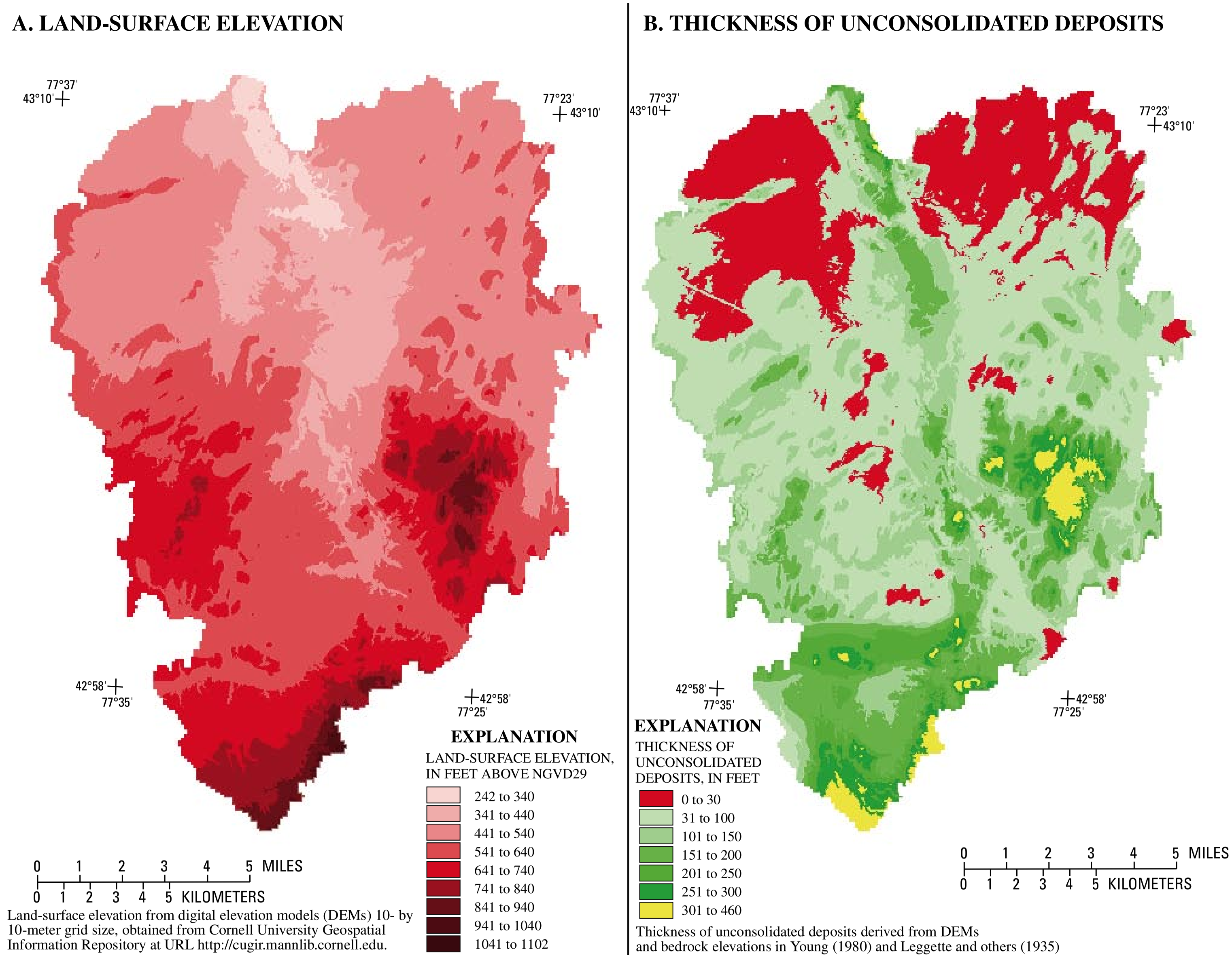


Figure 3. Generalized maps of (A) land-surface elevation and (B) thickness of unconsolidated deposits in the Irondequoit Creek basin, Monroe and Ontario Counties, N.Y.

Land Use and Land Cover

Virtually all of the Irondequoit Creek basin has been affected by human activity. Most of the land in the Irondequoit Creek and Allen Creek valleys was either cleared in the 19th century for farming (Hosley, 1993) or was heavily logged; as many as 19 saw mills were in operation along the banks of Irondequoit Creek during the mid-1800s (F.W. Pugsley, Town of Pittsford Historian, written commun., 1942). The large tracts of forests found in the basin today—mainly in steep-sloped rural areas—are second-growth forests that have grown since the 19th century. Urbanization increases from the southern part of the basin to the northwestern corner, which includes part of the City of Rochester (fig. 4A).

Land use and land cover can be classified by two methods—the NLCD (National Land Cover Data) method (U.S. Geological Survey, 1999), which is based on 30-meter satellite thematic mapper data, and the PTC (property-type classification) method (New York State Office of Real Property Services, 1996), which is used by county tax offices. Both methods indicate that more than 50 percent of the basin is in some form of developed condition, including residential (18.8 and 43.6 percent by NLCD and PTC, respectively), commercial, industrial, and transportation (5.0 and 10.2 percent by NLCD and PTC, respectively), agricultural (40.8 to 15.8 percent by NLCD and PTC, respectively), and public or recreational areas (8.1 to 11.8 percent by NLCD and PTC, respectively). The land-use and land-cover percentages obtained by both methods, and a "final" value that represents the percentages used in this study, are given in table 1. Discrepancies in this table are discussed in detail in the "Basin Representation" part of the "Precipitation-Runoff Model" section of this report.

The southern third of the basin is predominantly rural and agricultural and consists mostly of pasture, row crops, and forests; only a few areas in the Towns of Mendon and Victor are classified as residential or commercial (fig. 4A). Areas along the major transportation corridors have been subject to the pressures of development, however, and strip malls and business parks line most of New York State Route 96, which parallels Interstate Highway 490 across the basin (fig. 4A).

Suburban development increases northward across the basin and occupies large parts of the Towns of Henrietta, Pittsford, Perinton, and Penfield (fig. 4A), and the area north of the Erie (Barge) Canal (EBC) is mostly urban. Allen Creek and its main tributaries—East Branch Allen Creek and Buckland Creek—flow through suburban areas with moderate-density housing and commercial services and businesses. Similarly, Thomas Creek flows through areas that are increasingly undergoing suburban growth. The northwestern corner of the basin contains the Town of Brighton and City of Rochester, which consist of high-density residential, commercial, and industrial land. Land uses and covers for major subbasins in the Irondequoit Creek basin, and changes in the land-use-land-cover composition of the basin from upstream rural to downstream developed areas are shown in figure 4B.

Hydrology

Irondequoit Creek has a total length of about 32.6 mi and descends 525 ft from an elevation of 770 ft (above NGVD of 1929) at its head in Ontario County to 245 ft (mean elevation) at Irondequoit Bay. The creek flows northward down the approximate center of the basin with the Allen Creek subbasin to the west and the Thomas Creek subbasin to the east (fig. 5).

Surface Water

Allen Creek drains 20 percent of the Irondequoit Creek basin; of this, 8.7 percent is drained by East Branch Allen Creek and 3.4 percent by Buckland Creek. Thomas Creek drains 19 percent of the basin; of this, 9.5 percent is drained by its tributary, White Brook. The stream network in the basin is incised in glacial deposits; in only a few locations does the bedrock control channel shape and slope.

Wetland Areas

Almost 7 percent of the basin area consists of wetlands, lakes, and ponds (fig. 5). The headwater areas contain large lacustrine wetlands around Mendon Ponds. Extensive emergent wetlands, the largest of which is Thousand Acre Swamp, are found in the northeastern part of the basin, and collectively cover almost 11 percent of the Thomas Creek and White Brook subbasins on the eastern side of the basin. Riverine wetlands are found along much of Irondequoit Creek in the southern half of the basin and along many of its tributaries, and an extensive palustrine marsh lies at the mouth of Irondequoit Creek in Ellison Park (fig. 5).

New York State Erie (Barge) Canal

The Erie (Barge) Canal cuts across the basin and divides it into a northern section and a southern section. During the navigation season, generally May through November, water in the canal flows eastward from the at-grade confluence of the canal with the Genesee River toward the canalized Clyde River, east of the Irondequoit Creek basin. During the non-navigation season (December through April), a gate to the east of the Genesee River prevents the eastward flow of water, and the canal is allowed to drain to the east. The canal was constructed in or above the Vernon Shale Formation and, the southward bend in the canal in the central part of the basin between Pittsford and Fairport (fig. 1) follows the bedrock contact between the resistant Lockport dolostone and the relatively soft Vernon shale. (See fig. 2.) The canal was constructed in native material for most of its length across the basin, except for the Great Embankment, a 2-mi concrete-lined section from just east of Pittsford to Bushnell Basin (fig. 1). The canal crosses Irondequoit Creek along this section.

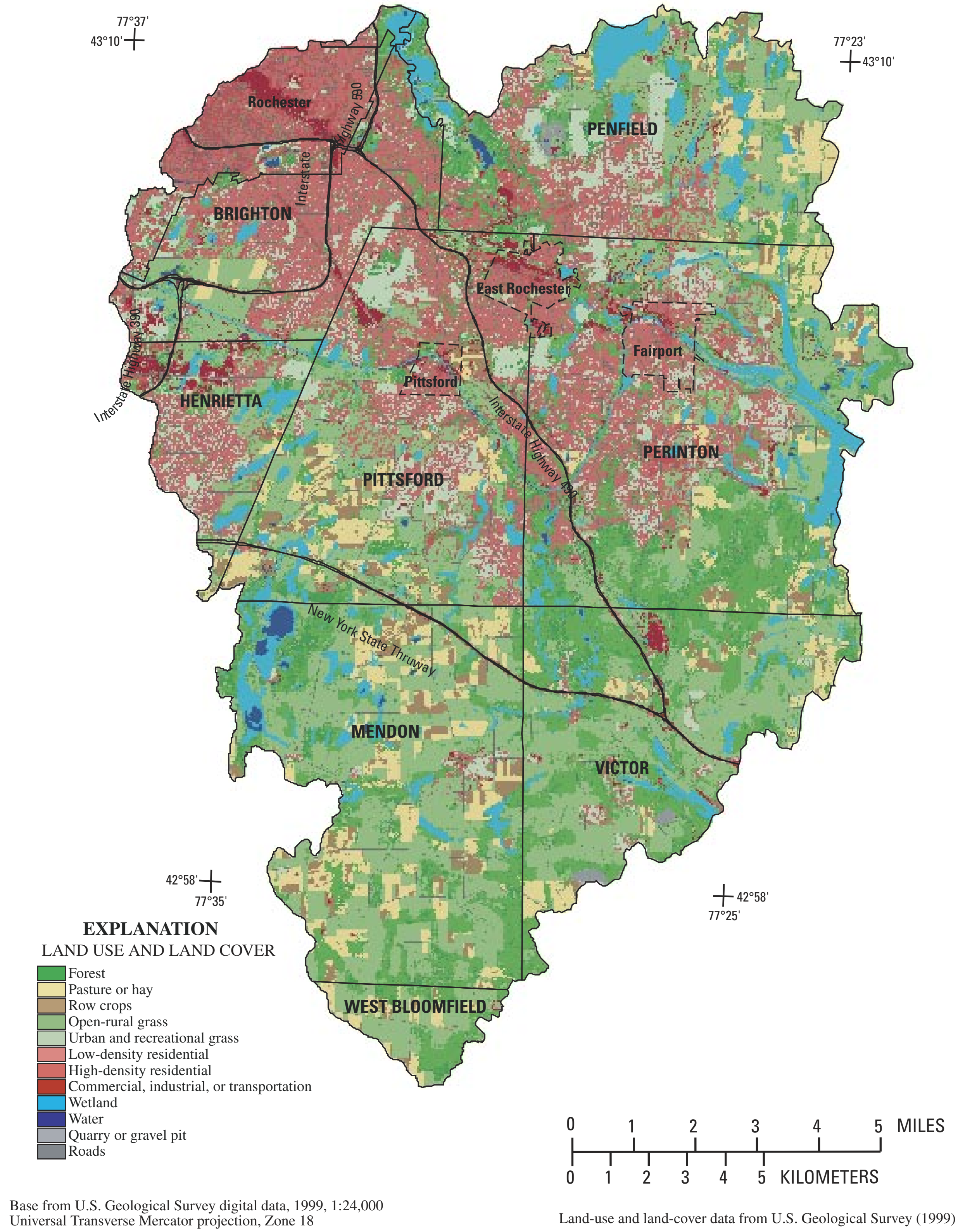


Figure 4A. Land use and land cover in the Irondequoit Creek basin, Monroe and Ontario Counties, N.Y.

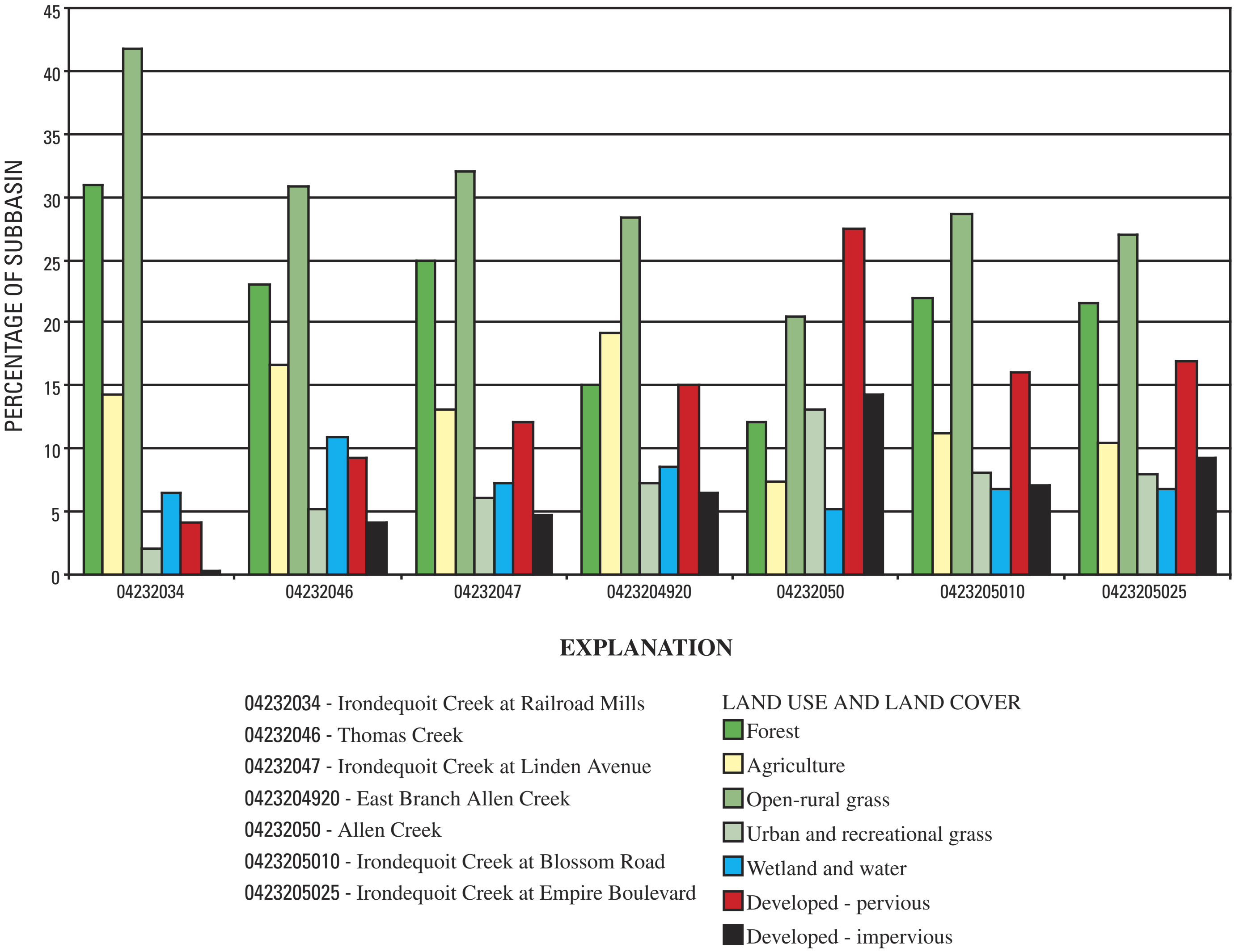


Figure 4B. Land use and land cover in each of seven subbasins, as percentage of total. (Locations are shown in fig. 1.)

Table 1. Land use and land cover in the Irondequoit Creek basin, Monroe and Ontario Counties, N.Y., 1991–92, as calculated by two methods.

[Values are percentages of entire basin. --, category not used by this classification method]

Land use and land cover	National Land Cover Data classification[1]	Property-type classification[2]	Irondequoit Creek model
Forest	25.7	--	21.5
Agriculture[3]	40.8	15.8	10.5
Former agriculture	--	18.6	0
Open and(or) rural grass	--	--	27.0
Urban and(or) recreational grass	8.1	--	8.0
Public land	--	11.8	0
Residential	18.8	43.6	17.9
Commercial, industrial, transportation, or high-density residential	5.0	--	8.3
Developed	--	10.2	0
Wetland or water	1.5	--	6.8

[1]U.S. Geological Survey, 1999.

[2]Christopher Sciacca, Monroe County Planning Board, written commun., 1998.

[3]"Agriculture" includes row crops, pasture, and hay for the National Land Cover Data and Property-type classifications, and only row crops for the Irondequoit Creek model.

The canal complicates the hydrology of the basin in several ways. Storm runoff enters the canal from adjacent areas along its entire length, and also from large areas around Pittsford, Fairport, and near the junction of the town boundaries of Henrietta, Brighton, and Penfield (fig. 1). Presumably little if any ground water enters the canal, except possibly from adjacent areas along the sections that are at grade with the surrounding area and built in native materials. Ground-water recharge from the canal is possible along its entire length and through cracks or seams in the concrete-lined section. The interaction between surface water and ground water has not been studied, nor have rates of ground-water discharge or recharge been estimated.

During the navigation season, canal water is diverted to the natural drainage system at four locations—Allen Creek, East Branch Allen Creek, Cartersville, and Fairport. Water is siphoned from the canal where it crosses Allen Creek and East Branch Allen Creek (sites A and B, fig. 1) for low-flow augmentation and golf-course water demands. Water also leaks around flood-control waste gates at Cartersville (east of Pittsford) and Fairport (sites C and D, fig. 1) and contributes to flows in Irondequoit and Thomas Creeks, respectively. Flows at these canal-diversion points are periodically measured, and water samples collected, by Monroe County. No leakage occurs at a third set of flood-control gates near the Pittsford-Perinton town lines and west of Bushnell Basin (fig. 1).

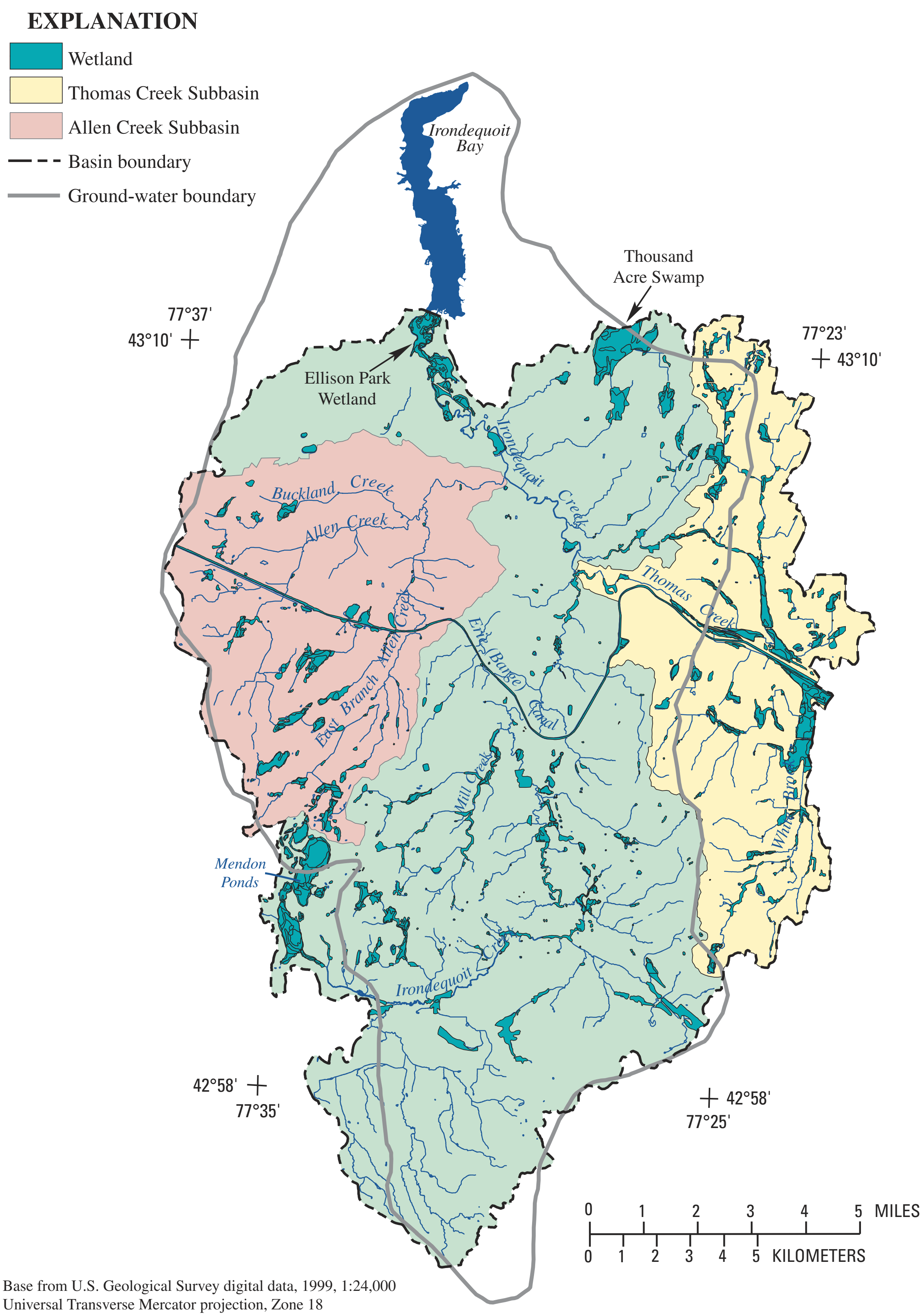
Parts of the canal can be isolated by locks and gates and dewatered to Irondequoit Creek or its tributaries through ports in the canal bottom during the navigation season, but dewatering is done rarely and only for maintenance purposes. These ports can be opened during the non-navigation season to permit drainage of runoff from adjacent areas and from small streams that flow into the canal. Leakage, seasonal drainage, or intentional releases from these ports are not measured.

Runoff from Rochester

Storm runoff within the city boundaries is controlled by a centralized sewer system. Runoff from the western part of the city that lies within the Irondequoit Creek basin is routed to an underground bedrock-tunnel system, which permits subsurface storage and subsequent routing to a wastewater-treatment plant that discharges to Lake Ontario. Runoff from the eastern part of the city that lies within the Irondequoit Creek basin is discharged to Irondequoit Creek through storm sewers between Blossom Road and Irondequoit Bay.

Ground Water

The Irondogenesee aquifer underlies the present-day Irondequoit Creek valley north of the Erie (Barge) Canal (Olcott, 1995) and presumably provides a ground-water flowpath from upgradient recharge areas in the southern part of the basin toward Irondequoit Creek north of East Rochester (Waller and Finch, 1982). The areal extent and hydraulic connectivity of the Irondogenesee aquifer are unknown, however (Kappel and Young, 1989). The aquifer probably also receives recharge through highly fractured near-surface bedrock, which is capable of transmitting substantial volumes of ground water (Yager and others, 1985), in addition to permeable deposits overlying and adjacent to the buried-valley walls.



Base from U.S. Geological Survey digital data, 1999, 1:24,000
Universal Transverse Mercator projection, Zone 18

Figure 5. Hydrology of the Irondequoit Creek basin, Monroe and Ontario Counties, N.Y.

Local ground-water flow generally is toward nearby streams, but regional movement is northward, toward Lake Ontario (Yager and others, 1985). Ground water generally follows the pattern of surface-water drainage, except where permeable deposits are hydraulically connected to the underlying Irondogenesee aquifer, in which case shallow ground water may travel vertically to deeper permeable units. The ground-water divide for most of the basin generally parallels the surface-water divide (fig. 5), except (1) along the eastern side of the basin, where it lies west of the surface-water divide, such that ground water in most of the White Brook subbasin and part of the Thomas Creek subbasin drains eastward, away from the Irondequoit Creek basin; (2) along the southwestern edge of the basin in the Town of Mendon, where the ground-water divide lies east of the surface-water divide and ground water in this area flows westward out of the basin; and (3) at the southern tip of the basin, where the ground-water divide extends south of the surface-water divide and encompasses an area where ground water presumably moves northward into the Irondequoit Creek basin (Yager and others, 1985). The delineated ground-water divide may change seasonally, depending on climatic conditions; but is considered representative of the average location of the divide in the basin. All assessments of ground-water movement in relation to the surface-water basin for purposes of model development were based on these conclusions.

Effects of Urbanization

The hydrologic effects of urbanization in a basin include changes in the relation between precipitation and runoff. Ordinarily this relation, when plotted to show cumulative runoff as a function of cumulative precipitation forms a straight line under stable precipitation-runoff conditions. This relation is illustrated in figure 6A, which represents a midbasin site (station 04232034 in fig. 1) whose drainage area has not undergone substantial urbanization, and a site at the downstream end of the basin (station 0423205010 in fig. 1), which represents a composite of all factors that can affect the hydrology in the basin. Both examples indicate a stable relation since the early 1980s. The relocation of the midbasin streamflow-monitoring site in 1991 is seen as a break in the straight-line relation; yet, the 1980s and 1990s line segments indicate generally stable relations.

The plot for a third site (fig. 6B), near the downstream end of the heavily urbanized Allen Creek subbasin (station 04232050 in fig. 1), covers a period twice as long as the other two sites and shows deviations from a stable precipitation-to-runoff relation. The pre-1970 period shows a gradual increase in runoff relative to precipitation—a result of the increase in impervious area. The slope of the plot stabilizes during 1970–79, either because the impervious area no longer increased during these years, or more likely runoff from new developments was controlled to maintain predevelopment levels. After 1980, a new equilibrium condition was reached, in which runoff decreased in relation to precipitation. This decrease coincided with the construction of a wastewater-interceptor system in the Irondequoit Creek basin during 1978–79 and the subsequent routing of a small percentage of storm runoff out of the basin, but it, as well as the apparent stability of the precipitation-runoff relation shown for the downstream site in figure 6A, might also reflect the efforts of the towns and counties to control storm runoff in response to the findings of the 1980–81 NURP study (U.S. Environmental Protection Agency, 1983; O’Brien and Gere, 1983; Kappel and others, 1986).

Stream-Water Quality

The quality of stream water in the Irondequoit Creek basin reflects the effects of human activities, such as agriculture and urban development. The drainage area of the most upstream water-quality-monitoring site (Railroad Mills; station 04232034 in fig. 1) is 31 percent forest, 42 percent and grass and shrubs, and more than 14 percent agriculture. Data collected at this site during 1991–2000 indicate that this rural subbasin annually generates, on average, 0.37 and 5.17 lb/acre of total phosphorus and total nitrogen, respectively, and 0.28 ton/acre of total suspended solids. The Allen Creek subbasin, which is 42 percent urbanized, annually generates, on average, 0.50 and 6.30 lb/acre of total phosphorus and total nitrogen, respectively, and 0.24 tons/acre of total suspended solids. The highest loading rates generally were in the East Branch Allen Creek subbasin, which represents about 32 percent of the Allen Creek basin. On average, the East Branch Allen Creek subbasin generates 0.61 and 9.32 lb/acre of total phosphorus and total nitrogen per year, respectively. In addition to being the smallest monitored subbasin in the Irondequoit Creek basin, with the smallest potential for dilution, East Branch Allen Creek has the highest percentage of agricultural land (19 percent). These loading rates are biased, however, because they include chemical loads carried by summer low-flow diversions from the EBC. The highest measured annual loading rates of total phosphorus and total suspended solids were near the downstream end of the basin (Irondequoit Creek at Blossom Road; station 0423205010 in fig. 1)—0.67 lb/acre of total phosphorus and 0.32 tons/acre of total suspended solids were measured. These loading rates may be biased to an unknown degree, however, by sediment from two points of severe streambank erosion less than 3 mi upstream—one on Irondequoit Creek, and one on Allen Creek; these areas presumably contributed large loads of sediment (Young and Burton, 1993) and associated constituents during 1991–2000.

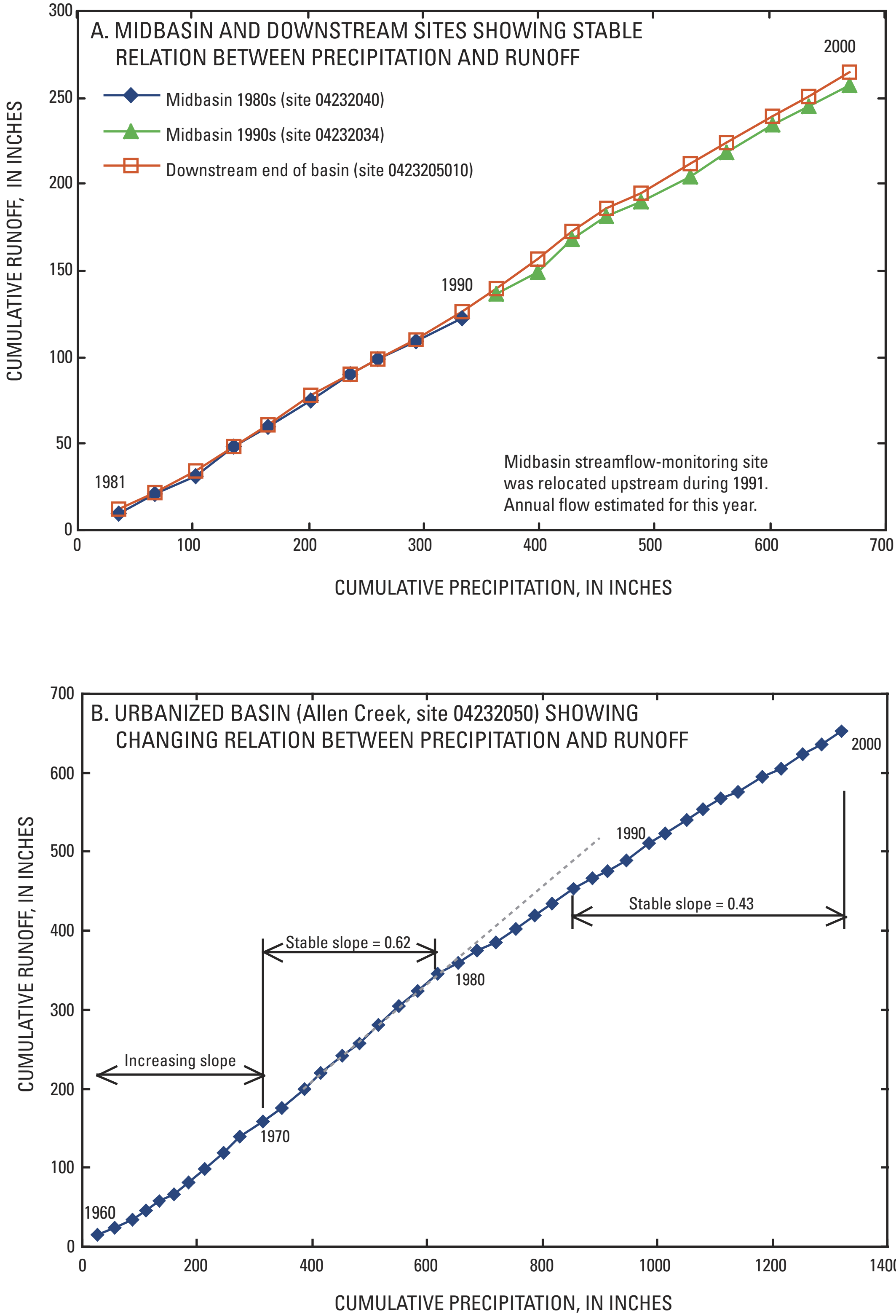


Figure 6. Relation between cumulative precipitation and cumulative runoff at selected streamflow monitoring sites, Irondequoit Creek basin, Monroe and Ontario Counties, N.Y.: (A.) Midbasin and downstream sites showing stable relation between precipitation and runoff. (B.) Urbanized basin showing changing relation between precipitation and runoff. (Site locations are shown in fig. 1.)

Precipitation-Runoff Model

A precipitation-runoff model was selected, developed for Irondequoit Creek basin, and calibrated and validated with data from five USGS streamflow- and water-quality-monitoring sites. Meteorological data were obtained from two National Weather Service stations. Geographical information system (GIS) coverages of hydrology, geology, soils, and land use and land cover were analyzed to assess the hydrologic and water-quality characteristics of the Irondequoit Creek basin and were consolidated for input to the model. The basin was divided into 82 subbasins and, within subbasins, into land segments, each of which was assumed to show consistent hydrologic and water-quality responses to precipitation and other meteorological factors. Model performance was assessed by graphical and statistical methods, and parameter sensitivity and model uncertainty were analyzed.

Model Selection

The model selected for simulation of runoff and chemical loads in response to precipitation was the Hydrological Simulation Program—FORTRAN (version 12; Bicknell and others, 1997), hereafter referred to as HSPF. HSPF, jointly developed by U.S. Environmental Protection Agency and USGS, is a mathematical model designed to simulate hydrologic and water-quality processes in natural and manmade water systems and is one of the most comprehensive and flexible models of watershed hydrology and water quality available (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) or instream detention basins (Donigian and others 1997) on flooding and water-quality conditions; (4) analyze surface-water and ground-water interactions (Zarriello and Reis, 2000); (5) evaluate the effects of best-management practices on agricultural and urban nonpoint-sources of pollution (Donigian and Love, 2002), and the effects of wetland restoration on runoff (Jones and Winterstein, 2000).

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 nitrogen and phosphorus; and (5) the effects of land-use changes and stormflow-detention basins on flooding and nonpoint-source pollution. Interflow, in the context of HSPF, refers to shallow, subsurface flow, and represents a flow component that has a faster response than ground-water flow, but slower response than surface runoff. 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 town personnel can use to help make future water-resource decisions.

Model Description

HSPF is a lumped-parameter, semidistributed, 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 set up 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 other factors that control the hydrologic and water-quality processes in the basin. HRUs are categorized as either pervious land segments (PERLNDs) or impervious land segments (IMPLNDs). Hydrologic and water-quality processes that occur in these land segments are simulated by different sections of the HSPF modules, PERLND and IMPLND, respectively; those that are pertinent to the Irondequoit Creek model are listed in table 2. 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 (table 2); flows and chemical loads are routed downstream from reach to reach by storage-routing (kinematic-wave) methods (Bicknell and others, 1997). For each RCHRES, a relation between water depth, surface area, storage volume, and outflow (discharge) is defined in a user-supplied function table (FTABLE module).

Two main mechanisms of surface-runoff generation have been identified—infiltration excess and saturation excess.

Table 2. Structure of Hydrological Simulation Program—FORTRAN (HSPF) for simulation of hydrologic and water-quality processes in the Irondequoit Creek basin, Monroe and Ontario Counties, N.Y.

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 in overland flow, interflow, and ground water
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)
	SPEC-ACTIONS Module for simulating unique or variable conditions
BMPRAC	Decrease in chemical-load resulting from best-management practice

Infiltration-excess runoff occurs when the precipitation rate exceeds the soil infiltration rate, whereas saturation-excess runoff occurs when the soil becomes saturated and additional precipitation cannot infiltrate. Both mechanisms may occur within a basin during a storm (Wood and others, 1990). HSPF simulates surface runoff primarily as an infiltration-excess process, whereby moisture inputs (precipitation and snowmelt) are separated into infiltrating and noninfiltrating fractions. Saturation-excess overland flow can be simulated, if needed, through adjustment of the exponent used in the infiltration equation (INFEXP), as well as the infiltration-capacity index and soil-moisture storage parameters (Berris, 1995). These adjustments allow inhibition of simulated overland flow during dry seasons, and generation of substantial runoff during wet periods. A comparison of HSPF with Soil Moisture Routing (Frankenberger and others, 1999), a saturation-excess overland flow model, in the upper part of the Irondequoit Creek basin, found saturation-excess flow to be the major flow mechanism, particularly in hillslope-dominated areas where vertical percolation was retarded by bedrock or a shallow, poorly permeable soil layer (Johnson and others, 2003). Despite the differences in structure and representation of hydrologic processes, the two models simulated streamflow with almost equal accuracy.

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 diversions and point-source chemical loads to appropriate RCHRESs. Hourly or daily time series of data required by HSPF are stored in a Watershed Data Management (WDM) file and input to the model through the EXT SOURCES module. Output type and storage locations in the WDM are identified through the EXT TARGETS module. Data time series can be input directly to a WDM through IOWDM (U.S. Geological Survey, 1998) and ANNIE (Flynn and others, 1995), or can be computed and automatically stored in a WDM through ANNIE or WDMUtil (U.S. Environmental Protection Agency, 1999). GenScn (Kittle and others, 1998), a graphical user interface that has many of the features of ANNIE and WDMUtil, has an improved capability to generate and analyze model scenarios and compare model results. WDMUtil or GenScn can also be used to check for and correct missing or erroneous data.

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. Information on diversions into and out of a basin, and their estimated flows and chemical loads, are also needed. Some of the instream water-quality processes simulated by HSPF also require water-temperature data, which can either be input from a recorded time series or generated by HSPF. The accumulation of chemical constituents on the land surface through either estimation of an accumulation rate or input of atmospheric-deposition data if available, can be simulated by HSPF. Observed streamflows, water temperatures, and chemical concentrations and loads are used to calibrate and validate 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.

Meteorological Data

Meteorological data for the model were obtained from two National Weather Service (NWS) stations (fig. 1; table 3). Meteorological data for 1970–2000, including hourly precipitation, air temperature, dewpoint temperature, wind speed, and percentage of cloud cover, were obtained from the station at the Greater Rochester International Airport. Estimates of solar radiation and potential evapotranspiration were calculated from data collected at the Rochester Airport by the methods contained in WDMUtil (U.S. Environmental Protection Agency, 1999). A second record of hourly precipitation was obtained from the NWS observation station at Victor, N.Y. for 1986–2000.

A major source of parameter-estimation 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). The two weather stations that provided data for the Irondequoit Creek model are located outside the Irondequoit Creek basin. Several county- or town-operated stations within the basin had missing or erroneous data and only short periods of record, and, therefore, could not be used.

Streamflow Data

Streamflow records were obtained from eight USGS streamflow-monitoring stations (fig. 1; table 3). These data sets were reviewed, and any missing or erroneous hourly values, such as occurred 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). Three of these stations were operated during the 1980s, and their data were used to calibrate a preliminary model that approximated the hydrologic characteristics of that decade. The data from one of these stations, Thomas Creek at Fairport, confirmed the loss of ground water from the White Brook and Thomas Creek subbasins, as discussed previously and were used to define the relations between surface water and ground water in these subbasins. The remaining five streamflow stations were operated during the simulated period and were used to calibrate and validate the model.

During the navigation season, water is diverted from the EBC to the local surface-water network at four locations—as siphoned flow to Allen Creek and East Branch Allen Creek (fig. 1, sites A and B) for low-flow augmentation and golf-course irrigation, and as leakage through flood-control waste gates to Irondequoit Creek at Cartersville and to Thomas Creek at Fairport (fig. 1, sites C and D) (table 3). Discharges at these points have been measured occasionally by Monroe County and were used to estimate daily diversions into the basin. The withdrawals from Allen Creek and East Branch Allen Creek for golf-course irrigation were estimated from the Allen Creek hydrograph, which indicated the occurrence of otherwise unexplainable decreases in flow. The estimated withdrawals were tested for two criteria—they did not exceed the combined estimated inflow from the two siphoning points and did not decrease flows at the Allen Creek monitoring site (station 04232050) below an acceptable low-flow limit of about 2 ft^3/s. The diversion estimates are considered poor, however, because (1) measurement of canal diversions was inconsistent during the 1991–2000 simulation period (from zero to 15 measurements in any one season) and (2) no records of golf-course withdrawals were available.

Water-Temperature Data

Records of surface-water temperatures measured every 15 minutes were available from the five USGS monitoring stations that were in operation from November 1994 through 2000 (table 3). Temperatures were measured with thermistors anchored near the stream bottom at each site. The accuracy of the recorded temperatures was checked by field measurements. These records were used to calibrate simulated water temperatures.

Initially, an attempt was made to use the recorded temperatures, rather than simulated temperatures, as input to the model as was done in the final version of the model. Periods of missing record at three sites precluded the use of all five data sets, but the data were sufficient for construction of three representative time series for water temperatures in (1) rural headwater reaches with cool temperatures (Irondequoit Creek at Railroad Mills record), (2) developed headwater reaches with warm temperatures (East Branch Allen Creek record), and (3) downstream reaches with varied development that receive water from a combination of land uses and with intermediate temperatures (records from Allen Creek and Irondequoit Creek at Blossom Road that exhibited similar daily and seasonal patterns and ranges in water temperature).

Table 3. Data-collection sites in the Irondequoit Creek basin, Monroe and Ontario Counties, N.Y.

[Site locations are shown in figure 1. mi^2, square miles]

Site (and subbasin identifier in model, where applicable)	Site-identification number	Drainage area (mi^2)	Data type	Period of record
National Weather Service meteorological-data collection sites				
Greater Rochester International Airport			Precipitation, air and dew-point temperatures, windspeed, and cloud cover	1/70–12/00
Observation station at Victor, N.Y.			Precipitation	1/86–12/00
U.S. Geological Survey streamflow, water-quality, and water-temperature-data collection sites				
Irondequoit Creek at Railroad Mills (IC6)	04232034	39.2	Streamflow Water quality Water temperature	7/91–9/00 7/91–9/99 2/95–9/00
Irondequoit Creek near Pittsford (IC9)	04232040	44.4	Streamflow and water quality	3/80–5/91
Thomas Creek at Fairport (TC5)	04232046	28.5	Streamflow and water quality	3/80–2/90
Irondequoit Creek at Linden Avenue (IC14)	04232047	101	Streamflow and water quality	8/73–3/89
East Branch Allen Creek at Pittsford (EB4)	0423204920	9.50	Streamflow Water quality Water temperature	4/90–9/00 4/90–9/99 11/94–9/00
Allen Creek near Rochester (AC5)	04232050	30.1	Streamflow Water quality Water temperature	11/59–9/00 10/83–9/99 11/94–9/00
Irondequoit Creek at Blossom Road (IC16)	0423205010	142	Streamflow and water quality Water temperature	12/80–9/00 11/94–9/00
Irondequoit Creek at Empire Boulevard (IC19)	0423205025	151	Streamflow and water quality Water temperature	6/90–9/00 11/94–9/00
Atmospheric-deposition collection sites				
Mendon Ponds	1		Water quality	10/83–9/00
Empire Boulevard (Ellison Park wetland)	2a		Water quality	10/92–6/97
Indian Landing School	2b		Water quality	10/97–9/00
New York State Erie (Barge) Canal diversion sites				
Allen Creek below Erie Canal siphon near Rochester	A		Streamflow and water quality	10/88–9/00
East Branch Allen Creek below Erie Canal siphon near Pittsford	B		Streamflow and water quality	10/88–9/00
Cartersville waste channel at Pittsford	C		Streamflow and water quality	10/88–9/00
Fairport waste channel at Fairport	D		Streamflow and water quality	10/88–9/00

The qualifying terms—cool and warm—refer to the general relation of a given temperature record to the other two and do not imply a particular temperature or temperature range. The option of directly inputting these temperature records to the model was abandoned because the simulation period would have been limited to the water-temperature-recording period—since November 1994—which would have precluded the use of earlier data for calibration purposes (table 3).

Ground-water temperatures have been measured as part of a Monroe County monitoring program since 1984. Selected temperature profiles were used to make initial estimates of monthly soil-water temperatures for the surface, upper, and lower soil layers, and for shallow ground water, as required by HSPF in the PERLND module PSTEMP (table 2).

Stream-Water-Quality Data

Calibration of the water-quality component of the model required measured or estimated loading rates of nonpoint-source constituents, as well as the concentrations or loads of these constituents in streamflow. In this report, the term “loading rate” refers to the average annual mass of a constituent that is removed from an acre of land, transported to a stream, and carried past the nearest downstream water-quality-monitoring site, where it is measured and subsequently included in load calculations. Loading rates are highly variable and depend on local physiographic and climatic characteristics, including land use, soil texture, slope, distance of overland flow, precipitation (quantity and intensity), and runoff rate (Beaulac and Reckhow, 1982). Loading rates can be strongly affected by agricultural and urban nonpoint-source contaminants and by best-management practices. Loading rates that are calculated for the basin of interest are the most reliable, but loading rates measured at locations outside the basin can be used as guides in calibrating simulated loads in a basin of interest. Loading rates for various land uses in the Irondequoit Creek basin were estimated by Kappel and others (1986; table 4) in the Nationwide Urban Runoff Program (U.S. Environmental Protection Agency, 1983). The annual loading rates for total phosphorus, as estimated from land-use and land-cover data, range from 0.1 lb/acre from forested land and 0.5 lb/acre from agricultural land to as much as 3.6 lb/acre for commercial-industrial areas. Total nitrogen loading rates range from 2.1 lb/acre from forested land and 6.8 lb/acre from agricultural land to 12.0 lb/acre for urban areas.

Table 4. Published estimated annual loading rates for nonpoint-source constituents, by land use.

[Values are in pounds per acre unless otherwise noted. SE, standard error. Dashes indicate no data]

Land use and land cover	Sediment[1] (tons/acre)	Total suspended solids[2] (tons/acre)	Total phosphorus	Total nitrogen[3]	Ammonia -plus- organic nitrogen[2]
Pervious land segments					
Forest	0.05–0.4	--	[3]0.1 (SE 0.03)	2.1 (SE 0.4)	--
Pasture or hay	.3–1.8	--	--	--	--
Agriculture	[4].5–7.0	--	[3].5 (SE 0.13)	6.8 (SE 2.0)	--
Mixed rural[5]	--	0.02–0.13	[2].18–0.26	--	1.78–2.25
Open	.5–2.0	--	--	--	--
Urban	.2–1.0	--	[3]1.5 (SE 0.2)	12.0 (SE 2.3)	--
Mixed urban[6]	--	.14	[2].48	--	4.47
Residential	--	.11	[2].61	--	4.46
Low density	.05–0.5	--	--	--	--
Medium density	.05–0.2	--	--	--	--
Commercial, industrial, transportation, or high-density residential	.1–0.2	.26–0.83	[2].67–3.6	--	4.92–21.2
Impervious land segments					
Residential	0.1–0.5	--	--	--	--
Low density					
Medium density	.1–0.5	--	--	--	--
Commercial	.2–0.5	--	--	--	--

[1]Donigian and others (1997); or Aqua Terra Consultants, HSPF training notes on Sediment Processes (2002).

[2]Data from Kappel and others (1986).

[3]Data from Frink (1991) *in* Donigian (2002).

[4]Crop dependent.

[5]High percentage of forest, pasture, and agricultural uses.

[6]High percentage of residential and commercial uses; also includes forest, pasture, and agricultural uses.

Water-quality data were obtained from the five sites at which streamflow was measured during the simulation period (fig. 1; table 3). Automated samplers that extracted water samples from the channel (near the centroid of flow) hourly and stored them in refrigerated bottles were maintained by the Monroe County Environmental Health Laboratory (MCEHL). Samples were retrieved twice weekly and delivered to MCEHL. Sampling periods were divided on the basis of three flow conditions—base or steady flow, and the rising and falling phases of a storm hydrograph. If base- or steady-flow conditions prevailed during the entire sampling cycle (3 to 4 days), equal volumes of water from all samples collected during that cycle were composited for a single analysis. During storms, samples collected during the rising phase were composited separately from those collected during the falling phase. Samples collected at or near the peak might have been separately composited and analyzed. Equal volumes of water from all samples collected during a given phase were composited for a single analysis. Laboratory analyses were done by MCEHL, which participated in the USGS quality-assurance program for cooperating analytical laboratories (U.S. Geological Survey, 2005).

Monthly loads for each analyzed constituent—orthophosphate, total phosphorus, ammonia, ammonia-plus-organic nitrogen, nitrate-plus-nitrite nitrogen, total suspended solids—were calculated from measured streamflows and composited constituent concentrations through the USGS program, ESTIMATOR (G. Baier, T. Cohn, and E. Gilroy, U.S. Geological Survey, written commun., 1995). The resulting data were used to calibrate monthly simulated loads of total suspended solids, total nitrogen, and total phosphorus.

Samples of canal-diversion water were collected periodically at the siphon and flood-control waste-gate locations during the navigation season. Frequency of sample collection at a given site ranged from 0 to 19 times per year. Missing concentrations were interpolated from measured data or represented by concentration data collected at a nearby diversion point. Loads of total suspended solids, ammonia, organic nitrogen, nitrate-plus-nitrite nitrogen, orthophosphate, and organic phosphorus were estimated from measured concentrations and flows at the four sites, and were input to the model as point sources of chemical loads. The estimates for these loads are considered to be poor, however, because few data were available.

Ground-water quality in the Irondequoit Creek basin has been monitored by Monroe County since 1984. Concentrations of chemicals in ground water were reviewed in an attempt to use these data as direct input to the model (interflow and ground-water concentrations in the PQUAL section of the PERLND module). The initial estimates of nitrate, ammonia, and phosphate concentrations required adjustment because they reflected integration of many land uses and could not be directly associated with specific PERLNDs. Final concentrations were selected through calibration to base flow concentrations and loads.

Atmospheric-Deposition-Quality Data

Monthly samples of dryfall and wetfall were collected from three monitoring sites—one in the southern part of the basin at Mendon Ponds, the other two in the northern part near Blossom Road at Ellison Park (fig. 1, table 3). The southern site provided atmospheric-deposition data for the entire simulation period. The combined data from the two northern sites provided a single nearly continuous record of atmospheric deposition. The original collection site was in the Ellison Park wetland near Empire Boulevard and was operated from October 1992 through June 1997, after which a replacement site at Indian Landing School was operated from October 1997 through September 2000.

The atmospheric-deposition data represented the mass of monthly dryfall and the mean concentration of monthly wetfall of selected constituents. Monthly dryfall mass (lb/acre) was divided into hourly quantities for model input; whereas the monthly wetfall concentrations (mg/L) were input “as is”, because HSPF combines the concentrations with precipitation quantities to compute the chemical loads in wetfall. Loads of ammonia, organic nitrogen, nitrate-plus-nitrite nitrogen, orthophosphate, and organic phosphorus were available for model input but were not used because they overestimated the quantities of nutrients that would be available for washoff from the land surface, and prevented calibration of the water-quality components of the model. Therefore, atmospheric deposition of selected constituents was simulated through adjustment of parameters within the PQUAL and IQUAL sections of the PERLND and IMPLND modules, respectively.

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. Each reach within the basin was inspected at several locations to identify the dominant bed material and to estimate or measure the mean particle size (D50). Gravel and other coarse-grained material were described by visual inspection, and a representative D50 value was selected on that basis. For sand and fine-grained bed material, a representative sample of the material was collected, and the D50 was calculated from a sieve particle-size analysis. The D50 for reaches where bed-material sizes were estimated or measured at several locations within a given RCHRES was calculated as the mean for that RCHRES.

HSPF also requires estimates of the sand, silt, and clay percentages in bed material of each RCHRES. The sand fraction in reaches that were dominated by gravel or larger particles was assumed to be the major component of the sand, silt, and clay material; therefore, sand, silt, and clay were assigned values of 90, 5, and 5 percent, respectively. The sand percentage for reaches that were dominated by sand (greater than 80 percent of all bed material) was computed directly from the sieve analyses. The remaining material was assumed to contain equal amounts of silt and clay. The sand percentage for fine-grained reaches, where sand constituted less than 80 percent of all bed material, was calculated directly from the sieve analysis, and the remaining amount was assumed to be about 80 percent silt and 20 percent clay. These latter percentages were estimated from detailed particle-size analyses of fine-grained bed-material samples collected in the Ellison Park wetland (Coon, 1997; Coon and others, 2000).

Bed-material porosity was estimated from the dominant particle size in a RCHRES and the corresponding average porosity values given in Fetter (1980), Davis and DeWiest (1966), and Freeze and Cherry (1979). Porosities of 45, 40, and 35 percent were used for stream channels where the D50 was silt sized, fine-sand sized, and coarse-sand sized, respectively. A porosity of 30 percent was used for gravel and coarser bed material.

Basin Representation

Primary segmentation of the basin, that is, delineation of subbasins, was based on the spatial distribution of precipitation; two areas were approximately defined by a Thiessen (1911) line generated for the two meteorological stations at the Rochester Airport and at Victor (fig. 7), whose precipitation records (recorded hourly) covered the calibration and validation periods and were assumed to be error free. This segmentation placed all of the Irondequoit Creek basin south of the EBC, as well as the Thomas Creek and White Brook subbasins, into the Victor precipitation area, and placed the Allen Creek subbasin, and its tributary, East Branch Allen Creek, into the Rochester Airport precipitation area. All other meteorological data that were input to the model were obtained directly from, or derived from data collected at, the Rochester Airport station, regardless of the precipitation source.

Further segmentation of the basin was based on seven other factors: (1) the confluences of major tributaries; (2) an approximation of reach length, such that flow time through an average RCHRES under mean flow conditions would approximate the simulation time step; (3) an arbitrary size limit that subbasins not exceed 3 percent of the total basin area; (4) 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) locations of calibration sites; (6) locations at which simulated discharge or chemical-load data were desired; and (7) locations of proposed stormflow-detention basins (fig. 8). This step resulted in division of the basin into 82 subbasins, each of which represented less than 2.8 percent of the total basin area (about 2,700 acres).

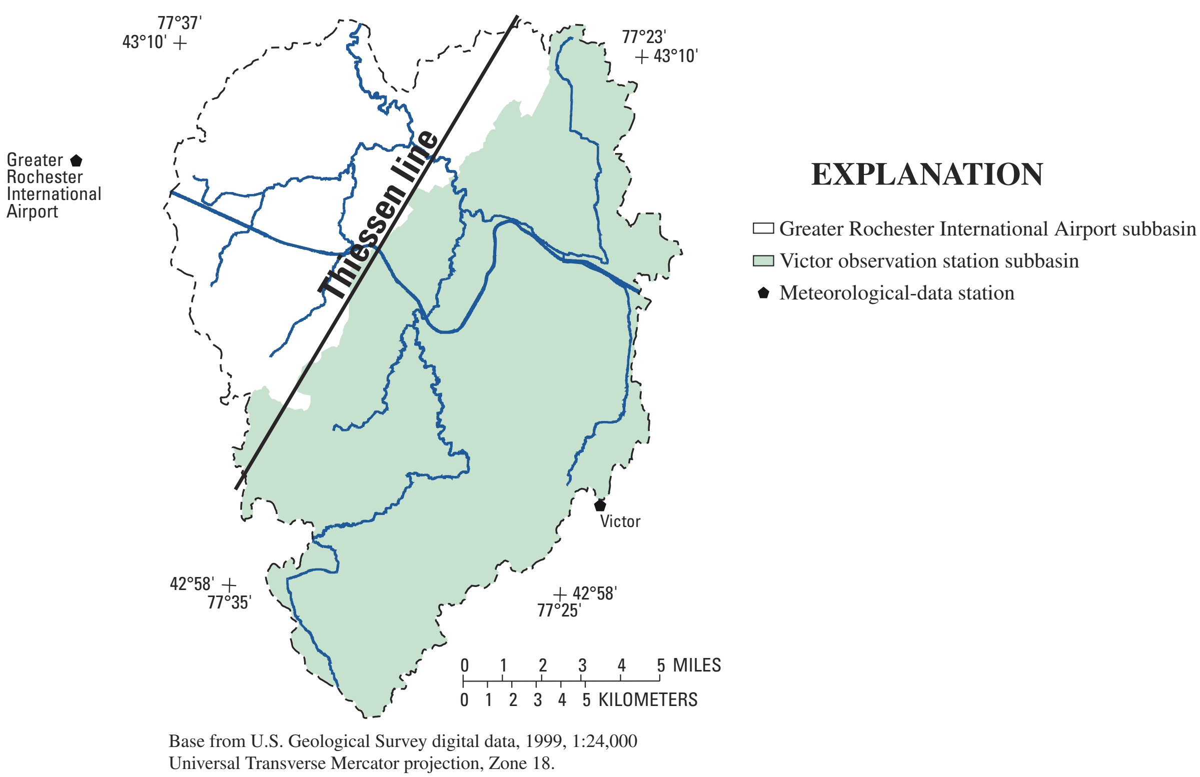


Figure 7. Segmentation of the Irondequoit Creek basin, Monroe County, N.Y., based on proximity to the National Weather Service precipitation stations, the data from which were input to the Hydrological Simulation Program—FORTRAN model.

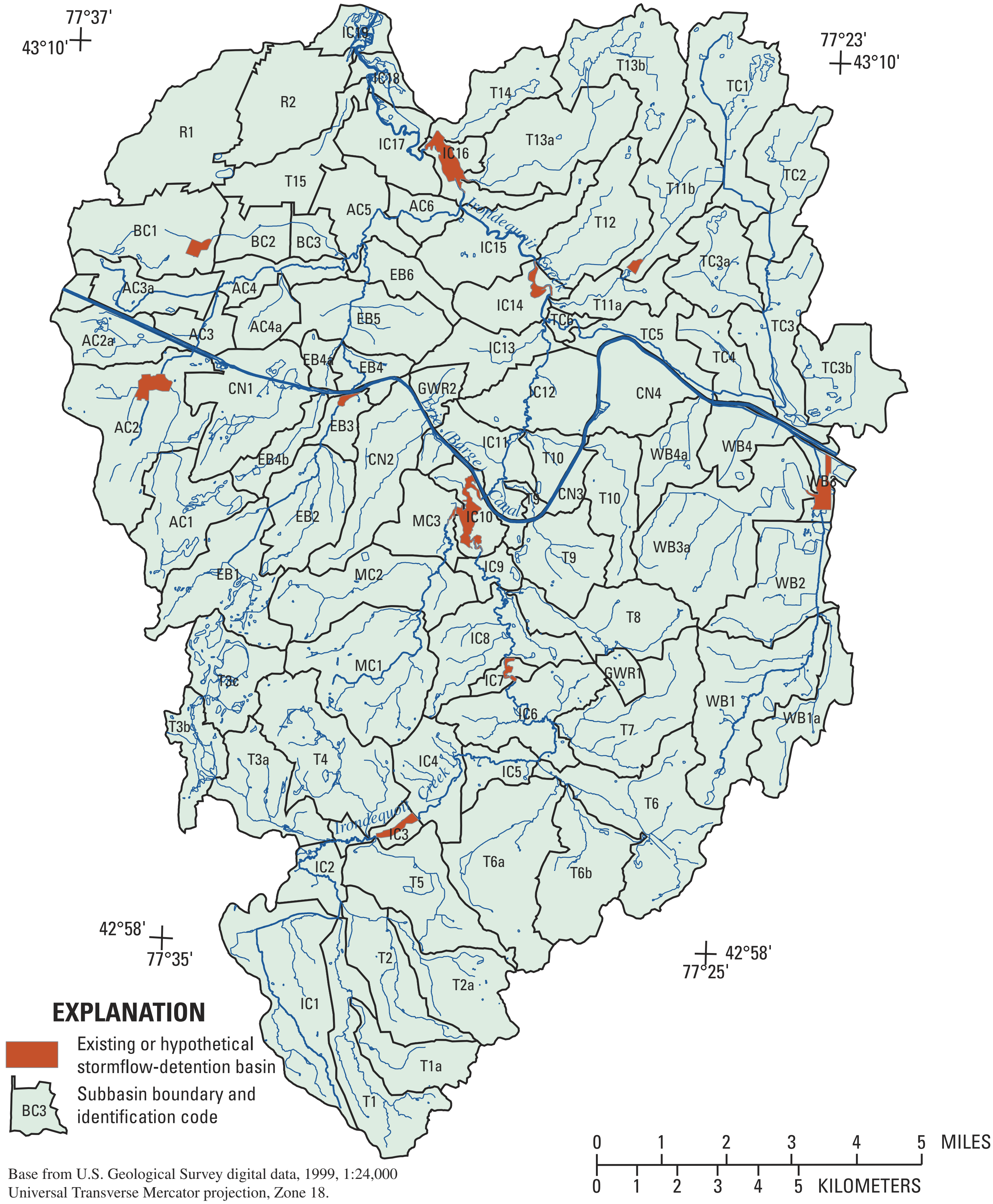


Figure 8. Subbasin boundaries and locations of existing or hypothetical stormflow-detention basins in the Irondequoit Creek basin, Monroe and Ontario Counties, N.Y.

Hydrologic-Response Units

The HRUs into which the basin was divided were assumed to show homogeneous hydrologic and water-quality responses to precipitation and other meteorological factors. Each HRU was designated as pervious land (PERLND) or impervious land (IMPLND). The basin characteristics that were initially expected to affect the hydrologic and water-quality responses of the pervious land segments were type of surficial material, soil permeability, land-surface slope, land use and land cover, and depth to fractured bedrock, as described below.

Pervious Land Segments (PERLNDs)

Surficial material (fig. 2) was initially considered to be a factor that would reflect the infiltration and percolation characteristics of the basin. Glacial material was assumed to have certain rates of infiltration and percolation; for example, outwash would have high rates, and till would have low rates. Comparison of specific glacial-deposit locations with the soil permeability indicated on soil-survey maps of those locations yielded inconsistent results, however. Therefore, surficial geology was not used in the development of PERLND HRUs.

Soil permeability varies widely and affects the rate at which water infiltrates the surface layer and percolates to the water table. Rate of surface infiltration depends upon many factors, including soil moisture and temperature, density of vegetation, slope, soil porosity, grain-size distribution and cohesion, intensity and duration of rainfall (Waller and others, 1982), and degree of soil compaction. Rate of percolation to the water table depends on many of these factors, as well as the presence or absence of a water-impeding layer or fragipan, depth to seasonal high-water table, and depth to bedrock. Permeability can vary through the soil profile; the factor that is generally used for modeling purposes is whichever factor is the most restrictive.

Permeability, as defined by the U.S. Department of Agriculture in county soil surveys (Heffner and Goodman, 1973; Pearson and Cline, 1958), was used to delineate HRUs because it provided a means to evaluate soil conditions regardless of surficial material or bedrock type. Permeability values were obtained from a generalized map of infiltration rates that represented the rate of vertical water movement in the B horizon, which is generally between 10 and 40 in. below land surface. Areas of equal infiltration rates were digitized from published data (Yager and others, 1985, plate 3), which were based on original data from soil surveys of Monroe County (Heffner and Goodman, 1973), Ontario County (Pearson and Cline, 1958), and Wayne County (Higgins and Neeley, 1978). Permeability values for areas classified in those reports as "urban with no permeability classification" were estimated from a generalized map of water-infiltration potential (Waller and others, 1982; Waller and Finch, 1982), which in turn was derived from data in Sweet and others (1938). The basin was divided into areas of low and high permeability—2 in/h or less, and greater than 2 in/h, respectively. Sixty-three percent of the basin had soils with low permeability, and the remaining 37 percent had highly permeable soils where the permeability ranged from 2 to more than 6 in/h (fig. 9).

Land-surface slope was selected for HRU delineation because it strongly affects erosion processes and the timing of storm runoff. A GIS grid of land-surface slope was derived from Digital Elevation Models (DEMs) of the basin through ArcView (Environmental Systems Research Institute, 1992). The basin was divided into low-slope areas (6 percent slope or less) and high-slope areas (greater than 6 percent) (fig. 9) from a histogram of grid slopes. The 6-percent demarcation was an arbitrary value that divided the basin into areas of slow and fast hydrologic responses, as well as into minor and major sources of sediment and chemicals relative to a given land use or land cover. The low-slope area encompassed 67 percent of the basin, and the high-slope area, which included slopes as high as 127 percent, encompassed the remaining 33 percent.

Land use and land cover were selected as a basis for HRU development because they 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) (U.S. Geological Survey, 1999) that were collected around 1992; an additional source was tax-related property-type classifications (PTC) (New York State Office of Real Property Services, 1996). Comparison of the two groups showed discrepancies; specifically the NLCD indicated greater percentages of forested and agricultural areas than the PTC, whereas the PTC identified larger percentages of residential and developed areas than the NLCD (table 1). These discrepancies resulted because the NLCD were developed from Landsat thematic mapper (TM) data (30-meter grid size) that were acquired by multiresolution land characterization and, therefore, classified the land primarily by land cover, whereas PTC classified the land primarily by land use for tax-assessment purposes.

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 three revisions to the NLCD were made to improve the land-use and land-cover data for the Irondequoit Creek model.

(1) The NLCD identified 40.8 percent of the basin as agricultural, that is, used for row crops and pasture or hay, whereas county PTC maps showed only 15.8 percent as agricultural (table 1). The PTC were assumed to correctly identify current agricultural land, and only those areas were classified as agricultural in the model. The remaining NLCD agricultural areas were reclassified as "open and(or) grass."

(2) The NLCD erroneously identified many emergent wetlands as row-crop land. 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 (New York State Department of Environmental Conservation, 2000),

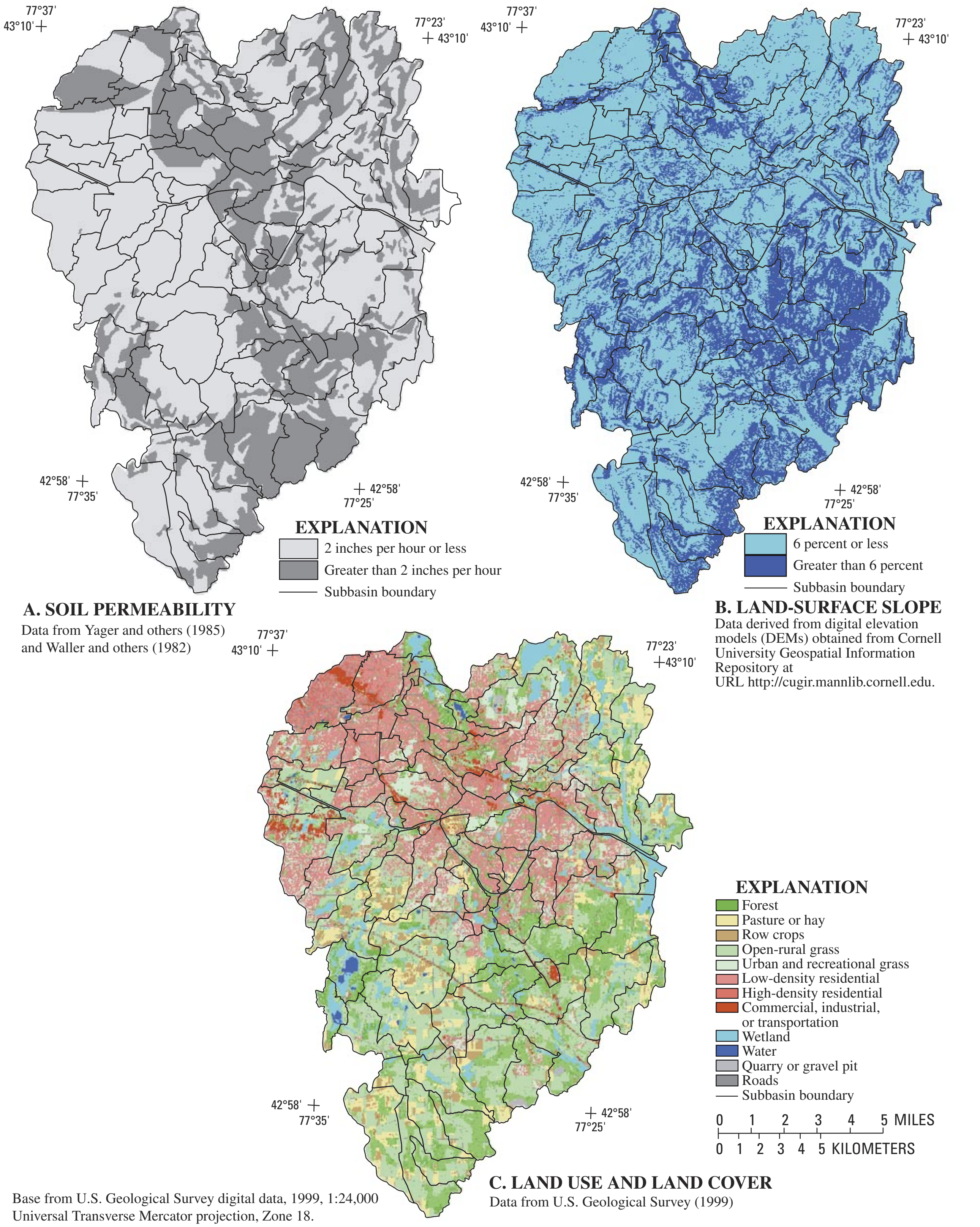


Figure 9. Data used in development of hydrologic-response units for precipitation-runoff model of Irondequoit Creek basin, Monroe and Ontario Counties, N.Y.: (A.) Soil permeability. (B.) Land-surface slope. (C.) Land use and land cover.

as well as those identified by municipalities in the Irondequoit Creek basin. This new wetland coverage was digitally incorporated into the NLCD coverage.

(3) Two large gravel pits near the southern boundary of the basin, classified by NLCD as commercial, were reclassified as low-slope, highly permeable, open and(or) grass areas. Similarly, two large golf courses in the southern part of the basin, which were classified as agricultural, were reclassified as urban and(or) recreational grass.

Impervious Land Segments (IMPLNDs)

The NLCD did not provide the amount of detail needed for the model in the developed areas of the basin. The NLCD contained only the following three categories of developed land uses:

(1) low-density residential, defined as areas with mostly single family housing where constructed materials (primarily buildings and pavement) account for 30 to 80 percent of the total area;

(2) high-density residential, defined as 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; and

(3) commercial-industrial-transportation, defined as all highly developed lands not classified as high-density residential.

Any developed area in which the land surface has been covered to some extent by constructed materials generally contains some amount of pervious land. A drainage study by the Monroe County Planning Council (1964) estimated that vegetated areas account for an average of 75 percent of a basin, even under conditions of maximum development, and that an urban environment containing pervious areas (cemeteries, golf courses, parks) in addition to its large impervious (commercially developed) areas can have approximately the same hydrologic characteristics as residential areas. Additionally, the modeling of impervious areas should distinguish between “effective” impervious areas—those that are hydraulically connected to the natural drainage system through ditches, culverts, and(or) a storm-sewer system—and “ineffective” impervious areas—those that are not hydraulically connected to the natural drainage system and drain to adjacent pervious areas.

A literature review (Alley and Veenhuis, 1983; Natural Resources Conservation Service, 1986; Dinicola, 1990; Berris, 1995; Zarriello, 1999; Zarriello and Reis, 2000; Lohani and others, 2001; Prisloe and others, 2000; and Center for Watershed Protection, 2001) indicated that most precipitation-runoff modelers, when modeling urban basins, attempted to develop a relation between average parcel or lot size and the percentage of the total or effective impervious areas of a basin. These studies had diverse objectives, but they all addressed simulation of urban runoff or the effects of urbanization on basin hydrology and nonpoint-source pollution, and many of them used HSPF. Only a few of these studies (Alley and Veenhuis, 1983; Lohani and others, 2001; Prisloe and other, 2000; Center for Watershed Protection, 2001) included actual measurements of total impervious area, but all the studies that presented effective-impervious-area values used estimated, and not measured, values, and gave widely differing relations between average lot size and effective impervious area. The data from these studies provided a basis for development of a relation between average lot size and effective impervious area for the Irondequoit Creek basin, however (table 5).

The detail of the areas classified as residential by NLCD was refined, and the amount of impervious area in the developed areas of the basin was estimated from county tax-parcel maps and associated parcel codes, which identified parcels that contained a “structure.” Some (3.4 percent) of the parcels were classified as commercial, including apartment buildings, 0.56 percent were classified as community and public services, and 0.36 percent as industrial (manufacturing and processing), but most (95.6 percent) of the parcels were classified as residential. The combined acreage of these parcels was divided by the number of parcels to obtain an average lot size (AVGLOTSIZE), which was used as an approximation of housing density and the degree of development within a given subbasin. This value, and the relation between average lot size and effective impervious area that was developed from the published data (table 5), were used to estimate the percentage of the area classified as residential or commercial that could be assumed to be effectively impervious. The acreage thus computed was placed in one of the IMPLND categories; the remaining area was assigned to a corresponding PERLND category. This method of impervious-area estimation resulted in paired relations between residential PERLNDs and IMPLNDs and between commercial PERLNDs and IMPLNDs.

Table 5. Percentages of residential or commercial areas assigned to pervious or impervious categories in the precipitation-runoff model of the Irondequoit Creek basin, Monroe and Ontario Counties, N.Y.

[PERLND, pervious land area; IMPLND, impervious land area; <, less than; >, greater than. Values are in percent]

Average residential lot (parcel) size in subbasin	Residential land use		Commercial land use	
Acres per parcel	PERLND	IMPLND	PERLND	IMPLND
> 1.5	100	0	100	0
0.751 to 1.5	95	5	60	40
0.55 to 0.75	86	14	14	86
0.21 to 0.54	80	20	14	86
< 0.21	52	48	14	86

Hydrologic Response Unit (HRU) Summary

The final classification of land use and land cover in the basin resulted in seven PERLND categories and three IMPLND categories (table 6). The seven PERLND categories were as follows:

(1) **Forest**—21.5 percent of the basin is covered with deciduous, evergreen, and mixed forests and orchards. Of this, evergreen trees were estimated to cover only 13 percent of the forested area.

(2) **Agriculture**—10.5 percent of the basin was estimated to be in active agricultural use, including row crops, pasture, and hay fields. This value was a result of the adjustments to the NLCD classification as described previously. Most agricultural land is south of the EBC.

(3) **Open and(or) rural grass**—27.0 percent of the basin is covered by nonforested rural areas that include abandoned agricultural fields and those areas classified by NLCD as pasture or hay fields that were not classified as "agricultural" by the county property-tax data.

(4) **Urban and(or) recreational grass** covers 8.0 percent of the basin and includes golf courses, public parks, and large expanses of residential lawns.

(5) **Residential**—17.9 percent of the basin is classified as residential, which includes low- and moderate-density residential areas. Of this amount, a calculated percentage of areas classified by NLCD as low-density residential was considered pervious; the remainder was considered impervious.

(6) **Commercial** uses, including commercial, industrial, transportation, and high-density residential uses, cover 8.3 percent of the basin. Of this amount, a calculated percentage of the commercial areas was considered pervious; the remainder was considered impervious.

(7) **Wetlands and(or) water** bodies (lakes and ponds) cover 6.8 percent of the basin. 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), regulatory freshwater wetlands (New York State Department of Environmental Conservation, 2000), and wetlands identified by town planning departments.

The final land-use and land-cover classification of the basin included two IMPLND categories—residential and commercial—which together represented the calculated effective-impervious portion of land classified by NLCD as residential and commercial.

These land-cover and land-use categories were further divided into low- and high-slope areas (6 percent or less and greater than 6 percent, respectively), and poorly and highly permeable areas (infiltration rate in the B soil horizon of 2 in/h or less and greater than 2 in/h, respectively). Theoretically, this division of the basin would have resulted in 28 PERLNDs (7 land covers or land uses × 2 slope classes × 2 permeability classes) and 4 IMPLNDs (2 land uses × 2 slope classes). Some categories were combined, however, because they either represented less than 1 percent of the basin or were assumed to have a hydrologic response similar to that of another PERLND or IMPLND, or because the distinctions between low and high slopes and(or) permeability were considered inconsequential for modeling a particular HRU. This consolidation resulted in a final set of 16 PERLNDs and 3 IMPLNDs (table 6). This set of HRUs was duplicated such that one set (PERLNDs 1–16 and IMPLNDs 1–3) was associated with the precipitation station at Victor; the other set (PERLNDs 21–36 and IMPLNDs 21–23) was associated with the National Weather Service station at the Greater Rochester International Airport (fig. 7). Each of these sets had an additional PERLND that was uniquely designed to simulate either a ground-water recharge site (infiltration basin; PERLND 20) or the Ellison Park wetland at the mouth of Irondequoit Creek (PERLND 38). Development of each of these PERLNDs is discussed in detail further on.

Thin soils underlain by fractured bedrock presented a unique hydrologic condition in the basin. Preliminary calibration of the model indicated a substantial difference between the hydrologic response of the Allen Creek subbasin and that of the upper Irondequoit Creek subbasin—a difference that the original set of HRUs failed to adequately simulate. This difference was attributed to large areas in the Allen Creek subbasin (and elsewhere in the northern half of the Irondequoit Creek basin) in which thin soils are underlain by fractured dolostone; this fracturing affects the water-storage and interflow and ground-water-flow characteristics, and increases ground-water loss from the subbasin. Therefore, a third set of PERLNDs was created for areas in which at least 50 percent of a subbasin contains 30 ft or less of overburden and is underlain by fractured dolostone, to permit simulation of flows in these "thin-soil" areas (fig. 3B). This set of PERLNDs (numbers 41–56) was associated with the precipitation record from the Greater Rochester International Airport (table 6).

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 USGS office, Troy, N.Y.). Stream reaches (RCHRESs) were delineated as part of the basin-segmentation process, and their lengths, change in elevation from upstream to downstream end, and median bed-material size (DB50) 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, 1979, 1980a, 1980b, 1981, 1982, 1983, 1984, 1992a, 1992b) 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, DEM elevations, or contour elevations on USGS topographic maps. The DB50 was estimated by field inspection of channels where the median particle size was obviously gravel or larger, or computed from sieve particle-

Table 6. Hydrologic-response units used in the precipitation-runoff model of the Irondequoit Creek basin, Monroe and Ontario Counties, N.Y.

[PERLND, pervious land segment; IMPLND, impervious land segment. Dashes indicate that the hydrologic response unit did not require division according to this basin characteristic or that a HRU number was not required]

Hydrologic response unit (HRU)			HRU number in model		
			Thick-soil[1] subbasin in indicated precipitation-record area		Thin-soil[1] subbasin in Rochester precipitation area
Land use or land cover	Slope[2]	Permeability[3]	Victor	Rochester	
Undeveloped PERLNDs					
Forest	Low	Low	1	21	41
Forest	Low	High	2	22	42
Forest	High	Low	3	23	43
Forest	High	High	4	24	44
Agriculture	Low	Low	5	25	45
Agriculture	Low	High	6	26	46
Agriculture	High	--	7	27	47
Open and(or) rural grass	Low	Low	8	28	48
Open and(or) rural grass	Low	High	9	29	49
Open and(or) rural grass	High	Low	10	30	50
Open and(or) rural grass	High	High	11	31	51
Urban or recreational grass	--	--	12	32	52
Upland wetland and water	--	--	13	33	53
Ground-water infiltration basin	--	--	20	--	--
At-mouth wetland	--	--	--	38	--
Developed PERLNDs					
Residential	Low	--	14	34	54
Residential	High	--	15	35	55
Commercial	--	--	16	36	56
IMPLNDs					
Residential	Low	--	1	21	21
Residential	High	--	2	22	22
Commercial	--	--	3	23	23

[1]Thin soil = 30 feet or less; thick soil = greater than 30 feet.

[2]Slope is average land-surface slope; low is 6 percent or less; high is greater than 6 percent.

[3]Permeability is average infiltration rate of the B soil horizon; low is 2 inches per hour or less; high is greater than 2 inches per hour.

size analyses of samples collected from several cross sections along the reach. The DB50 was used by HSPF for calculation of bed shear stress and shear velocity, as well as for sand-load computations.

Each RCHRES requires a function table (Ftable) that defines the relations between channel-storage volume and water depth, stream-surface area, and discharge. The depth-to-discharge relation is usually defined by the hydraulic properties at the downstream end of the reach, whereas the relation among surface area, volume, and discharge is a function of the hydraulic properties of the entire reach. Surface area and storage were calculated from cross-sectional data that was either collected for FEMA flood-insurance studies (FIS) or extracted from DEMs and modified by field measurements of channel top widths and depths. Relations between 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 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 high flows given in the FIS and to stage-to-discharge relations developed at USGS streamflow-monitoring stations. Calibration entailed adjusting the energy gradients and(or) roughness coefficients, 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), which used the top widths and cross-sectional areas computed by CGAP to compute water-surface area and channel-storage volume for each RCHRES.

Simulation Complexities

The Irondequoit Creek basin contains several complex hydrologic conditions, which required special handling for simulation by the model. Each of these complex conditions is described below.

Wetlands

As mentioned previously, lacustrine, palustrine, and riverine wetlands cover large percentages of some subbasins. These wetlands were simulated by a high infiltration value, large storage values for lower- and upper-soil zones, low slope, short overland-flow length, a large interflow quantity, high interflow- and ground-water-recession rates, and high evapotranspiration rates for active-ground-water and lower-zone storages. Collectively, this setup simulated retention and slow release of surface runoff, a high water table, and the removal of ground water through wetland-plant transpiration.

Upland wetlands (PERLNDs 13, 33, 53) function differently from the Ellison Park wetland at the mouth of Irondequoit Creek in three ways: (1) They are assumed to be regional ground-water recharge points, although they can become local ground-water discharge points; (2) their inflow and discharge are dominated by precipitation and evapotranspiration, respectively; and (3) they provide storm runoff storage. The Ellison Park wetland (PERLND 38), which has been studied in detail since 1990 by Coon (1997 and 2004) and Coon and others (2000), is, in combination with Irondequoit Bay, part of a regional ground-water-discharge area, although this function can vary seasonally (M. Traynor and R. Schneider, Department of Natural Resources, Cornell University, Ithaca, N.Y., written commun., 2002). Unlike the upland wetlands, flow patterns in the Ellison Park wetland are dominated by creek inflows, and water levels are seasonally controlled, not by surface inflow and evapotranspiration, but by the water-surface elevation of Irondequoit Bay and Lake Ontario. The Ellison Park wetland also provides peak-flow attenuation and particulate chemical load decreases through sedimentation (Coon and others, 2000). These characteristics were simulated by larger lower- and upper-zone storage values, a lower slope, larger interflow quantity, and higher interflow-recession rate in the Ellison Park wetland than the upland wetlands. The processes of sedimentation and nutrient retention and generation that occur in the wetland were, at least partly, simulated through adjustments of selected parameter values that are pertinent to these processes and are found in the model sections SEDMNT and PQUAL for PERLND 38 and in SEDTRN, NUTRX, and PLANK for the wetland RCHRESs (nos. 770 and 800). Additional adjustments were made through a separate mass-link (No. 19), which controlled the loads that were passed from reach to reach through the wetland.

Ground-Water Flow Out of the Basin

The eastern boundary of the ground-water divide for the Irondequoit Creek basin lies west of the surface-water divide (Yager and others, 1985), such that ground water in parts of the Thomas Creek and White Brook subbasins flows eastward out of the basin (fig. 5). A preliminary version of the model simulated runoff for part of the period for which streamflow records for Thomas Creek were available, September 1986 through March 1989. The resulting simulated total runoff at the Thomas Creek calibration point was more than 100 percent greater than the observed total runoff, but averaged only 25 percent greater at other calibration points. Therefore, a separate mass-link (No. 7) was established so that overland flow, interflow, and only 25 percent of ground-water flow (changed to 20 percent during calibration of the 1990–98 period) from the PERLNDs in the affected subbasins were routed to the appropriate RCHRESs. The remaining ground-water flow was routed out of the basin. (An alternative approach to simulating this condition might have been to duplicate the PERLNDs found in these subbasins and set the fraction of ground water that becomes “inactive” (DEEPFR) equal to 0.80.)

Surface-Water Losses to Fractured Bedrock

Seepage investigations in the Allen Creek and East Branch Allen Creek subbasins (table 7; Hornlein and others, 2002) indicated that base flows, as much as 1.8 ft^3/s, were lost from Allen Creek through fractures in the Lockport dolostone formation (dolomite and shale beds) and entered the ground-water system. This loss, which at times during July 2001 represented the total flow in the creek, presumably occurred through solution cavities and along bedding planes of the dolostone, and the water reentered the channel at springs along the creek about 0.4 mi downstream. Similar losses were not detected in East Branch Allen Creek. No revisions to the model were made to simulate this condition, however, because the channel losses and gains were within the boundaries of a single RCHRES (No. 580), and the overall water balance in the Allen Creek subbasin was unaffected.

Hydrologic Connections with the NYS Erie (Barge) Canal

The canal was excavated from native materials for most of its length, except for a 2-mi section (within subbasin CN3, fig. 8) starting at the Cartersville flood-control waste gate east of the Village of Pittsford and extending eastward to where Interstate Highway 490 crosses the canal just east of Bushnell Basin (fig. 1; T. Lippa, New York State Canal Corporation, Buffalo, N.Y., oral commun., 2001). This section of the canal, called the Great Embankment, is concrete lined where it crosses the Irondequoit Creek valley, and the only connection between the canal and the ground-water system in this area consists of leakage from the canal. Elsewhere, the canal is at grade with the surrounding area, such that a complete connection between the canal and the local ground-water system is possible.

The canal receives surface runoff from the adjacent areas, and the Villages of Pittsford and Fairport, as well as from several small subbasins between Allen Creek and East Branch Allen Creek. These contributing areas represent about 5,300 acres or 5.5 percent of the basin. Surface flow and interflow from these areas were routed to the canal, as was done with other PERLNDs and IMPLNDs (mass-link 11).

Routing of the ground-water component of flow was handled one of two ways:

(1) If most of the contributing area was drained by overland flow directly to the canal, as in subbasin CN3 (fig. 8), or short sewered segments, as in the Village of Fairport area (subbasin CN4), ground-water flow was routed to downgradient channels of the natural drainage system on the assumption that at least as much canal water was recharging ground water on the downgradient side of the canal as was entering the canal from the upgradient side (mass-link 6). The canal's contribution to ground water might be substantially more than assumed (M. Brewster, Town of Pittsford, and R. Cass, Town of Perinton, oral commun., 2001), but estimation of that quantity was beyond the scope of the study.

(2) If a large part of the contributing area was drained by a perennial stream, as subbasin CN1 between Allen Creek and East Branch Allen Creek, and subbasin CN2 in and south of the Village of Pittsford (fig. 8), then 20 percent of ground-water flow was routed to the canal as a base flow contribution to perennial streams (mass-link 14), and the remaining 80 percent was routed to downgradient channels as described in (1) (mass-link 15). The 20–80 percent split in ground-water contribution was estimated through calibration of the model to the observed streamflow records of Allen Creek and East Branch Allen Creek.

Diversions from the Erie (Barge) Canal

Variable amounts of water and chemical loads are diverted from the canal to nearby streams at four locations (fig. 1): two are siphoned withdrawals permitted by the New York State Canal Corporation, and two are points of leakage through or around canal flood-control waste gates. The siphoning points—one where the canal crosses Allen Creek, and the other where it crosses East Branch Allen Creek—maintain base flows in the stream channels and permit local golf courses to remove water for irrigation during the summer. The waste gates—one in the Village of Fairport, and the other at the Cartersville guard gate just east of the Village of Pittsford—were originally designed to permit discharge of excess water to relieve flooding eastward along the canalized-river part of the canal, but they have not been used for this purpose during recent years. A third flood-control gate in the Great-Embankment section of the canal near Bushnell Basin, has had no reported leakage.

Another potential point of canal-water discharge is a manhole in the bottom of the canal between Bushnell Basin and Fairport (fig. 1). The manhole cover can be removed during the nonnavigation season to dewater this section of the canal for maintenance activities to be performed. Manhole discharges occur only during the nonnavigation season, when the canal is drained of all but local inflow, whereas siphoning and leakage occur during the navigation season, when the canal is full.

Discharges at the siphoning and waste-gate leakage points were periodically measured by the Monroe County Environmental Health Laboratory. These measurements, as well as hydrographic comparison of observed and simulated flows at the calibration points, were used to estimate time series of daily flows at each location. Water samples from the canal diversions were collected and analyzed for chemical concentrations. Time series of ammonia, nitrate-plus-nitrite nitrogen, organic nitrogen, orthophosphate, and organic phosphorus loads were estimated and input to the model as point sources of contaminants. Discharges through the manhole between Bushnell Basin and Fairport was not simulated because (1) the contributing area to this point is unknown, (2) no flow data were available, and (3) such discharges, although possible during any given year, were observed only during the winter of 1998–99 (C. Knauf, Monroe County Environmental Health Laboratory, oral commun., 2001).

Table 7. Seepage investigation of Allen Creek subbasin, Monroe County, N.Y., July 3 and 6, 2001.

[Values are in cubic feet per second. no., number; NYS, New York State; USGS station, U.S. Geological Survey streamflow-monitoring station; na, not applicable. Dashes indicate no data]

Site no.	Site	July 3, 2001		July 6, 2001		Measurement accuracy[1]
		Discharge	Gain (+) or loss (-)	Discharge	Gain (+) or loss (-)	
1	Allen Creek above NYS Barge Canal	--	--	0.18	--	fair
2	Allen Creek below NYS Barge Canal	--	--	[2]1.31	+1.13	good
3	Allen Creek at Columbus Way	1.69	--	--	--	good
4	Allen Creek at Edgewood Avenue	1.84	+0.15	--	--	good
5	Allen Creek at Allens Creek Road	1.58	-.26	--	--	good
6	Allen Creek at Allendale Columbia School Drive	0	-1.58	0	-1.13	na
7	Allen Creek above Woodbury Place	.04	+.04	--	--	good
8a	Spring 1 below Woodbury Place	1.71	--	--	--	fair
8b	Spring 2 below Woodbury Place	[3].50	--	--	--	na
9	Allen Creek abover Buckland Creek (Sum of flow at Sites 7, 8a, and 8b.)	2.25	+2.21	--	--	na
10	Buckland Creek at mouth at Allens Creek Road	.09	--	--	--	fair
	Allen Creek below Buckland Creek (Sum of flow at Sites 9 and 10.)	2.34	+.09	--	--	na
11	Allen Creek above East Branch Allen Creek at Knollwood Drive	3.62	+1.28	--	--	fair
12	East Branch Allen Creek at Tobey Road	--	--	.04	--	fair
13	East Branch Allen Creek below NYS Barge Canal	--	--	[2]2.17	+2.13	good
14	West Brook at Tobey Road	--	--	.20	--	good
15	West Brook at West Brook Road	--	--	.21	--	fair
	East Branch Allen Creek below confluence with West Brook (Sum of flow at Sites 13 and 15.)	--	--	2.38	--	na
16	East Branch Allen Creek at USGS station	[4]2.39	--	[4]2.39	--	na
17	East Branch Allen Creek at mouth at Knollwood Dr.	3.29	--	--	--	fair
	Allen Creek below East Branch Allen Creek (Sum of flow at Sites 11 and 17.)	6.91	--	--	--	na
18	Allen Creek at USGS station	[4]6.70	--	--	--	na
18	Allen Creek at USGS station	--	--	3.65	--	poor

[1]Accuracy ratings of “good”, “fair”, and “poor” imply that the measured discharge is expected to be within 5 percent, within 8 percent, and greater than 8 percent, respectively, of the actual discharge.

[2]Mainly low-flow augmentation from New York State Erie (Barge) Canal siphons.

[3]Estimated value.

[4]From established stage-to-discharge relation.

Diversions to Golf Courses in Allen Creek Subbasin

As described above, siphoned flows from the canal into Allen Creek and East Branch Allen Creek were subsequently diverted to golf courses in the Allen Creek subbasin for irrigation. No records of irrigation withdrawals were available; therefore, diversion flows were estimated through a comparison of flows siphoned from the canal and those observed at the streamflow-monitoring sites downstream. Daily time series of flows were generated and input to the model in the EXT SOURCES module, then were removed through second exits that simulated withdrawals along RCHRES 580 of Allen Creek and RCHRESs 670 and 680 of East Branch Allen Creek. As with the siphoned flows, these diversion estimates were considered poor. Removal of chemical loads was simulated automatically with the diverted flows.

Ground-Water Recharge Sites

Two areas in the basin were identified as ground-water recharge sites. The first is associated with a large shopping mall east of Interstate Highway 490, in the northern part of the Town of Victor (fig. 4; labeled GWR1 in fig. 8). Stormwater from about 250 acres of commercial land is routed to two infiltration basins in depressions bounded on the east by the mall and on the west by the highway embankment (mass-links 4, 5, and 9). These ponds, which have no surface outflow (mass-link 6), were collectively simulated as a unique PERLND (No. 20) with high storage values for upper- and lower-soil zones, high rates of infiltration and ground-water recession, low slope, a long overland-flow length, and low interflow value and recession rate; all of which were selected to maximize infiltration and ground-water processes.

The second ground-water recharge area, which is in the Town of Pittsford (GWR2 in fig. 8), was identified by town personnel as one with highly permeable soils and an ephemeral stream (M. Brewster, Town of Pittsford, oral commun., 2001). The surface flow from IMPLNDs within subbasin GWR2 was routed to the low-slope, highly permeable forest and open-grass PERLNDs in the subbasin (mass-links 16 and 17). Parameter values that generally were set to reflect high infiltration rates elsewhere in the basin were considered applicable to this area as well; no unique parameter values specific to this area were required.

Excess Stormflow in White Brook

A flood-insurance study for the Town of Perinton (Federal Emergency Management Agency, 1992a) indicated that high flows in Thomas Creek caused backwater on the five 4-ft-diameter culverts that convey the flows of White Brook under the EBC. An overflow structure on the southern embankment of the canal about 6,700 ft upstream from the culverts permits about 90 percent of the 100-year discharge in White Brook to be diverted to the canal, and only 10 percent to pass downstream to Thomas Creek. Excess flows that enter the canal exit the basin at this point. This diversion was simulated by including a second outflow exit for RCHRES 420 (subbasin WB3; fig. 8). The outflow from this exit to the canal begins when the water-surface elevation in White Brook exceeds the full-pool elevation of the canal, about 462.4 ft (Todd Lippa, New York State Canal Corporation, Buffalo, N.Y., oral commun., 2000), or the RCHRES depth exceeds 3 ft at this location.

Jefferson Road Stormwater-Management Facility

A stormwater-management facility was constructed on East Branch Allen Creek between Jefferson Road and the EBC in the Town of Pittsford (subbasin EB3; fig 8) in 1995. This facility was designed primarily to control flooding and secondarily to improve water quality (Sherwood, 2004). A “front pond,” upstream from the main storage area, was designed to dissipate the energy of stormflows and to promote settling of suspended material. Water passes from the detention basin through a 30-in. pipe to a weir box at the bottom of an outlet control structure. High flows that are generated by low-frequency storms are controlled by a V-notch weir. When the water level in the basin falls below the apex of the weir, outflow is controlled by a 12-in. valve at the bottom of the weir box. This valve can be regulated to manipulate storage volume in the basin and to maintain summertime base flows (D. Anderson, ENSR International, Rochester, N.Y., written commun., 2001). Valve changes were not recorded during the study.

Three discharge relations were developed to represent flow conditions from the basin—a precontrol relation, and two postcontrol relations. The first postcontrol relation represented flows when the weir-box valve was closed, and, in general, gave better calibration results than a relation based on the weir-box valve in fully open position; this relation was used during most of the postcontrol period. The second postcontrol relation, which represented additional low-flow detention, was developed to resolve discrepancies that arose during three periods within the calibration period. A column-indicator file was created and stored in the WDM (DSN 6400) to permit switching from one discharge relation to another as desired. The initial switch from the precontrol to postcontrol relation occurred over a 10-day period during mid-August 1995, when the facility became operational (M. Brewster, Town of Pittsford, oral commun., 2001). Switches from one relation to another during the postcontrol period were determined through comparison of observed and simulated flows at the East Branch Allen Creek streamflow-monitoring station.

The stormwater-management facility had a substantial effect on loads of particulate constituents (Sherwood, 2004). Load data from the East Branch Allen Creek water-quality monitoring site, about 1.4 mi downstream from the facility, indicated a 22-percent decrease in total suspended solids

(TSS) and 10-percent decreases in ammonia-plus-organic nitrogen (TKN) and nitrate-plus-nitrite nitrogen (NOx). Median concentrations of TKN and NOx decreased by 23 and 36 percent, respectively. No statistically significant changes in total phosphorus (TP) loads or concentrations were noted. These removal rates were low—especially for TP, which has a close relation with sediment—compared to those measured at other detention basins (table 8), and might reflect the differences between removal efficiencies for instream and off-channel detention basins, as well as the contributions of constituent loads from canal discharges and the urbanized area between the Jefferson Road detention basin and the water-quality monitoring site. As a result of these differences, the removal rates were increased slightly from those computed by Sherwood (2004) to improve the match between simulated and observed loads at the East Branch Allen Creek site. In the UCI file, this stormwater-management facility was simulated as a best-management practice with the BMPRAC module of HSPF, which allows simulation of the effects of best-management practices by applying simple “removal” fractions to each constituent being simulated. Precontrol removal rates were set to zero in BMPRAC, and then were changed to the calibrated removal rates through the SPECIAL ACTIONS module beginning on August 15, 1995, and continuing though the postcontrol period.

Runoff from the City of Rochester

Two subbasins lie within the boundaries of the City of Rochester. Surface runoff in the western subbasin (R1; fig. 8) is conveyed by storm sewers to a bedrock-tunnel storage system under the city and has no connection with the rest of the Irondequoit Creek basin. A hypothetical Ftable was created to permit gradual depletion of water routed to tunnel storage. Surface runoff from the eastern subbasin (R2; fig. 8) was routed to Irondequoit Creek by means of mass-link 8. In both areas, interflow and ground-water flow were routed to a downgradient RCHRES because no direct connection exists between subsurface flow and flow in the culverts; mass-link 9 was used for this purpose.

Table 8. Published removal efficiency values for selected constituents for three types of stormwater-detention basins.

[Values are percents of total load that is removed. USEPA, U.S. Environmental Protection Agency. Dashes indicate no data]

Reference	Number of basins	Total suspended solids	Total phosphorus	Total nitrogen	Ammonia -plus- organic nitrogen	Nitrate -plus- nitrite nitrogen
Dry pond with or without extended detention						
USEPA, 1993	4–6	45	25	30	--	--
USEPA, 2001	15	47–61	19–20	25–31	--	-2–4
Simulated analyses (Donigian and others, 1997)	6	16–63	--	--	--	--
Wet pond (basin with permanent water pool)						
Nationwide Urban Runoff Program (USEPA, 1983)	14	90	65	--	50	50
Strecker and others, 1992	1–3	39–91	21–78	17–85	14	54–55
USEPA, 1993	9–18	60	45	35	--	--
USEPA, 2001	71	79–80	49–51	32–33	--	36–43
Simulated analyses (Donigian and others, 1997)	6	20–68	--	--	--	--
Irondequoit Creek basin, simulated analyses (Zarriello and Surface, 1989)	4	28–53	--	--	--	--
Jefferson Road Stormwater Management Facility, Town of Pittsford, N.Y. (Sherwood, 2004)	1	22	3	10	10	10
Wet pond with extended detention						
USEPA, 1993	1–3	80	65	55	--	--
USEPA, 2001	14	80	55	35	--	63
Simulated analyses (Donigian and others, 1997)	6	31–92	--	--	--	--
Irondequoit Creek basin, simulated analyses (Zarriello and Surface, 1989)	4	33–60	--	--	--	--

Areas of Severe Streambank Erosion

Severe streambank erosion of sand-and-silt bluffs along Irondequoit and Allen Creeks (RCHRESs 510 and 700, respectively) contributes large loads of sediment and associated constituents. These sites, which are about a mile above the confluence of Allen and Irondequoit Creeks, were estimated to contribute more than 50 percent of the sediment load measured in Irondequoit Creek at Blossom Road (Young and Burton, 1993). Stabilization of these streambanks was completed during 1999 and 2000, which is beyond the simulation period covered in this study. The estimated increases in sediment and particulate constituent loadings that were attributed to these sources were simulated through an adjustment of the pertinent multiplication factors assigned to these RCHRESs in mass-link 18.

Hypothetical Stormflow-Detention Basins

Nine hypothetical stormflow-detention basins of various sizes and contributing areas (fig. 8) were identified by members of the IWC and incorporated into the Irondequoit Creek model as alternative simulations of their respective RCHRESs and to assist in creation of scenarios that would illustrate the potential benefits of detention basins for controlling flooding and chemical loads. The hydrologic effects of a detention basin can be simulated by HSPF either through a separate "off-channel" RCHRES to which runoff from a part of the subbasin can be directed before discharging into the main-channel RCHRES, or as an instream detention basin. An off-channel detention basin permits flexibility in simulating the flow and water-quality effects of the basin, and might include the following modifications:

(1) the point of outflow might be raised in the RCHRES's Ftable to simulate permanent storage and extended detention time;

(2) sediment-transport and shear-stress values for scour and deposition might be increased to decrease sediment scour or to limit it to periods of extremely high discharges and velocities; and

(3) silt- and clay-settling velocities might be increased to simulate enhanced sedimentation (Donigian and others, 1997).

In contrast, an instream detention basin might be simulated with the following:

(1) permanent storage and extended detention time,

(2) increased storage volume, and(or)

(3) decreased outflow rate.

Detention simulated by either method could represent a single basin within a subbasin, or the aggregate effect of a number of small basins elsewhere in the subbasin, in which case, the Ftable for the detention basin would reflect the combined surface area and volume capacity of the several small basins.

All nine hypothetical detention basins were simulated as instream basins. Relations between channel-storage volume and water depth, surface area, and discharge relations (Ftables) were computed for each site on the basis of current conditions. A second table, in which the outflow rates and storage volumes could be adjusted to simulate various degrees of detention, was added to the UCI file for each respective RCHRES. Steps to make these revisions are described by Coon (2003). To a limited degree, these Ftable revisions will also simulate the water-quality effects of a detention basin; however, these effects can be simulated more precisely through the BMPRAC module of HSPF. Therefore, the Ftable revisions were included in the model to simulate the hydrologic effects of the detention basins, whereas the BMPRAC module was used to simulate the water-quality effects of the basins.

Removal efficiencies that were reported in studies of various types of detention basins (table 8) were evaluated to select representative values for the removal rates required in BMPRAC. These values were generally higher than those reported by Sherwood (2004) for the Jefferson Road stormwater-management facility and probably reflected the effects of off-stream basins that were specifically designed to optimize water-quality benefits. Removal efficiencies of TSS, TP, and total nitrogen (TN) for wet ponds with permanent water pools, which might be considered most similar in function to instream detention basins, were about 50, 50, and 40 percent, respectively. On the basis of these values, the removal rates used to simulate the water-quality effects of the Irondequoit Creek detention basins were 100, 50, and 10 percent for sand, silt, and clay, respectively; 100, 50, and 10 percent for ammonia and phosphate adsorbed to sand, silt, and clay particles, respectively; 50 percent for NOx, organic phosphorus, and organic carbon; and 30 percent for organic nitrogen.

The model was set up to enable simulation of the water-quality effects of eight of the nine hypothetical detention basins as described above. The ninth detention basin was in a RCHRES (No. 420) that was simulated with two exits, and HSPF does not support the use of BMPRAC for multiple outflows. Therefore, a unique mass-link (No. 22) was used to generate results for this basin that would be similar to those obtained for the other detention basins through BMPRAC. The limitation of this method of simulation is that outflow loads cannot be directly output to a WDM file; instead, the modeler will have to estimate the effect of the detention basin by comparing loads from the receiving RCHRES (No. 440) before and after simulating the detention-basin scenario.

Model Calibration and Performance

The hydrologic component of the Irondequoit Creek model was calibrated and validated first. After acceptable results were obtained, the model was calibrated to match observed water temperatures, and sediment and nutrient loads.

Hydrologic Component of Model

The hydrologic component of the model was calibrated to streamflow records collected from five sites (table 3; fig. 1) from October 1, 1991, through September 30, 1998; and was validated through comparison with records from October 1, 1998, through September 30, 2000. The precipitation-to-runoff relation was considered stable throughout the basin during this period (1991–2000; fig. 6); this stability was presumed on the basis of the following explanations:

(1) a subbasin was sufficiently developed by 1991 that subsequent changes in land use during this period had no detectable effect on the precipitation-to-runoff relation (as is likely to be the case in the northwestern part of the basin);

(2) the hydrologic effects of new developments were mitigated through adherence to zoning ordinances or construction of flow-attenuating measures, such as detention basins; or

(3) minimal development occurred during this period (as in the southern part of the basin).

The hydrologic component of the model was calibrated through HSPEXP (Lumb and others, 1994), an expert system for calibration of HSPF, and guidance provided by U.S. Environmental Protection Agency (2000) and Donigian and others (1984). Parameter values were adjusted through HSPEXP in a stepwise manner to obtain acceptable (1) annual mass balance, (2) low-flow volume and recession rates, (3) stormflow volume and peak discharges, and (4) seasonal flow volumes. During each step of the calibration process, a different set of parameters was evaluated through a comparison of simulated streamflow with observed streamflow. When calibration results indicated that a specific parameter value should be adjusted, reasonable replacement values were selected from models for basins with similar soil types, land uses, climatic zones, and drainage-basin size that were found in a HSPF parameter database, HSPFParm (Donigian and others, 1999), or in published reports. HSPEXP generated statistics that were used to evaluate the changes made in the model and the remaining error. Adjustment continued until the percent error between simulated and observed flows was minimized, or at least fell below a predefined acceptable limit for errors in total volume, low-flow recession rate, the 50-percent lowest flows, the 10-percent highest flows, storm volume, seasonal volume, and summer-storm volume.

The Irondequoit Creek model contained three sets of duplicate HRUs—one associated with the Victor precipitation record, one associated with the Rochester Airport precipitation record, and one associated with thin-soil areas underlain by fractured bedrock. Although values for some key parameters have been found to vary from one basin to another, even in the same geographic area (Donigian and others, 1983; Laroche and others, 1996; Carrubba, 2000), the parameter values assigned to a given HRU in the Irondequoit Creek model were assumed to be constant regardless of the precipitation record to which the HRU was related. If the basin characteristics that dominate the overland and within-channel flow processes were correctly identified, as was assumed, then no reason could be offered to justify changes to parameter values solely on the basis of a different precipitation record. In contrast, values for parameters that affect infiltration and subsurface flow can be and were modified for the HRUs in the thin-soiled, fractured-bedrock subbasins. Adherence to the guideline of consistent application of parameter values during the calibration process limited the precision of calibration that could be achieved at any given streamflow-monitoring site in the basin, and meant that, even though the best combination of parameter values at one calibration point might not have been the best at another, the values that were used in the final version of the model were those that collectively gave the best results and minimized the differences between observed and simulated values on a basinwide basis.

The percent errors of the calibrated model fell within the predefined default limits of HSPEXP at all five calibration sites and for all calibration criteria (table 9). Total volume error did not exceed 5.6 percent at any of the sites during the calibration period. Similarly, low-flow and high-flow errors were less than 5.9 percent. The error in storm volume did not exceed 7.2 percent at any site except the downstream site, Irondequoit Creek at Empire Boulevard, where the Ellison Park wetland attenuated the flow. Errors in summer-storm volume were large at some sites, but presumably resulted from local storms that were not reflected in the precipitation records used in model simulation. The low-flow-recession errors at the East Branch and main stem Allen Creek sites could not be resolved; decreasing the active-ground-water-recession coefficient (AGWRC) or increasing the active-ground-water-outflow modifier (KVARY) by an amount that would have corrected this error caused low-flow discrepancies between observed and simulated flow-duration plots. The likely causes of these errors were the lack of operational records from the Jefferson Road stormwater-management facility (subbasin EB3) and inaccuracies in the estimates of canal diversions and golf-course withdrawals from the Allen Creek subbasin. Summer-storm-volume errors in the East Branch and Allen Creek subbasins were large also. Adjusting the percentages of the pervious and effective impervious areas in the subbasin should have decreased the error by increasing runoff and summer-storm peaks, but converting all the pervious "developed" acreages to impervious areas failed to improve the results. Simulation of developed areas as entirely impervious surfaces was not reasonable; therefore, the original pervious and impervious acreages were retained. All HSPEXP error statistics for the validation period were greater than those for the calibration period, which indicated a limitation of the model for predictive purposes—in other words, the calibrated model can be used for comparison of scenarios, but should not be used to predict future streamflows.

Model Performance

In addition to the above measures, model performance during the calibration and validation simulation periods was assessed on the basis of the "weight of evidence" approach (Donigian, 2002), which incorporates qualitative and quantitative measures involving graphical comparisons and statistical tests. Graphical comparisons included (1) time-series plots of monthly observed and simulated values, (2) scatter plots of observed and simulated values in relation to a 45-degree

Table 9. Calibration criteria and errors for simulated streamflow at five streamflow-monitoring sites in the Irondequoit Creek basin, Monroe and Ontario Counties, N.Y.

[Results generated by HSPEXP, an expert system for calibration of Hydrological Simulation Program-FORTRAN models (Lumb and others, 1994). Values are in percent, except error in low-flow recession, which is unitless. Site locations are shown in figure 1]

Calibration criterion	Default value	Errors for (A) calibration period, October 1, 1991, through September 30, 1998, and (B) validation period, October 1, 1998, through September 30, 2000									
		Irondequoit Creek at Railroad Mills (04232034)		East Branch Allen Creek at Pittsford (0423204920)		Allen Creek near Rochester (04232050)		Irondequoit Creek at Blossom Road (0423205010)		Irondequoit Creek at Empire Boulevard (0423205025)	
		A	B	A	B	A	B	A	B	A	B
Error in total volume	10.0	2.0	-2.0	-5.6	-14.0	4.0	-10.8	-2.3	-9.5	-1.1	-12.5
Error in low-flow recession	.03	-.01	-.01	-.03	-.03	-.03	-.02	-.01	-.01	-.03	-.02
Error in 50-percent lowest flows	10.0	-3.6	-6.3	1.3	19.1	1.3	-18.1	-2.0	-6.7	-1.6	-9.9
Error in 10-percent highest flows	15.0	4.7	-17.7	-5.8	-13.5	1.5	-12.5	-3.3	-21.5	-1.5	-25.9
Error in storm volume	20.0	-3.8	-54.0	4.0	33.0	-4.8	-13.5	-7.2	-28.1	14.2	-7.8
Seasonal volume error	30.0	1.3	11.6	6.2	46.7	3.2	6.0	13.9	17.9	18.7	22.5
Summer storm volume error	50.0	12.4	9.0	-26.9	13.3	-20.6	9.7	5.0	8.7	.1	7.6

linear regression line, and (3) cumulative frequency distributions of observed and simulated values (flow-duration curves). Statistical tests included (1) error statistics (mean absolute error, mean error, and percent error); and (2) correlation tests (linear-correlation coefficient, coefficient of determination, and coefficient of model-fit efficiency).

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

$$\sum |S - O| / N , \quad (1)$$

where

S	=	simulated value,
O	=	observed value,
N	=	number of values in the sample,
Σ	=	sum, and
$\| \ \|$	=	absolute value.

The percent 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

$$100 \times \sum [\ |S - O| / O \ ] / N \ . \quad (2)$$

Mean error (ME), or bias, is the average of the differences between simulated and observed values and accounts for the positive or negative sign of the difference, and equals

$$\sum (S - O) / N . \quad (3)$$

ME indicates whether the model is biased—that is, overestimating or underestimating a given constituent.

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

$$100 \times \sum [\ (S - O) / O \ ] / N \ . \quad (4)$$

Root mean square error is the square root of the average of the squared differences between simulated and observed values, and equals

$$[\sum (S - O)^2 / N]^{0.5} . \quad (5)$$

The correlation coefficient, R, (Duncker and Melching, 1998) was calculated as

$$R = \frac{\sum (q_o - \bar{q}_o) \times (q_s - \bar{q}_s)}{\sqrt{\sum (q_o - \bar{q}_o)^2 \times \sum (q_s - \bar{q}_s)^2}} , \quad (6)$$

where

q_o	=	observed flow for given time step,
$\bar{q}_o$	=	average observed flow for given time step,
q_s	=	simulated flow for given time step, and
$\bar{q}_s$	=	average simulated flow for given time step.

The coefficient of determination, R^2, although redundant, was included along with the correlation coefficient to enable direct comparison with values published for other HSPF models.

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

$$E = \frac{\sum (q_o - \bar{q}_o)^2 - \sum (q_o - q_s)^2}{\sum (q_o - \bar{q}_o)^2} , \quad (7)$$

where the variables are defined as above.

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.

For HSPF simulations, the agreement between annual and monthly simulated and observed flows can be characterized as “very good” when the 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 10; Donigian, 2002). These criteria and the percent mean errors for the calibration sites (table 11), indicate the Irondequoit Creek model to be “very good” for daily and monthly flows at all sites except Allen Creek, for which it would be rated “good.”

The correlation coefficients for simulated-to-observed flows ranged from 0.81 to 0.93 for daily flows and 0.88 to 0.95 for monthly flows at the five calibration sites (table 11). These values fell within the range of published values for other HSPF models (table 12). The coefficients of model-fit efficiency ranged from 0.59 to 0.85 for daily flows and 0.75 to 0.90 for monthly flows at the Irondequoit Creek sites, which generally were in the low range of published values for daily flows and in the midrange for monthly flows.

Table 10. Selected criteria for evaluating Hydrological Simulation Program—FORTRAN (HSPF) model performance.

[Data from Donigian (2002)]

	Percent difference between observed and simulated monthly or annual values		
	Very good	**Good**	**Fair**
Streamflow	< 10	10–15	15–25
Sediment loads	< 20	20–30	30–45
Water temperature	< 7	8–12	13–18
Nutrient loads	< 15	15–25	25–35
	Correlation coefficient (R)		
Daily streamflow	0.89–0.95	0.84–0.89	0.77–0.84
Monthly streamflow	0.92–0.97	0.87–0.92	0.81–0.87
	Coefficient of determination (R^2)		
Daily streamflow	0.80–0.90	0.70–0.80	0.60–0.70
Monthly streamflow	0.85–0.95	0.75–0.85	0.65–0.75

Graphical comparison of observed and simulated daily and monthly flows (fig. 10) indicated that simulated flows were neither consistently low nor high in relation to observed flows at the calibration sites. Flow durations of simulated daily flows closely matched those of observed flows during the calibration period (fig. 11).

The statistical tests and graphical comparisons for the simulated and observed flows during the validation period gave varied results. Mean errors for Irondequoit Creek at Blossom Road and Empire Boulevard were higher during the validation period than the calibration period; whereas mean absolute errors for the two periods at each site were comparable (table 11). The correlation coefficients for the two periods were similar at most sites for both daily and monthly flows. The changes in coefficients of model-fit efficiency varied among the sites; model performance improved at the Allen Creek sites and either remained the same or diminished at the Irondequoit Creek sites (table 11). The graphical relations between daily and monthly observed and simulated flows during the validation period were similar to those during the calibration period (fig. 10). The flow durations for simulated daily flows differed more from observed flows during the validation period than during the calibration period; nonetheless, similar patterns in the flow-duration plots are evident (fig. 11).

Model Sensitivity to Parameter Values

Many published reports on HSPF models have included analyses of model sensitivity to parameter values, and researchers are in general agreement as to the specific parameters whose values have the greatest effect on model results. Laroche and others (1996) list the following 10 parameters that strongly affect the hydrologic component of an HSPF model:

- INFILT Index of soil-infiltration capacity;
- IRC Interflow-recession coefficient, an index for the rate of shallow subsurface flow;
- INTFW Interflow-inflow parameter, controls the amount of infiltrated water that becomes shallow subsurface flow;
- 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;
- LZETP Lower-zone evapotranspiration parameter, represents the density of deep-rooted vegetation that conveys water from the unsaturated zone upward to the atmosphere;
- AGWRC Ground-water recession coefficient, controls the rate at which ground water drains from the land;
- KVARY Ground-water outflow modifier, represents the variable influence that ground-water inflow has on ground-water outflow;
- INFEXP Infiltration equation exponent, controls the rate of infiltration decrease as a function of increasing soil moisture; and
- INFILD Ratio of maximum to mean infiltration rate.

The hydrologic results of the Irondequoit Creek model were strongly affected by the values assigned to all of these parameters. KVARY strongly affected the shape of the ground-water-recession curve, but AGWRC alone was sufficient to simulate this part of the hydrograph. Therefore, default values were used for KVARY, as well as for INFEXP and INFILD, for which no reason to alter their values was found. Four other parameters were found to affect the calibration of snowmelt periods:

- SHADE Fraction of the land surface shaded from solar radiation by trees or slope,
- COVIND Amount of snowfall required to completely cover the land surface,
- SNOEVP Snow-evaporation-adjustment factor, and
- CCFACT Condensation and convection melt-adjustment factor.

Two other snowmelt parameters—MWATER, the liquid-water storage capacity in the snowpack, and MGMELT, the rate of melt caused by ground heat—can strongly affect snowmelt processes but did not affect the Irondequoit Creek model; therefore, default values were used for these parameters.

Model Uncertainty

Sources of model uncertainty included (1) insufficient number of precipitation-monitoring sites to adequately represent the precipitation patterns over the basin, (2) inaccurate estimates of diversions, (3) misclassification of land-use and land-cover data, (4) changes in land use during the simulation period, and (5) differences in scale of the subbasins used for calibration and the consequent effect on parameter values.

Table 11. Model-performance statistics for simulated streamflow at five monitoring sites in the Irondequoit Creek basin, Monroe and Ontario Counties, N.Y.

[Locations of monitoring sites are shown in figure 1]

Statistic	Model performance statistics for (A) calibration period, October 1, 1991, through September 30, 1998, and (B) validation period, October 1, 1998, through September 30, 2000									
	Irondequoit Creek at Railroad Mills (04232034)		East Branch Allen Creek at Pittsford (0423204920)		Allen Creek near Rochester (04232050)		Irondequoit Creek at Blossom Road (0423205010)		Irondequoit Creek at Empire Boulevard (0423205025)	
	A	B	A	B	A	B	A	B	A	B
Daily mean streamflow										
Mean error and bias (percent)	-0.69 (-1.7)	-2.20 (-7.3)	0.47 (4.9)	-0.12 (-1.5)	3.32 (10.5)	-0.56 (-2.2)	-7.50 (-5.6)	-14.9 (-13.8)	-1.33 (-.93)	-16.0 (-13.7)
Mean absolute error (percent)	10.3 (26)	8.38 (28)	3.89 (41)	4.10 (52)	10.7 (34)	10.6 (40)	30.2 (22)	29.1 (27)	32.1 (22)	32.1 (28)
Root mean square error	20.7	18.2	10.3	8.79	29.1	26.9	62.9	63.3	69.2	66.1
Correlation coefficient	.90	.88	.81	.80	.85	.85	.93	.92	.91	.90
Coefficient of determination	.81	.77	.65	.65	.72	.72	.86	.85	.83	.82
Coefficient of model-fit efficiency	.80	.74	.59	.59	.69	.72	.85	.80	.82	.79
Monthly mean streamflow										
Mean error and bias (percent)	-.72 (-1.8)	-2.23 (-7.3)	.48 (5.1)	-.12 (-1.6)	3.36 (11)	-.56 (-2.1)	-7.54 (-5.6)	-15.0 (-14)	-1.39 (-1.0)	-16.1 (-14)
Mean absolute error (percent)	6.03 (15)	4.54 (15)	2.1 (22)	1.90 (24)	6.30 (20)	5.76 (22)	19.3 (14)	20.1 (19)	19.2 (13)	22.3 (19)
Root mean square error	8.32	6.38	3.10	2.58	9.17	7.18	27.5	31.9	29.7	34.6
Correlation coefficient	.95	.95	.88	.95	.91	.92	.95	.95	.94	.95
Coefficient of determination	.91	.91	.77	.91	.83	.84	.91	.90	.89	.89
Coefficient of model-fit efficiency	.89	.89	.75	.85	.78	.84	.90	.81	.89	.81

Some of these sources of uncertainty have been identified by other 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 five sources of uncertainty are described below.

1. Inadequate representation of precipitation patterns: 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, can fail to adequately represent nonuniform precipitation patterns across the basin, especially during local summer thunderstorms. This inadequacy, in turn, can produce a large uncertainty in the model results (Troutman, 1982, 1983; Chaubey and others, 1999; Straub and Bednar, 2000). The two precipitation-monitoring sites (Rochester Airport and Victor) that were available for model calibration were insufficient to capture the precipitation patterns across the basin, and actually lie outside of the Irondequoit Creek basin. Comparison of the records from the two sites indicates large differences in precipitation quantities and timing. For example, recorded precipitation at the Rochester Airport exceeded that at Victor by 6.8 in. during 1998 and by 8.7 in. during 1995. Whether these differences were real or reflect measurement error, using one rather than the other to simulate precipitation across the entire basin would have

Table 12. Published model-performance results for streamflow simulated by Hydrological Simulation Program—FORTRAN models.

[>, greater than. Dashes indicate no data]

Reference	Number of basins or calibration points	Analysis interval	Correlation coefficient (R)	Coefficient of determination (R^2)	Coefficient of model-fit efficiency (E)
Duncker and others (1995)	5 basins: individual (best-fit) calibration parameter set	monthly	0.93–0.97	--	0.87–0.93
	5 basins: regional-calibration parameter set	monthly	.93–0.95	--	.86–0.91
	2 basins: verification using regional parameter set	monthly	.93–0.94	--	.87–0.88
Duncker and Melching (1998)	3 basins: individual (best-fit) calibration parameter set	monthly	.93–0.96	--	.86–0.92
	3 basins: regional-calibration parameter set	monthly	.92–0.94	--	.83–0.86
	3 basins: verification using regional parameter set	monthly	.78–0.93	--	.34–0.82
	3 basins: recalibration using regional parameter set	monthly	.87–0.92	--	.76–0.83
James and Burgess (1982)	--	daily	> .98	--	> .98
Crawford and Linsley (1966)	7 basins	daily	.94–0.98	--	--
Chiew and others (1991)	1 basin	monthly	.8	--	--
Price (1994)	4 basins	monthly	.88–0.95	--	--
Jones and Winterstein (2000)	2 basins	monthly	.93	--	.83–0.85
Zarriello and Reis (2000)	2 calibration points	annual	--	0.85–0.99	.72–0.98
		monthly	--	.95–0.98	.90–0.95
		daily	--	.89–0.94	.79–0.88
Martin and others (2001)	2 calibration points	monthly	.98	--	.95–0.96
		daily	.98	--	.95–0.96
		hourly	.89–0.93	--	.79–0.86
Wicklein and Schiffer (2002)	2 calibration basins	monthly	.86–0.88	--	.72–0.75
	3 validation basins	monthly	.88–0.91	--	.68–0.78
Senior and Koerkle (2003)	9 calibration points	daily	.66–0.95	--	.42–0.85
		hourly	.24–0.91	--	.05–0.79
Donigian (2002)	2 calibration points	monthly	.93	.87	.87
		daily	.86	.74	.73

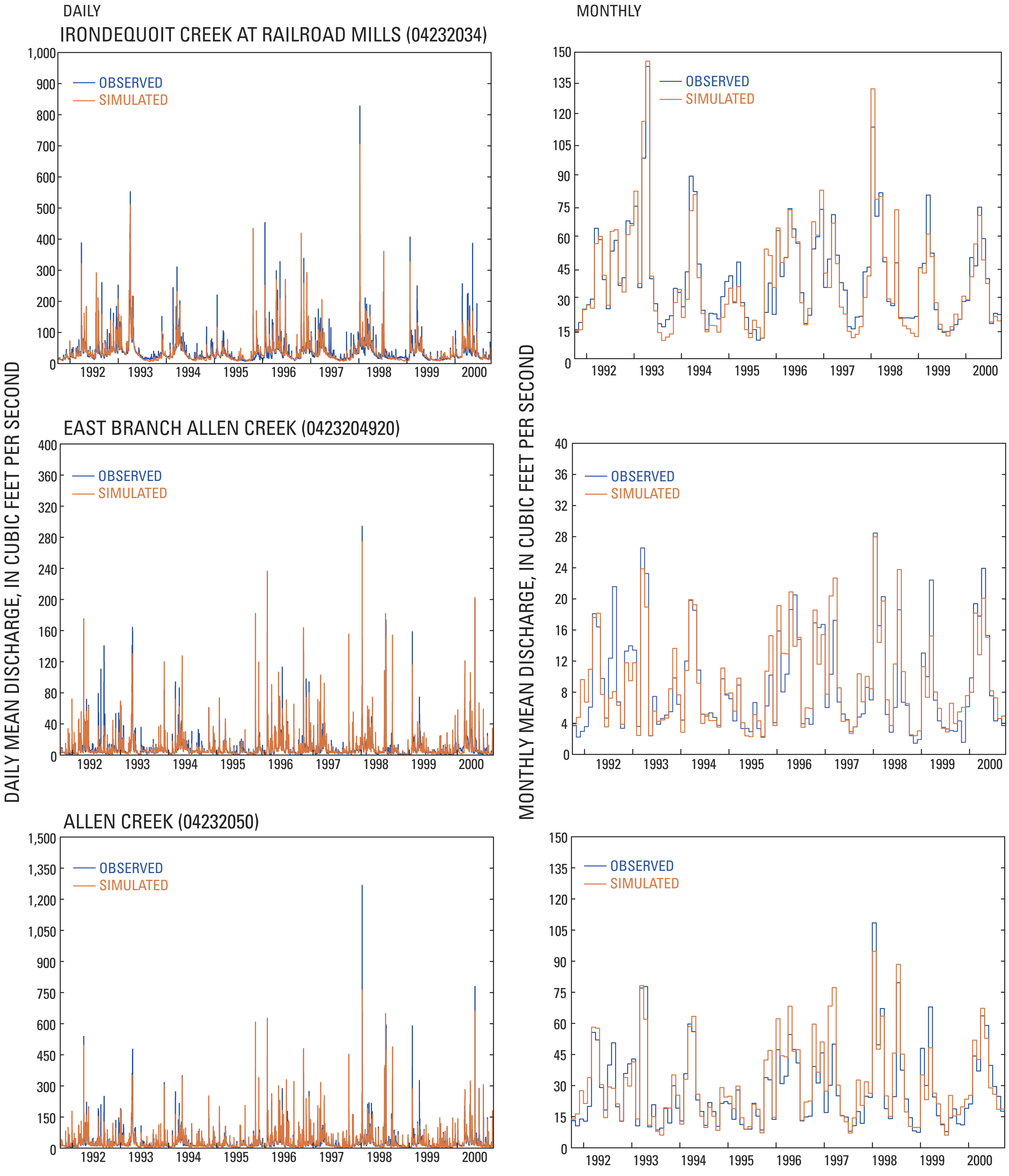


Figure 10. Daily and monthly observed and simulated flows at five calibration sites in the Irondequoit Creek basin, Monroe and Ontario Counties, N.Y. (Site locations are shown in figure 1.)

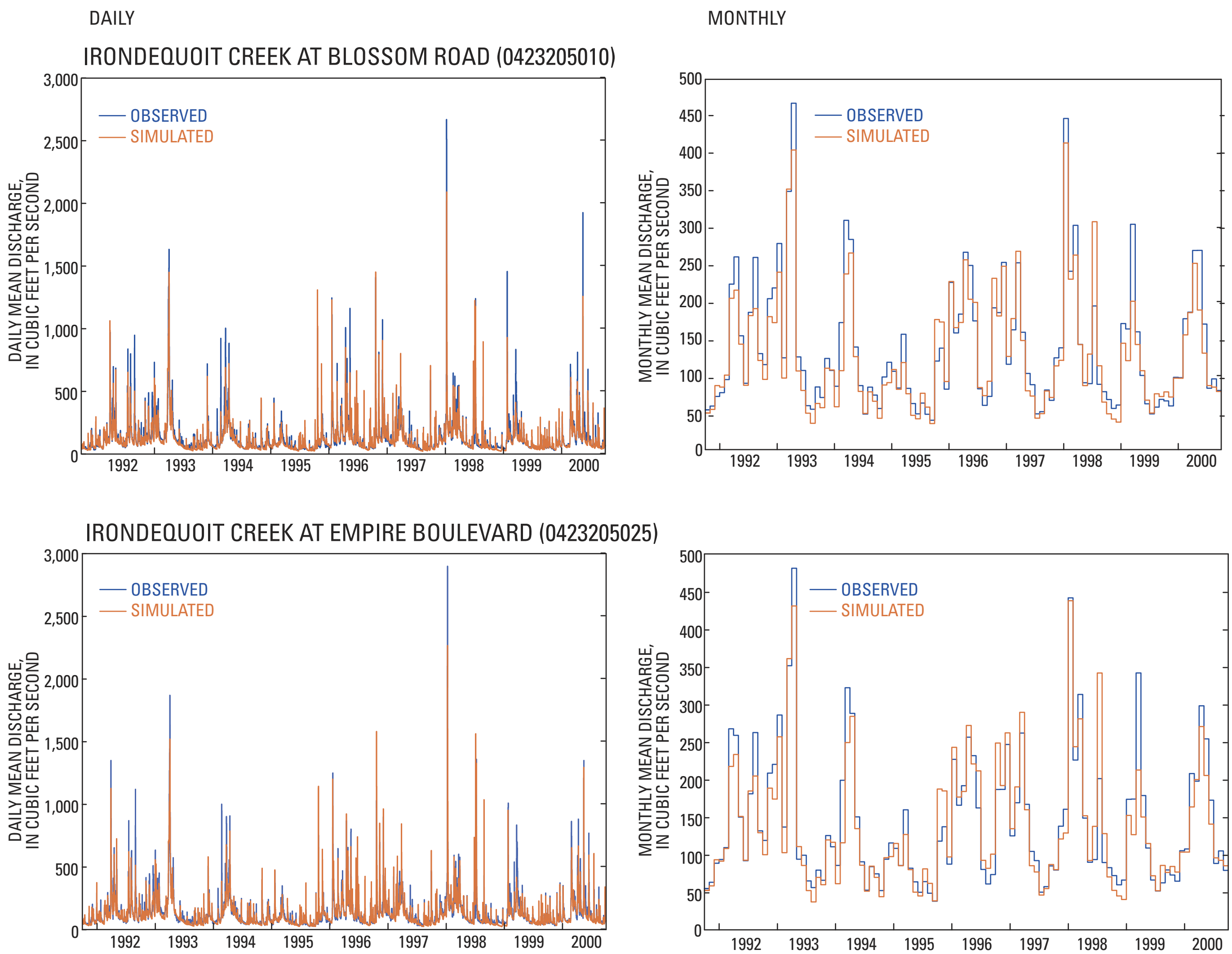


Figure 10. Daily and monthly observed and simulated flows at five calibration sites in the Irondequoit Creek basin, Monroe and Ontario Counties, N.Y. (Site locations are shown in figure 1.)—Continued.

introduced large errors that would have necessitated unwarranted adjustments to parameter values to improve the fit between observed and simulated flows. Two additional, though partial, records of precipitation within the southern half of the basin (Honeoye Falls-Lima and Mendon Ponds) indicated large differences in precipitation quantities, especially during the summers. These additional records were not used, however, because they were either incomplete or would have limited the period of simulation to an unacceptably short period. Additionally, continuation of these precipitation stations is not certain. The discrepancies among the precipitation records indicate that any single record cannot reliably represent the precipitation patterns throughout the basin.

2. Estimated inflows and diversions: The estimated inflows to the basin from the EBC siphons and from gate leakages, unknown outflow from the Jefferson Road stormwater-management facility (detention basin) on East Branch Allen Creek (subbasin EB3; fig. 8), and unrecorded withdrawals for golf-course irrigation in the Allen Creek subbasin were a second source of model uncertainty. Siphon and leakage diversions were estimated from infrequent discharge measurements. Outflow from the detention basin was regulated by a valve in the outflow structure, but valve-opening changes were not recorded and could be estimated only through comparison of observed and simulated flows at the East Branch Allen Creek monitoring station. The irrigation withdrawals also were not recorded and were estimated through a comparison of observed and simulated flows at the Allen Creek monitoring station. Although the magnitude of these inflows and diversions is relatively small in relation to the total annual flow in a given stream, they represent a large percentage of the summertime base flows in Thomas and Allen Creeks, and probably contributed to the difficulty in calibrating low-flow recessions and base flows in these subbasins.

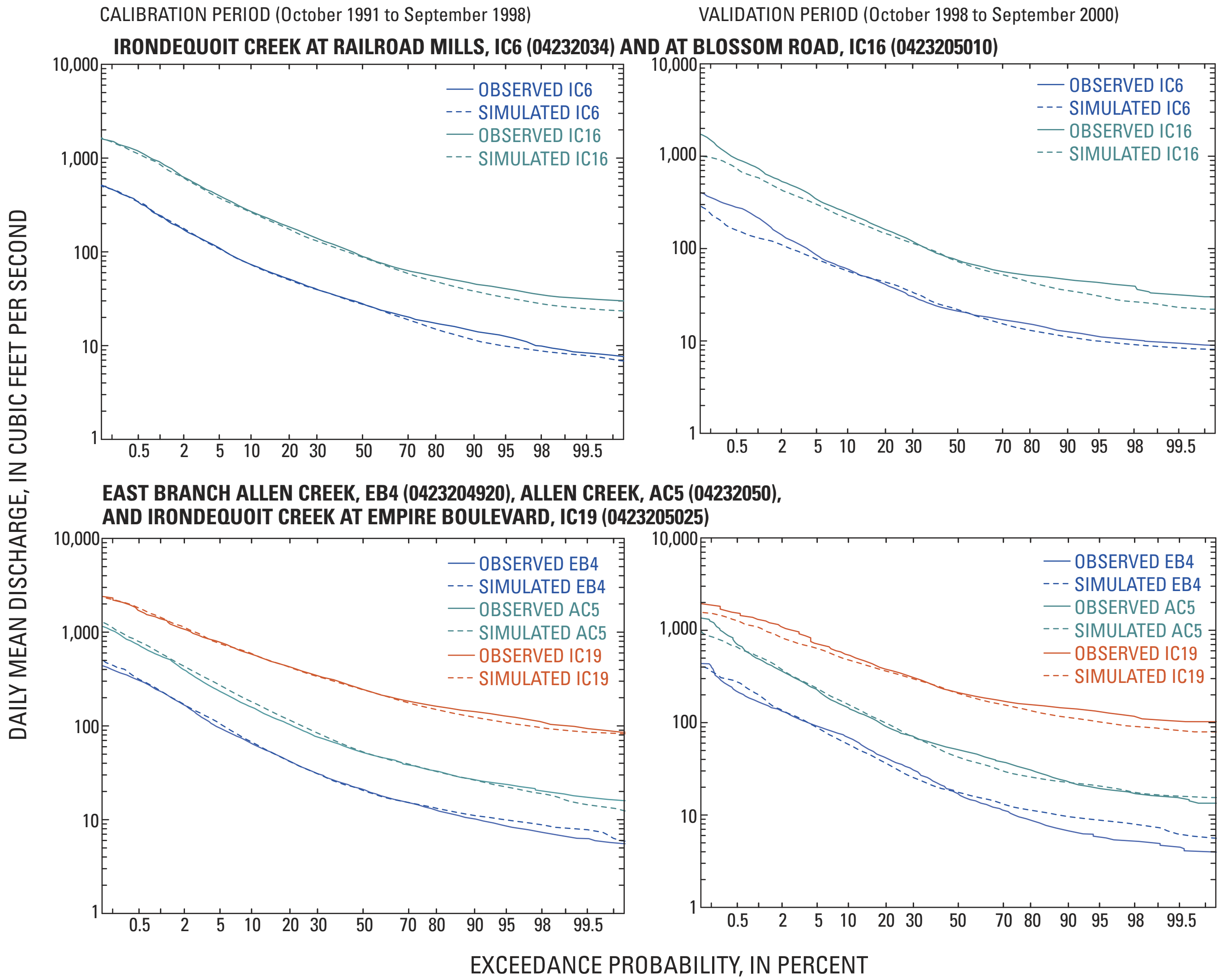


Figure 11. Flow-duration plots of observed and simulated flows at five calibration sites in the Irondequoit Creek basin, Monroe and Ontario Counties, N.Y. (Site locations are shown in figure 1.)

3. 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 were made as described previously. Errors in land-use or land-cover classification affect the acreage values assigned to HRUs, and, thus, the values of parameters assigned to simulate the hydrologic processes within these HRUs.

4. Changes in land use: The 1991–2000 simulation period was selected for model development because rainfall-runoff patterns appeared to be stable, especially in the urbanized subbasins (fig. 6); but this apparent stability probably reflected a counterbalancing of hydrologic processes. For example, increased runoff from newly developed impervious areas could be mitigated by on-site detention basins, but the requirement for inclusion of detention basins could vary from town to town. The selected values of parameters that would simulate runoff processes for a given HRU would not optimally simulate flows in either situation, but rather would be average values that simulated average conditions. Therefore, the predictive capability of the model would be limited by the changing conditions in the basin; that is, the parameter values that were used to minimize the simulated-to-observed streamflow error during the 1990s calibration period were probably not the optimum values to simulate flows during the previous or following decades.

5. Effect of subbasin scale: The development of the HRUs required assumptions and parameter values that represented average conditions over a range of slopes and permeability that were applicable at a basinwide scale. As subbasin size decreases, the ranges of slope and permeability narrow, and basin characteristics (actual slope, overland flow length, upper- and lower-zone nominal storages, infiltration-capacity, and interflow indices) become increasingly uniform, thus, the optimal parameter values 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; 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 or development scale, where the subbasin characteristics can differ substantially from the basinwide averages.

In summation of model uncertainty, therefore, unavoidable errors in the input data must inevitably affect the values selected for the related key parameters in the model, and adjustment of parameter values during model calibration to minimize the differences between observed and simulated values will also unavoidably be minimizing the errors in the input data.

Water-Quality Components of Model

The water-quality components of the Irondequoit Creek basin model included simulation of water temperature, sediment loads, and nutrient loads, which were calibrated to records collected at the five streamflow and water-quality monitoring sites from September 1, 1991, through September 30, 1998, and were validated through comparison with the records collected from October 1, 1998, through September 30, 2000. Guidance in the calibration of these constituents was provided by Donigian and others (1984). Calibration entailed comparison of graphs of daily water temperatures and monthly sediment and nutrient loads and adjustment of pertinent parameter values to minimize the percent error between annual observed and simulated loads. Model performance was evaluated through comparison of (1) percent differences between observed and simulated values with target values presented by Donigian (2002; table 10), and (2) simulated annual loading rates of the selected constituents with observed values. The simulations of all water-quality constituents in the Irondequoit Creek model were rated “good” to “very good.”

The parameter values for the water-quality components of the model were adjusted to provide the best fit of each constituent at all five water-quality monitoring sites. Precise calibration at a given monitoring site was not possible because two major assumptions could not be totally met; these assumptions were that (1) the primary basin characteristics that controlled the removal and transport of constituents in the basin had been identified, and (2) the parameter values used to represent these characteristics for a given HRU were not affected by the HRU’s location (in relation to its assigned precipitation record) in the basin. In other words, 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 and minimized the differences between observed and simulated values on a basinwide basis were selected.

Calibration of chemical loads was primarily dependent on the simulated flows. Any errors in flow would be incorporated into the simulations of sediment and nutrient loads. Calibration of the chemical loads was complicated by the differences in the major flow components at each monitoring site; for example, flow in Irondequoit and Thomas Creeks was dominated by ground-water inflow, followed by interflow, and then surface runoff; whereas, flow in Allen Creek and its East Branch was dominated by surface runoff. These distinctions added to the difficulties in calibrating the nutrient loads because the dominant removal and transport mechanisms changed from subbasin to subbasin along with the dominant flow component. The simulations of nutrient loads were also subject to (1) errors in simulated water temperature and dissolved oxygen concentrations, which strongly affect within-channel microbial activity and the transformations of nutrients, and (2) errors in the simulated processes of accumulation and removal of sediment from land surfaces and on the movement of that sediment from one reach to another, which controls the volume and transport of constituents associated with sediment.

Water Temperature

Graphical comparison of daily mean water temperatures indicated close agreement between observed and simulated values (fig. 12). Errors in the simulated temperatures showed a seasonal pattern; simulated temperatures generally were higher than observed temperatures from April through June, and lower than observed temperatures during December and January. The monthly percent differences between simulated and observed temperatures ranged from -16.3 to 10.6 percent among all five calibration sites, and the percent mean error was less than or equal to 5.0 percent, and the percent mean absolute error was less than or equal to 6.5 percent at the five calibration sites (table 13). The consistent negative percent mean errors at all sites indicated an underestimation bias in water-temperature simulations. Nonetheless, the water-temperature simulations were rated “very good” on the basis of the model-performance criteria as defined by Donigian (2002; table 10).

Sediment Loads

Sediment accumulation and washoff from land surfaces, and sediment transport within stream channels, was simulated to provide an option for improving the calibration for nutrients that had strong correlations with sediment load. No sediment-load data were available for the Irondequoit Creek basin; but total suspended solids (TSS) loads were measured throughout the study period, 1991–2000. TSS and suspended-sediment (SS) differ in how their concentrations are measured and in how they are generated in a basin. Both constituents are often similarly described as the solid-phase material suspended in a water-sediment mixture; however, the analytical procedures for measuring TSS from an aliquot of a sample and SS from the whole sample may produce considerably different results (Gray and others, 2000). This difference is especially evident

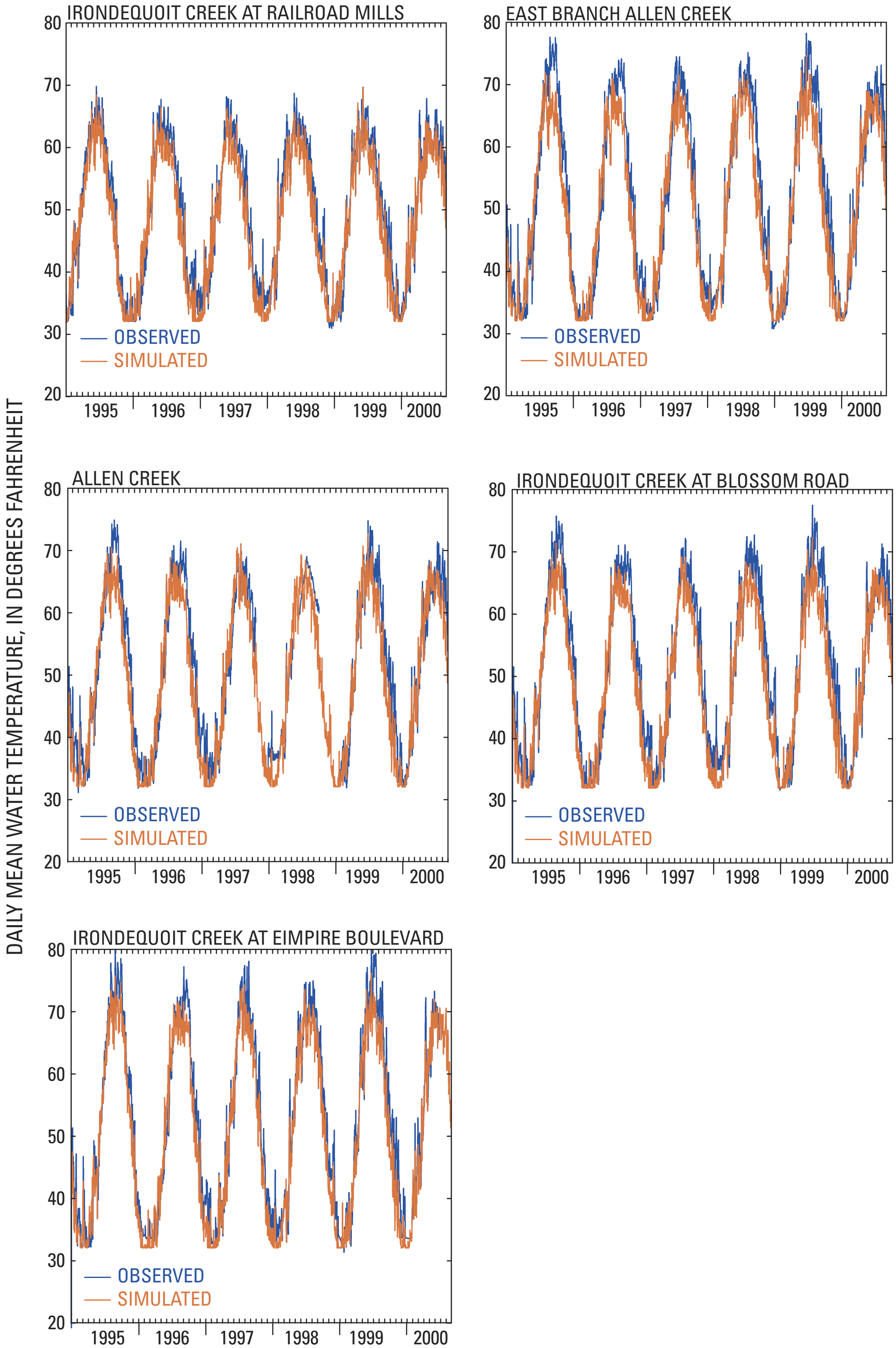


Figure 12. Daily observed and simulated water temperatures at five calibration sites in the Irondequoit Creek basin, Monroe and Ontario Counties, N.Y. (Site locations are shown in figure 1.)

Table 13. Model-performance statistics for monthly simulated water temperature, sediment loads, and chemical loads at five water-quality monitoring sites in the Irondequoit Creek basin, Monroe and Ontario Counties, N.Y.

[Locations of monitoring sites are shown in figure 1. Periods of records for observed water temperature and chemical loads are listed in table 3]

Statistic	Irondequoit Creek at Railroad Mills (04232034)	East Branch Allen Creek at Pittsford (0423204920)	Allen Creek near Rochester (04232050)	Irondequoit Creek at Blossom Road (0423205010)	Irondequoit Creek at Empire Boulevard (0423205025)
Mean water temperature					
Percent mean error (bias)	-3.6	-4.0	-3.0	-5.0	-3.3
Percent mean absolute error	4.8	6.5	6.1	6.1	5.2
Correlation coefficient	.98	.97	.91	.98	.95
Model-fit efficiency	.94	.92	.91	.92	.95
Observed total suspended solids and simulated sediment loads					
Percent mean error (bias)	-3.7	-0.8	12	12	5.3
Percent mean absolute error	55	65	56	57	46
Correlation coefficient	.60	.53	.66	.65	.64
Model-fit efficiency	.22	.25	.39	.39	.41
Orthophosphate loads					
Percent mean error (bias)	5.0	-10	18	12	13
Percent mean absolute error	38	66	55	37	39
Correlation coefficient	.82	.38	.50	.66	.60
Model-fit efficiency	.61	.13	.22	.39	.27
Total phosphorus loads					
Percent mean error (bias)	2.7	-2.9	18	-10	-2.1
Percent mean absolute error	33	67	49	54	41
Correlation coefficient	.87	.52	.65	.76	.72
Model-fit efficiency	.75	.27	.39	.44	.52
Ammonia loads					
Percent mean error (bias)	20	-14	17	6.2	5.4
Percent mean absolute error	62	78	59	48	24
Correlation coefficient	.51	.27	.43	.70	.85
Model-fit efficiency	.10	-.08	.07	.47	.71
Ammonia-plus-organic nitrogen loads					
Percent mean error (bias)	11	-0.7	19	1.3	4.3
Percent mean absolute error	31	40	33	29	27
Correlation coefficient	.83	.76	.80	.88	.86
Model-fit efficiency	.57	.58	.53	.77	.70
Nitrate-plus-nitrite nitrogen loads					
Percent mean error (bias)	7.6	-10	8.6	-2.8	3.8
Percent mean absolute error	21	51	28	18	21
Correlation coefficient	.90	.81	.90	.94	.92
Model-fit efficiency	.71	.56	.80	.87	.84

when a substantial percentage of the sediment in the sample consists of sand-sized material. Also, even though SS and TSS loads are generated mainly during periods of storm runoff or snowmelt, only TSS loads are measurable under all flow conditions. Therefore, observed TSS was used as a surrogate for SS for calibration of sediment loads to the pattern, if not the magnitude, of TSS loads (fig. 13).

The percent mean error between the monthly observed TSS and simulated sediment loads ranged from -3.7 to 12 percent; no bias in the simulations was indicated (table 13). The percent mean absolute errors were between 46 and 65 percent at the five calibration sites. The coefficients of correlation and model-fit efficiency were low, presumably because of the differences between TSS- and SS-load generation as described above. Simulated loading rates of sediment were comparable to observed TSS rates at all sites (table 14) and generally were in the low range of values found in the literature for single land-use sites (table 4). Simulated sediment loading rates varied little—from 0.28 ton/acre for mixed-rural land use to 0.25 ton/acre for combined rural and suburban use, and 0.27 for mixed-urban use. The highest simulated loading rate, 0.37 ton/acre, was at Irondequoit Creek at Blossom Road. This rate was more than twice the rate at Irondequoit Creek at Empire Boulevard as a result of the documented decrease in particulate loads through sedimentation in the Ellison Park wetland (Coon and others, 2000; Coon, 2004).

Nutrient Loads

Atmospheric contributions of nutrients, along with fertilizer-application data and manure-spreading rates, are often used in HSPF models where agricultural land covers a large percentage of the basin and detailed simulation of nutrient-transformation and uptake processes are required; this requirement does not apply to the Irondequoit Creek basin. Atmospheric contributions of phosphorus and nitrogen, although available for the Irondequoit Creek model for this period, were not used because their inclusion greatly overestimated the quantity of a particular constituent that would be available for wash off from a land surface and, thus, hindered calibration of the nutrient loads. Therefore, nutrient accumulation rates were estimated for the Irondequoit Creek model.

The simulations of nutrient loads were calibrated to the observed monthly loads of orthophosphate (PO_4), total phosphorus (TP), ammonia (NH_3), ammonia-plus-organic nitrogen (TKN), and nitrate-plus-nitrite nitrogen (NOx) at the five water-quality monitoring sites for October 1, 1991, through September 30, 1998; and were validated through comparison with monthly loads for October 1, 1998, through September 30, 2000. Nutrient loads were calibrated to minimize the differences between observed and simulated monthly and annual loads. Percent differences between observed and simulated monthly and annual nutrient loads are rated “very good” when the difference is less than 15 percent, “good” when the difference is between 15 to 25 percent, and “fair” when the difference is 25 to 35 percent (table 10; Donigian, 2002). Results of the calibrations of phosphorus and nitrogen loads are summarized below.

Phosphorus Constituents

Monthly observed and simulated PO_4 loads are presented in figure 14. Percent mean absolute errors ranged from 37 to 66 percent, but the percent mean errors were less than 15 at all five monitoring sites except Allen Creek, where it was 18 percent (table 13). Average annual simulated loading rates of PO_4 were essentially the same as the observed loading rates at all five sites; the greatest difference—0.02 lb/acre—was at East Branch Allen Creek (table 14). Overall, the PO_4 loads simulated by the Irondequoit Creek model are rated “good.”

Monthly observed and simulated TP loads are presented in figure 15. The fit between simulated and observed TP loads was similar to that of PO_4 loads. Percent mean absolute errors for TP ranged from 33 to 67 percent, and the percent mean errors were equal to or less than 10 percent at all monitoring sites except Allen Creek, where it was 18 percent (table 13). No bias in TP simulations was noted. Average annual simulated loading rates of TP were close to observed values at all monitoring sites, except Allen Creek, where the simulated loading rate of 0.64 lb/acre was substantially higher than the observed loading rate of 0.53 lb/acre. (table 14). The simulated loading rates at other sites were within 0.05 lb/acre of the respective observed loading rates. The decrease in the TP loading rate from Blossom Road to Empire Boulevard resulted from TP removal in the intervening Ellison Park wetland (Coon and others, 2000; Coon, 2004).

Total phosphorus was difficult to simulate at all stations under all flow conditions. Unlike some nutrients, which occur in a single form and are transported through a single process, phosphorus occurs in dissolved and particulate forms and in association with sediment and atmospheric deposition. Phosphorus is also affected by biological processes that vary with water temperature and the concentrations of dissolved oxygen, other nutrients (nitrogen), and microbial energy sources (carbon). The transport of phosphorus in a stream can be complicated by the deposition and scour of sediment to which phosphorus can adsorb. The simulated loads of TP failed to match observed loads at most monitoring sites during many peak-load months (fig. 15). Efforts to decrease these discrepancies at a given site increased the errors in simulated loads under other flow conditions or at other sites.

Nitrogen Constituents

Of the three nitrogen species simulated by the model—NH_3, TKN, and NOx—NH_3 made up only a small percentage of the total. Therefore, the fit of the latter two components was emphasized during the calibration process whenever a trade-off was necessary between the simulation accuracy of NH_3 and that of TKN or NOx.

Monthly observed and simulated NH_3 loads are presented in figure 16. Percent mean absolute errors ranged from 24 to 78 percent, and percent mean errors were equal to or less than

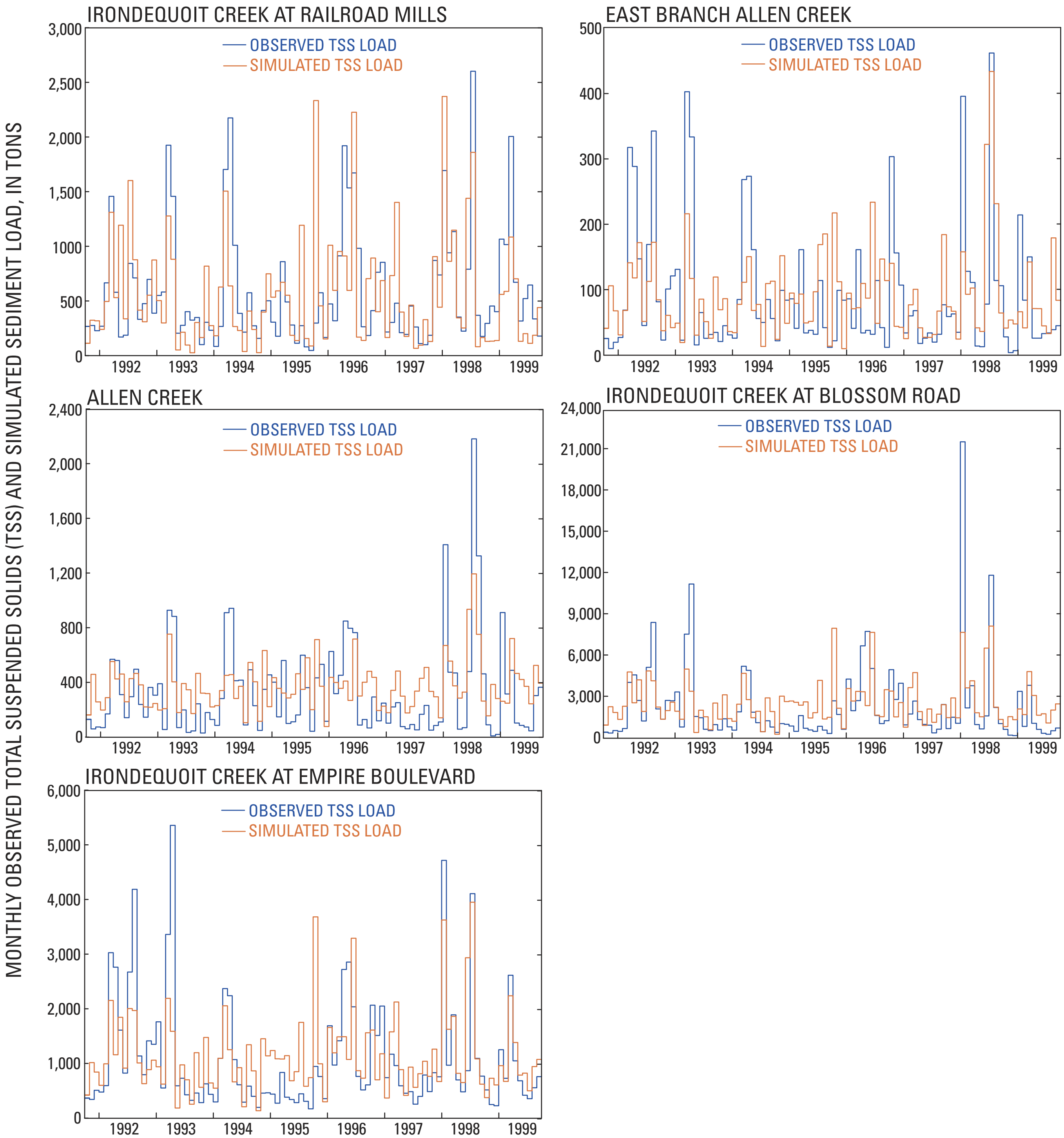


Figure 13. Monthly observed total suspended solids (TSS) and simulated sediment loads at five calibration sites in the Irondequoit Creek basin, Monroe and Ontario Counties, N.Y. (Site locations are shown in figure 1.)

Table 14. Observed and simulated annual loading rates for selected constituents at five water-quality monitoring sites in the Irondequoit Creek basin, Monroe and Ontario Counties, N.Y., 1991–98.

[Values are in pounds per acre unless otherwise noted. Obs., observed; Sim., simulated; PO_4, orthophosphate; TP, total phosphorus; NH_3, ammonia; TKN, ammonia-plus-organic nitrogen; NOx, nitrate-plus-nitrite nitrogen; TN, total nitrogen; TSS, total suspended solids; --, no value available or computed. Locations of monitoring sites are shown in figure 1]

Constituent	Irondequoit Creek at Railroad Mills (04232034)		East Branch Allen Creek at Pittsford (0423204920)		Allen Creek near Rochester (04232050)		Irondequoit Creek at Blossom Road (0423205010)		Irondequoit Creek at Empire Boulevard (0423205025)	
	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.
PO_4	0.03	0.03	0.12	0.10	0.08	0.09	0.04	0.05	0.06	0.06
TP	.39	.40	.65	.62	.53	.64	.69	.64	.38	.40
NH_3	.04	.05	.14	.11	.07	.09	.06	.06	.12	.13
TKN	2.06	2.28	3.39	3.31	2.82	3.39	2.67	2.68	2.42	2.55
NOx	3.36	3.65	6.52	5.81	3.82	4.19	3.46	3.38	3.26	3.42
TN	5.42	5.93	9.92	9.12	6.64	7.58	6.14	6.06	5.68	5.98
TSS, tons/acre	.28	--	.26	--	.25	--	.35	--	.15	--
Sediment, tons/acre	--	.28	--	.25	--	.27	--	.37	--	.16

20 percent at all monitoring sites (table 13). Average annual simulated NH_3 loading rates were comparable to the observed loading rates (table 14); the maximum difference was 0.03 lb/acre at the East Branch Allen Creek site.

Because NH_3 loads were small compared to total nitrogen loads, small changes in simulated loads could produce large percent differences. Simulated loads at Irondequoit Creek at Railroad Mills were particularly susceptible to this effect (fig. 16), especially during 1994 and 1995, when annual observed loads were less than 0.10 ton, and loads for some months were zero (Sherwood, 2001). In contrast, the simulated loads during these years were comparable to those simulated during other years within the calibration period. The extremely small observed loads resulted in magnified percent differences. The large increase in the NH_3 loading rate from Blossom Road to Empire Boulevard reflected the generation and export of NH_3 through wetland processes in the Ellison Park wetland (Coon and others, 2000; Coon, 2004).

Monthly observed and simulated TKN loads are presented in figure 17. Percent mean absolute errors ranged from 27 to 40 percent, and percent mean errors were less than 20 percent at all monitoring sites (table 13). Comparison of average annual observed loading rates with simulated values indicated varied results; values were comparable at three sites—East Branch Allen Creek, Irondequoit Creek at Blossom Road, and Irondequoit Creek at Empire Boulevard—whereas the simulated loading rates at Irondequoit Creek at Railroad Mills and Allen Creek were 0.22 and 0.57 lb/acre higher, respectively, than observed loading rates (table 14).

Monthly observed and simulated NOx loads are presented in figure 18. Percent mean absolute errors ranged from 18 to 51 percent, and percent mean errors were less than or equal to 10 percent at all monitoring sites (table 13). Comparison of average annual observed loading rates with simulated values indicated varied results; differences ranged from 0.08 lb/acre at Irondequoit Creek at Blossom Road to 0.71 lb/acre at East Branch Allen Creek (table 14).

Total nitrogen loads were computed as the sum of the TKN and NOx loads. Calibration and model-performance statistics, as well as simulated loading rates (table 14), reflect the combined effects of the simulations of these two constituents, and percent differences lie between those previously mentioned for these two constituents.

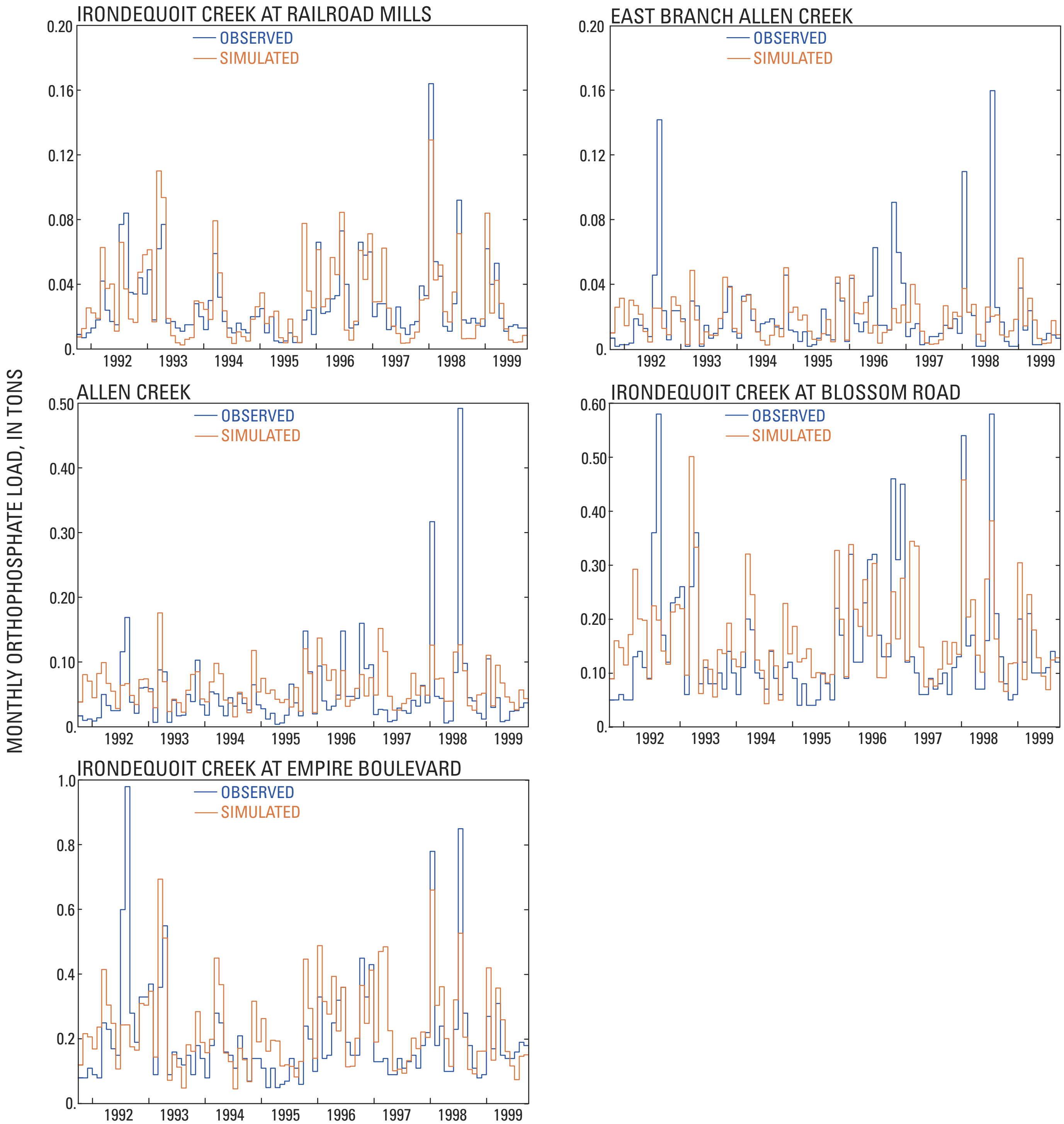


Figure 14. Monthly observed and simulated orthophosphate loads at five calibration sites in the Irondequoit Creek basin, Monroe and Ontario Counties, N.Y. (Site locations are shown in figure 1.)

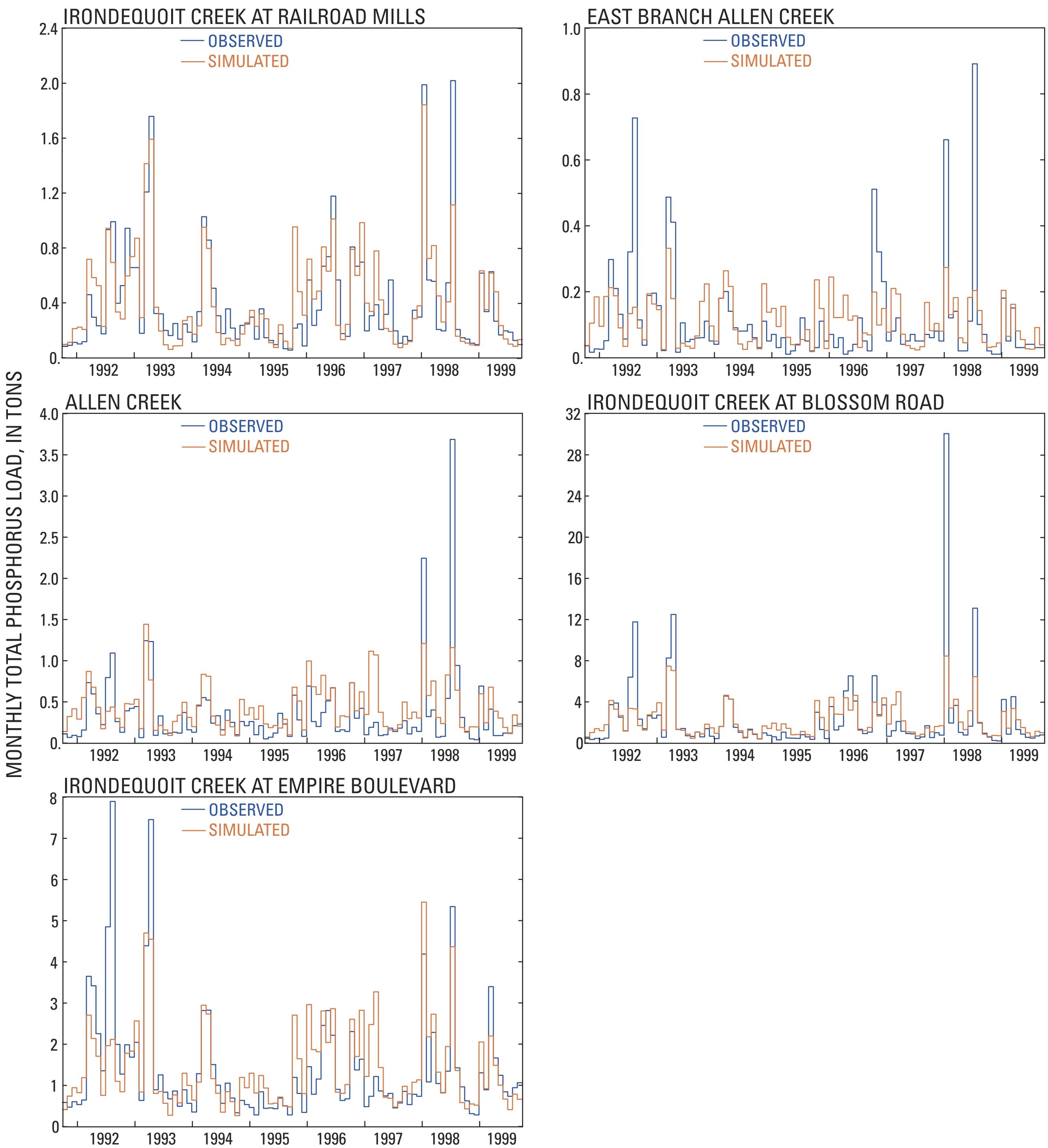


Figure 15. Monthly observed and simulated total phosphorus loads at five calibration sites in the Irondequoit Creek basin, Monroe and Ontario Counties, N.Y. (Site locations are shown in figure 1.)

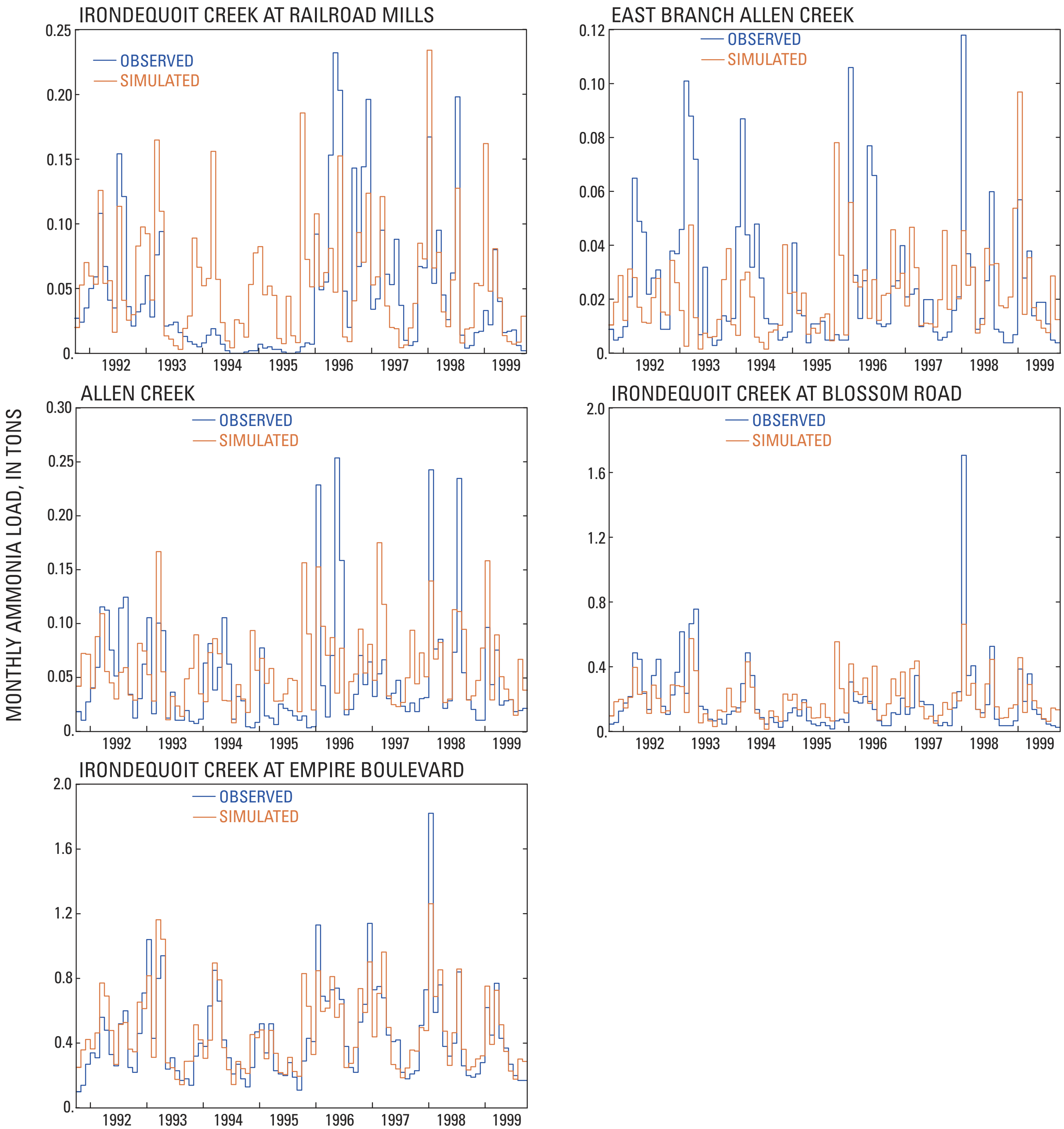


Figure 16. Monthly observed and simulated ammonia loads at five calibration sites in the Irondequoit Creek basin, Monroe and Ontario Counties, N.Y. (Site locations are shown in figure 1.)

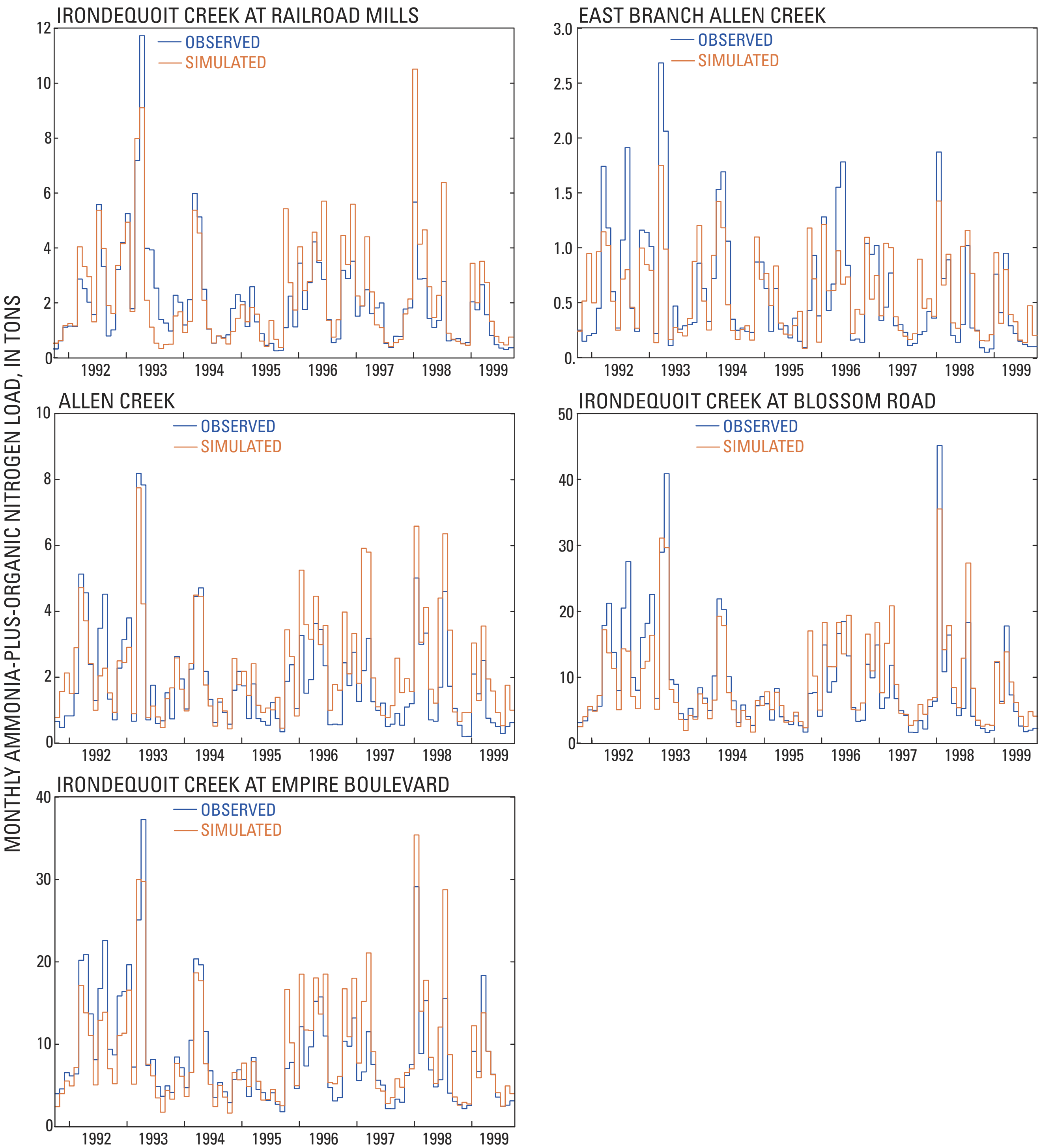


Figure 17. Monthly observed and simulated ammonia-plus-organic nitrogen loads at five calibration sites in the Irondequoit Creek basin, Monroe and Ontario Counties, N.Y. (Site locations are shown in figure 1.)

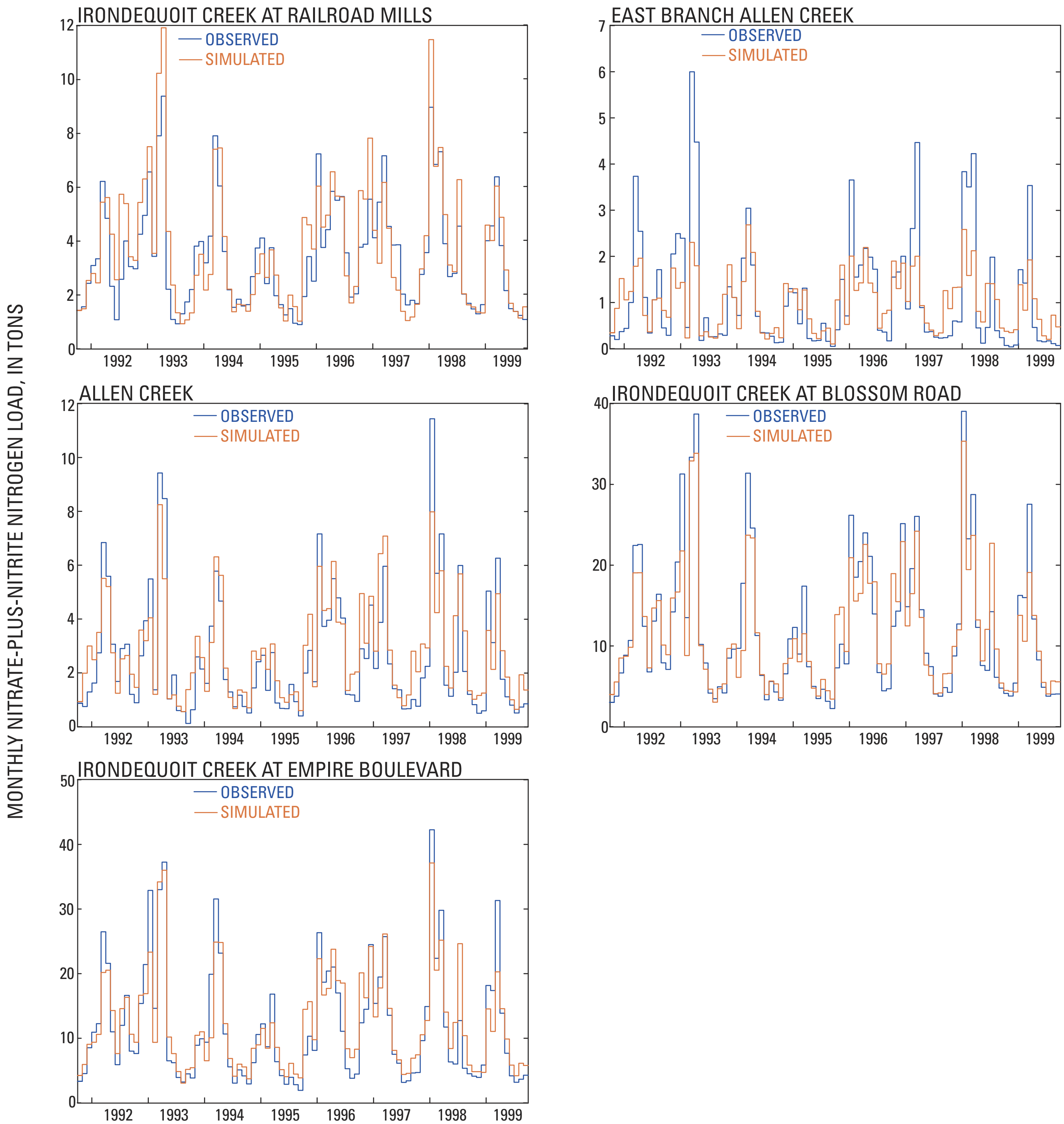


Figure 18. Monthly observed and simulated nitrate-plus-nitrite loads at five calibration sites in the Irondequoit Creek basin, Monroe and Ontario Counties, N.Y. (Site locations are shown in figure 1.)

Model Applications

Three analyses were performed as examples to illustrate the utility of the Irondequoit Creek model. The first simulated the effects of land-use changes on flooding and stream-water quality, and the second simulated the effects of a stormflow detention basin on flooding and water quality. The steps involved in the creation and analysis of land-use scenarios and detention basins in the Irondequoit Creek basin are provided in Coon (2003). The third analysis entailed computation of flood frequencies from model-generated annual peak flows for 1971–2000 (the period for which precipitation records were available), and comparison with those computed from annual peak flows recorded at two streamflow-monitoring sites. The model was then revised to simulate nine hypothetical instream detention basins of various sizes and drainage areas, and the resultant peak flows were then used to compute a third set of flood frequencies, from which the probable effects of the detention basins on flood magnitudes were assessed.

These comparative analyses were done through the computer program GenScn (Generation and Analysis of Model Simulation Scenarios for Watersheds) (Kittle and others, 1998). The WDM file was organized such that (1) flows generated from one or two land-use-change scenarios and one or two detention-basin scenarios could be uniquely stored for each RCHRES, as explained by Coon (2003); and (2) chemical loads of sediment, TP, TKN, NOx, and TN, from as many as three scenarios could be simulated and stored in uniquely identified files. A user-defined location (such as RCHRES 100 in subbasin T5) could have data stored from three water-quality scenarios—WQSCEN1, WQSCEN2, and WQSCEN3—as identified in the UCI and WDM files.

Land-Use Changes

The Irondequoit Creek basin is undergoing rapid changes in land use. Rural areas that were dominated by forests, farms, and pasture land are being converted to suburban residential developments and large technology parks and shopping malls. Development of the basin is spreading southward and eastward in the townships of Pittsford, Victor, Perinton, and Penfield (fig. 4). The Town of Mendon and the western part of the Town of Victor still retain their rural characteristics, except along major thoroughfares, which are subject to commercial "strip" development with office buildings, retail stores, restaurants, and other service-related businesses. Water-resources managers in the counties and towns are concerned with the effect that continued development might have on flooding and water quality in the basin. Therefore, a land-use-change scenario was simulated to illustrate the process by which the model could be used to assess these effects. In that scenario, 10 percent of the area in subbasin T5 in the southern part of the basin (fig. 8) was changed from open and(or) rural grass or forested designations to pervious and impervious developed areas by revising the acreages listed in the SCHEMATIC module of the UCI file as instructed by Coon (2003). The effects of these changes on streamflow and stream-water quality were automatically simulated by HSPF. The only other required revision to the UCI file (in the EXT TARGETS module) was to identify unique dataset numbers in the WDM file in which output would be stored. (For example, see WDM dataset numbers in tables 15 and 16). Unique DSNs enabled comparison of the original flows and chemical loads with those generated by the land-use-change scenario.

Effects on Streamflow

The effects of converting 10 percent of subbasin T5 from open and(or) rural grass or forested land to pervious and impervious developed areas were evaluated through a comparison of (1) the peak flows that occurred during eight rainstorms (table 15) and (2) the flow durations and storm hydrographs produced by the two scenarios (fig. 19). The hypothetical land-use change caused peak flows to increase by 43.3 percent, on average, which meant that infiltration had decreased and in turn caused base flows to decrease, as indicated by the change in flow duration and shown by the storm hydrographs of July 4–10, 1998.

Effects on Stream-Water Quality

Annual loads of sediment and total phosphorus increased by 11.0 and 3.6 percent, respectively, as a result of the land-use changes in subbasin T5. Loads of TKN and NOx were not appreciably affected by the increase in developed area of the basin (table 16).

Stormflow-Detention Basin

Mitigation of the adverse effects of urbanization on flooding has become a major objective of planning and development of populated watersheds. The optimal design objective for any flood-control measure would be to maintain postdevelopment discharges at or below predevelopment rates for specified storm frequencies. Methods to reduce the effects of increased runoff, such as infiltration trenches and pits, porous pavement, rooftop storage, and cisterns, can be expensive or constrained by site-specific limitations (Natural Resources Conservation Service, 1986). Detention basins are an effective alternative that has been widely used to control peak flows because they (1) are relatively inexpensive as compared to other flood-control measures, (2) can be designed to fit a wide variety of sites and outflow requirements, (3) can be incorporated into a proposed development plan, and (4) can be constructed in areas that are limited in their developmental potential by their susceptibility to flooding. A detention basin can use storage available in these areas for minor (5- to 20-year recurrence interval) floods without appreciably increasing the areal extent of flooding that occurs during major (50- to 100-year recurrence interval) floods.

Table 15. Changes in peak flows resulting from land-use-change and stormflow-detention scenarios in a subbasin of Irondequoit Creek basin, Monroe and Ontario Counties, N.Y.

[Flow values are in cubic feet per second. DSN, dataset number in Watershed Data Management file]

Date of storm	Base scenario (DSN 1001)	Land-use change scenario[1] (DSN 1004)		Detention basin scenario[2] (DSN 1002)	
	Peak flow	Peak flow	Percent difference	Peak flow	Percent difference
March 27, 1992	31.2	36.4	16.7	35.1	-3.6
August 28, 1992	19.7	44.2	124	34.6	-21.7
April 13, 1994	18.5	24.1	30.3	22.5	-6.6
April 13, 1996	30.2	39.3	30.1	33.5	-14.8
October 19, 1996	42.3	51.7	22.2	47.5	-8.1
December 2, 1996	82.4	97.8	18.7	68.0	-30.5
July 8, 1998	94.3	114	20.9	75.4	-33.9
May 13, 2000	37.8	69.3	83.3	51.5	-25.7
Average percent difference			**43.3**		**-18.1**

[1]Ten percent of the land area in subbasin T5 was converted from open and(or) rural grass or forested land to pervious and impervious developed areas.

[2]Stormflow detention in RCHRES T5 was simulated by modifying the outflow rates in the Ftable to 50 percent of the original rates.

Table 16. Changes in chemical loads resulting from land-use-change and stormflow-detention scenarios in a subbasin of the Irondequoit Creek basin, Monroe and Ontario Counties, N.Y.

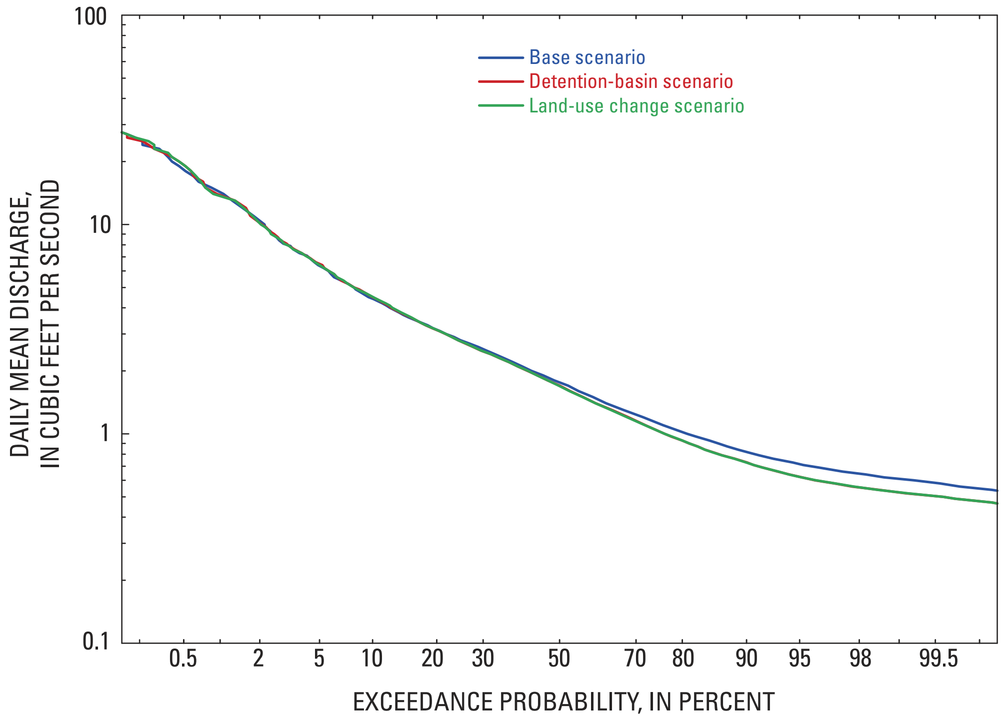
[Values are in tons. Loads are the sum of annual loads over a 9-year simulation period, 1992-2000. DSN, dataset number in Watershed Data Management file]

Constituent	Base scenario (WQSCEN1)		Land-use-change scenario[1] (WQSCEN2)			Detention-basin scenario[2] (WQSCEN3)		
	DSN	Load	DSN	Load	Percent difference	DSN	Load	Percent difference
Sediment	9100	5,974	9110	6,631	11.0	9120	4,281	-35.4
Total phosphorus	9101	3.806	9111	3.943	3.6	9121	2.025	-48.6
Ammonia-plus-organic nitrogen	9102	21.84	9112	22.14	1.4	9122	15.17	-31.5
Nitrate-plus-nitrite nitrogen	9103	26.10	9113	25.98	-0.5	9123	12.99	-50.0
Total nitrogen	9104	47.95	9114	48.13	0.4	9124	28.17	-41.5

[1]Ten percent of the land area in subbasin T5 was converted from open-grass or forested land to pervious and impervious developed areas.

[2]Stormflow detention in RCHRES T5 was simulated by modifying the outflow rates in the Ftable to 50 percent of the original rates.

A. FLOW-DURATION CURVE



B. STORMFLOW HYDROGRAPH

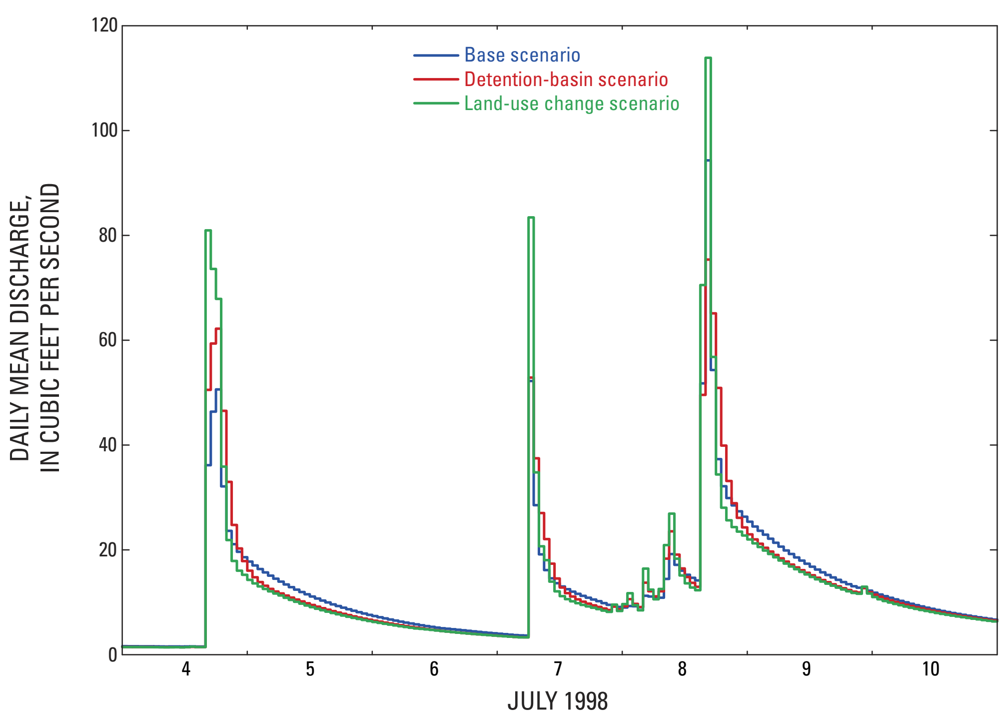


Figure 19. Effects of hypothetical land-use changes and stormflow detention on streamflow in subbasin T5 of Irondequoit Creek basin, Monroe and Ontario Counties, N.Y.: (A.) Flow duration. (B.) Hydrograph for storm of July 4–10, 1998. (Site location is shown in figure 8.)

Detention basins can be incorporated into a site-development plan to mitigate the effects of individual projects on flooding and sediment and nutrient loads, or, alternatively, large stormwater-management facilities can be installed adjacent to or within a stream channel to mitigate the cumulative effects of extensive urbanization. Often, detention basins are desired for multiple purposes—water-quality improvement as well as flood mitigation. A single detention basin might not fulfill both purposes, however, because flood control is optimized by providing the maximum storage capacity, whereas water-quality improvement is optimized by maximizing the detention time of stormwater. The longer the detention period, the less storage is available for a subsequent storm.

The effects of a detention basin on flooding and water quality were illustrated through a modification of the previous land-use-change scenario by simulation of an instream detention basin in subbasin T5; detention was simulated as a 50-percent decrease in the outflow rate, following the steps described by Coon (2003). The water-quality effects of this detention basin were simulated as a best-management practice through the BMPRAC module as discussed previously in the section “Simulation Complexities.” In addition to the steps described by Coon (2003), the following two steps were required to activate the BMPRAC option in the model:

(1) In the OPN SEQUENCE block, a line for the applicable BMPRAC was added as shown for the hypothetical detention basins included in the model.

(2) In the SCHEMATIC block, the RCHRES-to-RCHRES link was replaced by a pair of commands that route output from the RCHRES to the BMPRAC (with mass-link 20) and from the BMPRAC to the downstream RCHRES (with mass-link 21) as shown for the hypothetical detention basins included in the model. This substitution automatically identified the proper mass links and the removal fractions associated with each constituent that was affected by the detention basin. As with the land-use-change scenario, unique dataset numbers were identified in the EXT TARGETS module so that previously stored values in the WDM file that might be required for comparison with the current scenario would not be overwritten.

Effects on Streamflow

The inclusion of a detention basin in subbasin T5 decreased peak flows by an average of 18.1 percent below those simulated for the land-use-change scenario (table 15). The magnitude of the decrease in peak flow increased with an increase in the original (base scenario) peak flow. In other words, the detention basin caused a decrease in low and medium peak flows below those generated by the land-use change, but these peaks were not smaller than the original peaks. The effectiveness of the detention basin increased with increasing runoff, and peak flows were decreased, not only to below those of the land-use-change scenario, but also below the original flows.

Effects on Stream-Water Quality

Simulation of the detention basin in subbasin T5 for water-quality improvement resulted in substantial decreases in constituent loads (table 16) that paralleled the percent removals that were input to the model through the BMPRAC module. TP and NOx loads decreased by about 50 percent; TKN by 32 percent; and sediment by 35 percent. The basin decreased loads of all constituents below those simulated for the base scenario.

Flood-Frequency Analysis

Flooding in the Irondequoit Creek basin has been, and continues to be, a serious problem, especially in heavily developed areas, such as Panorama Plaza, a commercial development that lies on the flood plain and occupies almost the entire valley bottom near the confluence of Allen and Irondequoit Creeks (fig. 1). Various measures to control the frequency and magnitude of flooding in that area have been proposed; one is the construction of instream detention basins to decrease peak flows. The Irondequoit Creek model was used to assess the probable changes in flood frequencies that would result from one existing and nine hypothetical detention basins of various sizes and drainage areas at selected locations throughout the Irondequoit Creek basin (fig. 8).

The UCI file was revised to permit simulation of a longer period (1970–2000) than was used for calibration of the model. The first revision was application of the Rochester Airport precipitation record to the part of the basin that ordinarily would use the Victor record as precipitation input from 1970 to 1985 because the Victor precipitation record did not begin until January 1, 1986. This revision meant that only one precipitation record was used for the entire basin during this 16-year early period. This revision could have a substantial effect on the simulated flows because precipitation is a major driving force for the model. The second revision entailed omission of the estimated diversions from the NYS Erie (Barge) Canal into the basin. These estimates were based on intermittent measurements of discharges from the canal, which did not begin until the spring of 1986 at the siphon sites on Allen and East Branch Allen Creeks, and the spring of 1988 at the waste-gate sites at Cartersville and Fairport. The effect of this omission on model results was considered negligible, however, because this analysis was concerned only with annual peak flows. Two additional factors that affected model results were (1) extension of the simulation period beyond the calibration and validation periods (1990–2000), and (2) an occasional poor temporal match between observed and simulated peaks. The extension of the simulation period back to 1970 ignored the assumption of a stable precipitation-to-runoff relation during the 30-year extended simulation period. Differences in the timing of simulated peak flows in comparison to the dates of observed peaks was not unexpected, and the annual maximum simulated flows were used in the following calculations of flood frequencies regardless of their date of occurrence.

Flood frequencies were computed with the program PEAKFQ (Thomas and others, 1998), which fits the logarithms of the peak flows to a Pearson Type-III frequency distribution (Interagency Advisory Committee on Water Data, 1982). Flood frequencies for simulated annual peak flows were computed and compared with those for observed annual peak flows (fig. 20A; table 17). Differences between flood frequencies ranged from 10 to 760 ft^3/s for 5-yr and 500-yr recurrence-interval (RI) flows, respectively, on Allen Creek, and from 0 to 370 ft^3/s for 2-yr and 500-yr RI flows on Irondequoit Creek above Blossom Road. After simulation of 50-percent reductions in flow at the Jefferson Road stormwater-management facility and at the nine hypothetical detention basins, flood frequencies for the simulated annual peak flows were recomputed and indicated that these reductions would result in 14- to 17-percent decreases in peak flows on Allen Creek, and 17- to 18-percent decreases on Irondequoit Creek at Blossom Road (fig. 20B; table 17), if the basins were installed as proposed and designed to mimic the storage capacity and outflow rates as simulated by the Irondequoit Creek model. This analysis indicated, however, that even with the 50-percent decrease in flows at the 10 detention basins, overbank flooding (albeit with shallower depths than now occur) would probably occur at a similar frequency as is currently (2003) experienced, especially in the flood-plain area of Panorama Plaza. Thus, substantial decreases in overbank-flooding frequency would require larger detention basins that would control runoff from a greater percentage of the basin than those simulated by the model. The nine hypothetical detention-basin locations assessed in this analysis were points on a map selected by the IWC for simulation purposes. The feasibility of constructing any one of these basins was not evaluated and would require a site-specific survey to identify the hydraulic, economic, social, and environmental limitations of a given site, and the capability of such a basin to achieve the detention benefits that were simulated in this analysis.

Summary

The 150 mi^2 Irondequoit Creek basin in Monroe and Ontario Counties, N.Y. is underlain by sedimentary rock that dips gently to the south-southwest. Bedrock is overlain by glacial deposits throughout most of the basin. Sand-and-gravel outwash partly fills the buried preglacial Irondogenesee River valley and forms the present-day Irondogenesee aquifer. Soils in the basin are derived from glacial deposits, and their characteristics—permeability, erodibility, and runoff potential—are directly related to the parent materials in which they formed.

Virtually all of the Irondequoit Creek basin has been affected by human activity. Presently (2003), more than 50 percent of the basin is in some form of developed condition. The southern third of the basin is predominantly rural and agricultural and consists mostly of pasture, row crops, and forests. Suburban development increases northward across the basin and occupies large parts of the Towns of Henrietta, Pittsford, Perinton, and Penfield. High-density residential, commercial and industrial land uses dominate the northwestern corner of the basin, which includes parts of the Town of Brighton and the City of Rochester.

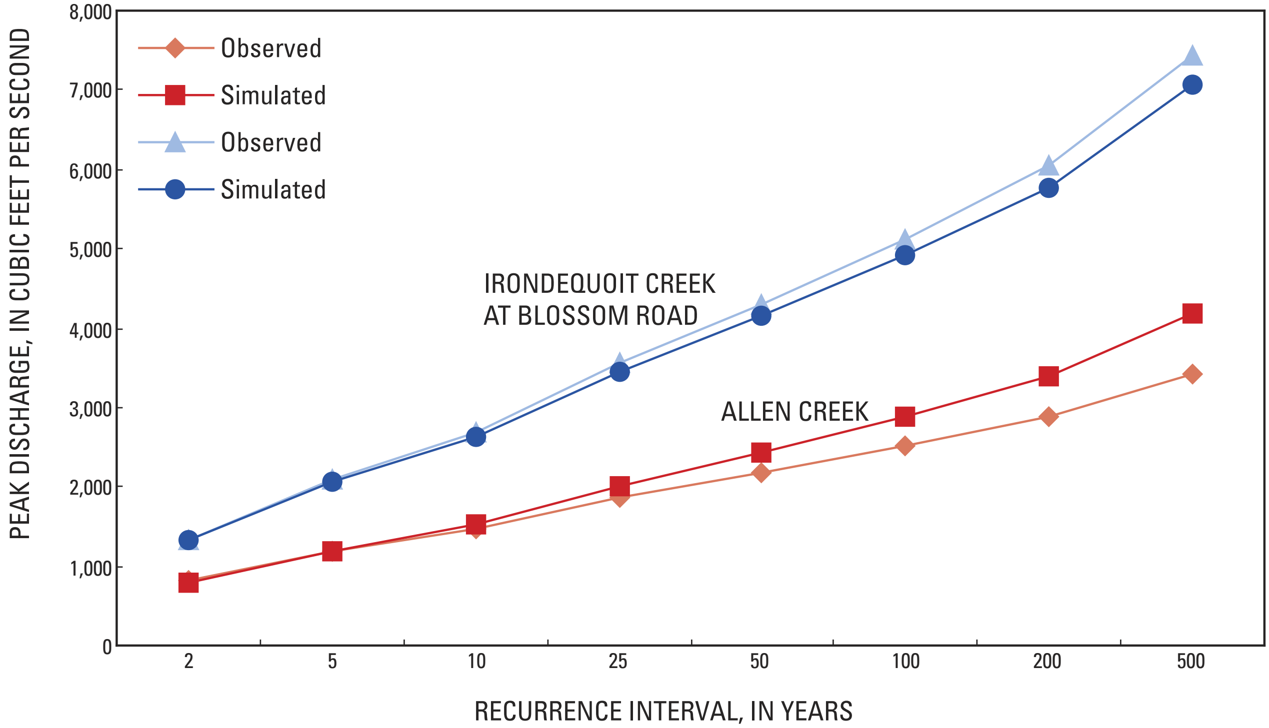
Irondequoit Creek flows northward down the approximate center of the basin with the Allen Creek subbasin to the west and the Thomas Creek subbasin to the east. The creek is 32.6 mi long and descends 525 ft at its head in Ontario County to its mouth at Irondequoit Bay. Almost 7 percent of the basin consists of wetlands, lakes, and ponds. The New York State Erie (Barge) Canal cuts across the basin, dividing it into northern and southern sections and complicating basin hydrology. Ground-water flow generally is toward nearby streams, although regional flow is northward toward Lake Ontario. Urbanization has aggravated flooding and, along with agricultural activities, has contributed to the degradation of stream-water quality in the basin.

A precipitation-runoff model of the basin that uses the HSPF (Hydrological Simulation Program—FORTRAN) model code was developed by the U.S. Geological Survey (USGS), in cooperation with the Irondequoit Creek Watershed Collaborative, to assist water-resource managers in addressing the problems of urbanization and to guide decisions regarding future development in the basin. The model enables simulation of the effects of land-use changes and stormflow-detention basins on flooding and nonpoint-source pollution on the basin. The hydrology, stream-water temperature, and sediment and nutrient loads of the basin were simulated and calibrated with data collected from five USGS streamflow and water-quality-monitoring sites. The basin was divided into hydrologic response units (HRUs)—areas where hydrologic and water-quality processes were assumed to be uniform—on the basis of land use and land cover, soil permeability, and slope.

The Irondequoit Creek basin presented many modeling complexities, including areas where ground water moves out of the surface-water-defined basin, hydrologic connections with and diversions from the Erie (Barge) Canal, and surface water lost to fractured bedrock or diverted out of the basin. Wetlands were simulated separately on the basis of their location in the basin and their dominant functions. One existing stormflow-detention basin and nine hypothetical ones were simulated to permit assessment of their individual and collective effects on flooding and water quality.

Model performance was evaluated through a combination of graphical comparisons and statistical tests and indicated "very good" agreement (mean error less than 10 percent) between observed and simulated daily and monthly streamflows, between observed and simulated monthly water temperatures, and between observed total suspended solids loads and simulated sediment loads. Agreement between monthly observed and simulated nutrient loads was "very good" (mean error less than 15 percent) or "good" (mean error between 15 and 25 percent).

A. FLOOD FREQUENCIES FOR OBSERVED AND SIMULATED PEAK DISCHARGES



B. CHANGES IN FLOOD FREQUENCIES RESULTING FROM DETENTION BASINS

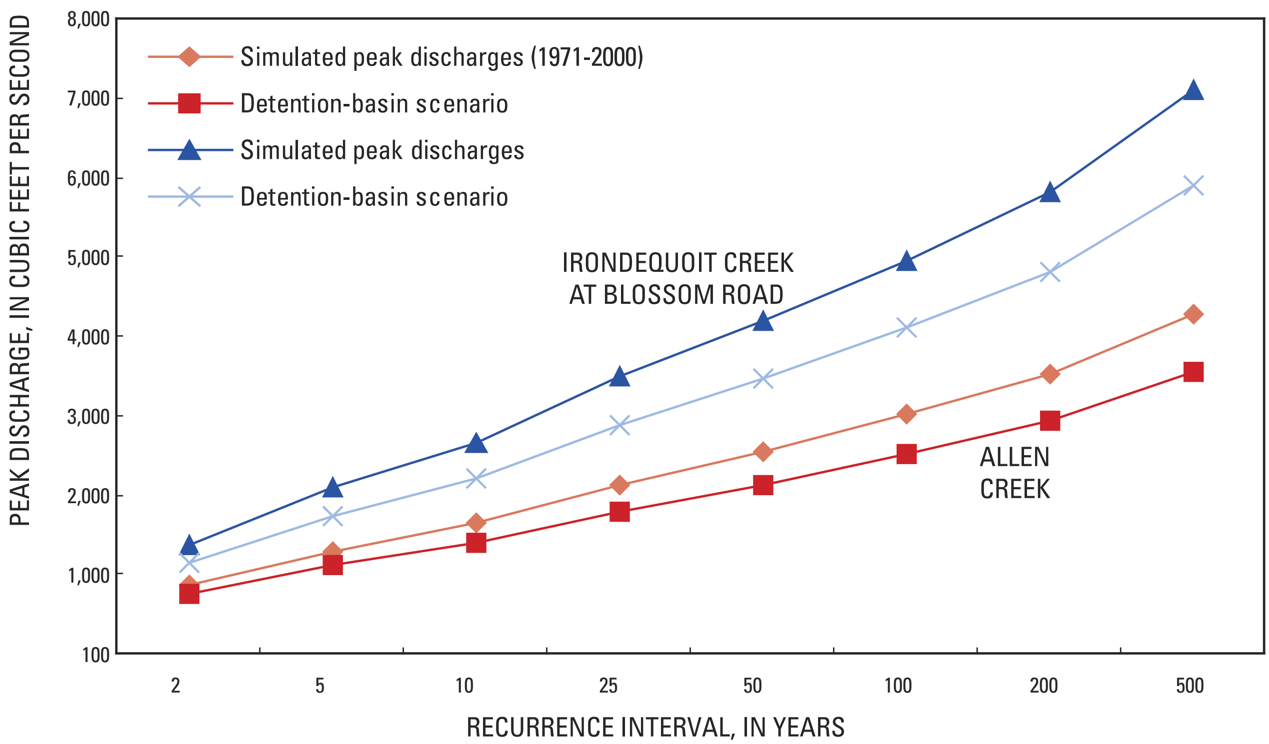


Figure 20. Flood frequencies for observed and simulated annual peak flows at two sites in the Irondequoit Creek basin, Monroe and Ontario Counties, N.Y.: (A.) Flood frequencies for observed and simulated peak discharges. (B.) Changes in flood frequencies resulting from detention basins. (Site locations are shown in figure 1.)

Table 17. Changes in flood frequency of annual peak flows resulting from one existing and nine hypothetical stormflow-detention basins at two sites in the Irondequoit Creek basin, Monroe and Ontario Counties, N.Y.

[Flows are in cubic feet per second. Site locations are shown in figure 1]

Peak-flow recurrence interval (years)	Allen Creek (04232050)					Irondequoit Creek above Blossom Road (0423205010), 1971 to 2000			
	Observed peaks, 1960-2000	Simulated peaks, 1960-2000[1]	Simulated peaks, 1971-2000[2]	Simulated peaks with detention basins, 1971-2000	Percent decrease in peak flow	Observed peaks[3]	Simulated peaks	Simulated peaks with detention basins	Percent decrease in peak flow
2	814	785	821	709	14	1,340	1,340	1,100	18
5	1,190	1,200	1,260	1,070	15	2,090	2,060	1,690	18
10	1,470	1,530	1,600	1,360	15	2,680	2,630	2,160	18
25	1,860	2,020	2,090	1,760	16	3,550	3,450	2,840	18
50	2,180	2,430	2,510	2,100	16	4,290	4,150	3,420	18
100	2,520	2,890	2,970	2,480	16	5,120	4,920	4,070	17
200	2,890	3,400	3,480	2,890	17	6,040	5,780	4,780	17
500	3,420	4,180	4,250	3,510	17	7,430	7,060	5,850	17

[1]Simulated peak flows were available from 1971 to 2000 only. Observed peaks were added from 1960 to 1970 to extend the period of record to a length comparable to the observed peak-flow record.

[2]Simulated peak flows were available from 1971 to 2000 only. The flood frequencies were recomputed for this time period to permit comparison with the flood frequencies computed from the peak flows for simulated detention basins.

[3]Observed peak flows were available for 1982 to 2000 only. Simulated peaks were added from 1971 to 1981 to extend the period of record to a length comparable to the simulated peak-flow record.

The model and associated files were designed to permit creation of scenarios that represent planned or hypothetical development in the basin, and assessment of flooding and chemical loads that are likely to result. These scenarios were created simply by changing the acreages associated with HRUs found in a subbasin. Instream stormflow-detention basins could subsequently be modeled in a separate scenario to assess the potential mitigative possibilities of this management practice. Several revisions to the model were required to simulate instream detention basins, including modification of a reach's storage capacity or outflow rates, and activation of a HSPF module (BMPRAC) that is designed to simulate chemical load reductions resulting from a best-management practice. A filing system for scenario output was established within a data-management file to facilitate use of the model by water-resource managers.

Three examples of model applications are presented: (1) assessment of land-use changes; (2) inclusion of a stormflow-detention basin at the downstream end of a subbasin; and (3) assessment of the combined effects of 10 stormflow-detention basins on peak flows. Flows and loads of sediment and nutrients that resulted from the land-use-change scenario, in which 10 percent of a rural subbasin was converted from forest and grassland to pervious and impervious developed areas, were compared with predevelopment values through a post-processing program that was directly linked to the data-management file. Peak flows and loads of sediment and total phosphorus increased. Inclusion of a stormflow-detention basin mitigated these effects by lowering peak flows, some to less than the original observed peaks, and substantially decreased the simulated loads of sediment, phosphorus, and nitrogen. The combined effects of one existing stormflow-detention basin and nine hypothetical basins on flooding were assessed through a flood-frequency analysis of the simulated annual peak flows on Allen Creek and Irondequoit Creek at Blossom Road. The model was revised to span a 30-year (1970–2000) period and to simulate 50-percent flow reductions from the detention basins. Flood flows decreased by 14 to 17 percent on Allen Creek and by 17 to 18 percent on Irondequoit Creek at Blossom Road.

Acknowledgments

Thanks are extended to those from the Monroe County Environmental Health Laboratory, who operated the streamflow and water-quality monitoring stations and analyzed the water samples collected from these sites, and to the many individuals from each of the towns and counties in the Irondequoit Creek Watershed Collaborative, who provided additional data.

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Appendix—Sources of Data

Sources of the Geographic Information System coverages, data—meteorological, soils, channel cross-section elevations, streamflow, and water-quality—and computer programs that were used in development of the Irondequoit Creek model are listed below.

Geographic Information System Coverages

Digital (Surface) Elevation Models (DEMs): 10- by 10-meter grid size; 0.1 meter elevation resolution; by 7.5 minute USGS quadrangles. Elevation accuracy is plus or minus half the contour interval. Obtained from Cornell University Geospatial Information Repository (CUGIR) at http://cugir.mannlib.cornell.edu.

Hydrology and drainage-area delineation: base maps obtained from U.S. Geological Survey, Troy, N.Y.

Wetlands: (1) U.S. Fish and Wildlife Service National Wetlands Inventory obtained from www.nwi.fws.gov/maps. (2) New York State Department of Environmental Conservation Regulatory Freshwater Wetlands for Monroe and Ontario counties obtained from CUGIR at http://cugir.mannlib.cornell.edu/Isite/CUGIR_DATA. (3) Areas delineated on town maps.

Land cover–land use: National Land Cover Data; 30- by 30-meter Landsat thematic mapper data acquired by the Multi-resolution Land Characterization Consortium; nominal-1992 acquisitions. Obtained from New York State GIS Clearinghouse at www.nysgis.state.ny.us, or CUGIR at http://cugir.mannlib.cornell.edu. Revisions based on Monroe and Ontario Counties tax-parcel maps, obtained from respective county offices.

Surficial and bedrock geology: obtained from New York State Museum Publications Department at www.nysm.nysed.gov.

Bedrock elevation: contours digitized from Young (1980) for Monroe County and from Leggette and others (1935) for Ontario County.

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

Slope data: derived in GIS program, ArcInfo (Environmental Systems Research Institute, 1994), from DEM data.

Ground-water divide: digitized from plate 4, Yager and others (1985).

Miscellaneous Data

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

Soil permeability: areas were digitized from Plate 3, Yager and others (1985); these original data were extracted from Monroe, Ontario, and Wayne Counties' soil surveys (Heffner and Goodman, 1973; Pearson and Cline, 1958; Higgins and Neeley, 1978, respectively). Permeability for areas identified as "urban with no permeability classification" in these references were obtained from a generalized map of water-infiltration potential (Waller and others, 1982); the source of which data was Sweet and others (1938).

Channel cross-section data: obtained from town and village Federal Emergency Management Agency (FEMA) Flood Insurance Studies (hydraulic data for water-surface profile analyses), or extracted from DEMs using ArcInfo (Environmental Systems Research Institute, 1994) GIS programs and adjusted by field measurements of channel widths and depths.

Streamflow data: obtained from USGS database, ADAPS.

Water- and atmospheric-deposition quality data: obtained from USGS database, QWDATA.

Computer Programs

HSPF, ANNIE, IOWDM, HSPEXP, and CGAP: all obtained from USGS web site http://water.usgs.gov/software.

WDMUtil and HSPFParm: obtained from http://www.epa.gov/OST/BASINS/

GenScn: obtained from ftp://hspf.com/GenScn.

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