In cooperation with the
Delaware Department of Natural Resources and Environmental Control
and the
Delaware Geological Survey

Development, Calibration, and Analysis of a Hydrologic and Water-Quality Model of the Delaware Inland Bays Watershed

Water-Resources Investigations
Report 03-4124

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

Cover. Digital Elevation Model (DEM) of the Delaware Inland Bays watershed developed at the University of Delaware Spatial Analysis Lab, 2000.

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

Development, Calibration, and Analysis of a Hydrologic and Water-Quality Model of the Delaware Inland Bays Watershed

by Angélica L. Gutiérrez-Magness and Jeff P. Raffensperger

Water-Resources Investigations Report 03-4124

In cooperation with the
Delaware Department of Natural Resources and Environmental Control
and the
Delaware Geological Survey

Baltimore, Maryland
2003

U.S. Department of the Interior
GALE A. NORTON, Secretary

U.S. Geological Survey
Charles G. Groat, Director

For additional information contact:

District Chief
U.S. Geological Survey
8987 Yellow Brick Road
Baltimore, MD 21237

Copies of this report can be purchased from:

U.S. Geological Survey
Branch of Information Services
Box 25286
Denver, CO 80225-0286

CONTENTS

Figures

Tables

Tables—Continued

Conversion Factors and Abbreviations

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
	Area	
square meter (m^2)	0.0002471	acre
hectare (ha)	2.471	acre
square kilometer (km^2)	247.1	acre
hectare (ha)	0.003861	square mile
square kilometer (km^2)	0.3861	square mile
	Volume	
liter (L)	33.82	ounce, fluid
liter (L)	0.2642	gallon
	Flow rate	
liter per day(L/d)	0.2642	gallon per day
	Mass	
kilogram (kg)	2.205	pound avoirdupois
kilogram (kg)	0.001102	ton (T)
	Application rate	
kilogram per hectare per year [(kg/ha)/yr]	0.8924	pound per acre per year

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

$$°F = (1.8 \times °C) + 32$$

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), millimoles per liter (mmol/L), or micromoles per liter (µmol/L).

Development, Calibration, and Analysis of a Hydrologic and Water-Quality Model of the Delaware Inland Bays Watershed

By Angélica L. Gutiérrez-Magness and Jeff P. Raffensperger

Abstract

Excessive nutrients and sediment are among the most significant environmental stressors in the Delaware Inland Bays (Rehoboth, Indian River, and Little Assawoman Bays). Sources of nutrients, sediment, and other contaminants within the Inland Bays watershed include point-source discharges from industries and wastewater-treatment plants, runoff and infiltration to ground water from agricultural fields and poultry operations, effluent from on-site wastewater disposal systems, and atmospheric deposition. To determine the most effective restoration methods for the Inland Bays, it is necessary to understand the relative distribution and contribution of each of the possible sources of nutrients, sediment, and other contaminants.

A cooperative study involving the Delaware Department of Natural Resources and Environmental Control, the Delaware Geological Survey, and the U.S. Geological Survey was initiated in 2000 to develop a hydrologic and water-quality model of the Delaware Inland Bays watershed that can be used as a water-resources planning and management tool. The model code Hydrological Simulation Program - FORTRAN (HSPF) was used. The 719-square-kilometer watershed was divided into 45 model segments, and the model was calibrated using streamflow and water-quality data for January 1999 through April 2000 from six U.S. Geological Survey stream-gaging stations within the watershed. Calibration for some parameters was accomplished using PEST, a model-independent parameter estimator. Model parameters were adjusted systematically so that the discrepancies between the simulated values and the corresponding observations were minimized.

Modeling results indicate that soil and aquifer permeability, ditching, dominant land-use class, and land-use practices affect the amount of runoff, the mechanism or flow path (surface flow, interflow, or base flow), and the loads of sediment and nutrients. In general, the edge-of-stream total suspended solids yields in the Inland Bays watershed are low in comparison to yields reported for the Eastern Shore from the Chesapeake Bay watershed model. The flatness of the terrain and the low annual surface runoff are important factors in determining the amount of detached sediment from the land that is delivered to streams. The highest total suspended solids yields were found in the southern part of the watershed, associated with high total streamflow and a high surface runoff component, and related to soil and aquifer permeability and land use. Nutrient yields from watershed model segments in the southern part of the Inland Bays watershed were the highest of all calibrated segments, due to high runoff and the substantial amount of available organic fertilizer (animal waste), which results in over-application of organic fertilizer to crops.

Time series of simulated hourly total nitrogen concentrations and observed instantaneous values indicate a seasonal pattern, with the lowest values occurring during the summer and the highest during the winter months. Total phosphorus and total suspended solids concentrations are somewhat less seasonal. During storm events, total nitrogen concentrations tend to be diluted and total phosphorus concentrations tend to rise sharply. Nitrogen is transported mainly in the aqueous phase and primarily through ground water, whereas phosphorus is strongly associated with sediment, which washes off during precipitation events.

Introduction

Increases in sediment and nutrient loads to coastal bays and estuaries in the Chesapeake Bay (Sprague and others, 2000), Maryland Coastal Bays (Dillow and Greene, 1999), and Delaware Inland Bays (Ullman and others, 2002) have been attributed to agricultural, domestic, municipal, and industrial practices. Within the Delaware Inland Bays watershed (fig. 1a–b), these impacts have been well documented by the Delaware Geological Survey (DGS), the Delaware Department of Natural Resources and Environmental Control (DNREC), the U.S. Environmental Protection Agency's (USEPA) National Estuary Program, the Delaware Center for the Inland Bays, the University of Delaware, and other agencies. Excessive nutrients and sediment are among the most significant environmental stressors in the Inland Bays. The sources of nutrients, sediment, and other contaminants include point-source discharges from industries and wastewater-treatment plants, runoff and infiltration to ground water from agricultural fields and poultry operations, effluent from on-site wastewater disposal (septic) systems, and atmospheric deposition. In addition, the practice of agricultural ditching has further aggravated the environmental conditions in some areas of the Inland Bays watershed.

To determine the most effective restoration methods for the Inland Bays, it is necessary to understand the relative distribution and contribution of each of the potential sources of nutrients, sediment, and other contaminants. It is also important to understand the hydrology of the Inland Bays watershed, because the loads (masses of chemical constituents delivered to a water body over a specific time period) are strongly dependent on the flow volumes and flow paths (such as ground-water discharge or overland flow). Understanding the complex interrelations and interactions between hydrologic processes and the sources of contaminants is a prerequisite to effective restoration.

A cooperative study involving DNREC, DGS, and the U.S. Geological Survey (USGS) was initiated in 2000 to develop a hydrologic and water-quality model of the Delaware Inland Bays watershed that can be used as a water-resources planning and management tool. The water-quality constituents of concern are suspended solids and nutrients (nitrogen and phosphorus). A well-documented model code, Hydrological Simulation Program-FORTRAN (HSPF) (Donigian and others, 1995; Bicknell and others, 1996), was used to develop the site-specific model of the Inland Bays watershed. A major goal in developing a watershed model for the Delaware Inland Bays was to allow prediction of loads.

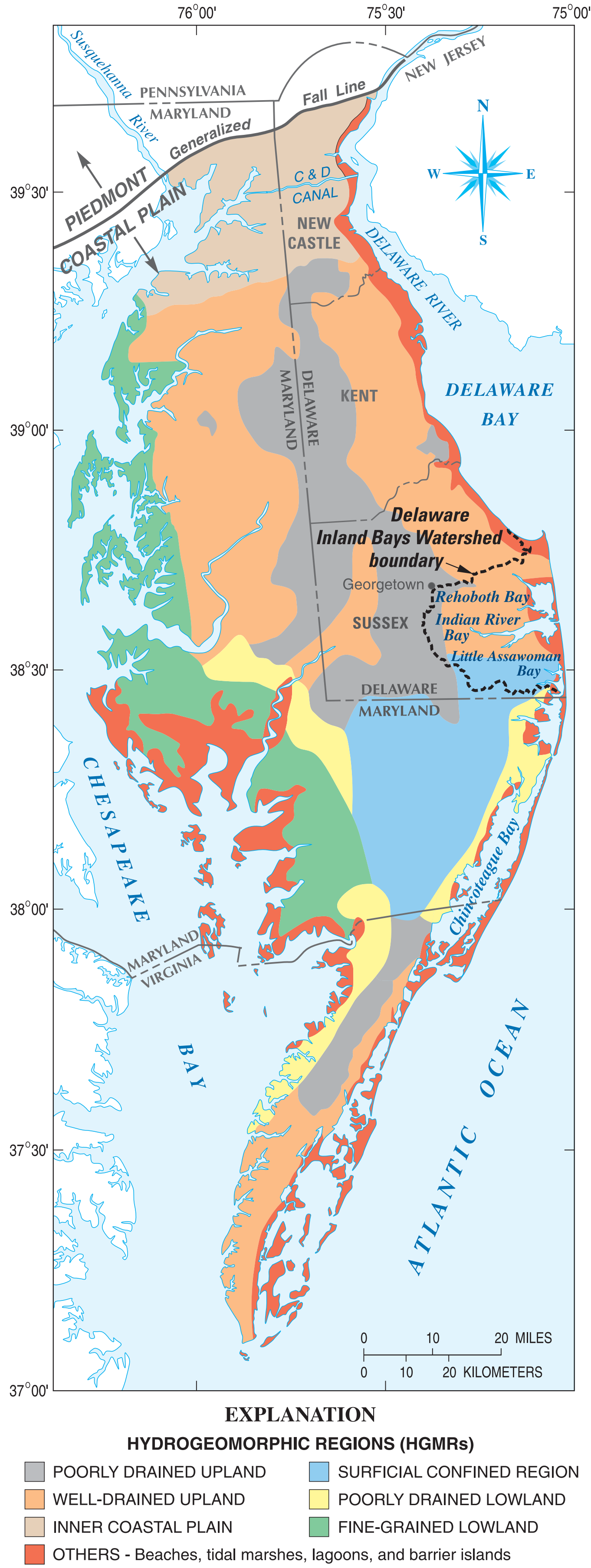

Figure 1a. Hydrogeomorphic regions of the Delmarva Peninsula and location of the Delaware Inland Bays watershed (modified from Shedlock and others, 1999).

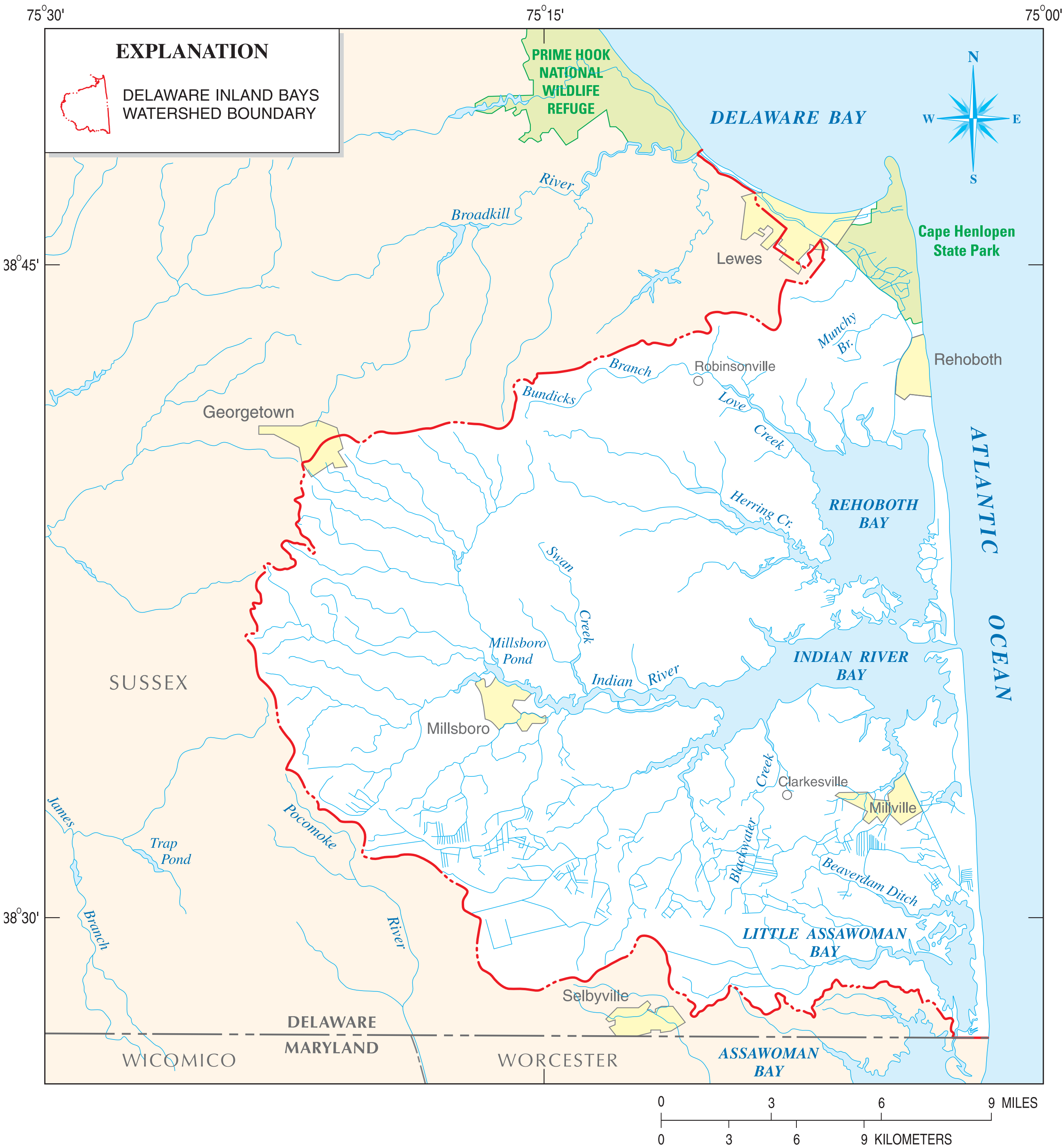

Figure 1b. Detailed view of the Delaware Inland Bays watershed, Sussex County, Delaware.

Purpose and Scope

The purpose of this report is to (1) document the development and structure of the Inland Bays watershed model of streamflow, sediment, and nutrient loading, (2) present the methods for model calibration and the results of the calibration, and (3) provide findings and analysis of the model results and implications for the understanding of hydrologic and nutrient processing functions in the Inland Bays watershed. Hydrologic, agricultural, meteorological, and water-quality data were compiled for 1998 through 2000, and used for the development and calibration of the model. The 719-square-kilometer (km^2) watershed was divided into 45 model segments and the model was calibrated using streamflow and water-quality data for water year 1999 [A] and part of water year 2000 (October 1998 through April 2000) from six USGS stream-gaging stations within the watershed. The watershed model segmentation was based on several factors including the location of impaired streams in the Inland Bays watershed listed in the 303(d) list for 1998 from the State of Delaware (Delaware Department of Natural Resources and Environmental Control, 1998), the location of USGS stream-gaging stations and water-quality monitoring stations, and the location of point sources. Calibration for some parameters was accomplished using PEST, a model-independent parameter estimator (Doherty, 2000). Model parameters were adjusted systematically so that the discrepancies between the simulated values and the corresponding observations were minimized.

Previous Investigations

Nutrient contamination of ground water and surface water in the Inland Bays watershed has been studied for decades. Nitrate contamination in the surficial sediments has been documented in several previous studies (Miller, 1972; Robertson, 1977; Denver, 1989; Andres, 1991; Hamilton and others, 1993). Elevated concentrations of nitrate were found in surface water, especially in well-drained watersheds associated with agricultural land use (Phillips and Bachman, 1996). Base-flow nitrate concentrations in surface water have been attributed to the discharge of shallow ground water (Shedlock and others, 1999). Concentrations of nitrate in ground water were highest in sandy soils underlying well-drained agricultural fields where poultry manure and inorganic fertilizer were applied, and lowest where soils were poorly drained and dissolved oxygen was absent. Concentrations in surface water follow similar patterns, although other processes (such as biological uptake and denitrification) in stream channels can also affect nutrient concentrations in surface water. Nitrate concentrations in ground water and surface water have been attributed in part to on-site wastewater disposal systems and confined animal feeding operations.

Phosphorus is not commonly present in ground water at elevated concentrations, but is present in high concentrations on soil particles, especially in areas where poultry manure has been applied to agricultural fields (Sims and Wolf, 1993). Phosphorus transport is primarily attributed to overland flow that transports sediment with attached phosphorus ions.

A regional assessment of ground-water quality in the Delmarva Peninsula, which includes the Delaware Inland Bays, was conducted under the USGS National Water-Quality Assessment (NAWQA) Program (Hamilton and others, 1993; Shedlock and others, 1999), using data collected through 1991. Several wells sampled during the study were in the Inland Bays watershed. The results indicate that the chemical character of water in the surficial sediments is affected by agricultural activities over most of the Delmarva Peninsula. The surficial sediments contain large volumes of ground water with elevated concentrations of nitrate in nearly all areas of the peninsula. Hydrogeomorphic Regions (HGMRs) that describe different physical settings with characteristic patterns of ground-water flow and water quality were delineated for the Delmarva Peninsula on the basis of geologic and geomorphic features, drainage patterns, soil types, and land-use patterns (Hamilton and others, 1993) (fig. 1a). The Inland Bays watershed includes four of these regions: (1) a poorly drained upland unit at the western edge of the watershed; (2) a well-drained upland unit covering most of the northern and central parts of the watershed; (3) a surficial confined region in the southern part; and (4) a unit described as “Others” (beaches, tidal marshes, lagoons, and barrier islands) that covers the part of the watershed close to the Atlantic Coast and immediately surrounding the Inland Bays themselves. The potential effect on nutrient transport and transformation in each HGMR is related to differences in soil characteristics and aquifer configuration that determine the movement of water and the potential for oxidation and reduction in the aquifer and streams.

A cooperative study between DNREC, the University of Delaware College of Marine Studies and DGS began in 1998 to collect water samples from six streams discharging to the Inland Bays during base-flow and storm-event conditions (Ullman and others, 2002). The water samples were analyzed for nutrients and total suspended solids (TSS). Streamflow data also were collected at the sites. Streamflow, nutrient and total suspended solids concentration data were used to determine annual and seasonal base-flow and storm-event loads and yields (load per unit watershed area). Although no simple statistical relation between land use or land cover and the estimated loads or yields was found, the data resulting from the project provide information that is critical to the understanding of nutrient and sediment loading within the Inland Bays watershed.

[A]. Water year 1999 is from October 1, 1998 through September 30, 1999.

Acknowledgments

The authors gratefully acknowledge the assistance of Richard Greene and Hassan Mirsajadi (Delaware Department of Natural Resources and Environmental Control), Scott Andres (Delaware Geological Survey), William Ullman and Joseph Scudlark (University of Delaware), Richard McCuen and Ken Staver (University of Maryland), and Kent Price (Center for the Inland Bays) who provided information on land use/land cover, fertilizer and manure application rates, animal population statistics, and feedback on the model results and analysis. John Doherty (Watermark Numerical Computing) provided assistance with the PEST software. The authors also wish to acknowledge Joseph Vrabel and Sarah Martucci of the USGS for their technical expertise in compiling spatial data and providing graphical post-processing of model results; Valerie Gaine for editorial insight, Timothy Auer for his work on illustrations, and Donna Knight for report layout.

Description of the Study Area

The Inland Bays watershed encompasses approximately 803 km^2 in southeastern Sussex County, Delaware. The bays are 84 km^2 and the remaining 719 km^2 is land. Several major and many smaller streams drain to the three bays (Rehoboth, Indian River, and Little Assawoman; fig. 1b). Land use/cover in the watershed, based on 1997 estimates, is 32 percent agriculture (including crops, orchard, and pasture), 21.5 percent forest (including brush), 30 percent water (including the bays, wetlands, and barren areas), 14.3 percent residential (including low-, medium-, and high-density), and 2.2 percent urban (institutional/government, industrial, and commercial land uses) (Delaware Office of State Planning Coordination, 2002).

Climate The climate of the region is humid-continental with four distinct seasons, which are moderated by the proximity of the Atlantic Ocean. The area receives average annual precipitation of 1,110 millimeters (mm), of which approximately 400 mm may recharge the unconfined aquifer, although this amount varies spatially and annually (Johnston, 1976). The prevailing direction of storms is from the west-northwest from November through April, and it shifts to the south during May through September. The fall, winter, and early spring storms tend to be of longer duration and lower intensity than the summer storms. During summer, convective uplift may produce storms that occur during the late afternoon and early evening, characterized by scattered high-intensity storm cells that may produce significant amounts of rain in a short time span. On the basis of National Weather Service (NWS) data, thunderstorms occur approximately 30 days per year, with the majority occurring from May through August.

Hydrology, Soils, and Topography Indian River Bay, Rehoboth Bay, and Little Assawoman Bay are inland bays that are protected by a narrow barrier island located between the bays and the Atlantic Ocean (fig. 1b). Indian River Bay and Rehoboth Bay are connected by a shallow channel; Indian River Bay and Little Assawoman Bay are connected by a canal. A narrow passageway—the Indian River Inlet—connects the bays and the ocean.

The western part of the Inland Bays watershed is drained by the Indian River. A millpond dam at the west end of Indian River Bay separates the tidal and nontidal reaches of the Indian River. The northern part of the watershed is drained by several small streams. The southern part of the watershed is dominated by poorly drained soils and extensive networks of drainage ditches have been constructed to promote drainage for agriculture. Throughout the watershed, precipitation recharges the unconfined aquifer, which provides ground-water discharge to the streams (referred to as base flow) and directly to the bays and at the eastern margin of the watershed, to the ocean.

The study area is located in the Atlantic Coastal Plain Physiographic Province. The Coastal Plain is underlain by a seaward-dipping wedge of unconsolidated to semiconsolidated marine and nonmarine sediments composed of gravel, sand, silt, and clay. In the Inland Bays watershed, the uppermost Coastal Plain sediments form an unconfined aquifer that is referred to as the Columbia aquifer (Bachman and Wilson, 1984). The primary units that constitute the Columbia aquifer in Sussex County are the Beaverdam and Omar Formations of Pliocene to Pleistocene age (Andres, 1987; Talley, 1988; Delaware Geological Survey, 2003). The Beaverdam Formation is a medium to coarse quartz sand with variable amounts of fine sand and gravel, and ranges from 18 to 37 m (meters) thick in eastern Sussex County. It is overlain in the southern part of the County by the Omar Formation, which consists of alternating beds of sand and silt. The Omar Formation was deposited in a back-barrier lagoon environment and has an average thickness of 14 m in the study area. Thick, discontinuous layers of clay and silt in the Omar Formation result in confined or semi-confined aquifer conditions. The sediments that underlie the Inland Bays include estuarine, lagoon, and barrier island materials that may reach 46 m in thickness in buried stream channels. All of these sediments are underlain by many tens of hundreds of meters of older Coastal Plain sediments.

The HGMRs defined in the study area (fig. 1a, table 1) range from the well-drained uplands with soils with relatively low organic matter content in the east and north, to less permeable, more organic-rich and poorly drained areas in the western and southern parts of the watershed (fig. 2). The central-northern part of the watershed is dominated by permeable sandy and sandy loam soils that are well drained. The southern part of the study area, which corresponds approximately to the surficial confined HGMR shown in figure 1a, is a more poorly drained region with higher organic matter content (fig. 2).

Topography in the Inland Bays watershed is flat, typical of the Atlantic Coastal Plain Physiographic Province. The altitudes in the watershed range from 0 to 22.9 m above sea level with a mean of 6.9 m above sea level, on the basis of 30-m Digital Elevation Model (DEM) data (University of Delaware Spatial Analysis Lab, 2003). Slopes in the watershed are generally very gradual. Streams in the uplands may

Table 1. *Characteristics of Hydrogeomorphic Regions (HGMRs) on the Delmarva Peninsula within the Delaware Inland Bays watershed*

[Modified from Shedlock and others (1999), table 3; m, meters]

HGMR	CHARACTERISTICS
Poorly drained upland	• Poorly drained forested areas containing wetlands are interspersed with moderately well to well-drained agricultural areas. • Streams flow through shallowly incised valleys with low gradients. Ditching to promote soil drainage is common in drainage headwaters. • Water table generally within 3 m of land surface. • Poor drainage is related to shallow stream incision and high water table, not to fine-grained sediments.
Well-drained upland	• Relatively flat to gently rolling with a high degree of stream incision. • Nontidal streams are mostly short, steep tributaries that drain the narrow interfluves between tidal rivers. • Most of the upland area is used for agriculture. • Wooded areas are generally confined to narrow riparian zones. • Depth to the water table ranges from 3 to 9 m below land surface beneath topographic highs to land surface in riparian discharge areas.
Surficial confined	• Stream incision is shallow and ditching to promote soil drainage is widespread. • The complex set of fine-grained sediments acts as a confining bed over much of the region. • The water table is generally less than 3 m below land surface and occurs in the upper sand unit.
Others	• Unvegetated areas such as beaches, tidal wetlands, and barrier islands.

be incised, especially in the well-drained upland HGMR. The land surface in the surficial confined HGMR (fig. 1a) is extremely flat.

Water Use In 1995, total freshwater withdrawals in Sussex County were estimated to be 3.52×10^8 liters per day (L/d), or about 12 percent of the freshwater withdrawals in the State (Wheeler, 1999). Nearly 90 percent of the estimated total freshwater withdrawals in Sussex County were ground water used by industries and for irrigation. Public water suppliers in Sussex County relied solely on groundwater sources and withdrew 4.16×10^7 L/d. Another 1.27×10^7 L/d were withdrawn for livestock use.

Model Development

A modeling framework for the watershed was developed to provide load estimates for a hydrodynamic and water-quality model of the Inland Bays, and to provide a tool for managers and planners to estimate the effects of various growth and management scenarios on water quality. The modeling framework consists of a set of input files with calibrated parameter values for use with HSPF.

Overview of the Hydrological Simulation Program-FORTRAN (HSPF)

The HSPF model simulates flow, sediment transport, temperature variations, and water-quality processes over the entire hydrologic cycle. Processes controlling water flow and chemical constituent concentrations can be represented at various levels of detail using HSPF, and simulated for land and in-stream (river reach, reservoir) environments. These choices are made by specifying the HSPF modules and code compartments (Donigian and others, 1995) that are used, and the choices subsequently establish the model structure used for any one situation. In addition to the choice of modules and code compartments, other types of information must be supplied for the HSPF calculations, including model parameters and time series of input data. Time series of input data for this application include meteorological data, point sources, and atmospheric deposition.

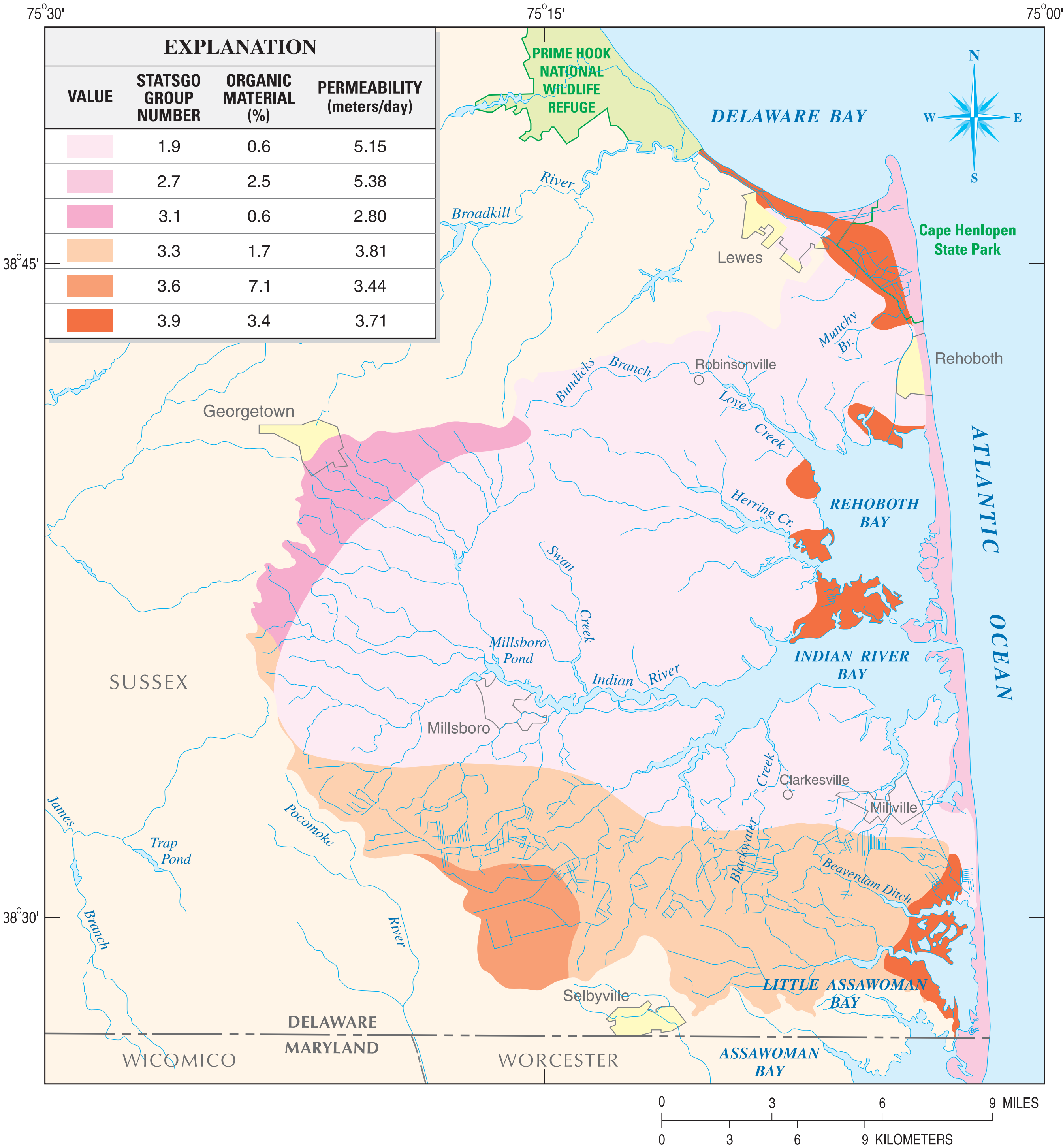

Figure 2. Soils map for the Inland Bays watershed showing percent organic material, soil permeability, and a hydrologic characteristics grouping code (STATSGO group number). *[Data are from the STATSGO data base (Schwarz and Alexander, 1995).]*

Two distinct sets of processes are represented in HSPF: (1) processes that determine the fate and transport of water and chemical constituents at or below the land surface for pervious (HSPF module PERLND) and impervious (HSPF module IMPLND) areas; and (2) in-stream processes (HSPF module RCHRES). The first step in the modeling process is to subdivide a watershed into land segments. The boundaries of the segments are established according to the modeler's needs, but generally, a segment is defined as an area with similar hydrologic characteristics. For modeling purposes, water, sediment, and water-quality constituents leaving each segment move laterally to a downslope land segment or to a reach or reservoir. For this project, the NAWQA data and HGMRs provide a background and framework for watershed model development and spatial extrapolation of watershed characteristics and model parameter values.

Within a model segment, multiple land-use types can be simulated, each using different modules and different model parameters. HSPF is a lumped model that does not take into account spatial variation, and simulates the water mass balance within land areas as a series of storages with flows between the storages determined by empirical (constitutive) relations.

Simulated loads from land or watershed processes before they reach the stream are known as “edge-of-stream” loads. In terms of simulation, all processes are computed for a spatial unit of 1 acre [B]. The number of acres of each land use in a given model segment multiplied by the edge-of-stream values (fluxes, loads) computed for the corresponding area provide the total edge-of-stream load for the land part of the watershed model segment.

The RCHRES module is used to simulate in-stream processes in either a river reach or reservoir (such as flow, sediment transport, water temperature variations, and water quality) that affect the delivery of water and solutes from the edge of the stream to another body of water. HSPF models the flow through a reach or reservoir as unidirectional, with constituents that are uniformly dispersed in the water body moving at the same horizontal velocity as the water. The inflow and outflow of materials are based on a mass balance. HSPF uses a convex-routing method to move mass within the reach. Outflow may leave the reach in one of three ways (irrigation, municipal and industrial water use, or flow to a downstream reach), and the processes in the reach will be influenced by precipitation, evaporation, and other fluxes.

Stream geometry in the model is represented as a set of functional relations between two or more variables. This information is entered into the model in the form of a table (referred to as an F-table) of reach or reservoir depth, surface area, volume, and volume-dependent discharge. The information contained within the F-tables and the convex-routing physical parameters control the routing of water within the reach or reservoir.

Model Assumptions

A number of assumptions and other decisions were made in modeling the Inland Bays watershed. The spatial distribution of precipitation was estimated from meteorological stations at Lewes, Georgetown, and Selbyville, Delaware. Agricultural information such as crop type was estimated from the Delaware Office of State Planning Coordination (DOSPC) land-use data (Delaware Office of State Planning Coordination, 2002) and the 1997 Census of Agriculture Data (U.S. Department of Agriculture: National Agricultural Statistics Service, 1997a). Nutrient application rates were derived from information on animal counts in the watershed provided by DNREC in the form of geographic information system (GIS) spatial datasets and overlain on the model segmentation. Ditching in the southern part of the watershed was not taken into consideration when calculating the length of the stream to be simulated because of model limitations. Although the model simulation is performed on a temporal basis, land-use information was not assumed to change with time.

Watershed Segmentation

The watershed model segmentation was based on several factors including the location of impaired streams in the Inland Bays watershed listed in the 303(d) list for 1998 from the State of Delaware (Delaware Department of Natural Resources and Environmental Control, 1998), the location of stream-gaging stations and water-quality monitoring stations, and the location of point sources. Section 303(d) of the 1972 Clean Water Act (U.S. Environmental Protection Agency, 2003) requires states to develop a list of water bodies that need additional pollution reduction beyond that provided by the application of existing conventional controls. The overall objective of a Total Maximum Daily Load (TMDL) is to determine the pollutants causing water-quality impairments, to identify the maximum permissible load capacity for the impaired water body, and to assign load allocation for each pollutant. On the basis of these factors, the watershed was divided into 45 segments, with segment areas ranging from 1.3 to 53 km^2 (fig. 3). The sub-basin draining to the Millsboro Pond Outlet stream-gaging station was divided into a single network of 12 segments to provide better resolution for the allocation of loads to the listed impaired streams.

Land Use

Land-use information was derived from the 1997 DOSPC land use/land cover data (Delaware Office of State Planning Coordination, 2002). The hectares of each land use within each model segment are shown in table 2. The DOSPC categories were aggregated into a broader classification as follows: (1) forest, wetland, barren, and brush categories were aggregated into a “forest” classification; (2) crop and orchard categories were aggregated into “crops;” (3) the pasture category was termed “pasture;” and (4) low-,

---

[B] Although the simulations were set to operate on a per-acre basis, hectares (ha) will be the unit for area used in this report. One hectare is equal to 10^4 square meters (m^2) or 2.471 acres.

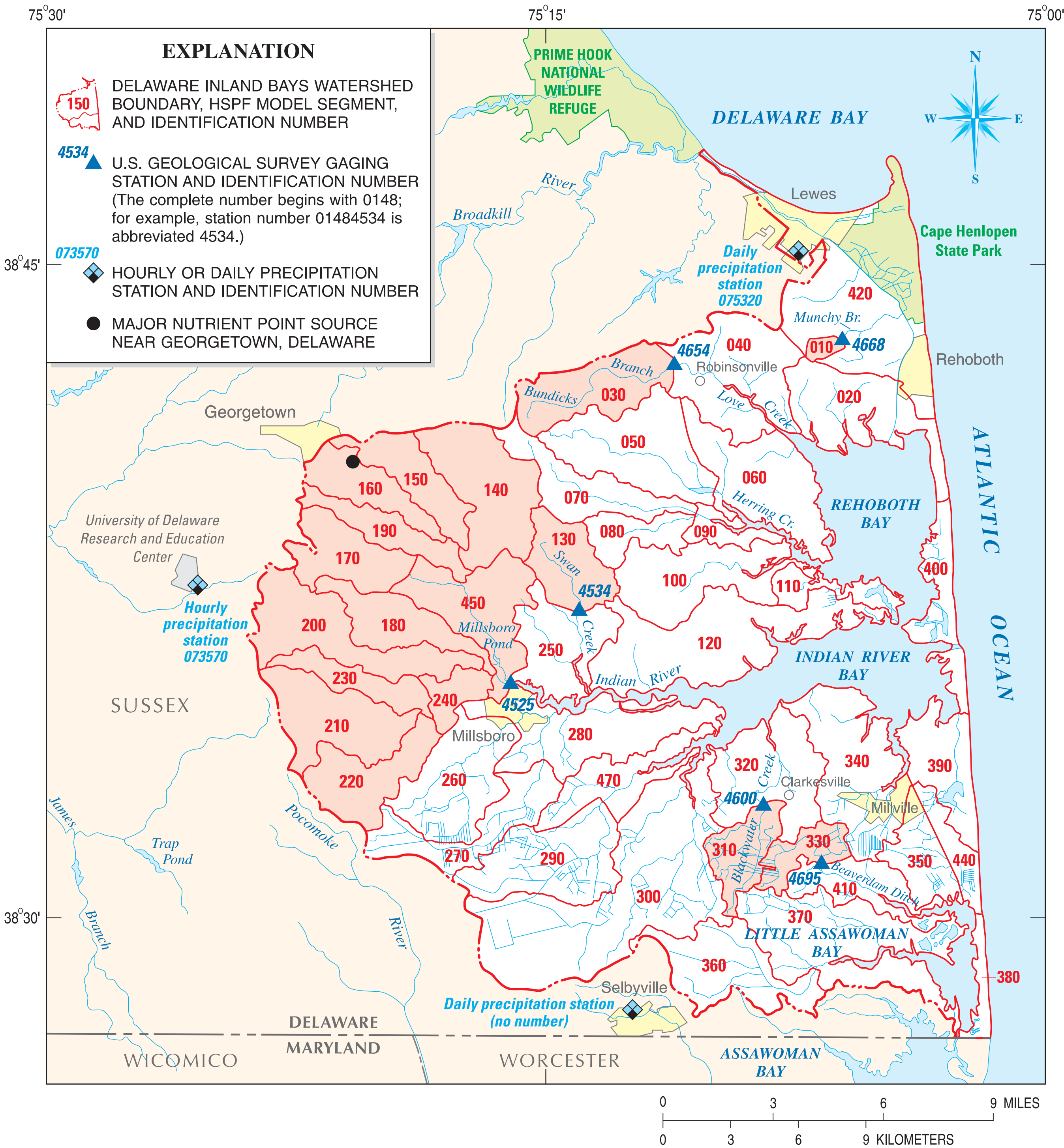

Figure 3. Hydrological Simulation Program - FORTRAN (HSPF) Inland Bays watershed model segmentation, locations of U.S. Geological Survey stream-gaging stations, hourly and daily precipitation stations, and the major nutrient point source near Georgetown, Delaware. *[Light red shaded areas represent the watersheds used to calibrate the HSPF model. Segments are numbered 010 through 470, in increments of 10; there are no segments numbered 430 or 460.]*

Table 2. *Land-use categories with number of hectares per watershed model segment*

[Estimates are for 1997; values from Delaware Office of State Planning Coordination (2002)]

Segment	Water	Forest	Wetland	Barren	Brush	Crops	Orchard	Pasture	Low-density residential	Medium-density residential	High-density residential	Institutional	Industrial	Commercial	TOTAL
010	0.0	6.2	4.3	0.0	0.0	35.6	0.0	0.0	45.9	0.0	10.4	0.0	4.2	26.4	133
020	95.2	165.6	306.9	44.6	35.0	318.9	0.0	0.0	630.8	0.0	217.7	8.0	41.1	71.6	1,936
030	0.2	613.4	84.1	3.8	7.4	778.6	0.0	6.8	110.3	6.5	0.0	0.0	7.9	0.0	1,619
040	62.1	617.9	205.6	46.8	0.8	1,094.6	0.0	32.7	295.6	4.0	50.6	0.0	0.0	4.8	2,416
050	0.8	908.2	154.7	5.7	90.6	801.7	0.0	0.0	252.5	2.3	0.0	0.0	15.6	0.0	2,232
060	58.4	613.0	412.6	88.2	5.2	462.8	0.0	7.6	313.3	0.0	151.4	0.0	0.0	0.0	2,112
070	0.0	395.4	73.9	1.5	43.8	729.7	0.0	5.3	55.8	2.1	28.2	0.0	9.0	0.0	1,345
080	0.3	254.3	36.8	16.3	9.3	363.4	0.0	0.0	35.2	0.0	21.4	0.0	3.6	0.0	741
090	6.4	127.7	30.9	2.8	0.7	110.6	0.0	0.0	119.2	0.0	14.9	0.0	0.0	0.0	413
100	31.4	565.7	113.1	162.9	113.8	588.6	0.0	14.2	204.5	3.2	134.5	0.0	20.0	21.8	1,974
110	37.6	61.2	191.5	20.2	12.5	66.2	0.0	9.3	7.3	0.0	129.4	0.0	0.0	5.2	541
120	122.1	801.1	338.0	59.3	41.0	921.1	0.0	16.8	416.4	8.3	534.7	0.0	9.6	39.2	3,308
130	0.6	706.7	15.2	1.9	94.1	256.3	0.0	0.0	59.1	2.0	34.4	0.0	4.9	0.0	1,175
140	14.1	997.7	244.8	10.3	42.9	572.0	0.0	5.5	184.7	17.2	5.3	0.0	10.8	0.6	2,106
150	1.7	418.0	71.7	6.4	35.8	209.6	7.0	0.0	123.8	3.8	13.7	0.0	193.1	3.3	1,088
160	5.4	197.2	169.5	28.1	48.8	291.8	0.0	11.0	168.4	10.5	20.5	11.7	16.6	25.6	1,005
170	15.4	155.1	237.9	20.0	0.5	622.8	0.0	0.0	124.2	20.0	0.0	1.5	32.3	31.5	1,261
180	17.5	373.9	67.8	6.8	9.2	539.1	0.0	2.8	111.0	14.3	23.8	2.3	12.7	0.0	1,181
190	14.9	88.5	65.1	1.2	1.6	501.4	0.0	0.0	116.2	7.6	15.0	33.1	6.2	24.8	876
200	3.9	491.3	410.4	18.5	27.5	969.0	0.0	5.2	66.6	32.7	8.2	0.0	3.2	0.0	2,037
210	25.2	859.0	157.5	9.0	25.2	593.2	0.0	0.0	73.8	21.2	15.8	0.0	6.7	0.0	1,787
220	2.9	387.3	278.6	12.2	40.7	545.3	0.0	0.7	82.3	16.1	22.9	0.0	5.7	0.0	1,395
230	11.6	241.4	25.9	6.5	5.5	423.6	0.0	0.0	31.6	15.3	15.7	0.0	0.0	0.0	777
240	42.6	50.3	27.1	11.8	26.5	208.2	0.0	0.0	85.7	10.8	31.4	0.0	8.4	0.0	503
250	32.3	343.3	69.6	6.4	53.2	897.3	0.0	0.0	33.4	8.7	26.8	0.0	55.2	0.0	1,526
260	12.1	257.5	429.5	11.5	55.9	1,055.2	0.0	3.3	102.0	28.3	10.1	0.0	13.0	10.4	1,989
270	0.7	78.9	487.6	0.0	6.4	795.3	0.0	0.0	27.3	14.9	27.9	0.0	15.5	0.0	1,454
280	43.5	594.5	432.5	112.4	29.3	491.8	0.0	7.3	198.3	34.6	165.1	5.6	127.6	57.2	2,300
290	1.4	149.9	617.6	4.0	25.4	1,057.2	0.0	15.6	61.4	37.6	85.0	10.9	15.7	5.7	2,088
300	37.2	766.1	1,884.0	64.0	12.3	2,043.6	0.0	5.5	237.4	90.9	117.6	5.1	33.2	4.4	5,301
310	3.9	131.8	73.3	0.7	6.8	596.8	0.0	2.4	52.4	31.8	2.1	0.0	0.0	0.0	902
320	33.3	552.2	238.6	33.6	17.8	595.1	0.0	29.2	334.1	71.8	66.5	0.0	0.0	0.0	1,972
330	4.7	39.0	42.9	15.3	0.0	446.0	0.0	3.0	64.0	26.8	0.9	0.0	0.8	0.0	643
340	42.1	453.7	352.2	42.9	15.3	730.4	0.0	11.4	588.3	28.1	99.0	0.0	0.0	45.2	2,409
350	31.8	96.1	276.6	29.1	5.5	251.3	0.0	0.0	147.7	3.5	49.9	0.0	15.3	5.9	913
360	9.6	139.6	293.2	33.4	25.7	1,066.3	0.0	17.0	101.9	56.4	29.4	0.0	0.0	0.0	1,773
370	156.2	417.6	661.3	31.9	10.1	1,153.0	0.0	27.0	225.8	62.4	106.4	0.0	0.0	5.2	2,857
380	48.4	4.1	94.9	65.8	0.0	8.3	0.0	0.0	65.0	0.0	20.6	0.0	15.7	29.6	352
390	107.7	118.8	262.4	48.0	64.6	141.7	0.0	0.0	366.1	4.4	107.1	17.7	35.9	30.0	1,304
400	120.1	22.6	460.1	146.6	48.8	0.0	0.0	0.0	48.5	0.0	9.6	0.0	46.4	2.7	905
410	32.8	243.7	325.3	4.4	15.6	259.9	0.0	10.7	74.1	27.2	72.4	0.0	1.5	0.0	1,068
420	235.1	630.6	1,125.3	353.9	121.7	692.7	0.0	21.3	852.7	0.0	171.0	91.8	74.2	160.9	4,531
440	59.0	32.5	44.7	24.7	4.4	0.4	0.0	6.6	300.8	0.0	68.5	0.0	13.8	11.3	567
450	41.7	621.3	121.1	0.0	82.3	696.9	0.0	0.0	95.7	24.3	89.9	58.2	5.5	0.4	1,837
470	18.2	173.0	134.8	31.7	1.5	547.1	0.0	10.2	141.3	41.2	84.0	3.8	25.7	6.9	1,219
TOTAL	**1,642**	**15,963**	**12,152**	**1,645**	**1,321**	**25,531**	**7**	**289**	**7,832**	**791**	**2,910**	**250**	**907**	**631**	**71,871**

Table 3. *Estimated percentage of impervious surface within specific land-use categories, Sussex County, Delaware*

[Estimates are for 1997 and were provided by the Delaware Department of Natural Resources and Environmental Control; the remaining percentage of each category is pervious.]

Land use	Estimated percentage of impervious surface
Institutional	35
Industrial	72
Commercial	60
Low-density residential	30
Medium/high-density residential	65

medium-, and high-density residential and institutional, industrial, and commercial categories were aggregated into an "urban" classification (fig. 4). The wetlands category is simulated as forest because of HSPF limitations in simulating chemical processes in wetlands.

Although estimates of the percentage of impervious area for the urban land-use categories were available (table 3), these were modified during calibration for a number of reasons. Because HSPF does not consider the location of the impervious areas with respect to the stream, there is no attenuation between the edge of the impervious areas and the stream, which is likely to occur wherever the actual flow path crosses other land types or re-enters the subsurface. In addition, the provided estimates were at the county level and not specific to the Inland Bays watershed. The final calibrated values for percentage of effective impervious area ranged from 15 to 30 percent throughout the watershed.

The 1997 Census of Agriculture (U.S. Department of Agriculture: National Agricultural Statistics Service, 1997a) was used to determine crop-type proportions, which were assumed to be uniform throughout the county (fig. 5). Similarity in nutrient uptake, tillage practices, and planting time were used to derive the final five classifications shown in table 4: corn, double crops, full-season soybeans, vegetables, and hay.

Double-crop hectares are simulated as a "composite" crop. The term "composite" denotes more than one major crop category within the simulated land use. Differences in the simulation of agricultural landuse are sometimes related to the development of parameters for simulated composite crops because of aggregated processes. This aggregation would occur because wheat is planted during the fall (after the corn or soybeans have been harvested), and grown until spring of the following year (before the corn or soybeans are planted). Because harvesting is not simulated in the current model framework, soil conditions are reset at the beginning of each simulation year. This introduces greater problems if the resetting date is the beginning of the calendar year (January), when the winter crops or wheat are in the middle of the growing season. Determining a "composite parameterization" is difficult in this case. The problem can be overcome by basing the simulation on the water year, however, which allows for the complete cycle of the double crop (planting and harvesting) within the simulation year. In the Inland Bays watershed model, soil conditions were reset using this approach when crops were not on the ground.

Development of Nutrient Application Rates

Mineral (commercial) and organic (animal waste) fertilizer calculations were based on methodologies developed for the Chesapeake Bay watershed model (U.S. Environmental Protection Agency, 1998). Work at the University of Maryland Wye Research and Education Center guided modifications to these methodologies (Staver and Brinsfield, 1998). Nutrient application rates were based on a mass balance between the animal wastes produced within each model segment and the expected average crop yield in Sussex County, as reported in the 1998 Delaware Agricultural Statistics (U.S. Department of Agriculture: National Agricultural Statistics Service, 2003). Mineral fertilizer was used to supplement the amount needed for the expected average crop yield when the available organic fertilizer was insufficient.

Animal Counts, Animal Units, and the Manure Land-Use Category The development of organic fertilizer application rates is based on the number and type of animals in the watershed. These data are transformed into "animal units" as a means of normalizing the nutrient availability from different animal types. One animal unit is equivalent to the amount of waste produced by one beef cow. The Sussex Conservation District of the State of Delaware provided animal count information for 1999 (Karin H. Grosz, Sussex Conservation District, written commun., 2001). The information was provided in GIS format, which was overlain on the model segmentation to allocate the animal numbers to the model segments (table 5). These data were used to calculate the amount of animal waste available for application to cropland, and to calculate the number of hectares to be modeled as a "manure" land use.

"Manure hectares" is a derived land-use category used to represent what is susceptible to runoff from confined feeding operations, and it represents less than 1 percent of the total loads in the Inland Bays watershed. All animal categories except poultry were used to calculate manure hectares; poultry manure is applied only to cropland in the simulation. The number of manure hectares was determined by dividing the number of animals in each model segment by the conversion factors found in table 6 to obtain animal units, multiplying by the fraction of time confined, and dividing by an assumed animal density in confined feeding operations (358 animal units per hectare) (U.S. Environmental Protection Agency, 1998).

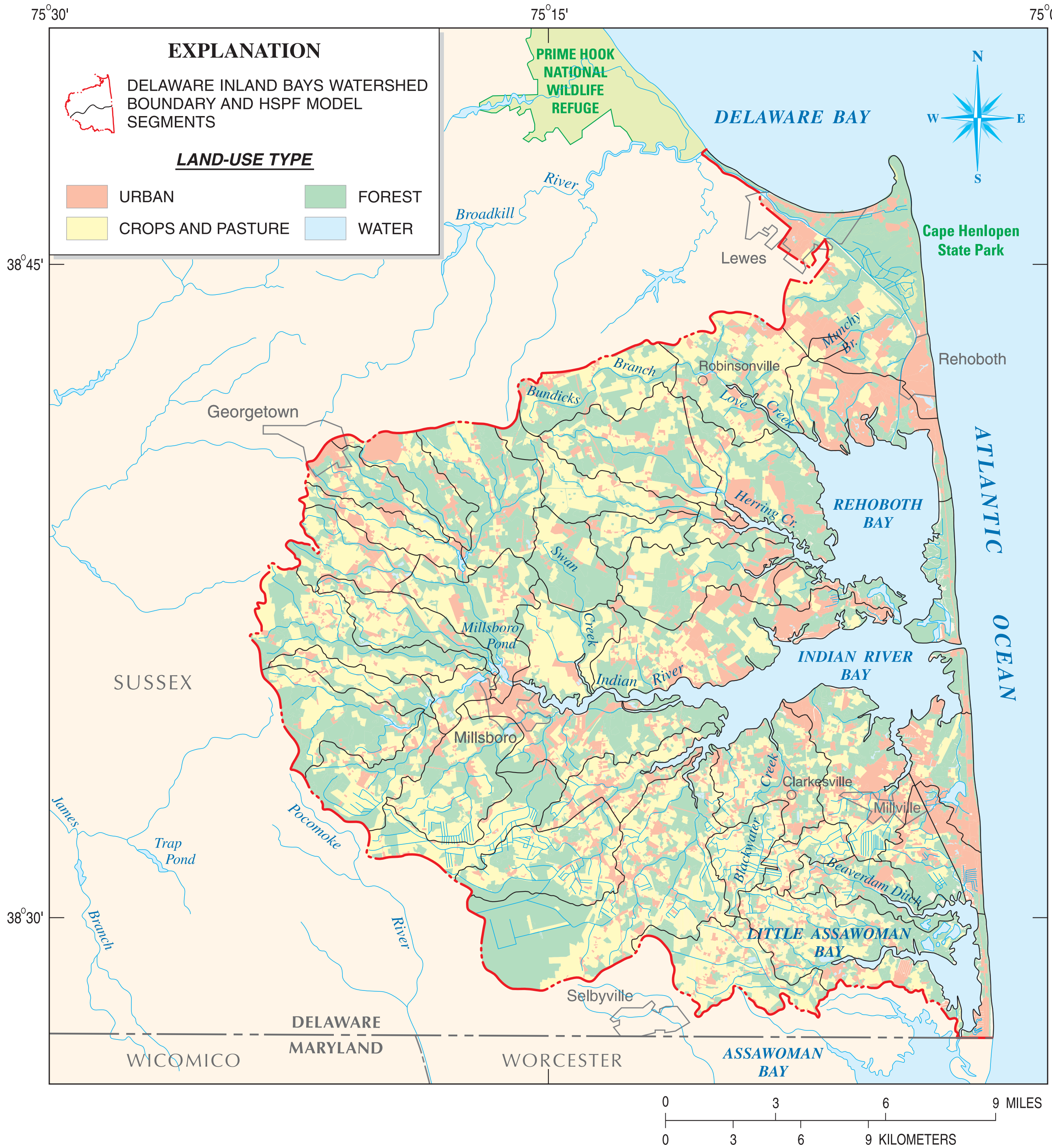

Figure 4. Generalized land-use map of the Delaware Inland Bays watershed. *[Original data are from the Delaware Office of State Planning Coordination (2002).]*

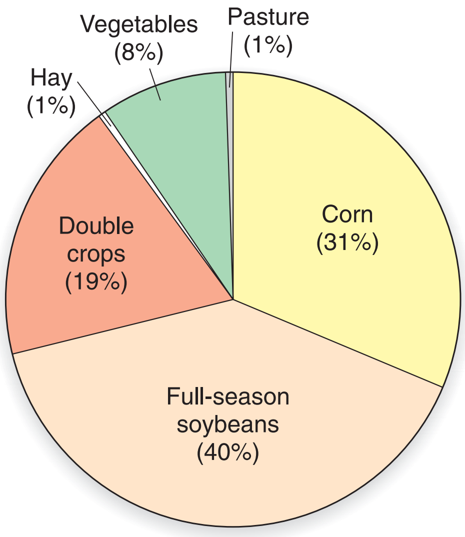

Figure 5. Crop hectare allocations for the model. *[Estimates were determined using 1997 Census of Agriculture data (U.S. Department of Agriculture: National Agricultural Statistics Service, 1997a) and information provided by the Delaware Department of Natural Resources and Environmental Control, Division of Soil and Water Conservation.]*

The number of animals per animal unit for sheep and horses was estimated on the basis of an assumed weight of 59 kg (kilograms) for a sheep and 650 kg for a horse; their time of confinement was also estimated. These estimates have a relatively minor impact on the overall nutrient production in the model segments where these animals are found, because poultry animal units far outnumber those of other animals. The calculated manure hectares were subtracted from the pasture land-use category, assuming manure is stored and treated through the implementation of control programs, and that some of these hectares would revert to pasture hectares.

Organic Fertilizer Calculations Animal waste applied to cropland was calculated on the assumption that manure was stored throughout the year for spring and fall applications; for pasture, it was assumed that animal waste is applied throughout the year except during the months of December, January, and February. As recommended by DNREC and the Delaware Inland Bays Scientific and Technical Advisory Committee (STAC), the allocation of animal waste to crops was based on the assumption that animal waste generated in a segment was applied to the crops in the same segment. For cases in which land-use records indicated that crops were cultivated in a particular segment and organic fertilizer was not available for application within that segment, it was assumed that mineral fertilizer was applied at the rate recommended by DNREC and the Delaware Inland Bays STAC.

According to the animal population data reported by the Sussex Conservation District, 99 percent of the organic fertilizer comes from poultry waste and less than 1 percent is derived from the waste of other animals. As recommended by the Delaware Inland Bays STAC, poultry was assumed to be a broiler type for the nutrient calculations. The count was defined in terms of animal units using values from table 6, and the poultry waste was applied to cropland, following the assumption that the animals were always confined.

The amounts of nutrients from manure generated within each model segment were then expressed as a mass of nitrogen and phosphorus per animal unit as excreted (table 7). The calculated amounts of nutrients generated within each model segment were reduced by the runoff and volatilization fractions (table 8) to obtain the amounts of nitrogen and phosphorus available for application to pasture and cropland. These amounts were then multiplied by the mass fractions of individual nitrogen and phosphorus species (table 9) to derive the masses of the forms of nitrogen and phosphorus simulated by HSPF. For animal waste, these forms include: (1) ammonia (adsorbed and dissolved); (2) organic nitrogen; (3) orthophosphate (adsorbed and dissolved); and (4) organic phosphorus.

Nutrient Requirements and Goal Yields The “nutrient requirement” is the amount of fertilizer that a farmer applies and expects to be used by the crops during their growing cycle. The “goal yield” refers to a representative or reference yield under normal conditions; the actual yield of the crop, however, will increase or decrease from year to year based on growing conditions in the area. The goal yields were used in the model to establish the nutrient application amounts.

Crop goal yields (table 10) for corn, double crops, and full-season soybeans are the average of reported yields for Sussex County, Delaware (U.S. Department of Agriculture: National Agricultural Statistics Service, 2003) from 1995 through 1999. In the case of double crops, reported yields from wheat, barley, and soybeans were averaged from 1995 through 1999 to obtain the goal yield. Goal yields for hay and vegetables are values reported for 1999. Because the potatoes category is the largest reported vegetable crop in Sussex County, the reported yield for potatoes for 1999 was used as the goal yield for the vegetables land-use class.

Plant composition values are shown in table 11 (Lander and others, 1998). This information was used to calculate the total annual target for plant uptake of nitrogen and phosphorus for all soil layers during a simulated year (table 12). The plant uptake rate for potatoes was used as the uptake for the vegetables land-use class.

Total Nutrient Applications The total nutrient applications were based on the type of crop and the crop nutrient requirements. In the case of full-season soybeans, nitrogen fixation was simulated, and phosphorus was supplied by mineral fertilizer. If organic fertilizer was applied in a specific model segment because of manure generation in that segment, then phosphorus in the mineral form was not applied.

Table 4. *Land-use classes for the watershed simulation with number of hectares per model segment*

Segment	Corn	Double crops	Full-season soybeans	Vegetables	Hay	Forest	Pasture	Pervious urban	Impervious urban	TOTAL
010	11.3	6.8	14.3	3.0	0.2	10.5	0.0	78.9	8.1	133
020	101.6	61.0	127.7	26.7	2.0	552.3	0.0	678.4	290.7	1,840
030	248.0	148.8	311.8	65.2	4.9	708.7	6.8	87.3	37.4	1,619
040	348.6	209.2	438.3	91.6	6.9	871.2	32.7	248.5	106.5	2,354
050	255.3	153.2	321.0	67.1	5.1	1,159.3	0.0	189.3	81.1	2,231
060	147.4	88.4	185.3	38.7	2.9	1,119.0	7.6	325.2	139.4	2,054
070	232.4	139.4	292.2	61.1	4.6	514.7	5.3	66.6	28.5	1,345
080	115.7	69.4	145.5	30.4	2.3	316.8	0.0	42.2	18.1	740
090	35.2	21.1	44.3	9.3	0.7	162.1	0.0	93.9	40.2	407
100	187.5	112.5	235.7	49.3	3.7	955.4	14.2	268.8	115.2	1,942
110	21.1	12.7	26.5	5.5	0.4	285.5	9.3	99.3	42.6	503
120	293.4	176.0	368.8	77.1	5.8	1,239.4	16.8	705.8	302.5	3,186
130	81.6	49.0	102.6	21.5	1.6	817.9	0.0	90.3	10.0	1,175
140	182.2	109.3	229.0	47.9	3.6	1,295.7	5.5	153.0	65.6	2,092
150	69.0	41.4	86.7	18.1	1.4	531.9	0.0	236.4	101.3	1,086
160	92.9	55.8	116.8	24.4	1.8	443.6	11.0	177.3	76.0	1,000
170	198.4	119.0	249.4	52.1	3.9	413.5	0.0	146.6	62.8	1,246
180	171.7	103.0	215.9	45.1	3.4	457.7	2.8	114.9	49.2	1,164
190	159.7	95.8	200.8	42.0	3.2	156.3	0.0	142.1	60.9	861
200	308.6	185.2	388.0	81.1	6.1	947.7	5.2	77.5	33.2	2,033
210	188.9	113.4	237.5	49.7	3.7	1,050.8	0.0	82.3	35.3	1,762
220	173.7	104.2	218.3	45.6	3.4	718.8	0.7	88.9	38.1	1,392
230	134.9	81.0	169.6	35.5	2.7	279.3	0.0	43.8	18.8	766
240	66.3	39.8	83.4	17.4	1.3	115.7	0.0	95.4	40.9	460
250	285.8	171.5	359.3	75.1	5.7	472.6	0.0	86.9	37.2	1,494
260	336.1	201.6	422.5	88.3	6.6	754.4	3.3	114.7	49.1	1,977
270	253.3	152.0	318.4	66.6	5.0	572.9	0.0	59.9	25.7	1,454
280	156.6	94.0	196.9	41.2	3.1	1,168.7	7.3	411.8	176.5	2,256
290	336.7	202.0	423.3	88.5	6.7	796.9	15.6	151.5	64.9	2,086
300	650.9	390.5	818.3	171.1	12.9	2,726.5	5.5	342.0	146.6	5,264
310	190.1	114.0	238.9	49.9	3.8	212.6	2.4	60.8	25.7	898
320	189.5	113.7	238.3	49.8	3.7	842.1	29.2	330.7	141.7	1,939
330	142.1	85.2	178.6	37.3	2.8	97.2	3.0	70.9	21.6	639
340	232.6	139.6	292.5	61.1	4.6	864.1	11.4	532.4	228.2	2,367
350	80.0	48.0	100.6	21.0	1.6	407.4	0.0	155.6	66.7	881
360	339.6	203.8	426.9	89.2	6.7	491.9	17.0	131.4	56.3	1,763
370	367.2	220.3	461.7	96.5	7.3	1,121.0	27.0	279.8	119.9	2,701
380	2.7	1.6	3.3	0.7	0.1	164.8	0.0	91.7	39.3	304
390	45.1	27.1	56.7	11.9	0.9	493.9	0.0	392.8	168.4	1,197
400	0.0	0.0	0.0	0.0	0.0	678.2	0.0	75.1	32.2	785
410	82.8	49.7	104.1	21.8	1.6	589.0	10.7	122.6	52.5	1,035
420	220.6	132.4	277.4	58.0	4.4	2,231.5	21.3	945.4	405.2	4,296
440	0.1	0.1	0.2	0.0	0.0	106.2	6.6	276.1	118.3	508
450	222.0	133.2	279.0	58.3	4.4	824.7	0.0	191.8	82.2	1,796
470	174.3	104.6	219.1	45.8	3.4	341.0	10.2	212.1	90.9	1,201
TOTAL	**8,134**	**4,880**	**10,225**	**2,137**	**161**	**31,081**	**289**	**9,369**	**3,952**	**70,228**

Table 5. *Animal count by animal type and model segment*

[Provided by Karin H. Grosz, Sussex Conservation District, written commun., 2001]

Segment	Beef cattle	Dairy cattle	Swine	Horses	Sheep	Poultry [1]
010	0	0	0	0	0	0
020	0	0	0	0	0	0
030	50	0	0	0	0	273,800
040	100	0	0	24	0	185,600
050	0	0	0	0	0	56,000
060	0	0	0	0	0	0
070	0	0	0	0	0	0
080	41	0	0	0	0	0
090	39	0	0	0	0	0
100	0	0	0	0	0	32,000
110	0	0	0	0	0	0
120	0	0	0	0	20	80,000
130	0	0	0	0	0	0
140	20	0	0	0	0	305,000
150	0	0	0	0	0	36,000
160	0	0	0	0	0	186,200
170	0	0	0	0	0	379,000
180	0	0	0	0	0	366,900
190	0	0	0	0	0	230,000
200	0	0	0	0	0	289,667
210	0	0	0	0	0	248,200
220	0	0	0	0	0	278,900
230	0	0	0	0	0	228,500
240	0	0	0	0	0	318,000
250	0	0	0	0	0	131,000
260	0	0	0	0	0	403,800
270	0	0	200	0	0	294,000
280	0	0	1,050	0	0	478,000
290	0	0	0	0	0	475,100
300	0	0	1,536	0	0	1,464,500
310	0	0	0	0	0	402,000
320	0	0	100	0	0	1,207,600
330	0	0	0	0	0	441,000
340	0	0	0	50	0	318,000
350	0	0	0	0	0	32,000
360	0	0	200	0	0	1,129,200
370	0	0	0	0	0	809,800
380	0	0	0	0	0	0
390	0	0	0	0	0	54,000
400	0	0	0	0	0	0
410	0	0	0	0	0	282,000
420	0	150	0	0	0	0
440	0	0	0	0	0	0
450	0	0	0	0	0	431,800
470	130	0	0	0	0	1,004,000
TOTAL	**380**	**150**	**3,086**	**74**	**20**	**12,851,567**

[1] For this study, poultry was assumed to be a "Broiler" type.

Table 6. *Factors used to calculate the number of animal units and the number of manure hectares based on the fraction of time in confinement, by animal type*

Animal type	Animals/ animal unit	Fraction of time confined	Fraction of time unconfined
Beef cattle	1.0	0.2	0.8
Dairy cattle	0.71	0.8	0.2
Swine	2.7	1.0	0.0
Sheep	7.7	0.5	0.5
Horses	0.7	0.5	0.5
Poultry	455	1.0	0.0

Table 7. *Mass of nitrogen and phosphorus generated from manure per animal unit per year by animal type*

[Poultry values are based on capacity, assuming 6.0 flocks per year; values in parentheses indicate per flock values; values from U.S. Environmental Protection Agency (1998) and U.S. Department of Agriculture: Natural Resources Conservation Service (2003)]

Animal type	Nitrogen per animal unit (kilograms per year)	Phosphorus per animal unit (kilograms per year)
Beef cattle	51.3	18.2
Dairy cattle	74.5	11.6
Swine	69.5	26.5
Poultry	182.1 (30.4)	56.5 (9.4)
Sheep	13.2	11.8
Horses	8.6	6.3

Table 8. *Fractions of nitrogen and phosphorus lost to runoff or volatilization by animal type*

[Values from U.S. Environmental Protection Agency (1998)]

Animal type	Fraction volatilized or lost to runoff	
	Nitrogen	Phosphorus
Beef cattle, sheep, horses	0.70	0.15
Dairy cattle	0.60	0.15
Swine	0.75	0.15
Poultry	0.40	0.15

Table 9. *Mass fractions of nitrogen and phosphorus species by animal type*

[Values from U.S. Environmental Protection Agency (1998) and Ken Staver, University of Maryland, written commun., 2002]

Animal type	Ammonia	Organic nitrogen	Ortho-phosphate	Organic Phosphorus
Beef cattle, dairy cattle, swine, sheep, horses	0.48	0.52	0.175	0.825
Poultry	0.22	0.78	0.38	0.62

Table 10. *Crop goal yields for the five simulated crop types*

[Values from U.S. Department of Agriculture: National Agricultural Statistics Service (2003); cwt, hundredweight or 100-pound unit]

Crop type	Goal yield	Units
Corn	275.8	bushels per hectare
Double crops	77.2	bushels per hectare
Full-season soybeans	67.6	bushels per hectare
Hay	7.4	tons per hectare
Vegetables	618	cwt per hectare

As suggested by the Delaware Inland Bays STAC, the fertilizer application rates were increased by 10 percent of the recommended values to account for the over-application of fertilizer. The sequence of application within the model is as follows:

1. Organic fertilizer is applied to fulfill 110 percent of the nutrient requirement for up to 75 percent of the corn hectares in the model segment; the remaining hectares receive mineral fertilizer.
2. If organic fertilizer remains after application to corn hectares, it is applied to fulfill 110 percent of the nutrient requirement for up to 10 percent of the double-crop hectares. The remaining double-crop hectares receive mineral fertilizer.
3. If organic fertilizer remains after application to double crops, it is applied to fulfill 110 percent of the nutrient requirement for full-season soybeans for up to 50 percent of the full-season-soybeans hectares. The remaining full-season-soybeans hectares will fix nitrogen from atmospheric deposition and will receive the required phosphorus in the mineral form.
4. If organic fertilizer remains after application to full-season soybeans, it is applied to fulfill 110 percent of the nutrient requirement for vegetables for up to 50 percent of the vegetables hectares. The remaining vegetables hectares receive mineral fertilizer.
5. If organic fertilizer remains after application to vegetables, it is applied to fulfill 110 percent of the nutrient requirement for hay for up to 20 percent of the hay hectares. The remaining hay hectares receive mineral fertilizer.
6. If organic fertilizer remains, steps 1 through 5 begin again, with over-application of organic fertilizer to 50 percent of the remaining corn hectares receiving only mineral fertilizer in the first cycle.

Table 11. *Plant nutrient composition for the five simulated crop types*

[Values from Lander and others (1998) ; cwt, hundredweight or 100-pound unit]

Crop type	Units	Plant composition (dry matter basis)	
		Nitrogen	Phosphorus
Corn	kilograms per bushel	0.36	0.07
Double crops	kilograms per bushel	0.41	0.08
Full-season soybeans	kilograms per bushel	1.6	0.16
Hay (average between alfalfa hay and small grain hay values)	kilograms per ton	17.3	2.1
Vegetables (Irish potatoes) with 77 percent moisture content	kilograms per cwt	0.16	0.03

Table 12. *Calculated total annual target nitrogen and phosphorus uptake rates by crop type*

Crop type	Total nitrogen uptake rate (kilograms per hectare per year)	Total phosphorus uptake rate (kilograms per hectare per year)
Corn	99	19
Double crops	32	6.2
Full-season soybeans	108	11
Hay	128	16
Vegetables	99	19

If the application of organic fertilizer fulfills the phosphorus requirement, but not the nitrogen requirement, then nitrogen will be the only mineral applied. If the nutrient requirements for nitrogen and phosphorus are not fulfilled by the application of organic fertilizer, then the ratio of nitrogen to phosphorus in mineral fertilizer is assumed to be 5:1, except for applications to double crops, which is assumed to be 2.5:1. The results of the calculations of animal units, manure hectares, and organic fertilizer applications are shown in table 13.

Method of Fertilizer Application The HSPF model only allows the simulation of a "broadcast" type fertilizer application, which provides a uniform distribution of nutrients within the simulated hectare; therefore, all the fertilizer applications were assumed to be of a broadcast type. For the application of mineral fertilizer to all crops and organic fertilizer to corn and double crops, 10 percent of the application was delivered to the surface layer (first cm, or centimeter, of soil), and the remaining 90 percent was delivered to the upper soil layer (next 29 cm of soil). For the application of organic fertilizer to the full-season soybeans, hay, and vegetables, 50 percent was applied to the surface layer and 50 percent to the upper soil layer.

Schedule of Organic Fertilizer Application Organic fertilizer was applied to specific soil layers according to the schedule shown in table 14. For pasture, organic fertilizer was applied throughout the year, except during December, January, and February.

Schedule of Mineral Fertilizer Application Mineral fertilizer was applied according to the following schedule:

Corn	20 percent of the application at planting distributed over 6 days 80 percent of application 30 to 40 days after planting distributed over 18 days
Double crops	10 percent of nitrogen application distributed over 10 days in October 20 percent of nitrogen application distributed over 10 days in February 70 percent of nitrogen application distributed over 15 days in March 100 percent of phosphorus application distributed over 10 days in October
Full-season soybeans	100 percent of phosphorus application distributed over 10 days in May
Hay	50 percent of nitrogen and phosphorus application distributed over 12 days in April 50 percent of nitrogen and phosphorus application distributed over 12 days in July
Vegetables	50 percent of nitrogen and phosphorus application distributed over 12 days in April 50 percent of nitrogen and phosphorus application distributed over 12 days in May
Pervious urban	22.7 kg of nitrogen distributed between March and October with a weekly application

Table 13. *Animal units, manure hectares, and organic fertilizer applications by model segment*

Segment	Animal units	Manure hectares	Kilograms of organic fertilizer applied to crops	Kilograms of organic fertilizer applied to pasture
010	0	0.00	0	0
020	0	0.00	0	0
030	652	0.28	8,066,821	391,837
040	542	0.27	5,765,677	951,603
050	123	0.05	1,629,862	0
060	0	0.00	0	0
070	0	0.00	0	0
080	41	0.02	80,327	321,306
090	39	0.02	76,408	305,633
100	70	0.03	931,350	0
110	0	0.00	0	0
120	178	0.08	2,339,801	11,426
130	0	0.00	0	0
140	690	0.29	8,916,112	156,735
150	79	0.03	1,047,769	0
160	409	0.17	5,419,292	0
170	833	0.35	11,030,675	0
180	806	0.34	10,678,508	0
190	505	0.21	6,694,077	0
200	637	0.27	8,430,666	0
210	545	0.23	7,223,782	0
220	613	0.26	8,117,296	0
230	502	0.21	6,650,420	0
240	699	0.29	9,255,289	0
250	288	0.12	3,812,713	0
260	887	0.37	11,752,471	0
270	720	0.48	9,330,103	0
280	1,439	1.53	17,972,003	0
290	1,044	0.44	13,827,634	0
300	3,788	2.94	48,562,955	0
310	884	0.37	11,700,082	0
320	2,691	1.21	35,533,477	0
330	969	0.41	12,835,165	0
340	770	0.39	9,605,143	349,854
350	70	0.03	931,350	0
360	2,556	1.25	33,638,334	0
370	1,780	0.75	23,568,972	0
380	0	0.00	0	0
390	119	0.05	1,571,653	0
400	0	0.00	0	0
410	620	0.26	8,207,520	0
420	211	0.47	2,238,191	559,548
440	0	0.00	0	0
450	949	0.40	12,567,402	0
470	2,337	1.00	29,475,795	1,018,776
TOTAL	**30,088**	**15.85**	**389,485,094**	**4,066,717**

Table 14. *Fraction of organic fertilizer application by crop type and month*

[–, no fertilizer was applied]

Crop type	Fraction of organic fertilizer applied						
	March	April	May	September	October	November	December
Corn	0.25	0.25	–	0.10	0.20	0.10	0.10
Double crops	0.10	0.10	–	–	0.80	–	–
Full-season soybeans	0.40	0.30	0.30	–	–	–	–
Hay	0.40	0.30	0.30	–	–	–	–
Vegetables	0.40	0.30	0.30	–	–	–	–

A uniform distribution of fertilizer over 10 days for the cropland and 4 days for the pervious urban land in the corresponding month was adopted, because not all farmers within a given model segment apply fertilizer on the exact same day, and because the applications in the simulation represent an average date of application.

Planting and Harvesting Dates Information on planting and harvesting times for the State of Delaware was obtained from U.S. Department of Agriculture: National Agricultural Statistics Service (1997b), which reports "usual" planting and harvesting dates, with beginning date, most-active phase dates, and end date for many different crops. The "usual" planting dates represent the times when crops are usually planted in the fields. The "usual" harvesting dates represent the periods during which harvest of the crop actually occurs. The beginning dates for planting from U.S. Department of Agriculture: National Agricultural Statistics Service (1997b) were used as the planting dates for nutrient application; the values for the end of the most-active phase of harvesting were used in the model as the harvesting date, or end of the period of crop nutrient uptake (table 15).

Atmospheric Deposition

Atmospheric nitrogen deposition data for the HSPF model simulations are from Scudlark and Church (2001). The application rates for dry and wet deposition are as follows:

Wet flux:

Nitrate = 20 millimoles per liter of rainfall (mmol/L);
Ammonium = 17.1 mmol/L;
Organic N = 9.1 mmol/L.

Dry deposition:

Nitrate = 1.08 kilograms of nitrogen per hectare per year (kg N/ha/yr);
Ammonium = 0.33 kg N/ha/yr;
Organic N = 0.46 kg N/ha/yr.

Table 15. *Modeled planting and harvesting dates by crop type*

Crop type	Planting date	Harvesting date
Corn	April 20	October 15
Double crops, crop 1	June 26	October 5
Double crops, crop 2	October 15	June 12
Full-season soybeans	April 28	August 15
Hay	May 10	November 19
Vegetables	April 15	September 15

On-Site Wastewater Disposal System Information

GIS methodologies were used to determine the on-site wastewater disposal (septic) system information by model segment. The Inland Bays watershed model segmentation was overlain on the GIS layer (provided by DNREC) containing the on-site wastewater disposal system information to determine the number of on-site wastewater disposal systems by model segment. Mean nitrate and orthophosphate edge-of-septic-field loading rates of 0.014 and 0.0006 kg/day/system, respectively (Maizel and others, 1997; U.S. Environmental Protection Agency, 1998) were used to generate estimated edge-of-stream loads for each model segment, which were incorporated into the simulation as additions to the edge-of-stream loads. The edge-of-septic-field nitrate loads were attenuated by 65 percent (Maizel and others, 1997) to represent volatilization to the atmosphere, denitrification, and other losses. An estimate for orthophosphate load attenuation of 95 percent (primarily due to soil retention) was used.

Point Sources

Point source information was obtained from DNREC, who provided data from the Permit Compliance System

Table 16. *Monitoring stations used in the analysis of precipitation data*

[NOAA, National Oceanic and Atmospheric Administration; HR, hourly; DY, daily; NA, not applicable]

Agency	Data type	Station number	Location	Available period of record	Period of record used	Segments calibrated	Comments
University of Delaware	HR	073570	Georgetown, DE	1984 - 2002	1/1998 - 4/2000	130, 450	Used to allocate daily into hourly precipitation and for the simulation of the Millsboro Pond Outlet basin
NOAA	DY	075320	Lewes, DE	1984 - 2002	1/1998 - 4/2000	010, 030	Data allocated into hourly precipitation using proportions from 073570
Town of Selbyville	DY	NA	Selbyville, DE	1984 - 2002	1/1998 - 4/2000	310, 330	Data allocated into hourly precipitation using proportions from 073570

(PCS). The PCS is a data-base management system that supports the National Pollutant Discharge Elimination System (NPDES) regulations. Loads from the municipal facility located in Georgetown, Delaware (fig. 3) were incorporated in the simulation because of the location of the facility in the nontidal area. Flow and concentrations are reported as monthly average values in units of million gallons per day (Mgal/d) for flow, and milligrams per liter (mg/L) for concentrations. This information was input into the model as a load in pounds per day (lb/d) in a time-series format for the following constituents: biological oxygen demand (BOD), TSS, dissolved oxygen (DO), ammonia, nitrate, orthophosphate, and discharge.

Meteorological Data

HSPF simulations are mostly influenced by precipitation; therefore, the quality of the simulation will be greatly influenced by the quality of the precipitation data. For the Inland Bays watershed model, simulations were run on an hourly basis and the period during which the streamflow was recorded at the stream-gaging station established the period of the calibration; however, the period of simulation was extended from January 1998 to April 2000. For the majority of the streams in the Inland Bays watershed, this period started in the fall of 1998 and ended during the spring of 2000, with the exception of the basins draining to Millsboro Pond Outlet (station number 01484525) and Beaverdam Ditch (station number 01484695) for which streamflow records are still collected. Daily precipitation data for the station located in Lewes, Delaware (fig. 3) were obtained from the National Climatic Data Center (National Oceanic and Atmospheric Administration, 2001). Hourly precipitation data for the Georgetown, Delaware location were obtained from the University of Delaware (N. Dean Dey, Research and Education Center, University of Delaware, written commun., 2001). Daily precipitation data collected at the wastewater treatment plant in Selbyville, Delaware were obtained from the Town of Selbyville, Delaware (Scott Andres, Delaware Geological Survey, written commun., 2001). Daily precipitation amounts were allocated using the distribution of hourly precipitation at the Georgetown station (table 16). To guarantee the complete allocation of the daily precipitation, a default allocation of 1/24 (uniform distribution across 24 hours) was used for days in which precipitation did not occur at the Georgetown station.

Minimum and maximum air temperatures were obtained at the Georgetown and Lewes stations and were used to derive time series of potential evapotranspiration using the Hamon (1961) method. Data for the Georgetown station were obtained from the University of Delaware (N. Dean Dey, Research and Education Center, University of Delaware, written commun., 2001). For the simulation of snow and ice, the following meteorological data were input to the simulation in the form of time series: cloud cover, wind speed, radiation, and dew point; this information was obtained from data developed by the U.S. Environmental Protection Agency (1997).

Table 17. *Carbon, nitrogen, and phosphorus constituents with reported units and units required for Hydrological Simulation Program–FORTRAN calibration and their derivation from reported units*

[Derived constituents are in **bold**; µmol/L, micromoles per liter; mg/L, milligrams per liter; C, carbon; N, nitrogen; P, phosphorus]

Reported or derived parameter	Symbol	Reported concentration unit	Required concentration unit	Derivation
Dissolved Organic Carbon	DOC	µmol/L	mg/L as C	
Particulate Organic Carbon	POC	µmol/L	mg/L as C	
Total Organic Carbon	**TOC**		**mg/L as C**	**TOC = POC + DOC**
Nitrate + Nitrite	NO23	µmol/L	mg/L as N	
Ammonium	NH4	µmol/L	mg/L as N	
Total Dissolved Nitrogen	TDN	µmol/L	mg/L as N	
Particulate Organic Nitrogen	PON	µmol/L	mg/L as N	
Dissolved Inorganic Nitrogen	**DIN**		**mg/L as N**	**DIN = NO23 + NH4**
Dissolved Organic Nitrogen	**DON**		**mg/L as N**	**DON = TDN – DIN**
Total Organic Nitrogen	**TON**		**mg/L as N**	**TON = PON + DON**
Total Nitrogen	**TN**		**mg/L as N**	**TN = PON + TDN**
Phosphate	PO4	µmol/L	mg/L as P	
Total Dissolved Phosphorus	TDP	µmol/L	mg/L as P	
Particulate Organic Phosphorus	POP	µmol/L	mg/L as P	
Dissolved Organic Phosphorus	**DOP**		**mg/L as P**	**DOP = TDP - PO4**
Total Organic Phosphorus	**TOP**		**mg/L as P**	**TOP = POP + DOP**
Total Phosphorus	**TP**		**mg/L as P**	**TP = TDP + POP**

Development of Water-Quality Data Base for Model Calibration

All water-quality data used for model calibration (including field parameters and laboratory analyses of nitrogen and phosphorus species concentrations and TSS concentrations) were provided by DNREC. These data are from the Inland Bays TMDL data base, version 6.62 (Andres and others, 2002). All methods used for sample collection, processing, preservation, and analysis are described in Ullman and others (2002). The constituents analyzed and specified concentration units are shown in table 17. Two additional steps were performed to make the data directly comparable with HSPF-simulated constituents. The first step was to convert concentrations in micromoles per liter (µmol /L) to concentrations in mg/L (as C, N, or P), by multiplying the reported values by the atomic weights of carbon (12.011 grams per mole, or g/M), nitrogen (14.0067 g/M), or phosphorus (30.97376 g/M), and then dividing by 1,000. The second step was to derive a number of other quantities, such as total nitrogen and total phosphorus, that are necessary for model calibration and that were not reported by DNREC. The derivations of these quantities are also shown in table 17.

Model Calibration Approach

Limited initial model calibration was performed using PEST, a parameter estimator (Doherty, 2000). Due to the brevity of the observation record, only limited parameter sensitivity was performed, which for hydrologic parameters indicated strong sensitivity dependence on the volume of annual runoff (Gutiérrez-Magness and McCuen, 2002). Model performance was evaluated for the period January through December of 1999. To allow time for the model to reach reasonable initial conditions, the simulation was started in January of 1998 with arbitrary initial conditions and allowed to run for one year. During calibration, these initial conditions were manually adjusted to improve the calibration. Simulations were carried out through April of 2000, which provided a hydrologically contrasting period (1999 was a very dry year and the spring of 2000 was relatively wet) for model verification. During calibration of TSS and nutrients, manual adjustment of hydrologic parameters was performed to improve the overall model predictions.

Table 18. *U.S. Geological Survey stream-gaging stations used for model calibration*

Station number	Station name	Segments drained	Period of record	Total area drained (square kilometers)
01484668	Munchy Branch near Rehoboth Beach, DE	010	August 1998 to September 2000	1.33
01484654	Bundicks Branch at Robinsonville, DE	030	August 1998 to March 2000	16.19
01484534	Swan Creek near Millsboro, DE	130	August 1998 to March 2000	11.75
01484600	Blackwater Creek near Clarkesville, DE	310	October 1998 to March 2000	9.02
01484695	Beaverdam Ditch near Millville, DE	330	August 1998 to September 2002 (continuing)	6.43
01484525	Millsboro Pond Outlet at Millsboro, DE	140, 150, 160, 170, 180, 190, 200, 210, 220, 230, 240, 450	May 1986 to September 1988 and March 1991 to September 2002 (continuing)	158.53

Calibration of Hydrology

Initial model calibration for hydrology was performed using PEST (Doherty, 2000), and the observed data for six basins with gaged outlets (table 18, fig. 3). Although a USGS stream-gaging station is located at the outlet of segment 170, this segment was not calibrated because information was not available about an upstream diversion from a gravel facility. The hydrologic calibration was performed with the available streamflow records between October 1998 and April 2000.

Parameter Estimation During the calibration process, the largest land-use class in each basin (table 19) was selected for parameter estimation because it would have the greatest impact on the hydrology. Parameter values for other land-use classes were tied to those estimated by a ratio. HSPF allows some of the hydrologic parameters to vary monthly, or to remain constant throughout the year. The parameters controlling the interception storage capacity and the lower zone evapotranspiration (an index to the density of deep-rooted vegetation) were allowed to vary monthly during the calibration. For these calculations, the maximum and minimum values of the parameter were selected, and included in an equation that would describe the annual seasonality of the estimated parameter.

Objective Function for Parameter Estimation PEST uses nonlinear techniques to estimate optimal parameter values, based on a user-determined objective function, which is generally some relation between observed values and model output. A multiple-criterion objective function was used in the calibration process. The four criteria are briefly discussed below. The objective function used for each calibrated segment was taken as a weighted average of these criteria.

Daily flows Part of the objective function was residuals calculated by subtracting model-generated daily flows from their measured counterparts. Daily rather than hourly flows were used for this purpose because of the potential for timing errors because the precipitation supplied to the model was measured at a rain gage situated at some distance from the watershed.

Table 19. *Selected land-use classes for hydrologic parameter estimation*

Location	Land-use class
Munchy Branch	Pervious and impervious urban
Bundicks Branch, Blackwater Creek, and Beaverdam Ditch	Forest
Swan Creek	Forest and pervious urban
Millsboro Pond Outlet	Forest and corn

Flow differences Kuczera (1983) suggested that model output consist of a time series in which the entry for a particular day consists of the flow measured that day minus part of the flow measured on the previous day. This is then matched to an observation time series that is calculated in the same way. In this study, a similar procedure was undertaken. Using a time-series manipulation utility that accompanies the PEST software (Doherty, 2000), a time series consisting of the differences between hourly simulated and observed flows was calculated. Extensive application of this method during model calibration demonstrated that it helped to preserve the rapid rise and fall of the stream hydrograph for Swan Creek, for example, because the discrepancy between model outputs and field measurements was reduced.

Monthly volumes Model-calculated and observed monthly volumes were used in the calibration process.

Exceedance times Thresholds of specified flow depths were used as the probability that an event of specified depth will occur during the period of calibration.

Calibration of Total Suspended Solids and Nutrients

Calibration for the simulation of TSS was performed manually, taking into consideration the reduction of erosion achieved by the use of best management practices. Parameters related to the edge-of-stream loads were set based on HGMR, soils information, and a visual comparison of the simulated and observed in-stream concentrations. For each land-use class, average values of parameters controlling the sediment loads used in the Chesapeake Bay watershed model were taken as initial estimates in the calibration. Tillage practices were incorporated for the simulation of corn, double crops, and vegetables.

Manual calibration, soils information, and other studies in the watershed were used to determine the best set of parameters for the simulation of nutrients. Nitrogen and phosphorus first-order reaction parameters were estimated for the surface, upper, lower, and active ground-water layers through simultaneous calibration of the land and in-stream nutrient processes.

For the simulation of the manure hectare land-use class, loading rates of BOD, organic nitrogen, and organic phosphorus were obtained from the Chesapeake Bay watershed model (U.S. Environmental Protection Agency, 1998). BOD was expressed in terms of nitrogen (labile and refractory) with an assumed yield of 1,615 kg/ha (kilograms per hectare). The contributions of organic nitrogen and phosphorus were also expressed in terms of labile and refractory nitrogen with the following assumed loads: organic nitrogen (refractory) = 76.2 kg/ha; organic nitrogen (labile) = 9.3 kg/ha; organic phosphorus (refractory) = 3.8 kg/ha, and organic phosphorus (labile) = 0.98 kg/ha.

For the forest land-use class, a more detailed simulation of the behavior of nitrogen in the soil profile was performed, in which ammonium and two forms of particulate organic nitrogen (labile and refractory) were allowed to adsorb onto sediment. These forms of nitrogen, once adsorbed, could potentially be removed from storage on the land surface during surface runoff.

Predicted total nitrogen and total phosphorus edge-of-stream yields for croplands were compared to the range of values from work conducted at the University of Maryland Wye Research and Education Center (Staver and Brinsfield, 1998); the purpose of this comparison was to ensure that the model predictions were within the observed range of values.

Accumulation and depletion rates of constituents simulated in the impervious land (ammonium, nitrate, phosphate, and BOD) were determined through the calibration of the Munchy Branch Basin. This basin was selected because 30 percent of it is impervious land, and the load contribution of the impervious area was crucial in obtaining a good calibration. These rates were adopted for the simulation of impervious areas in the remaining model segments.

The in-stream simulation includes the primary processes that determine the balance of inorganic nitrogen and phosphorus in natural waters. The processes are:

1. longitudinal advection of dissolved nitrate, nitrite, ammonia, and orthophosphate;
2. benthic release of ammonia and orthophosphate;
3. benthic uptake of nitrate, ammonia, and orthophosphate;
4. ammonia ionization (ammonia/ammonium equilibrium);
5. ammonia vaporization;
6. nitrification of ammonia and nitrite;
7. denitrification;
8. ammonification due to degradation of BOD materials;
9. adsorption/desorption of ammonia and orthophosphate to/from inorganic sediment in the water column; and
10. deposition/scour and longitudinal advection of adsorbed ammonia and orthophosphate.

Phytoplankton (free-floating photosynthetic algae) and benthic algae (the state variable for algae attached to the benthic surface) were included in the simulation after analysis of observed data for phosphate. Benthic algae uptake of phosphate occurs primarily during the winter, and phytoplankton uptake occurs primarily during the summer.

Analysis of Model Calibration and Results

Parameter estimation techniques and manual calibration were used to determine the best hydrologic parameters for the model, using observations of hourly and mean daily streamflow from the five single-segment calibration sites (segment numbers 010, 030, 130, 310, and 330) for the period of record (table 18). Parameter values for the calibration of water-quality components were obtained through manual calibration. Model parameters were extrapolated to the non-calibrated model segments on the basis of HGMR and soils characteristics and proximity to calibrated segments (fig. 6).

The accuracy of the model was evaluated in several ways. During calibration, goodness-of-fit statistics and visual examination were used to refine parameter estimates. Time series of simulated streamflow, simulated edge-of-stream streamflow components, observed streamflow, and simulated and observed water chemistry, at hourly and daily time steps, were developed during calibration. These were analyzed during the calibration process to determine how well the model represented the natural system dynamics. Edge-of-stream nutrient loads were checked following calibration to ensure consistency with expected values and results of other modeling efforts in the region.

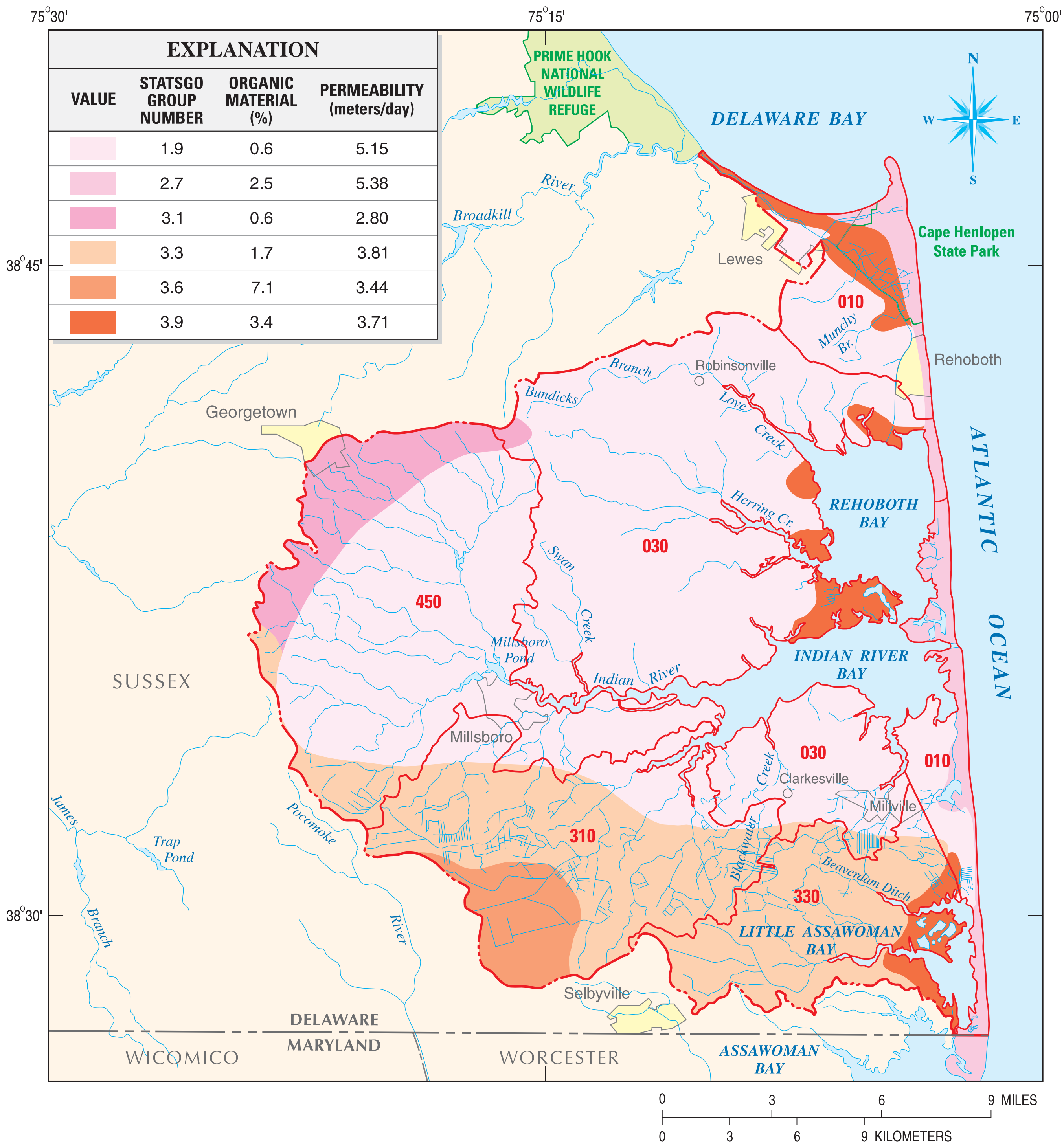

Figure 6. Grouping of model segments with identical parameter values, indicating the calibration model segment source for those values. *[Soils data are from the STATSGO data base (Schwarz and Alexander, 1995).]*

Once calibrated, the output was summarized by integrating over months or years to produce monthly and annual streamflow and loads; loads could then be divided by segment area to determine yields for each of the 45 model segments. Model parameters for all land uses varied spatially and (in some cases) temporally; these variations were generally consistent with soil type, properties of the aquifer, topography, degree of ditching and other human influences, and observations of annual streamflow during the periods for which data were available.

Calibration of Hydrology

Goodness-of-fit statistics were calculated between the observed and simulated daily streamflow values to evaluate the model performance for the six calibrated basins (table 20). Results for the relative bias indicate that the simulations were within 19 percent of the observed values for all basins. The relative standard error is large for Beaverdam Ditch, which may be related in part to uncertainty in the precipitation data (especially timing) and the fact that only one channel rather than a network of channels is simulated within a model segment.

Annual and Monthly Water Balance Simulated annual streamflow provided a critical check on model performance. The simulated annual streamflow from the six calibrated watersheds (table 20) was consistent, within 20 percent, with the observed values (see relative bias in table 20). Streamflow was lower throughout the watershed in 1999 because of the drought, with Swan Creek only discharging 46 mm of streamflow, while receiving more than 1,000 mm of precipitation. Higher streamflow was observed in the southern part of the watershed (segments 310 and 330) than in the northern part (segments 010, 030, and 130). This was expected because the sub-basins are located in the surficial confined HGMR (fig. 1a), where the storage capacity of the aquifer material is expected to be relatively low. This is reflected in the model parameter values for the lower zone nominal storage (LZSN), which are 150 mm for Beaverdam Creek and 230 mm for Blackwater Creek. These storage values are low in comparison to those in the northern basins in the well-drained upland HGMR, which are 380 mm for Swan Creek and 520 mm for Bundicks Branch. Ditching is a common practice, especially in the southern basins, to increase drainage capacity and to maintain optimal soil conditions for crops. The effects of ditching from a hydrologic standpoint are shorter ground-water-flow paths and larger amounts of streamflow.

Monthly simulated and observed streamflow values (fig. 7) show good agreement, with most simulated values within 30 percent of the observed values. Seasonality in streamflow was captured by the model, in part due to the seasonality in available moisture, but also through adjustment of storage parameters that varied monthly. Streamflow in September 1999 reflected the contribution from Hurricane Floyd in mid-September. The model was generally able to capture this large event and the simulated and observed streamflow for September are in close agreement for all segments with one exception. Streamflow during September 1999 at Swan Creek was over-simulated, possibly due to the difficulty in handling wetlands, which dominate the riparian area in the lower part of the basin.

Table 20. *Goodness-of-fit statistics for comparison of simulated and observed mean daily streamflow at the six calibration stations for 1999*

[mm, millimeters]

Station name	Annual precipitation (mm)	Predicted annual streamflow (mm)	Observed annual streamflow (mm)	Number of values, *N*	Relative bias [1]	Relative standard error [2]
Munchy Branch near Rehoboth Beach, DE	1,072	176	170	365	0.03	0.45
Bundicks Branch at Robinsonville, DE	1,072	111	112	365	-0.01	0.55
Swan Creek near Millsboro, DE	1,090	52	46	365	0.13	0.80
Blackwater Creek near Clarkesville, DE	1,090	301	253	365	0.19	0.63
Beaverdam Ditch near Millville, DE	1,090	473	432	365	0.09	1.35
Millsboro Pond Outlet at Millsboro, DE	1,092	387	376	365	0.03	0.95

[1] Relative bias = sum[(simulated – observed)/*N*]/mean observed

[2] Relative standard error = $\mathrm{sqrt}[\mathrm{sum}(\text{simulated} - \text{observed})^2/(N-1)]/\mathrm{sqrt}[\mathrm{sum}(\text{mean observed} - \text{observed})^2/(N-1)]$

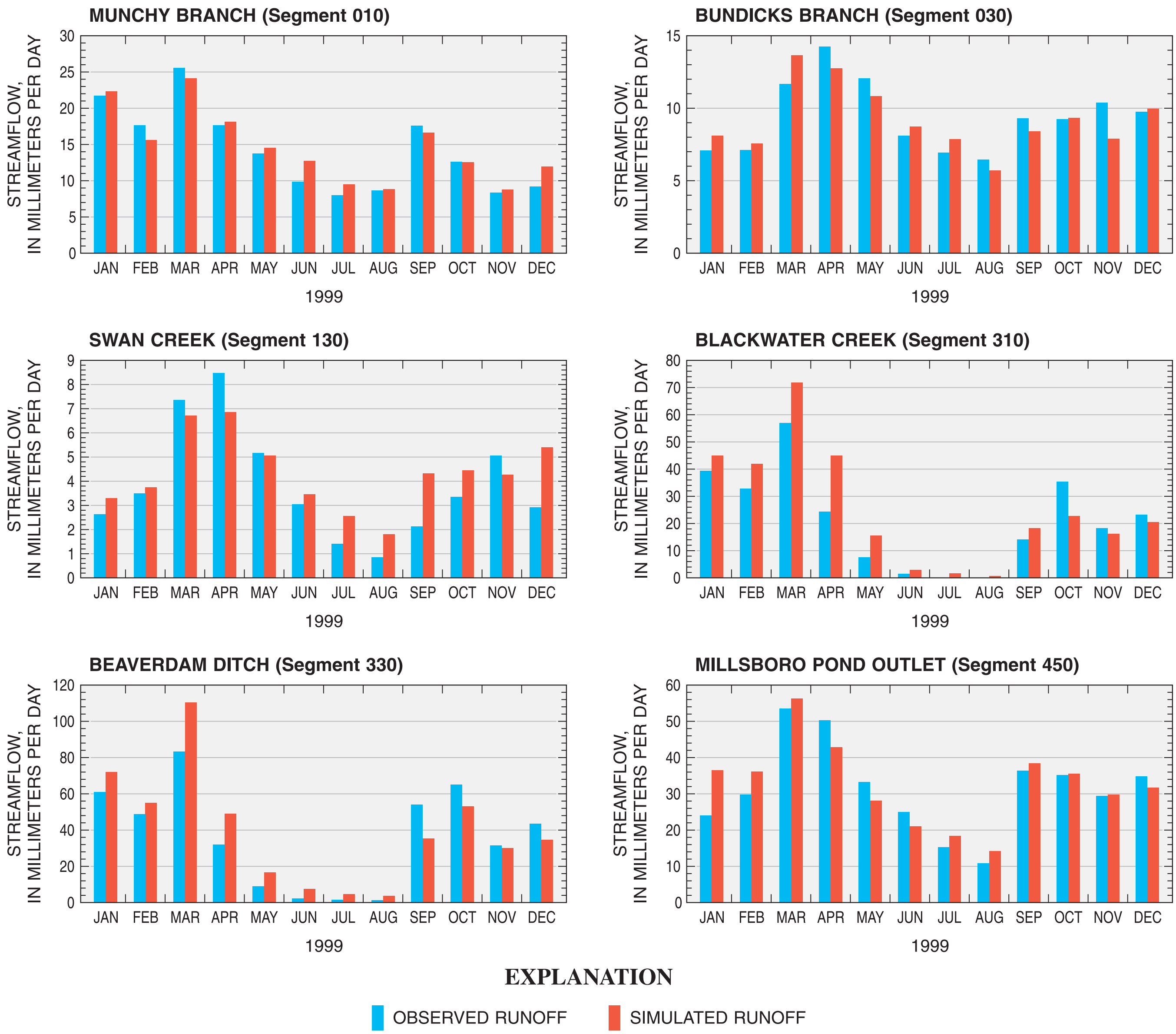

Figure 7. Monthly simulated and observed streamflow for the six calibrated basins during 1999.

Mean Daily Streamflow Time Series Time series of daily simulated and observed flows (fig. 8) and the edge-of-stream streamflow components (base flow, or active ground-water discharge, interflow, and surface runoff; fig. 9) were used to assess the model's ability to capture dynamic features of the hydrologic response in each of the calibrated basins. Streamflow response in these basins may be characterized by the rate of hydrograph rise in response to precipitation, the magnitude of peak flows, and the rate of recession. In addition, seasonality in base flow and total streamflow reflect the processes occurring in the Inland Bays watershed, and the flow paths responsible for chemical loading.

Recession rate is a critical aspect of watershed hydrologic response. Parameters in the model were adjusted so that the base-flow and interflow recession rates closely matched observations. Base-flow recession is fastest in Blackwater Creek (segment 310) and Beaverdam Ditch (segment 330) within the surficial confined HGMR (fig. 1a) where soils are generally less permeable than in other parts of the watershed (fig. 2). A strong seasonality to base flow is also observed in these basins (fig. 8), indicating the importance of seasonal variations in moisture supply and evapotranspiration.

Interflow is more important in the southern basins than in the northern basins (Blackwater Creek and Beaverdam Ditch basins, fig. 9). In this case, it seems that the processes represented by the model show the effects of ditching, which shortens the ground-water flow paths, thereby increasing the amount of interflow during the fall, winter, and spring.

The effects of soil type, aquifer properties, and land use on runoff response are shown by the total runoff of each component for the calibrated basins (table 21). The predominantly urban watershed drained by Munchy Branch (segment 010) has a major surface-runoff component, as would be expected for an area that is largely impervious. In 1999, 31 percent of the simulated streamflow for Munchy Branch was from overland flow. The remainder was predominantly base flow. The intermediate interflow reservoir is not a significant contributor to streamflow, accounting for only 7 percent of the total. Bundicks Branch Basin (segment 030) has less urban area and is almost one-half agricultural (table 2), and therefore has lower surface runoff. Soil type and aquifer properties in the Bundicks Branch Basin are similar to those of the Munchy Branch Basin, with relatively high permeability and infiltration rate; base flow is the largest component of runoff in both watersheds. Further west and southwest, Swan Creek (segment 130) has the highest amount of base flow, as would be expected during a drought year in a forested watershed with relatively permeable aquifer materials. As land use changes from urban through agriculture to forest, base flow increases and surface runoff decreases.

Table 21. *Simulated annual edge-of-stream runoff components for the five single-segment calibrated basins during 1999*

[mm, millimeters]

		Edge-of-stream components					
		Base flow		Interflow		Surface runoff	
Segment	Name	mm	fraction of total	mm	fraction of total	mm	fraction of total
010	Munchy Branch near Rehoboth Beach, DE	108	0.62	12	0.07	53	0.31
030	Bundicks Branch at Robinsonville, DE	85	0.77	4.8	0.04	21	0.19
130	Swan Creek near Millsboro, DE	44	0.84	3.3	0.06	4.9	0.09
310	Blackwater Creek near Clarkesville, DE	172	0.57	108	0.36	21	0.07
330	Beaverdam Ditch near Millville, DE	221	0.47	114	0.24	135	0.29

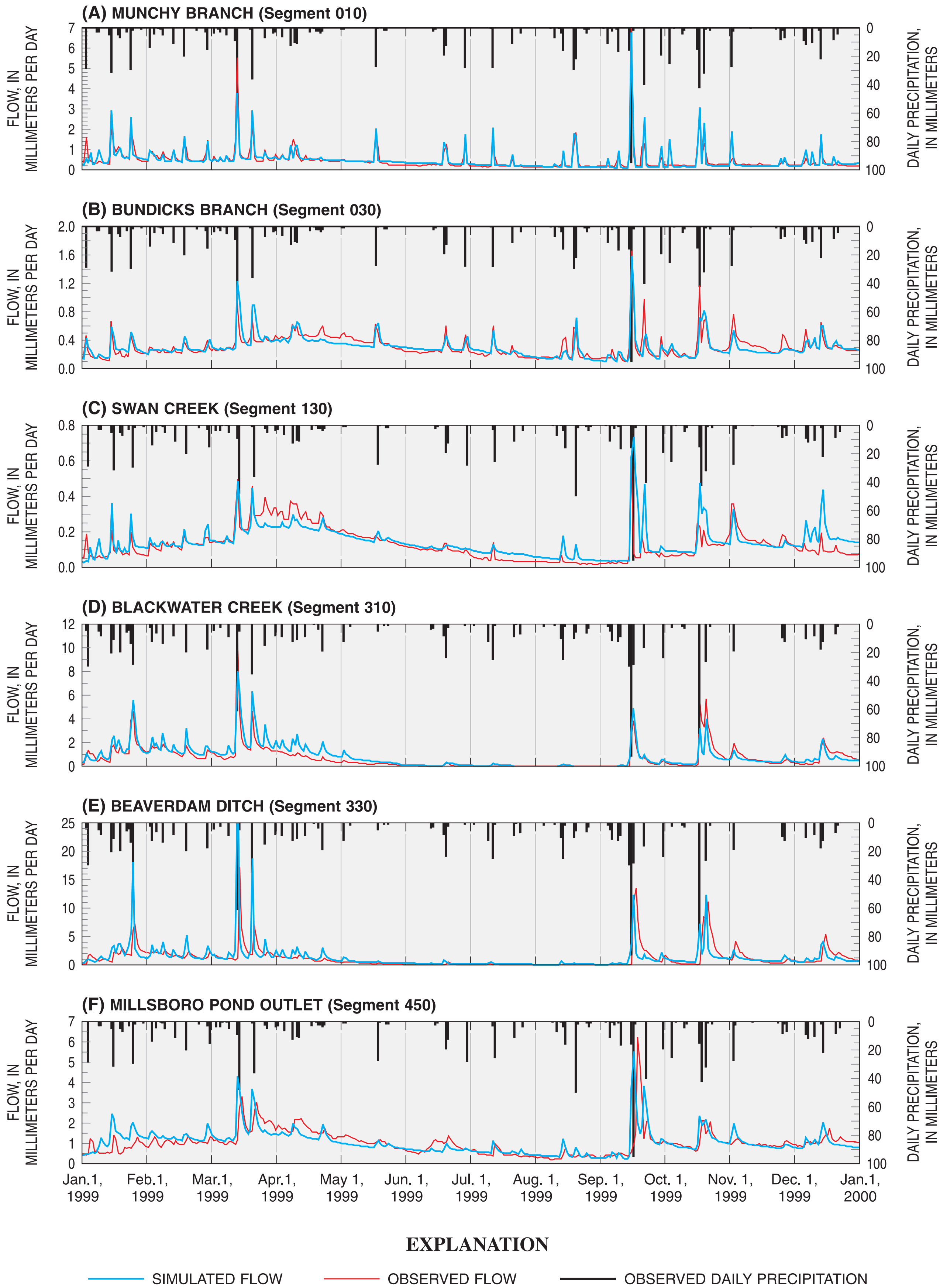

Figure 8. Simulated and observed daily flows, with daily precipitation intensity, for the six calibrated basins during 1999.

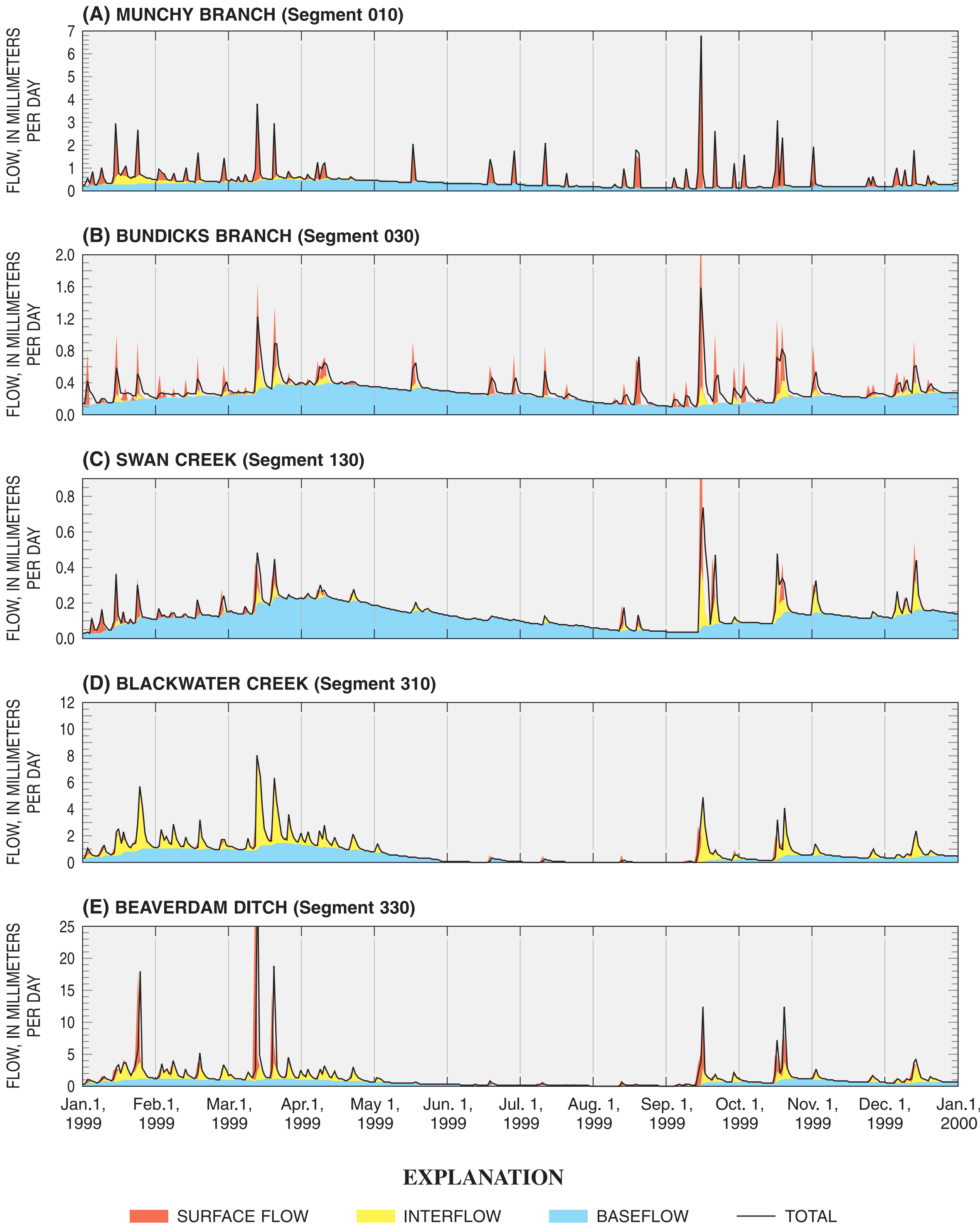

Figure 9. Simulated daily edge-of-stream streamflow components and total streamflow simulated at the end of the reach for the five single-segment calibrated basins during 1999.

Table 22. *Simulated edge-of-stream total suspended solids yields by land-use class for the five single-segment calibrated basins during water year 1999*

[All values are in kilograms per hectare per year]

Segment	Forest	Corn	Double crops	Full-season soybeans	Hay	Vegetables	Pasture	Pervious urban	Impervious urban	Weighted average
010	0.0	1.7×10^{-4}	2.2×10^{-4}	2.2×10^{-4}	3.3×10^{-4}	3.1×10^{-4}	3.6×10^{-4}	0.0	43	26
030	3.9×10^{-4}	1.5×10^{-4}	1.0×10^{-4}	1.6×10^{-4}	2.0×10^{-4}	2.0×10^{-4}	2.6×10^{-4}	5.2×10^{-2}	140	3.2
130	3.7×10^{-3}	2.0×10^{-2}	1.7×10^{-2}	2.5×10^{-2}	2.9×10^{-2}	2.8×10^{-2}	3.8×10^{-2}	3.8×10^{-2}	92	0.8
310	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1,300	36
330	140	130	83	130	130	130	130	120	410	130

Calibration of Total Suspended Solids

The accuracy of the model was evaluated through examination of time series of observed and simulated TSS concentrations. Because of the strong positive correlation between streamflow and sediment concentration, it was often necessary to make small adjustments to the hydrology parameters to achieve a more accurate simulation of TSS.

Annual Edge-Of-Stream Yields TSS simulated edge-of-stream yields (table 22) during water year 1999[C] may not be representative of the loads during an average hydrologic year. The drought of 1999 and Hurricane Floyd in September provided two extreme hydroclimatological conditions that must be taken into account when extrapolating the simulated edge-of-stream yields to other years.

In general, the amount of surface runoff, the degree of urbanization, and the presence or absence of riparian buffers or wetlands influences the amount of detached sediment delivered to the streams. Simulated TSS yields are strongly linked to annual streamflow, and are generally lower in the northern basins than in the southern basins (fig. 10).

The difference in yields in the northern and southern basins can be explained in terms of the HGMR classification and the agricultural practices in both areas. The amount of organic material and permeability are lower in the southern basins than in the northern basins; intense ditching is commonly practiced in the southern basins to increase drainage and maintain optimum soil conditions for the crops. In the northern basins, higher organic matter content and higher permeability reduce the potential for TSS transport. In addition, ditching and ditch maintenance in the southern basins provide a possible additional source of sediment.

Relative to other northern basins, the TSS yield for Munchy Branch is high (table 22), which may result from the predominance of urban land within the basin, and the location of the basin outlet within an urban area. In contrast, Swan Creek is predominantly a forested basin with significant vegetated buffers and wetlands along the stream that attenuate the loads from all land uses. TSS is transported only in overland flow and therefore may have a zero yield for land-use classes with no simulated overland flow, as is the case for forest and pervious urban land-use classes in the Munchy Branch Basin and all land-use classes except impervious urban in the Blackwater Creek Basin.

Hourly Concentration Time Series Time series of hourly simulated and observed TSS concentrations (fig. 11) were used to assess the model's ability to capture dynamic features of the sediment runoff response in each of the calibrated segments. Because sediment runoff increases with streamflow and the fraction of streamflow that is surface or overland flow, TSS dynamics closely resemble the dynamics of streamflow and surface runoff (see figs. 9 and 11). TSS also includes organic material and may therefore display a seasonality related to summer growth of algae.

Calibration of Nutrients

Nutrient applications varied in type (organic or mineral fertilizer), amount, and timing of application. The type is determined by the location of manure production throughout the watershed. For the Munchy Branch and Swan Creek Basins, only mineral fertilizer was applied to fulfill the crops' nutrient requirement; the amount applied was assumed to be 110 percent of the amount necessary to meet the crop goal yield. The timing was assumed to be optimum, just prior to the growing season. The effect of these assumed conditions can be seen mainly in the concentrations of total nitrogen, which are generally lower in Munchy Branch and Swan Creek than in any other monitored stream.

[C] Total suspended solids and nutrient yields are reported on a water year basis rather than a calendar year basis, because soil conditions were reset in the model at the beginning of each water year. Water year 1999 is October 1, 1998 through September 30, 1999.

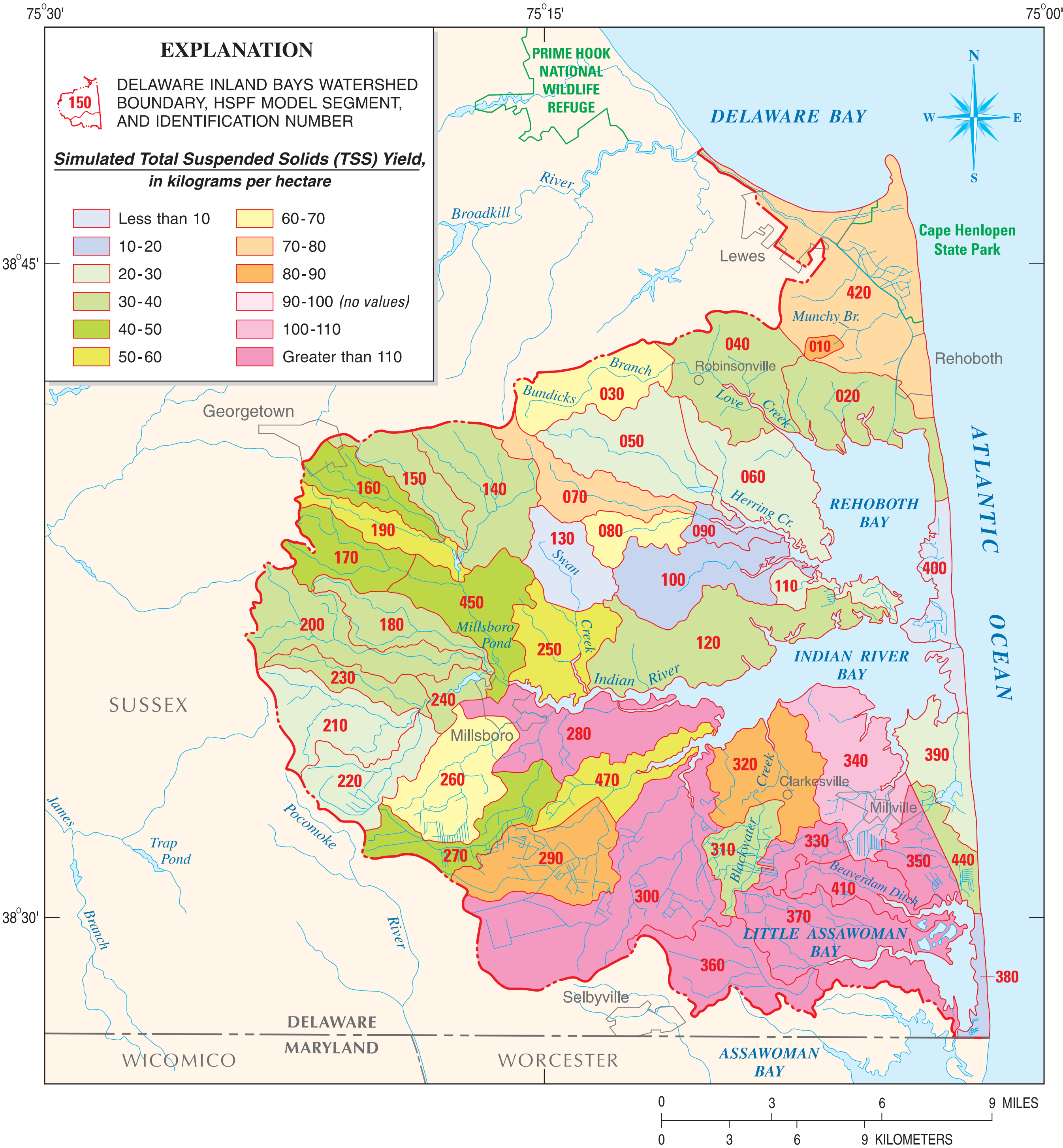

Figure 10. Simulated total suspended solids yield during water year 1999 by model segment.

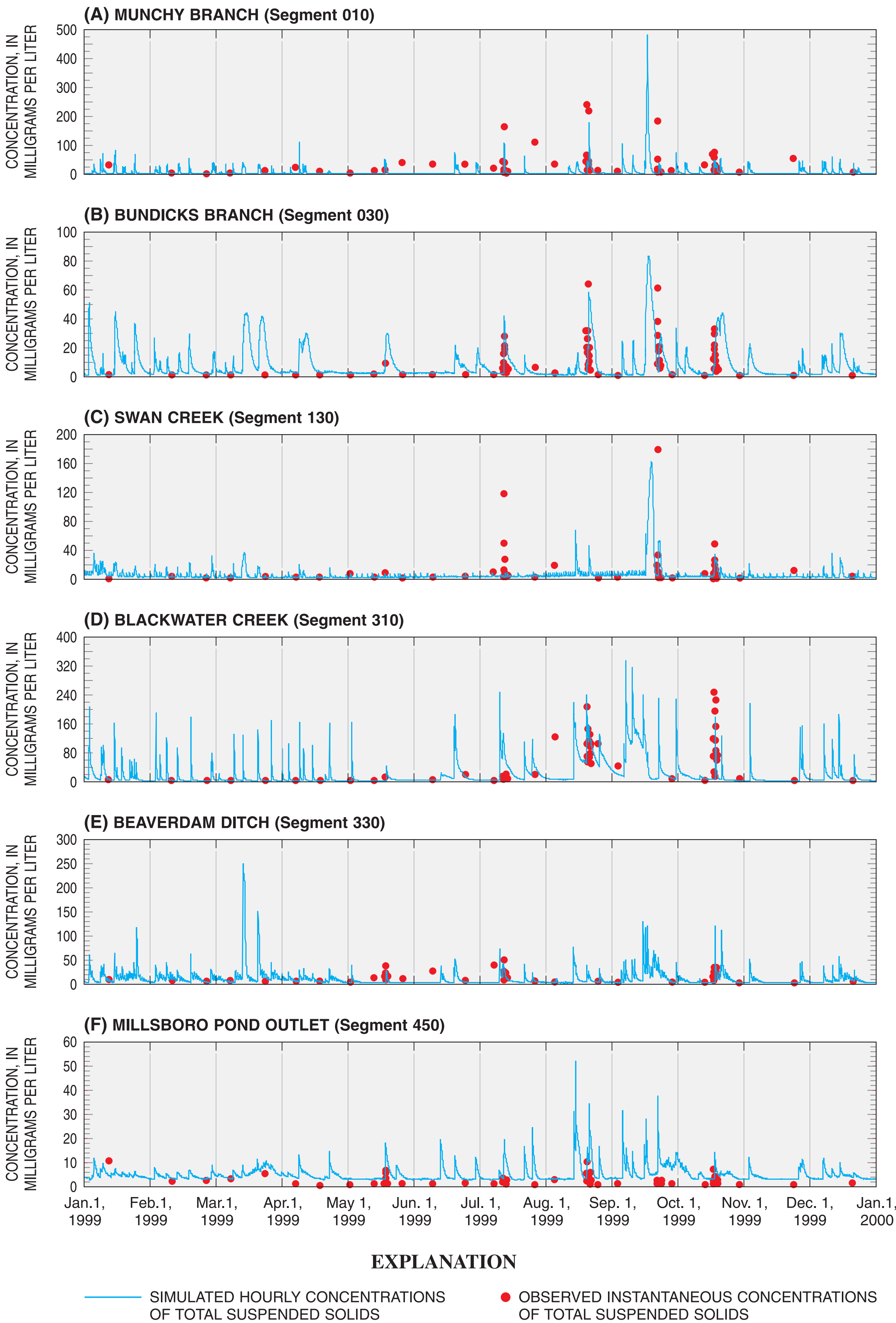

Figure 11. Simulated hourly total suspended solids concentrations and observed instantaneous values for the six calibrated basins during 1999.

Table 23. *Simulated edge-of-stream total nitrogen yields by land-use class for the five single-segment calibrated basins during water year 1999*

[All values are in units of kilograms per hectare per year]

Segment	Forest	Corn	Double crops	Full-season soybeans	Hay	Vegetables	Pasture	Pervious urban	Impervious urban	Weighted average
010	0.17	3.2	3.0	3.2	2.9	3.2	1.0	1.5	4.4	2.0
030	0.41	8.8	9.4	4.9	44	8.3	2.0	1.8	5.4	4.0
130	0.27	1.8	1.4	0.96	0.68	1.3	0.32	0.28	3.7	0.53
310	0.90	27	23	20	130	22	3.9	4.1	5.3	16
330	2.6	28	19	22	71	20	3.8	4.5	6.2	18

Table 24. *Simulated edge-of-stream total phosphorus yields by land-use class for the five single-segment calibrated basins during water year 1999*

[All values are in units of kilograms per hectare per year]

Segment	Forest	Corn	Double crops	Full-season soybeans	Hay	Vegetables	Pasture	Pervious urban	Impervious Urban	Weighted average
010	2.3×10^{-2}	2.9×10^{-2}	2.2×10^{-2}	2.6×10^{-2}	1.2×10^{-2}	6.9×10^{-2}	1.2×10^{-2}	1.7×10^{-2}	6.5×10^{-1}	5.9×10^{-2}
030	6.3×10^{-3}	2.1×10^{-2}	2.0×10^{-2}	9.3×10^{-3}	2.1×10^{-2}	2.0×10^{-2}	2.2×10^{-2}	6.0×10^{-2}	8.5×10^{-1}	3.4×10^{-2}
130	6.6×10^{-4}	5.0×10^{-3}	4.2×10^{-3}	9.3×10^{-3}	4.3×10^{-3}	1.0×10^{-2}	7.8×10^{-3}	1.8×10^{-2}	5.0×10^{-1}	7.7×10^{-3}
310	1.6×10^{-2}	6.7×10^{-1}	2.4×10^{-2}	1.6×10^{-1}	9.0×10^{-1}	8.9×10^{-1}	1.5×10^{-1}	1.5×10^{-1}	2.4×10^{-1}	2.6×10^{-1}
330	3.7×10^{-2}	6.2×10^{-1}	1.8×10^{-1}	2.1	1.9	2.1	3.1×10^{-1}	2.1×10^{-1}	9.3×10^{-1}	9.4×10^{-1}

Annual Edge-Of-Stream Yields The simulation of hydrologic and chemical processes in the soil and aquifer leads to the simulation of edge-of-stream loads and yields (tables 23 and 24). Due to the dry conditions during water year 1999, low edge-of-stream yields were expected. For total nitrogen (table 23), the simulated forest land had the lowest yields for all calibrated segments in comparison to yields from other land-use classes, and a trend of increasing total nitrogen yield is observed from north to south (fig. 12). The main nitrogen species in the edge-of-stream yields from forest land is organic nitrogen, whereas phosphorus is primarily in the inorganic form (orthophosphate).

In water year 1999, total nitrogen yields from cropland were higher for the southern basins (segments 310 and 330) than for the northern basins (table 23). In the southern basins, the application of organic fertilizer (animal waste) exceeded the recommended rates, and annual streamflow was higher. In the simulation of cropland and forest land, the majority of inorganic nutrient (nitrate, orthophosphate) loads are transported through base flow, followed by interflow. As was expected for all of the simulated constituents, the impervious urban yields were higher than yields from the pervious urban category. Pervious urban yields for total nitrogen ranged from 0.28 kg/ha/yr to 4.5 kg/ha/yr in water year 1999, compared to the impervious urban yields, which ranged from 3.7 kg/ha/yr to 6.2 kg/ha/yr. Pervious urban areas provided the major load during base flow, and the impervious land provided the load during storm events.

In Munchy Branch, the calibration emphasizes the urban land response; 66 percent of the basin area is urban. The lowest total nitrogen yields occurred in Munchy Branch (segment 010) and Swan Creek (segment 130), where the nutrient application was limited to mineral fertilizer at the optimum rate and timing, and the streamflow was low during 1999 (Munchy Branch had 170 mm and Swan Creek had 46 mm). Significant attenuation of loads between the

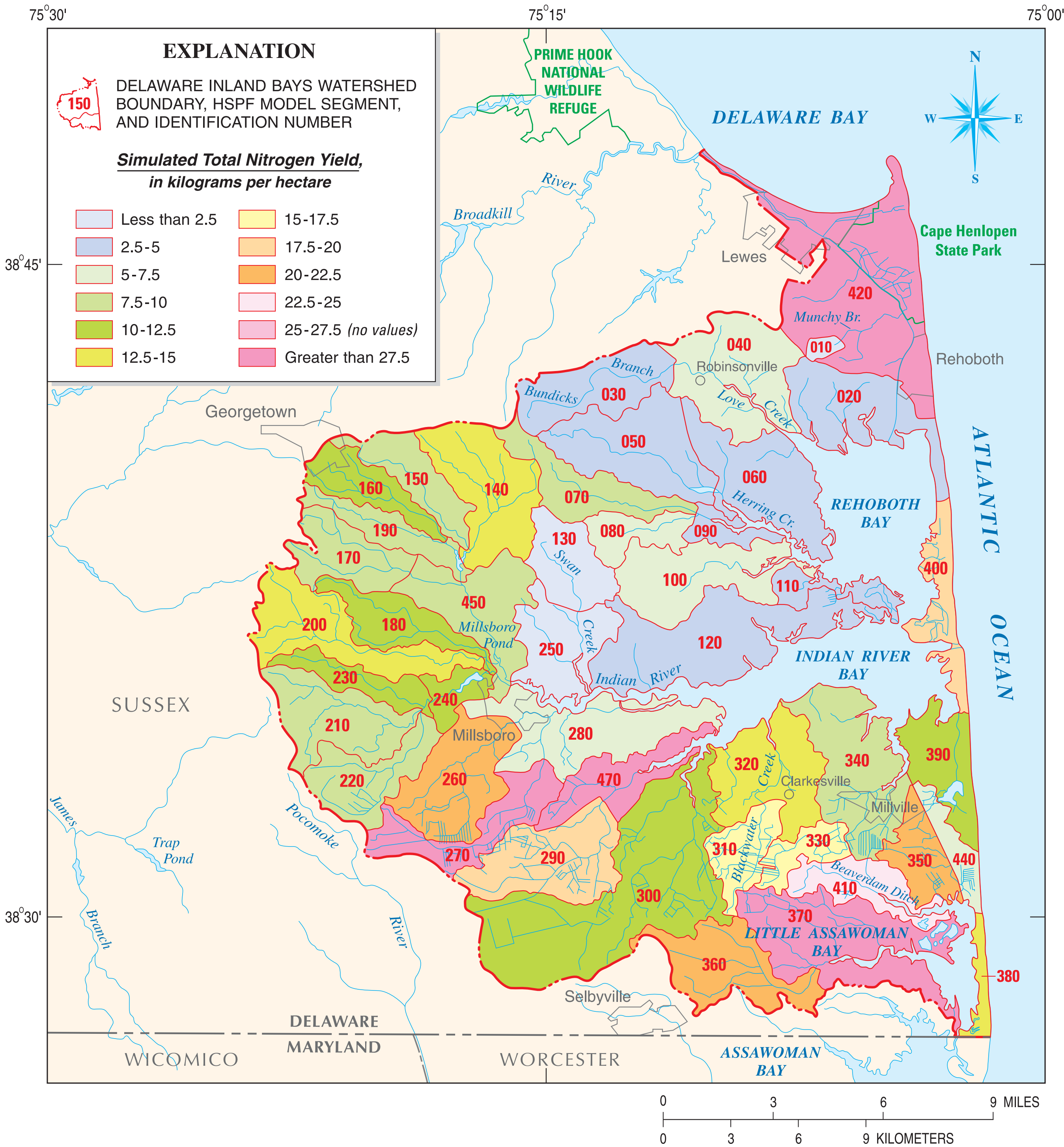

Figure 12. Simulated total nitrogen yield during water year 1999 by model segment.

edge-of-stream and the end-of-reach occurs in Swan Creek, due to processing within forested buffers and riparian wetlands.

Phosphorus yields (fig. 13) were linked to sediment yields (see figs. 11 and 14), because phosphorus attaches strongly to soil particles, and therefore appears in low concentrations in water but in high concentrations on the soil particles. For the northern basins, the amount of nutrients immobilized through sorption was higher near the surface, whereas for the southern basins, immobilization increased with depth.

Three of the basins were predominantly agricultural: Bundicks Branch with 48 percent of the total area, Blackwater Creek with 66 percent of the total area, and Beaverdam Ditch with 70 percent of the total area. However, several factors caused the edge-of-stream yields for these three basins to vary by as much as an order of magnitude. Bundicks Branch is in the northern part of the watershed within a well-drained terrain, the nutrient application was at the recommended rates (although there was application of organic fertilizer), and there is relatively little ditching; thus it was expected that the edge-of-stream yields would be lower than in Blackwater Creek or Beaverdam Ditch. In contrast, Blackwater Creek and Beaverdam Ditch are in the southern part of the watershed within a poorly drained region, where ditching is widespread to promote soil drainage, shallow stream incision is observed, and there is a need to over-apply organic fertilizer to dispose of the manure production; these factors contributed to the highest expected values of the edge-of-stream yields in the watershed. In Beaverdam Ditch Basin, for example, the application rate for the croplands was twice the recommended rate for nitrogen and phosphorus.

Hourly Concentration Time Series The primary goal in developing a watershed model for the Delaware Inland Bays was to allow prediction of loads. In general, watershed models perform better when model output and observations are integrated or averaged over longer times. Therefore, it is more likely that dynamic watershed models will perform best when comparing simulated and observed monthly or annual loads or flows. Due to the nature of the temporal variance in nutrient concentrations in streams, however, it is conceptually possible for a watershed model to accurately predict annual flow or load, yet incorrectly capture the dynamics of the processes responsible. Therefore, hourly simulated and instantaneous observed values were compared during the calibration process to improve the ability of the model to predict loading and natural process dynamics.

Time series of simulated hourly total nitrogen and phosphorus concentrations and observed instantaneous values are shown in figures 14 and 15. Seasonality was reflected in the observed and simulated total nitrogen concentrations, with the lowest values during the summer and the highest during the winter. During storm events, total nitrogen concentrations tend to be diluted and total phosphorus concentrations tend to rise sharply. Nitrogen is transported mainly in the aqueous phase and largely through ground water, although phosphorus is strongly associated with sediment that washes off during precipitation events. There are exceptions to these generalizations, but figures 14 and 15 demonstrate the ability of the model to simulate the dynamic processes responsible for in-stream nutrient concentrations on an hourly basis.

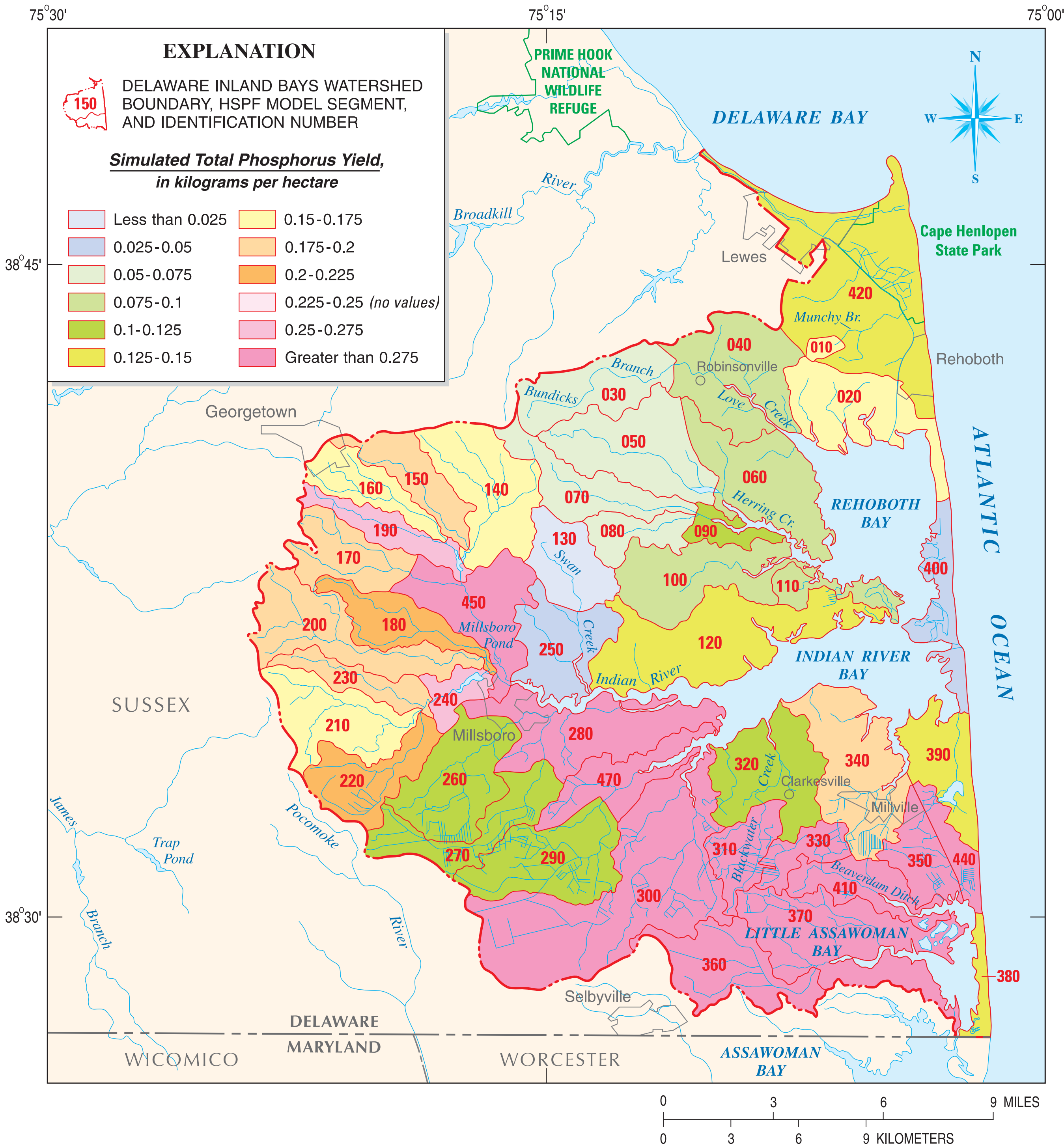

Figure 13. Simulated total phosphorus yield during water year 1999 by model segment.

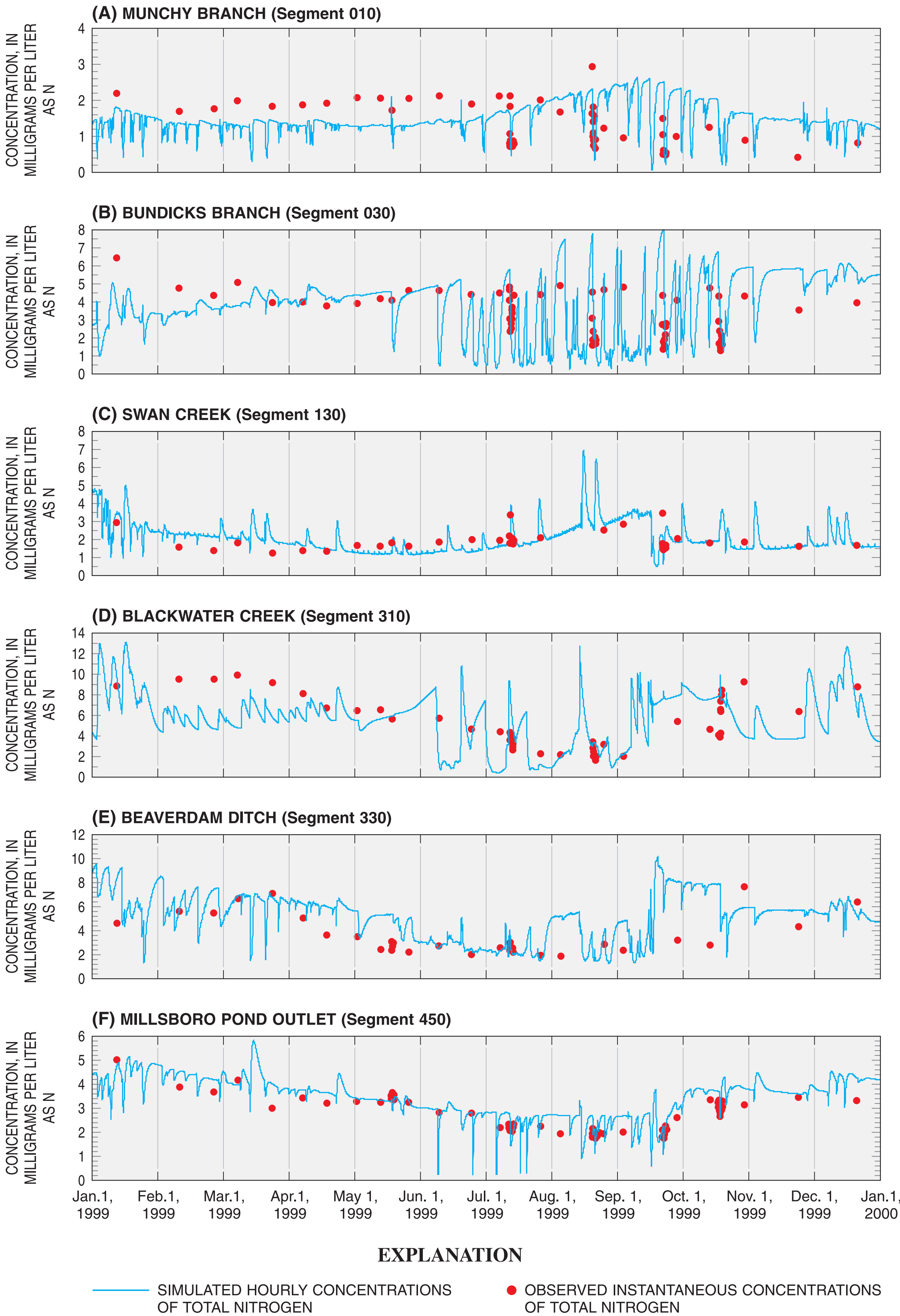

Figure 14. Simulated hourly total nitrogen concentrations and observed instantaneous values for the six calibrated basins during 1999.

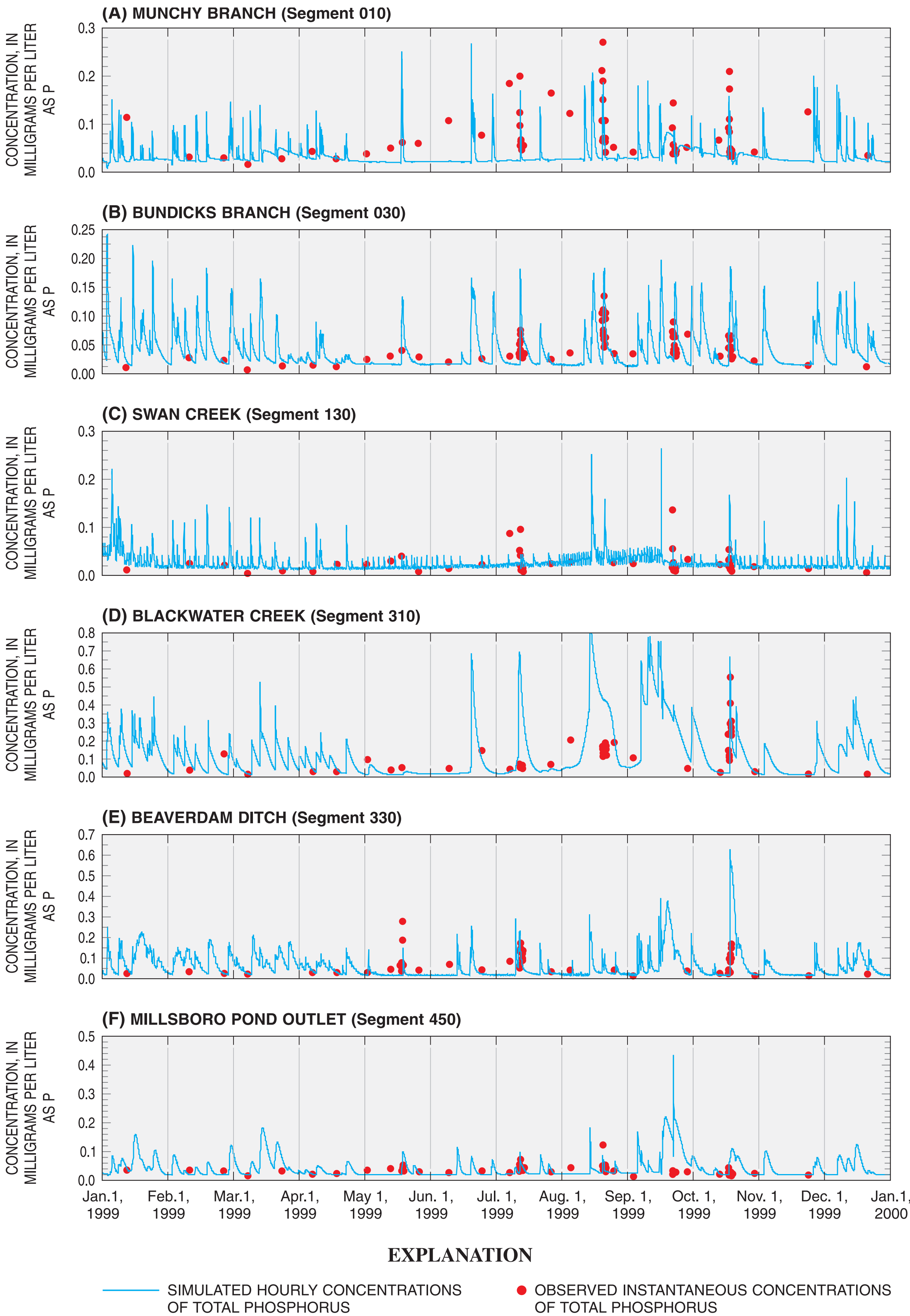

Figure 15. Simulated hourly total phosphorus concentrations and observed instantaneous values for the six calibrated basins during 1999.

Summary and Conclusions

A cooperative study involving the Delaware Department of Natural Resources and Environmental Control, the Delaware Geological Survey, and the U.S. Geological Survey was initiated in 2000 to develop a hydrologic and water-quality model of the Delaware Inland Bays watershed that can be used as a water-resources planning and management tool. The model code used was Hydrological Simulation Program-FORTRAN (HSPF), which is well documented. Hydrologic, agricultural, meteorological, and water-quality data were compiled from 1998 through 2000, and used for the development and calibration of the model. The 719-square-kilometer watershed was divided into 45 model segments and the model was calibrated using streamflow and water-quality data from six U.S. Geological Survey stream-gaging stations within the watershed. Calibration for some parameters was accomplished using PEST, a model-independent parameter estimator. Model parameters were adjusted systematically so that the discrepancies between the simulated values and the corresponding observations were minimized.

Model accuracy was evaluated in several ways. During calibration, goodness-of-fit statistics and visual examination were used to refine parameter estimates. Time series of simulated streamflow, simulated edge-of-stream runoff components, observed streamflow, and simulated and observed water chemistry, at hourly and daily time steps, were developed during calibration. These were examined during the calibration process to determine how well the model represented the natural system dynamics. Edge-of-stream nutrient loads were checked following calibration to ensure consistency with expected values and results of other modeling efforts in the region.

Model parameters for all land uses varied spatially and (in some cases) temporally; these variations were generally consistent with soil type, aquifer properties, topography, degree of ditching and other human influences, and observations of annual streamflow during the period of available data. The simulated annual streamflow from the six calibrated watersheds was consistent with the observed values, and was reduced throughout the watershed in 1999 because of the drought. Soil and aquifer permeability, ditching, and land-use practices affect the amount of streamflow and the hydrologic mechanism or flow path (surface flow, interflow, or base flow). Greater streamflow was observed in the southern part of the watershed than in the northern part. The flatness of the terrain and the low annual surface runoff are important factors in the amount of detached sediment from the land that was delivered to streams. The highest total suspended solids yields occurred in the southern part of the watershed. Blackwater Creek and Beaverdam Ditch Basins had high sediment yields associated with high streamflow and a high fraction of surface runoff.

In the simulation of agricultural and forest land throughout the Inland Bays watershed, the majority of inorganic nutrient (nitrate, orthophosphate) loads are transported through base flow, followed by interflow. Nutrient yields from Beaverdam Ditch and Blackwater Creek Basins were the highest of all calibrated basins, because both basins experienced high streamflow, and the amount of organic fertilizer (animal waste) available in both basins led to over-application of organic fertilizer to the crops.

Time series of simulated hourly total nitrogen and phosphorus concentrations and observed instantaneous values indicate seasonality in the observed and simulated concentrations for total nitrogen, with the lowest values during the summer and the highest during the winter months. Phosphorus is somewhat less seasonal; in general, base-flow total phosphorus concentrations were low, typically less than 0.05 milligrams per liter. During storm events, total nitrogen concentrations tend to be diluted and total phosphorus concentrations tend to rise sharply. Nitrogen is transported mainly in the aqueous phase and primarily through ground water, whereas phosphorus is strongly associated with sediment, which washes off during precipitation events.

References Cited

Andres, A.S., 1987, Geohydrology of the northern coastal area, Delaware-sheet 2, Geohydrology of the Columbia aquifer: Delaware Geological Survey Hydrologic Map Series No. 5, scale 1:24,000.

______1991, Results of the coastal Sussex County, Delaware ground-water quality survey: Delaware Geological Survey Report of Investigations No. 49, 28 p.

Andres, A.S., Savidge, K.B., Scudlark, J.R., and Ullman, W.J., 2002, Delaware Inland Bays tributary Total Maximum Daily Load water-quality database: Delaware Geological Survey Digital Product No.02–02, version 6.62.

Bachman, L.J., and Wilson, J.M., 1984, The Columbia aquifer of the Eastern Shore of Maryland: Maryland Geological Survey Report of Investigations No. 40, 144 p.

Bicknell, B.R., Imhoff, J.C., Kittle, J.L., Jr., and Donigian, A.S., Jr., 1996, Hydrological Simulation Program-FORTRAN user's manual for Release 11: U.S. Environmental Protection Agency, 755 p.

Delaware Department of Natural Resources and Environmental Control, 1998, Final determination for the State of Delaware 1998 Clean Water Act Section 303(d) list of waters needing TMDLs, accessed May 6, 2003 at *http://www.dnrec.state.de.us/dnrec2000/Library/Water/303(d)list.pdf*

Delaware Geological Survey, 2003, Correlation of hydrologic units to geologic units recognized in Delaware by the Delaware Geological Survey in the Delaware Coastal Plain, accessed April 17, 2003 at *http://www.udel.edu/dgs/Hydrology/hydrostrat.html*

Delaware Office of State Planning Coordination, 2002, 1997 Landuse/Landcover Data–GIS Data, accessed April 21, 2003 at *http://www.state.de.us/planning/info/lulcdata/lulc.htm*

Denver, J.M., 1989, Effects of agricultural practices and septic-system effluent on the quality of water in the unconfined aquifer in parts of eastern Sussex County, Delaware: University of Delaware Report of Investigations No. 45, 66 p.

Dillow, J.J.A., and Greene, E.A., 1999, Ground-water discharge and nitrate loadings to the coastal bays of Maryland: U.S. Geological Survey Water-Resources Investigations Report 99–4167, 8 p.

Doherty, J., 2000, PEST: Model-independent parameter estimation: Watermark Numerical Computing, 247 p.

Donigian, A.S., Jr., Bicknell, B.R., and Imhoff, J.C., 1995, Hydrological Simulation Program - FORTRAN (HSPF), *in* Singh, V.P., ed., Computer models of watershed hydrology: Water Resources Publications, p. 395–442.

Gutiérrez-Magness, A.L., and McCuen, R.H., 2002, Is automatic fitting automatic in model optimization?: Eos, Transactions, American Geophysical Union, Spring Meeting Supplement, Abstract H52B–02, v. 83, no. 19.

Hamilton, P.A., Denver, J.M., Phillips, P.J., and Shedlock, R.J., 1993, Water-quality assessment of the Delmarva Peninsula, Delaware, Maryland, and Virginia–Effects of agricultural activities on, and distribution of, nitrate and other inorganic consituents in the surficial aquifer: U.S. Geological Survey Open-File Report 93–40, 87 p.

Hamon, W.R., 1961, Estimating potential evapotranspiration: Journal of the Hydraulics Division, American Society of Civil Engineers, v. 87, p. 107–120.

Johnston, R.H., 1976, Relation of ground water to surface water in four small basins of the Delaware Coastal Plain: Delaware Geological Survey Report of Investigations No. 24, 56 p.

Kuczera, G., 1983, Improved parameter inference in catchment models. 1. Evaluating parameter uncertainty: Water Resources Research, v. 19, no. 5, p. 1,151–1,172.

Lander, C.H., Moffitt, D., and Klaus, A., 1998, Nutrients available from livestock manure relative to crop growth requirements: Appendix I—Nutrient uptake and removal: U.S. Department of Agriculture: Natural Resources Conservation Service, accessed April 21, 2003 at *http://www.nrcs.usda.gov/technical/land/pubs/nlapp1a.html*

Maizel, M.S., Muehlbach, G., Baynham, P., Zoerkler, J., Monds, D., Iivari, T., Welle, P., Robbin, J., and Wiles, J., 1997, The potential for nutrient loadings from septic systems to ground and surface water resources and the Chesapeake Bay: U.S. Environmental Protection Agency EPA #903–R–97–006, 280 p.

Miller, J.C., 1972, Nitrate contamination of the water-table aquifer in Delaware: Delaware Geological Survey Report of Investigations No. 20, 36 p.

National Oceanic and Atmospheric Administration, 2001, National Climatic Data Center, accessed May 8, 2003 at *http://www.ncdc.noaa.gov/oa/ncdc.html*

Phillips, P.J., and Bachman, L.J., 1996, Hydrologic landscapes on the Delmarva Peninsula - Part 1: Drainage basin type and base-flow chemistry: Journal of the American Water Resources Association, v. 32, no. 4, p. 767–778.

Robertson, F.N., 1977, The quality and potential problems of the ground-water in coastal Sussex County, Delaware: University of Delaware Water Resources Center, 58 p.

Schwarz, G.E., and Alexander, R.B., 1995, State soil geographic (STATSGO) data base for the conterminous United States version 1.1 (scale 1:250,000): U.S. Geological Survey Open-File Report 95–449.

Scudlark, J.R., and Church, T.M., 2001, A comprehensive reexamination of the input of atmospheric nitrogen to the Rehoboth and Indian River Estuaries: Delaware Center for the Inland Bays, 39 p.

Shedlock, R.J., Denver, J.M., Hayes, M.A., Hamilton, P.A., Koterba, M.T., Bachman, L.J., Phillips, P.J., and Banks, W.S.L., 1999, Water-quality assessment of the Delmarva Peninsula, Delaware, Maryland, and Virginia: Results of investigations, 1987–91: U.S. Geological Survey Water-Supply Paper 2355–A, 41 p.

Sims, J.T., and Wolf, D.C., 1993, Poultry waste management: Agricultural and environmental issues: Advances in Agronomy, v. 52, p. 1–81.

Sprague, L.A., Langland, M.J., Yochum, S.E., Edwards, R.E., Blomquist, J.D., Phillips, S.W., Shenk, G.W., and Preston, S.D., 2000, Factors affecting nutrient trends in major rivers of the Chesapeake Bay Watershed: U.S. Geological Survey Water-Resources Investigations Report 00–4218, 98 p.

Staver, K.W., and Brinsfield, R.B., 1998, Using cereal grains to minimize nitrogen leaching losses: University of Maryland, College of Agriculture and Natural Rersources, Wye Research and Education Center Final Report - Grant 98107, [variously paged].

Talley, J.H., 1988, Geohydrology of the southern coastal area, Delaware-sheet 2, Geohydrology of the Columbia aquifer: Delaware Geological Survey Hydrologic Map Series No. 7, scale 1:24,000.

U.S. Department of Agriculture: National Agricultural Statistics Service, 1997a, Census of agriculture, accessed April 18, 2003 at *http://www.nass.usda.gov/census/*

______ 1997b, Usual planting and harvesting dates for U.S. field crops, accessed April 22, 2003 *at http://www.usda.gov/nass/pubs/uph97.htm*

______ 2003, Delaware Agricultural Statistics Service, accessed April 21, 2003 at *http://www.nass.usda.gov/de/*

U.S. Department of Agriculture: Natural Resources Conservation Service, 2003, CNMP Workbook: manure application rates, accessed July 18, 2003 *at http://www.wy.nrcs.usda.gov/technical/wycnmp/sec13.html*

U.S. Environmental Protection Agency, 1997, Chesapeake Bay Watershed model application and calculation of nutrient and sediment loadings, Appendix D: Phase IV Chesapeake Bay Watershed model precipitation and meteorological data development and atmospheric nutrient deposition: U.S. Environmental Protection Agency, 58 p.

______ 1998, Chesapeake Bay Watershed model application and calculation of nutrient and sediment loadings, Appendix H: Tracking best management practice nutrient reductions in the Chesapeake Bay Program: U.S. Environmental Protection Agency, 91 p.

______ 2003, Clean water act, accessed May 6, 2003 at *http://www.epa.gov/region5/water/cwa.htm*

Ullman, W.J., Andres, A.S., Scudlark, J.R., and Savidge, K.B., 2002, Storm-water and base-flow sampling and analysis in the Delaware Inland Bays: Preliminary report of findings, 1998-2000: Delaware Geological Survey Open-File Report No. 44, 40 p.

University of Delaware Spatial Analysis Lab, 2003, 30-meter resolution Digital Elevation Models for Delaware and Chester County, PA, accessed May 7, 2003 at *http://www.udel.edu/FREC/spatlab/dems/dem_intro.html*

Wheeler, J.C., 1999, Freshwater use in Delaware, 1995: U.S. Geological Survey Fact Sheet FS-126-99, 2 p.