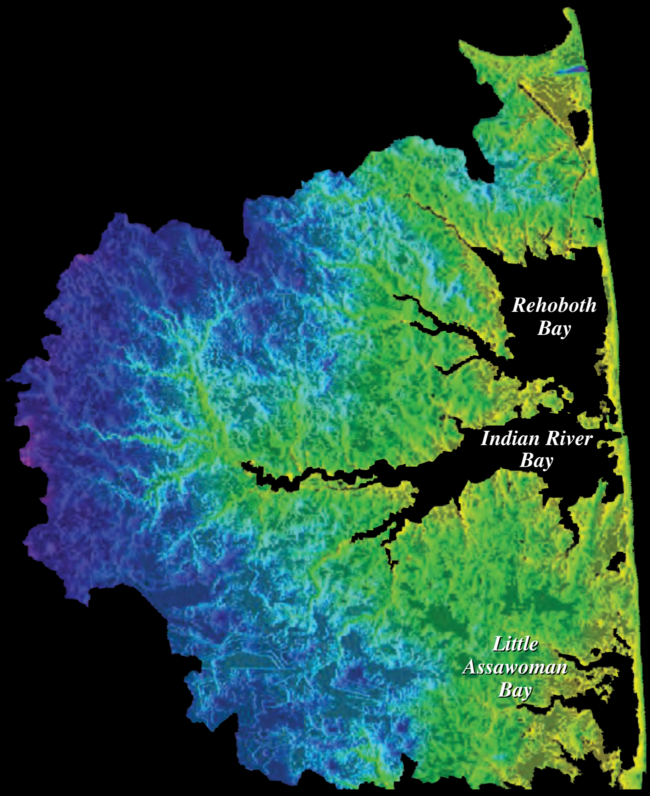
In cooperation with the
Delaware Department of Natural Resources and Environmental Control
and the
Delaware Geological Survey

Simulation of Nutrient and Sediment Concentrations and Loads in the Delaware Inland Bays Watershed: Extension of the Hydrologic and Water-Quality Model to Ungaged Segments



Scientific Investigations Report 2006-5038

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

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By Angélica L. Gutiérrez-Magness

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Contents

Figures

Tables

Conversion Factors and Vertical Datum

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	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 (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
liter (L)	33.82	ounce, fluid (fl. oz)
liter (L)	0.2642	gallon (gal)
	Flow rate	
liter per day (L/d)	0.2642	gallon per day (gal/d)
	Mass	
kilogram (kg)	2.205	pound, avoirdupois (lb)
kilogram (kg)	0.001102	ton (T)
	Application rate	
kilograms per hectare per year [(kg/ha)/yr]	0.8921	pounds, per acre per year [(lb/acre)/yr]

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 in milligrams per liter (mg/L).

Elevations are referenced to the North American Vertical Datum of 1983 (NAVD 83).

Water year is the 12-month period October 1 through September 30. The water year is designated by the calendar year in which it ends, and includes 9 of the 12 months. Thus, the year ending September 30, 1999 is called the “1999 water year.”

Simulation of Nutrient and Sediment Concentrations and Loads in the Delaware Inland Bays Watershed: Extension of the Hydrologic and Water-Quality Model to Ungaged Segments

By Angélica L. Gutiérrez-Magness

Abstract

Rapid population increases, agriculture, and industrial practices have been identified as important sources of excessive nutrients and sediments in the Delaware Inland Bays watershed. The amount and effect of excessive nutrients and sediments in the Inland Bays watershed have been well documented by the Delaware Geological Survey, the Delaware Department of Natural Resources and Environmental Control, the U.S. Environmental Protection Agency's National Estuary Program, the Delaware Center for Inland Bays, the University of Delaware, and other agencies. This documentation and data previously were used to develop a hydrologic and water-quality model of the Delaware Inland Bays watershed to simulate nutrients and sediment concentrations and loads, and to calibrate the model by comparing concentrations and streamflow data at six stations in the watershed over a limited period of time (October 1998 through April 2000). Although the model predictions of nutrient and sediment concentrations for the calibrated segments were fairly accurate, the predictions for the 28 ungaged segments located near tidal areas, where stream data were not available, were above the range of values measured in the area.

The cooperative study established in 2000 by the Delaware Department of Natural Resources and Environmental Control, the Delaware Geological Survey, and the U.S. Geological Survey was extended to evaluate the model predictions in ungaged segments and to ensure that the model, developed as a planning and management tool, could accurately predict nutrient and sediment concentrations within the measured range of values in the area. The evaluation of the predictions was limited to the period of calibration (1999) of the 2003 model.

To develop estimates on ungaged watersheds, parameter values from calibrated segments are transferred to the ungaged segments; however, accurate predictions are unlikely where parameter transference is subject to error. The unexpected nutrient and sediment concentrations simulated with the 2003 model were likely the result of inappropriate criteria for the transference of parameter values. From a model-simulation perspective, it is a common practice to transfer parameter values based on the similarity of soils or the similarity of land-use proportions between segments. For the Inland Bays model, the similarity of soils between segments was used as the basis to transfer parameter values. An alternative approach, which is documented in this report, is based on the similarity of the spatial distribution of the land use between segments and the similarity of land-use proportions, as these can be important factors for the transference of parameter values in lumped models. Previous work determined that the difference in the variation of runoff due to various spatial distributions of land use within a watershed can cause substantial loss of accuracy in the model predictions.

The incorporation of the spatial distribution of land use to transfer parameter values from calibrated to uncalibrated segments provided more consistent and rational predictions of flow, especially during the summer, and consequently, predictions of lower nutrient concentrations during the same period. For the segments where the similarity of spatial distribution of land use was not clearly established with a calibrated segment, the similarity of the location of the most impervious areas was also used as a criterion for the transference of parameter values.

The model predictions from the 28 ungaged segments were verified through comparison with measured in-stream concentrations from local and nearby streams provided by the Delaware Department of Natural Resources and Environmental Control. Model results indicated that the predicted edge-of-stream total suspended solids loads in the Inland Bays watershed were low in comparison to loads reported for the Eastern Shore of Maryland 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 predicted total suspended solids loads were found in the southern part of the watershed, where the values are associated with high total streamflow and a high surface-runoff component, and related to soil and aquifer

permeability and land use. Nutrient loads from model segments in the southern part of the Inland Bays watershed were also higher than those measured in the northern part of the basin, due to relatively high runoff and the substantial amount of available organic fertilizer (animal waste) that results in over-application of organic fertilizer to crops.

Time series of simulated hourly concentrations indicated a seasonal pattern in the simulated base flow for total nitrogen, with the lowest values occurring during the summer and the highest values during the winter months. Total phosphorus and total-suspended-solids concentrations were less seasonal and were more storm-dependent; in general, base-flow concentrations of total phosphorus and total suspended solids were low. During storm events, the total nitrogen concentrations tended to be diluted and total phosphorus concentrations tended to rise sharply. Nitrogen was transported mainly in the aqueous phase and largely through ground water, whereas phosphorus was strongly associated with sediment, which washes off during rainfall events.

Introduction

Rapid population increases, agriculture, and industrial practices have been identified as important sources of excessive nutrients and sediments in the Delaware Inland Bays watershed (fig. 1). In order to better understand nutrient and sediment concentration loads in the watershed, a published hydrologic and water-quality model of the Delaware Inland Bays watershed (Gutiérrez-Magness and Raffensperger, 2003) was calibrated through comparison of concentration and streamflow data at six stations in the watershed over a limited time period (October 1998 through April 2000). Model-simulation results indicated that soil and aquifer permeability, ditching, dominant land-use class, and land-use practices affected the amount of runoff, the mechanism or flow path (surface flow, interflow, or base flow), and the concentrations of sediment and nutrients. Although the spatial distribution of nutrient and sediment concentrations averaged over watershed land uses were represented reasonably in the model simulation, unexpected concentrations were sometimes predicted for certain land uses of model segments located near the tidal areas where stream data were not available to calibrate model parameters. Because the Hydrological Simulation Program-FORTRAN (HSPF) model predictions were used not only to address contamination problems in local streams, but also in connection with a hydrodynamic model to develop the Total Maximum Daily Loads (TMDLs) for the Bays, it became necessary to address the unexpected model predictions.

The cooperative study established in 2000 by the Delaware Department of Natural Resources and Environmental Control (DNREC), the Delaware Geological Survey (DGS), and the U.S. Geological Survey (USGS) was extended to evaluate the model predictions in ungaged watersheds and to ensure that the model, developed as a planning and management tool, could accurately predict nutrient and sediment concentrations within the measured range of values in the area. The simulation period included the calendar years 1998 and 1999; however, the simulation for 1998 was used only to account for the unknown initial conditions of the watershed system.

Purpose and Scope

The purpose of this report is to (1) document the model predictions for the 28 ungaged segments where streamflow and water-quality data were not available for calibration, (2) document the approach used to transfer parameter values from calibrated to uncalibrated model segments, and (3) provide findings, analysis, and implications of the predictions from model simulation for the understanding of hydrologic and nutrient processing functions in the uncalibrated segments of the Inland Bays watershed. Water-quality data from the U.S. Environmental Protection Agency's (USEPA) STORET database, the DNREC's General Assessment Monitoring Network (GAMN), and the DNREC's Total Maximum Daily Load (TMDL) monitoring network, were used to compare in-stream measured and edge-of-stream predicted model concentrations. Although the 719-square kilometer (km^2) watershed was divided into 45 model segments, only 28 of these segments are located near tidal areas. The predictions of concentrations and loads for these 28 ungaged segments are documented in this report. Model parameters were adjusted systematically so that the discrepancies between the simulated values and the observations from nearby streams 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 various previous studies (Miller, 1972; Robertson, 1977; Denver, 1989; Andres, 1991; Hamilton and others, 1993). Elevated concentrations of nitrate (above background levels) are 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.

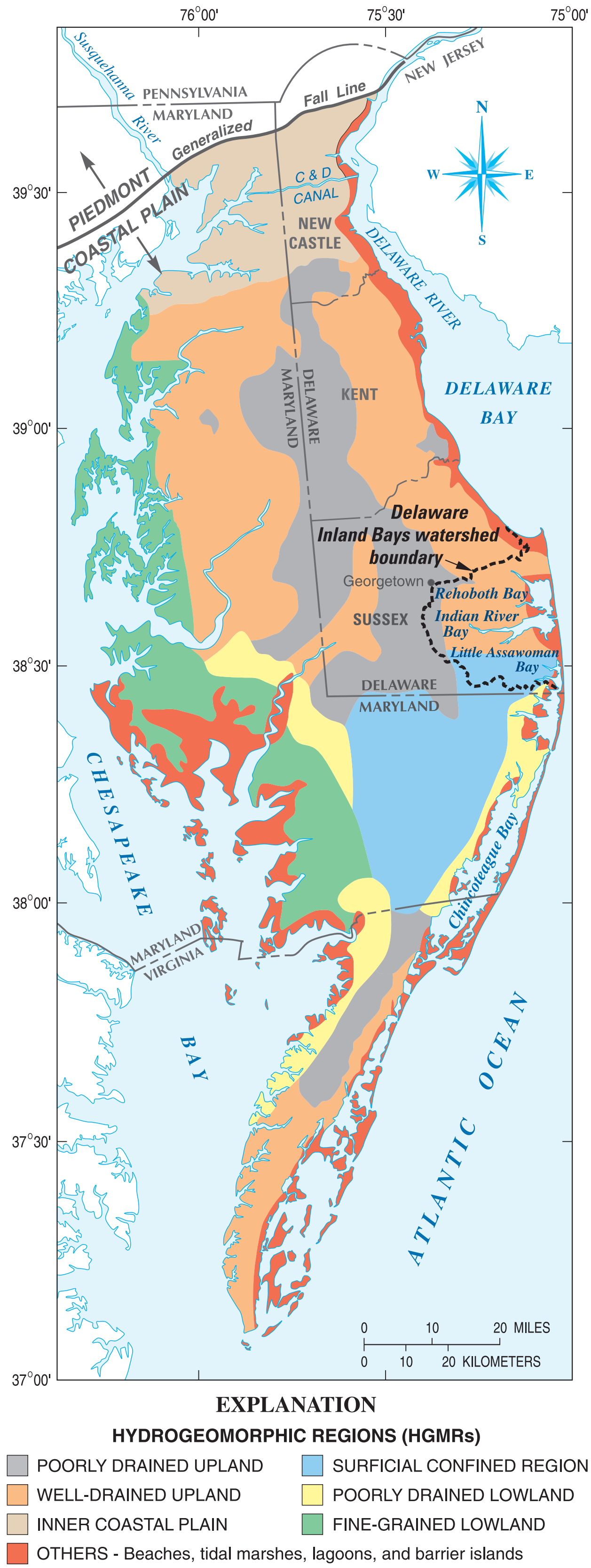

Figure 1. Hydrogeomorphic regions of the Delmarva Peninsula and location of the Delaware Inland Bays watershed, Delaware, Maryland, and Virginia (modified from Shedlock and others, 1999).

Phosphorus is not commonly present in ground water at elevated concentrations, but when it is attached to soil particles, it is present in high concentrations (above background levels), 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 (that 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. Various wells sampled during the study in 1999 were in the Inland Bays watershed. The results indicated that the chemical character of water in the surficial sediments is affected by agricultural activities over most of the Delmarva Peninsula. Elevated concentrations of nitrate were found in the surficial sediments 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). 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 closest 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, slope, drainage properties, and aquifer configurations that determine the movement of water and the potential for oxidation and reduction in the aquifer and streams.

Description of Study Area

The Inland Bays watershed encompasses approximately 803 km^2 in southeastern Sussex County, Delaware (figs. 1 and 2). The Bays themselves cover 84 km^2, and the remaining 719 km^2 are land. Various major and many smaller streams drain to the three bays (Rehoboth, Indian River, and Little Assawoman; (fig. 2). 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).

Topography in the Inland Bays watershed is flat, typical of the Atlantic Coastal Plain Physiographic Province. The

Figure 2. Detailed view of the Delaware Inland Bays watershed, Sussex County, Delaware.

elevations in the watershed range from 0 to 22.9 (m) meters, based on 30-m Digital Elevation Model (DEM) data, North American Datum 1983, (University of Delaware Spatial Analysis Lab, 2003), with a mean of 6.9 m. Slopes in the watershed are generally very small (less than 1 percent). Streams in the uplands may be incised, especially in the well-drained upland region. The land surface in the surficial confined region is flat.

Watershed Segmentation

The watershed-model segmentation was delineated on the basis of various 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 flow gages and water-quality monitoring stations, and the location of point sources. 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). Twenty-eight of the 45 segments are located in tidal areas and were modeled to drain directly to the Bay. Since flow through a reach in the HSPF model is assumed to be unidirectional, streams were not simulated in these 28 ungaged segments. To validate the accuracy of the model-predicted concentrations in the ungaged segments, the simulated concentrations from the land, referred to as the "edge-of-stream" concentrations, were compared to the measured in-stream concentrations from streams located near the individual segments.

Land Use

Land-use information was derived from 1997 land-use/land-cover data (Delaware Office of State Planning Coordination, 2002). The hectares of each land use within each model segment are described in Gutiérrez-Magness and Raffensperger (2003). The 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-, medium-, and high-density residential as well as institutional, industrial, and commercial categories were aggregated into an "urban" classification. The wetlands category was simulated as forest because of HSPF limitations in simulating chemical processes in wetlands. These aggregated categories were used to determine the source of parameter values for the 28 ungaged segments located in tidal areas. A generalized land-use map with the forest and pasture categories aggregated as vegetation is shown in figure 4.

Development of Water-Quality Database for Model Calibration

All water-quality data used for the validation of the model predictions in the segments located near tidal areas were provided by DNREC. Delaware maintains two networks, the GAMN, and the TMDL monitoring network. Whereas GAMN stations are considered long-term stations, TMDL monitoring stations are generally in place for 1 to 2 years to support data needs for TMDL model development and calibration. The data from these two networks are stored in the USEPA's STORET database. DNREC's ambient water-quality-monitoring-program data from 1998 through 2000 were retrieved from USEPA's STORET database to supplement the Inland Bays TMDL database, version 6.62 (Andres and others, 2002). All methods used for sample collection, processing, preservation, and analysis are described in Ullman and others (2002). For the validation of the model predictions, 14 of the ungaged segments were paired to a TMDL or GAMN station with water-quality data during 1999 (table 1). Because of the brevity of the observation record, however, the predictions were also compared to the water-quality data from the nearest calibrated model segment. The constituents analyzed and specified concentration units are described in Gutiérrez-Magness and Raffensperger (2003).

Parameter Transference Approach

The transfer of parameter values is an important consideration in making accurate predictions for ungaged watersheds. The lack of measured streamflow and water-quality data makes it difficult to validate the model predictions in ungaged watersheds. When using lumped models, such as HSPF, criteria based on the similarity of soils or land-use proportions between gaged and ungaged segments are commonly used to transfer parameter values. Whereas the similarity of soils assumes that the accuracy of all parameters is the same after calibration, the similarity of land-use proportions recognizes that the accuracy of the parameters varies according to the importance of the land-use class on the simulated processes; parameters for larger land-use classes may be the most accurately calibrated as they may drive the accuracy of the predictions. Although the criteria take into account the similarities of the physical system, the criteria ignore fundamental simplifications of lumped models specific to the spatial variation of the data.

Lumped models do not explicitly take into account the spatial variability of inputs, outputs, or parameters. Lumped models are usually structured to utilize average values of the watershed characteristics that affect runoff volumes. Thus, averaging a certain parameter also implicitly averages the

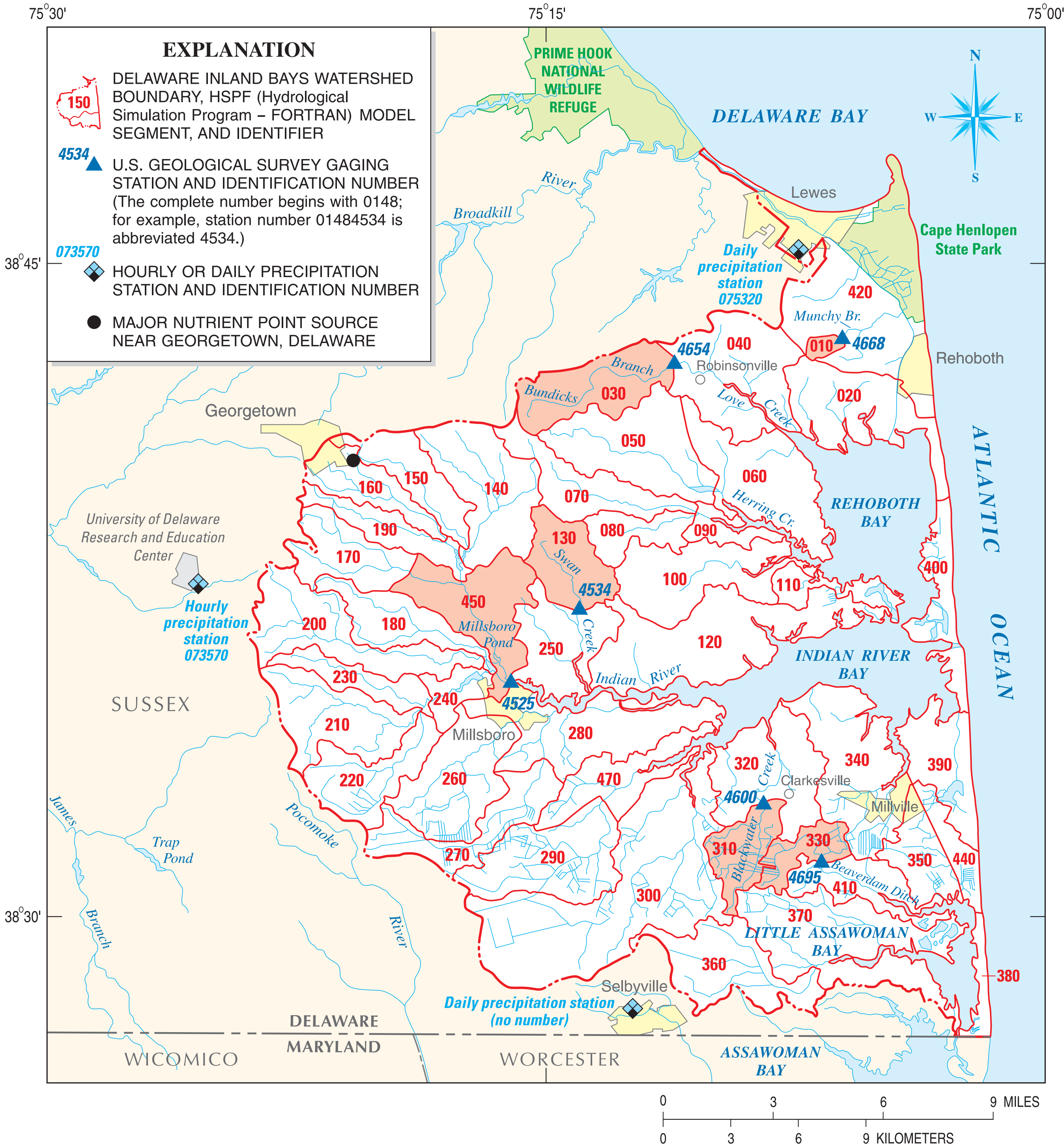

Figure 3. Hydrological Simulation Program - FORTRAN (HSPF) Inland Bays model segmentation and location of U.S. Geological Survey gaging stations in the Inland Bays watershed, hourly and daily precipitation stations in the study area, and major nutrient point source from the municipal facility located in Georgetown, Delaware. [*Red shaded areas represent the six calibrated watersheds that were used as the source of parameter values for the uncalibrated watersheds.*]

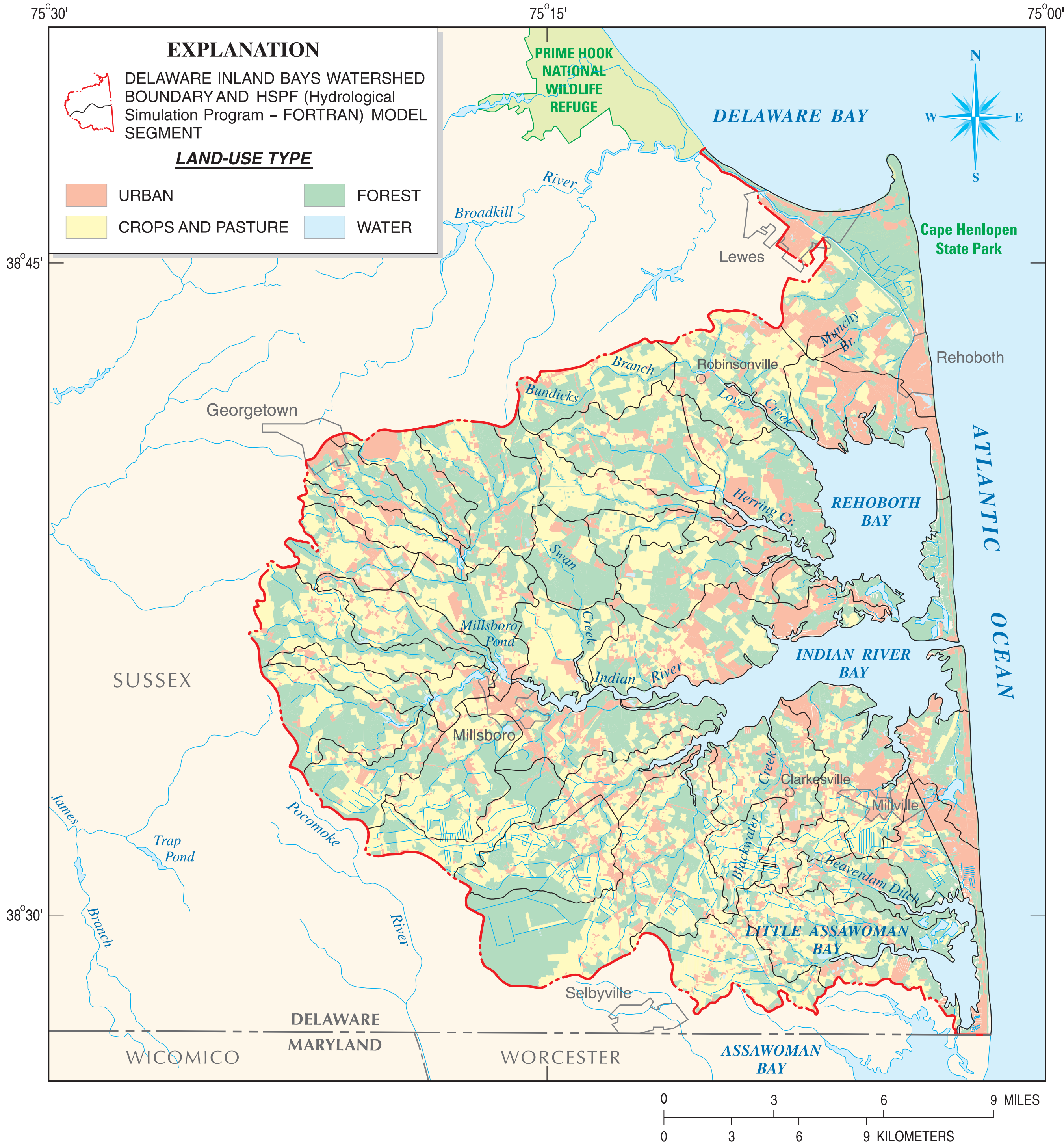

Figure 4. Aggregated land-use categories in the Delaware Inland Bays watershed.

Table 1. Ungaged model segment and Total Maximum Daily Load stations for the Delaware Inland Bays watershed from which measured data were used for the validation of model predictions.

[TMDL, total maximum daily load; GAMN, General Assessment Monitoring Network; locations of segments shown in figure 3; ———, data not available]

Model segment	TMDL	GAMN
020	LR305011	———
040	IR308291	———
050	———	IR308301
100	RB308051	———-
110	———	IR306111
120	———	IR306321
250	———	IR308301
260	———	IR309021
270	———	IR309041
290	———	IR308091
350	LA312041	———
370	———	LA310031
410	LA310101	———
420	LR305011	———

process being represented—because of nonlinearity and threshold values, this condition can lead to significant errors. In the case of the HSPF model, all processes are computed for a spatial unit of 1 acre[1] for each of the simulated land uses; to obtain the total edge-of-stream load for the land part of a given model segment, the fluxes and loads computed for the spatial unit are multiplied by the number of acres of each land use.

When the land use in a watershed is spatially nonhomogeneous, the calibration of a spatially lumped model may distort the calibrated parameters. Ultimately, this would introduce error variation, both systematic and nonsystematic, into the predictions. Calibrated parameter values for a watershed with flashy runoff will likely indicate low infiltration and low values of retention storage. Conversely, runoff from a watershed that is forested at the outlet would be considerably different than runoff from a watershed where impervious land use is near the outlet. If the parameters from a watershed with an impervious area near the outlet were to be transferred for predictions in a watershed with similar soils, but with a forested area located at the outlet of the watershed, predicted runoff rates would likely be erroneous. Thus, when transferring parameters between watersheds, it is important to apply criteria that account for both the physical characteristics of the watershed system and the model simplifications.

[1] 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 $10^4 m^2$ (square meters) or 2.471 acres.

The similarity of the spatial distribution of land use between the uncalibrated and the calibrated segments was determined through a visual examination of the generalized land-use map shown in fig. 4. The similarity of the land-use proportions between the segments was determined from the land-use classes (Gutiérrez-Magness and Raffensperger, 2003). The similarity of the spatial distribution of land use, followed by the similarity of land-use proportions between uncalibrated and calibrated segments, were the criteria for the transference of model parameters. For the ungaged segments, where the similarity of spatial distribution of land use was not clearly established with a calibrated segment, the similarity of the location of the most impervious areas was used as an alternative.

Five groups were defined for the transference of the parameter values, with each group consisting of a calibrated segment and a set of ungaged segments as shown in table 2. The calibrated segments in table 2 are referred to as the “source” segments, whereas the ungaged segments are referred to as the “recipient” segments. The calibrated parameters of segments 010, 030, 130, 310, and 450, discussed in the report by (Gutiérrez-Magness and Raffensperger, (2003), were the values transferred to the recipient segments. Parameters from the calibrated segment at Beaverdam Ditch (segment 330) were not transferred to ungaged segments, as the land-use proportions and the spatial distribution of land-use criteria were difficult to meet. The transferred values corresponded to the inland parameters that control the hydrologic processes and to the parameters that control the edge-of-stream concentrations of nitrogen, phosphorus, and sediment. In the case of ungaged segments, where a stream was simulated (segments 260, 270, 290, and 360), the parameters that control the in-stream processes were also transferred. The names and descriptions of the parameters controlling these processes are documented in the user’s manual of the HSPF model (Bicknell and others, 1997).

Simulation of Nutrient and Sediment Concentrations and Loads

The accuracy of the simulation for the prediction of nutrient and sediment concentrations and loads was evaluated using comparisons of water balances and comparisons of predicted and measured nutrient and sediment concentrations. Although the similarity of water balances between the measured and predicted flows was important, priority was given to the accuracy of the predicted concentrations in the individual segments. The water mass balance within land areas was simulated as a series of storages with flows between the storages determined by empirical (constitutive) relations.

The annual and monthly water balances were calculated using the measured streamflow at the source segments, and the edge-of-stream flows at the corresponding recipient segments. For segments 260, 270, 290, and 360, where a stream was

Table 2. Groups of segments defined for the transference of parameter values for source and recipient model segments for the Delaware Inland Bays watershed.

[Locations of segments shown in figure 3]

Source segments		Recipient segments
Station number (segment number)	Station name	
01484668 (010)	Munchy Branch near Rehoboth Beach, DE	020, 100, 380, 390, 400, 420, 440
01484654 (030)	Bundicks Branch at Robinsonville, DE	040, 050, 070, 080, 250, 260
01484534 (130)	Swan Creek near Millsboro, DE	060, 090, 110, 270, 350, 410
01484600 (310)	Blackwater Creek near Clarkesville, DE	290, 360
01484525 (450)	Millsboro Pond Outlet at Millsboro, DE	120, 280, 300, 320, 340, 370, 470

simulated, the water balances were calculated using the predicted streamflow. The predicted annual and monthly water balances were calculated as the average of the predicted values for the individual recipient segments; these averages were compared to the water balances of the measured streamflow. Differences between the measured and the predicted water balances were expected, because in some cases the precipitation data used in the source and recipient segments were different, or because during the evaluation of the predicted nutrient or sediment edge-of-stream concentrations, modifications were applied to the hydrologic parameters that control the amount of water lost to deep percolation and the amount of evaporation from base flow and ground water.

The validation of the water-quality model predictions for the ungaged segments was performed using DNREC's ambient water-quality data collected in the area during 1999. The predicted edge-of-stream concentrations were compared to the monitored in-stream concentrations from streams within or near the assessed model segment. The primary objective when comparing the predicted edge-of-stream concentrations in ungaged segments (020, 040, 050, 110, 120, 290, and 420) to the in-stream concentrations from the calibrated segments was to guarantee that the model predictions were within the range of the water-quality measurements, rather than a perfect match between the individual predicted and measured values. A similar rationale was applied when the predicted concentrations of all the remaining ungaged segments were compared to measured water-quality data from streams within or near the assessed model segment.

Although it is a common practice to validate model predictions from ungaged watersheds using the edge-of-stream average annual loads by land-use class, the predictions in the ungaged segments were validated using the predicted concentrations as the climatic conditions prior to and during the calibration period were not the long-term average. During 1998, the recorded precipitation for the northern and southern parts of the watershed was below average by -53.3 mm (millimeters) and -198.1 mm, respectively; during 1999, the recorded precipitation was the long-term average for the northern area, whereas the precipitation was still below average (-55.88 mm) for the southern area (Lewes, Delaware) (National Oceanic and Atmospheric Administration, 2001).

The predicted edge-of-stream concentrations for total nitrogen (TN) were expected to be lower than or similar to the in-stream concentrations measured in the monitored ambient data. The rationale for the expectation was a dilution effect recognized during the calibration of the 2003 model with reduced in-stream concentrations during storm events. In contrast, the predicted edge-of-stream concentrations of total phosphorus (TP) were expected to be a function of the delivered sediments and within the range of values measured in the monitored in-stream concentrations. The hourly predictions of nutrients and sediment concentrations were plotted for visual examination and the total annual loads were computed for each of the ungaged segments.

Annual and Monthly Water Balance

The amount of runoff from a watershed is a function of climate, topographic relief, water retention, soil properties, and the geologic structure of the basin. Approximate values representing these factors are included in the model simulation of the watershed and the values are calibrated against monitored discharge data. In the case of ungaged basins, however, the amount of runoff will also be a function of the criteria applied for the transference of parameter values and the accuracy of the calibrated parameter values.

The predicted annual water balances (fig. 5) of the recipient segments using parameters from the calibrated segments 010, 030, 310, and 450 were within 25 percent of the measured values. The large difference when using parameters from segment 130 between the measured and predicted average annual streamflow for the recipient segments is in part explained by the reduction of the parameters DEEPFR, BASETP, and AGWETP (the fraction of ground-water inflow lost from the watershed system as deep percolation, the fraction of potential evapotranspiration from base flow, and the

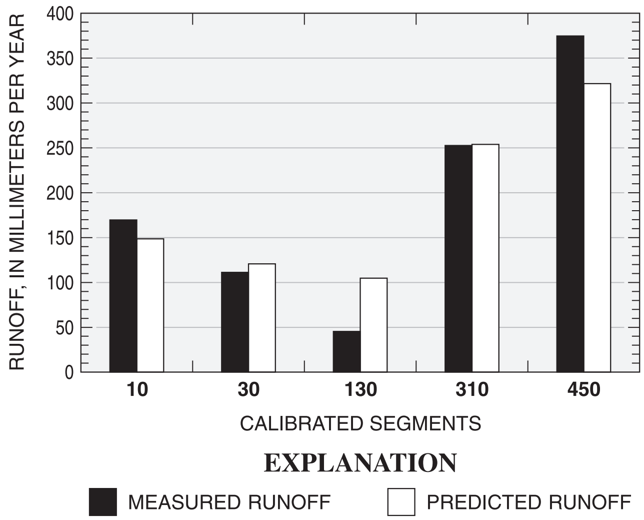

Figure 5. Annual measured and predicted runoff for the source and recipient segments for the Delaware Inland Bays watershed during 1999.

fraction of potential evapotranspiration from ground water, respectively) from 0.055, 0.001, and 0.01, respectively, to a zero value for all the recipient segments. High concentrations of ammonia, nitrate, and phosphate were caused by the almost zero flows during the summer season. Once these parameter values were reduced, the amount of water lost to evaporation or deep percolation was added to the edge-of-stream flow throughout the year, and the predicted concentrations of TN and TP were within the range of the measured values. In addition, the precipitation used for the predictions in segments 270, 350, and 410 was different than the precipitation measured near the segment source.

Streamflow was lower throughout the watershed in 1999, with Swan Creek (segment 130) only discharging 46 mm of streamflow, while receiving more than 1,000 mm of precipitation. Higher streamflow was measured in the southern part of the watershed (segments 310 and 450) than in the northern part (segments 010, 030, and 130). This result was anticipated because the sub-watersheds in the southern area are located in the surficial confined aquifer region, where the storage capacity of the aquifer material is expected to be relatively low compared to the storage capacity of watersheds located in the northern area.

The monthly water balances for the groups using parameters from segments 010, 030, 310, and 450 show good agreement, with most predicted values within 35 percent of the measured values (fig. 6). In the group using parameters from segment 130, the amount of water is significantly larger because of the reduction of evapotranspiration from base flow and ground water (BASETP and AGWETP, respectively) and the elimination of deep percolation (DEEPR) from the watershed system. Seasonality in the edge-of-stream flow and streamflow was properly simulated by the model, although some overprediction resulted during the summer season. The overprediction was also observed for the streamflow of the calibrated segments (Gutiérrez-Magness and Raffensperger, 2003).

Predicted Sediment Concentrations

The validation of model predictions through the analyses of predicted concentrations rather than through the evaluation of monthly or annual predicted loads is important to ensure that the model properly represents the dynamics of the simulated processes. The significance of this analysis increases when the climatological conditions under which the model has been calibrated are different from the long-term average. The accuracy of the model was evaluated through visual examination of time series of the hourly total suspended-sediment concentrations at the edge-of-stream. Time series of predicted hourly edge-of-stream and measured in-stream total-suspended-solids (TSS) concentrations (fig. 7) were used to assess the capacity of the model to represent dynamic features of the sediment runoff response in each of the ungaged segments. The primary objective of these comparisons was to guarantee that the model predictions were within the range of the water-quality measurements rather than to have a perfect match between the individual predicted and measured values.

Stormflow concentrations were appreciably higher than base-flow concentrations for TSS in all segments. Differences in concentrations among ungaged segments were most likely related to the differences in land use and the storage capacity of the aquifer material, with relatively lower values in the southern part of the watershed. Higher concentrations were predicted in segments located in the southern part of the watershed, with concentrations up to 500 mg/L (milligrams per liter) (segment 290). The predictions closely resemble the dynamics of the surface runoff, with higher values occurring during storm events. The predictions of sediment concentrations for all segments in the northern area were below 100 mg/L.

Predicted Total Nitrogen Concentrations

Concentrations in mg/L are the mass of a constituent present in a given volume of water sample. Seasonality was reflected in the measured and simulated TN concentrations, with the lowest values during the summer and the highest values during the winter months. Nitrogen was transported mainly in the aqueous phase and largely through ground water in the form of nitrate/nitrite. Stormflow concentrations were appreciably higher than base-flow concentrations for organic nitrogen at all tributaries and for ammonia in segments with a high application of organic fertilizer, and in segments with large urban areas. During storm events, TN concentrations (fig. 8) tended to be diluted as the concentrations of nitrate and nitrite in the surface runoff were appreciably lower than the concentrations observed during base flow. The dilution effect

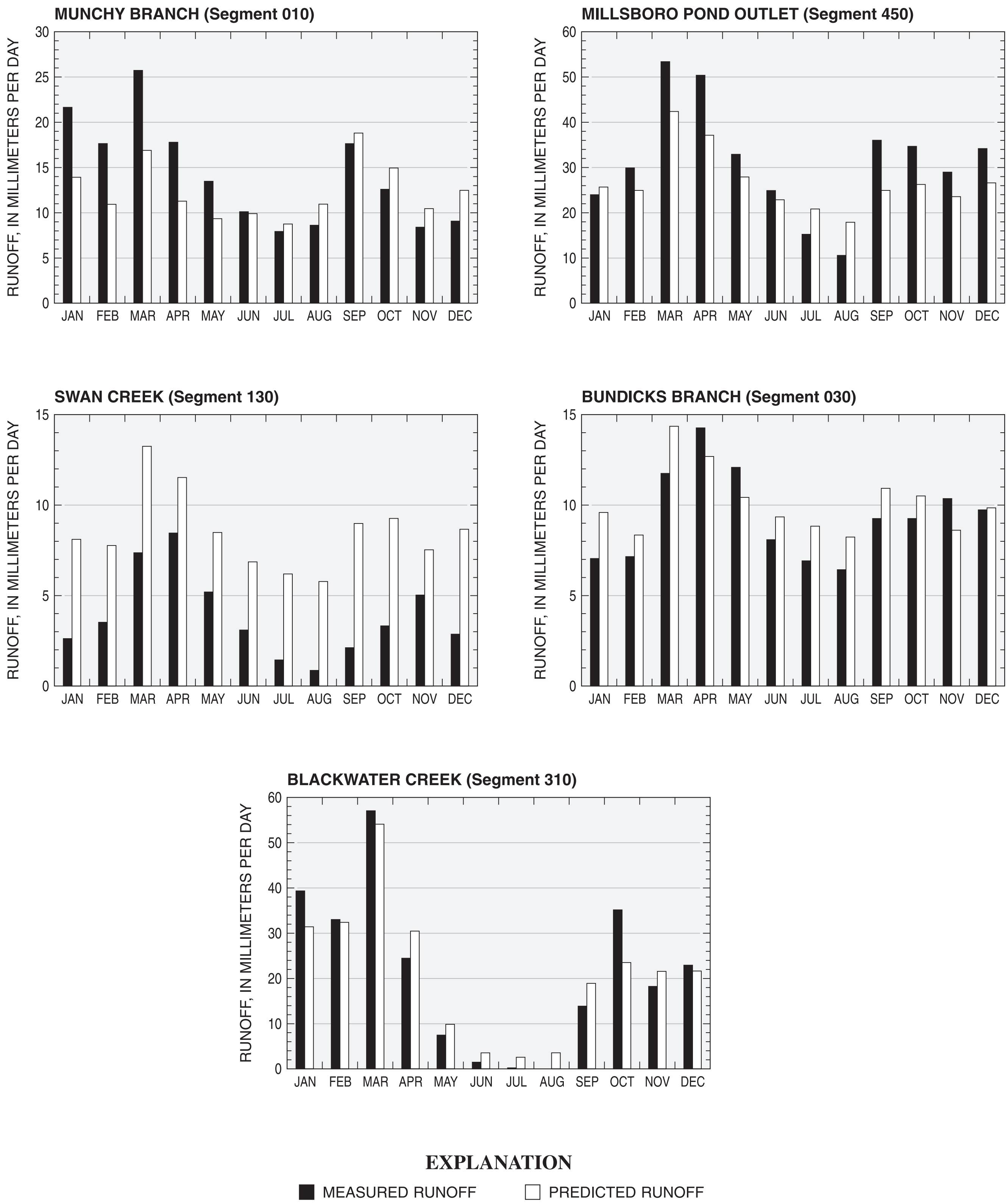

Figure 6. Monthly measured runoff at calibrated stream segments (010, 030, 130, 310, and 450) and monthly predicted runoff averaged over the recipient segments for the Delaware Inland Bays watershed during 1999. (See figure 3 for location of stream segments.)

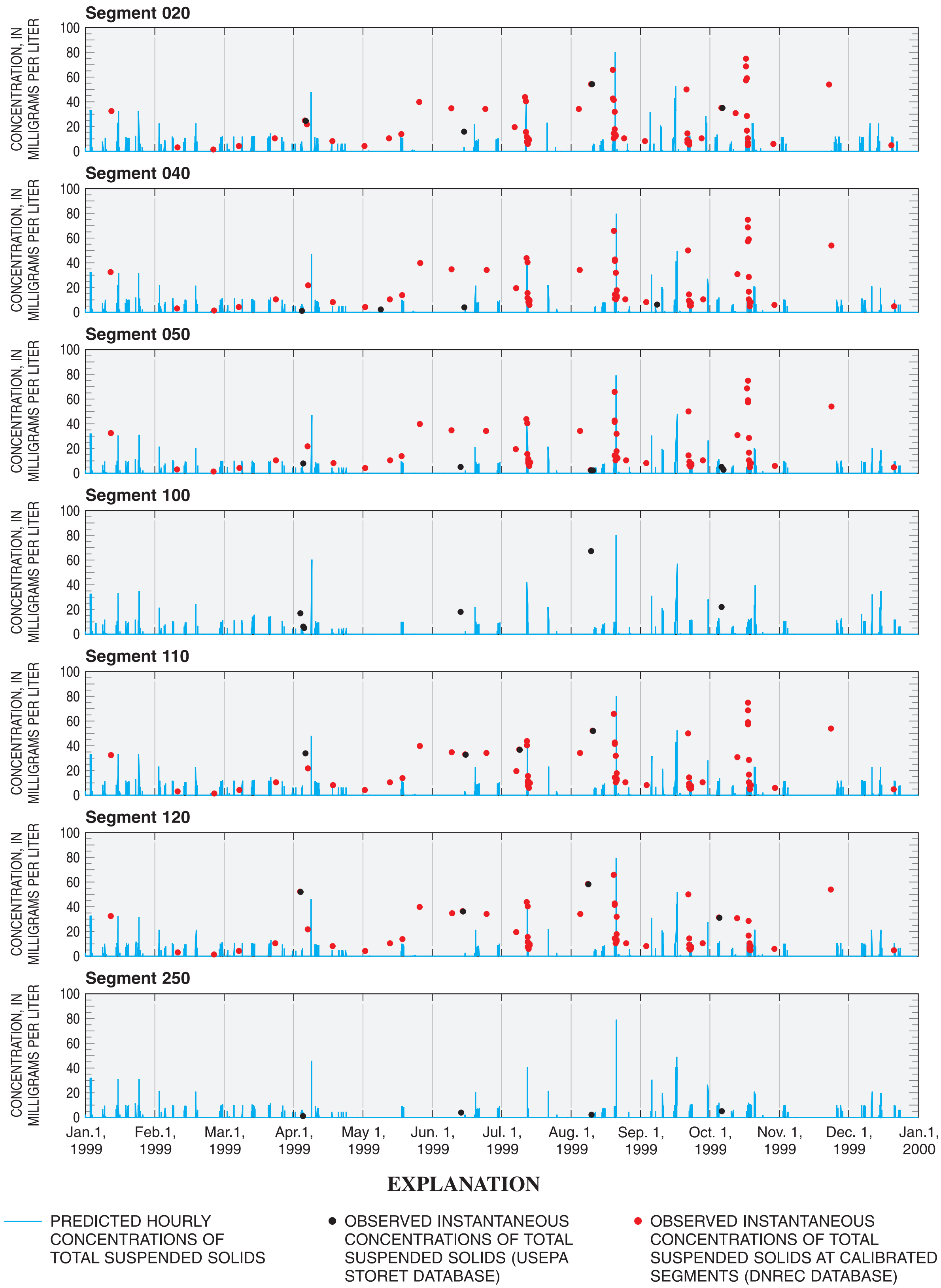

Figure 7. Simulated hourly total-suspended-solids concentrations and measured instantaneous values for the nearest calibrated basin for the Delaware Inland Bays watershed (segment source of parameter values), and U.S. Environmental Protection Agency's (USEPA) STORET database during 1999. [Delaware Department of Natural Resources and Environmental Control (DNREC)]. (See figure 3 for location of stream segments.)

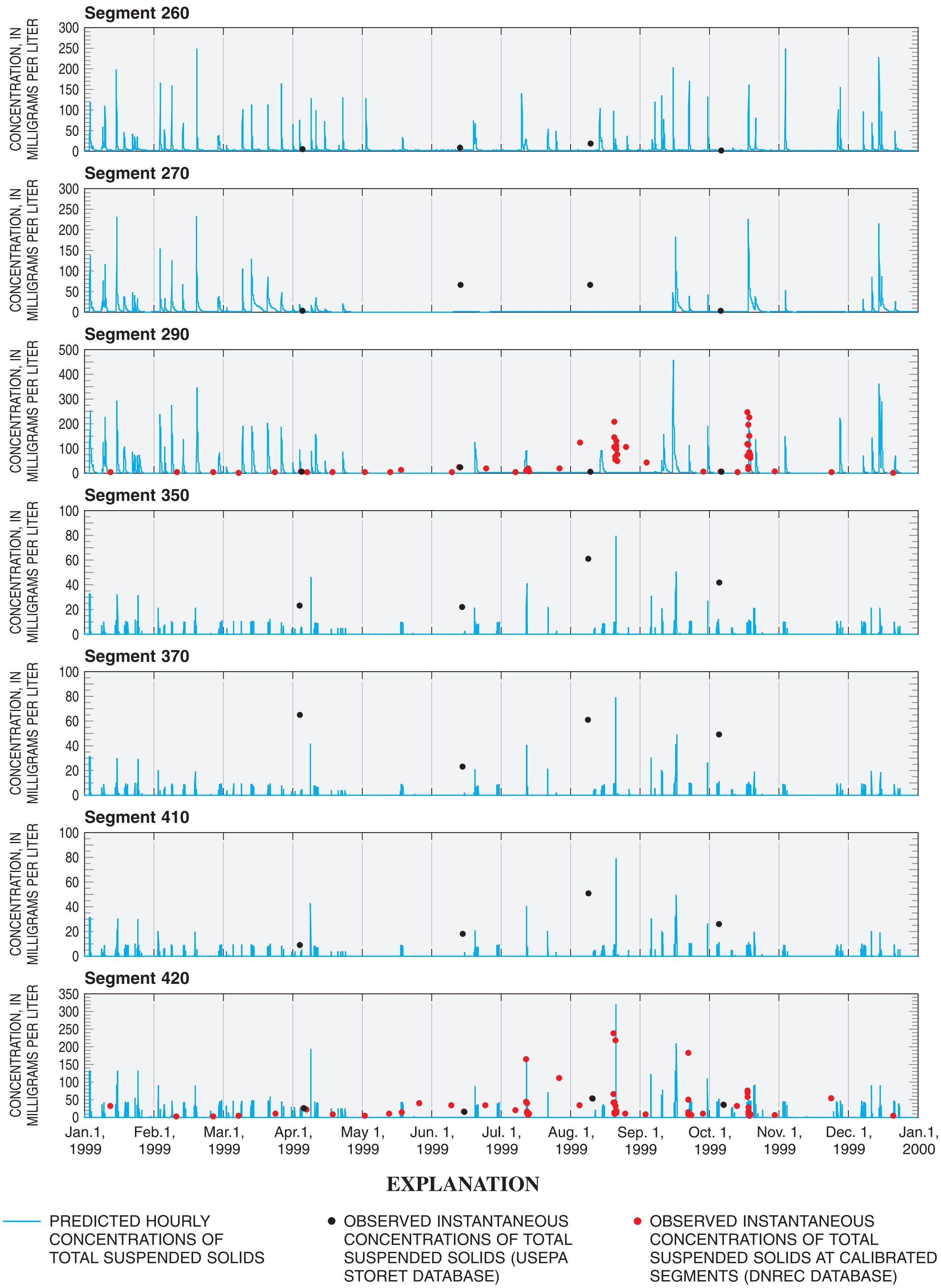

Figure 7. Simulated hourly total-suspended-solids concentrations and measured instantaneous values for the nearest calibrated basin for the Delaware Inland Bays watershed (segment source of parameter values), and U.S. Environmental Protection Agency's (USEPA) STORET database during 1999. [Delaware Department of Natural Resources and Environmental Control (DNREC)]. (See figure 3 for location of stream segments.)—Continued

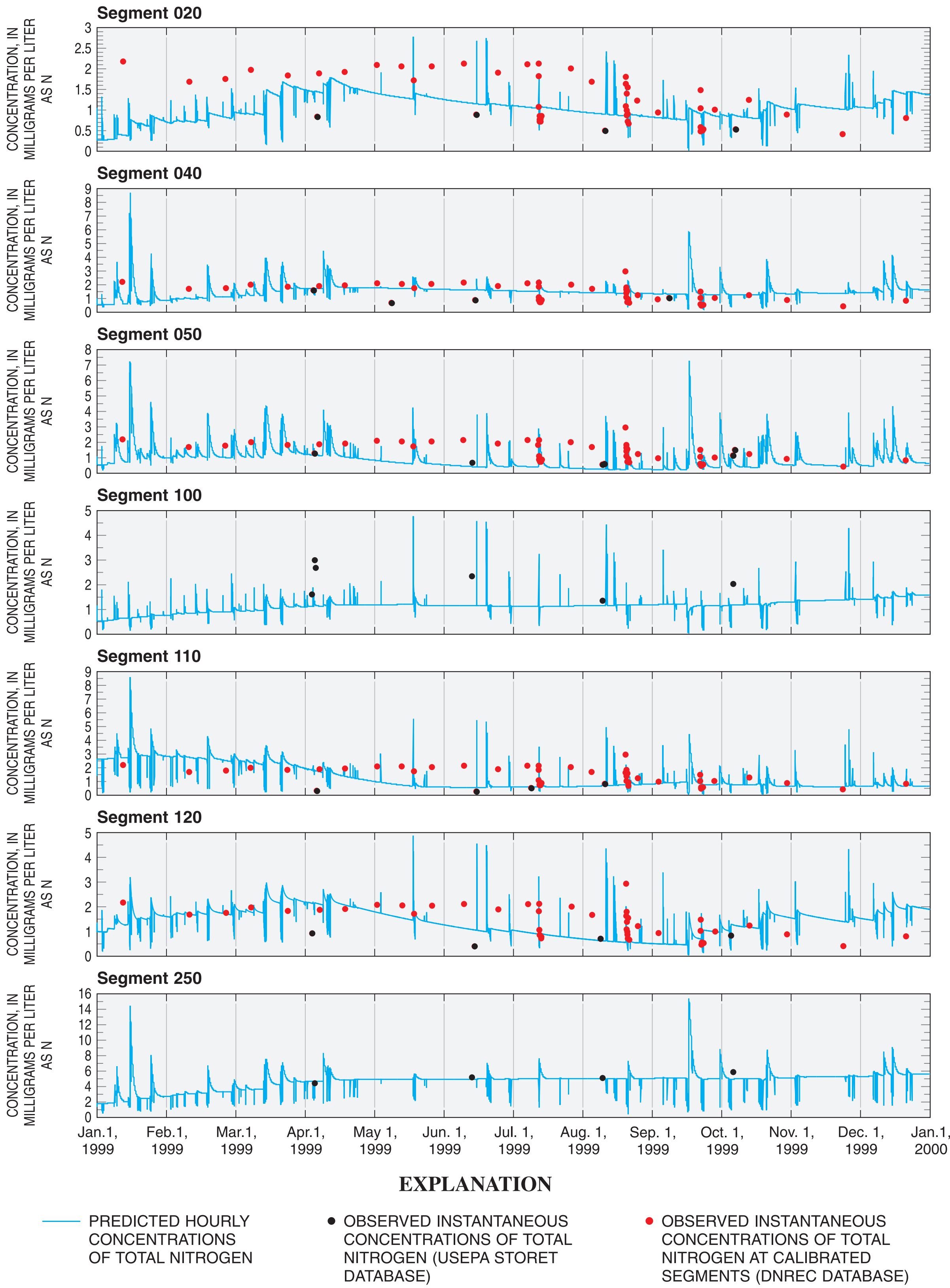

Figure 8. Simulated hourly total nitrogen concentrations and measured instantaneous values for the nearest calibrated basin for the Delaware Inland Bays watershed (segment source of parameter values), and U.S. Environmental Protection Agency's (USEPA) STORET database during 1999. [Delaware Department of Natural Resources and Environmental Control (DNREC)]. (See figure 3 for location of stream segments.)

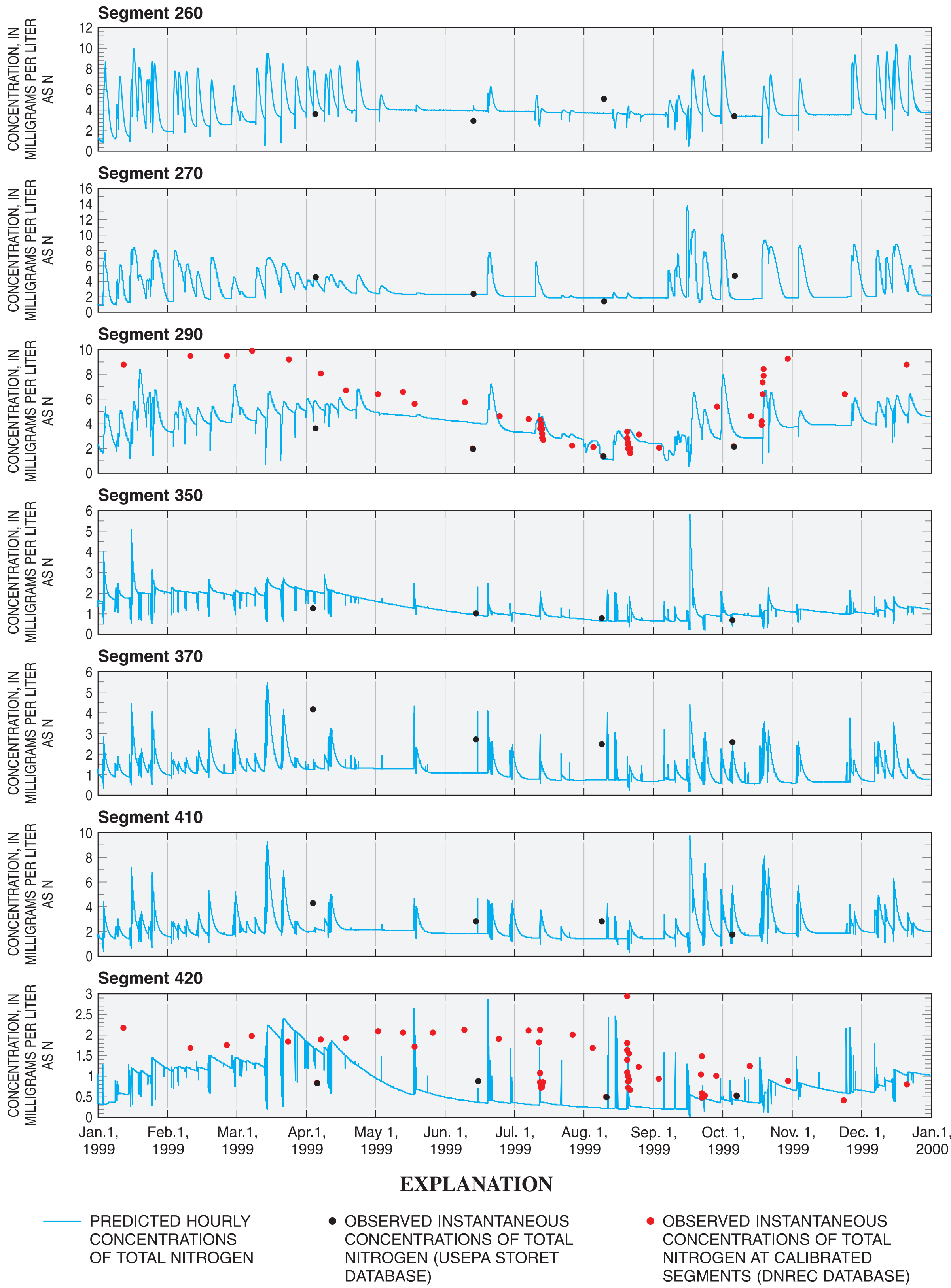

Figure 8. Simulated hourly total nitrogen concentrations and measured instantaneous values for the nearest calibrated basin for the Delaware Inland Bays watershed (segment source of parameter values), and U.S. Environmental Protection Agency's (USEPA) STORET database during 1999. [Delaware Department of Natural Resources and Environmental Control (DNREC)]. (See figure 3 for location of stream segments.)—Continued

exhibited seasonal variability, with stronger dilution rates during the spring, fall, and winter months, and lower dilution rates during the summer months. The dilution effect was also stronger for predictions in ungaged segments located in the southern part of the watershed than for those in the northern part. The contribution to TN concentrations by constituent was as follows: between 1 percent and 5 percent ammonia, between 90 percent and 95 percent nitrate, and between 5 percent and 10 percent organic nitrogen. The contribution of nitrate was higher at segments located in the lower part of the watershed and in segments where the application of organic fertilizer was higher than the recommended crop rates (U.S. Department of Agriculture, Natural Resources Conservation Service, 2000).

Nutrient applications varied by type (organic or mineral fertilizer), amount, and timing of application. The type of fertilizer applied was determined by the proximity of manure production throughout the watershed. For segments 020, 060, 070, and 110, only mineral fertilizer was applied, and the amount applied was assumed to be 110 percent of the amount necessary to meet the crop goal yield. The timing of the applications was prior to the growing season. The effect of these assumed conditions can be seen mainly in the concentrations of TN, which are generally lower in these segments than in segment 290, for example, where the nutrient application rates more noticeably exceeded the recommended amounts (U.S. Department of Agriculture, 2000).

Predicted Total Phosphorus Concentrations

Soil amendment with animal waste is a common practice in the Delaware Inland Bays watershed that introduces a substantial amount of phosphorus (P) that is present in both organic and inorganic forms. In general, 30 percent of the total P from manure applied to soils in solid or liquid forms is inorganic, mostly as orthophosphate (Hansen and others, 2004). Phosphates are strongly sorbed to clays and oxyhydroxides of iron in soils, and consequently, phosphates are resistant to leaching. Some fraction of the remaining total P in soils is available for plant uptake. Off-site transport of phosphates to surface water is therefore strongly associated with sediment that washes off during precipitation events. When the fertilizer is applied above the recommended plant uptake rates, the amount of phosphates stored in the soil will be excessive, and may be carried into surface water with storm runoff.

Time series of simulated hourly TP concentrations and measured instantaneous values are shown in (fig. 9). The contribution of inorganic P to the concentration of TP was about 35 percent in the northern segments and about 50 percent for segments located in the southern part of the watershed. During storm events, total P concentrations tended to rise sharply with average predictions of about 0.4 mg/L (segment 110). No national or state guidelines have been established for concentrations of TP in water; however, the USEPA recommends that concentrations should not exceed 0.05 mg/L in a stream at a point where it enters a lake or reservoir, and should not exceed 0.1 mg/L in streams that do not discharge directly into lakes or reservoirs (Mueller and Helsel, 1999). During storm events, these values were exceeded throughout the watershed as shown in the measured and predicted data.

Predicted Sediment and Nutrient Loads

The hydrologic conditions under which the model was calibrated (below-average precipitation) made it difficult to evaluate the predicted edge-of-stream loads by land-use class in the ungaged segments. The edge-of-stream loads and yields (table 3) for total nitrogen, total phosphorus, and total suspended sediment were computed using the predicted edge-of-stream concentrations, the predicted edge-of-stream flow yielded by model segment, and the surface area of the model segments. Due to the drought during 1998 and 1999, and to Hurricane Floyd in September 1999, the predicted loads and yields during water year 1999 may not be representative of the loads during an average water year. These conditions should be taken into consideration when using the model results to formulate load reductions or establishing programs for pollution control.

Predicted edge-of-stream loads of TSS are strongly linked to annual streamflow, and higher edge-of-stream loads of TSS were calculated in the southern watersheds than in the northern watersheds. This result is a consequence of the low permeability in the southern watersheds as well as the intense ditching, a common practice in the region to increase drainage and maintain optimum soil conditions for the crops. In the northern watersheds, higher permeability reduces the annual streamflow and thus, the potential for TSS transport.

Under the applied parameter transference criteria discussed earlier, the predicted edge-of-stream loads at the ungaged segments were affected by the annual streamflow and the application of organic fertilizer (animal waste). In water year 1999, the highest edge-of-stream loads of TN were predicted in the southern and western segments (such as segments 300 and 360), largely because of the application of organic fertilizer exceeding the recommended rates. In the case of the predicted edge-of-stream loads of TP, the pattern of higher values in the southern watersheds was not as evident as the pattern found for TSS or TN predictions. The uncertainty of these predictions is linked to the uncertainty of the calibrated parameters using extreme hydrologic conditions (in this case during drought) and the short period of calibration. It is important to emphasize that the concentrations of TP shown in figure 9, however, indicate that the predicted model concentrations of TP were within the range of measured values at nearby gaged stations.

Using the new criteria for the transference of parameter values discussed earlier, the edge-of-stream yields for TSS, TN, and TP were lower than the edge-of-stream yields calculated using the criteria based on the similarity of soils

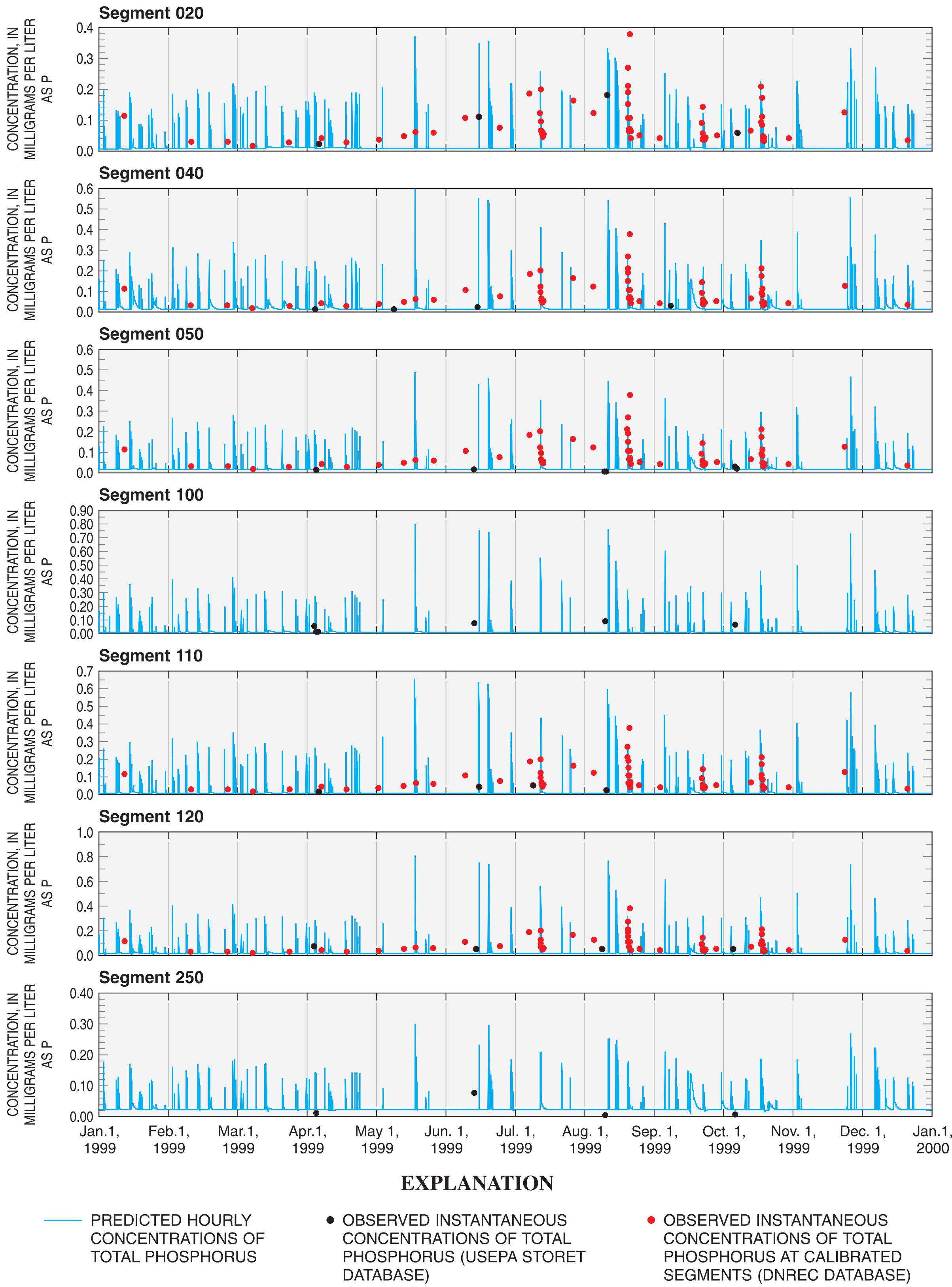

Figure 9. Simulated hourly total phosphorus concentrations and measured instantaneous values for the nearest calibrated basin for the Delaware Inland Bays watershed (segment source of parameter values), and U.S. Environmental Protection Agency's (USEPA) STORET database during 1999. [Delaware Department of Natural Resources and Environmental Control (DNREC)]. (See figure 3 for location of stream segments.)

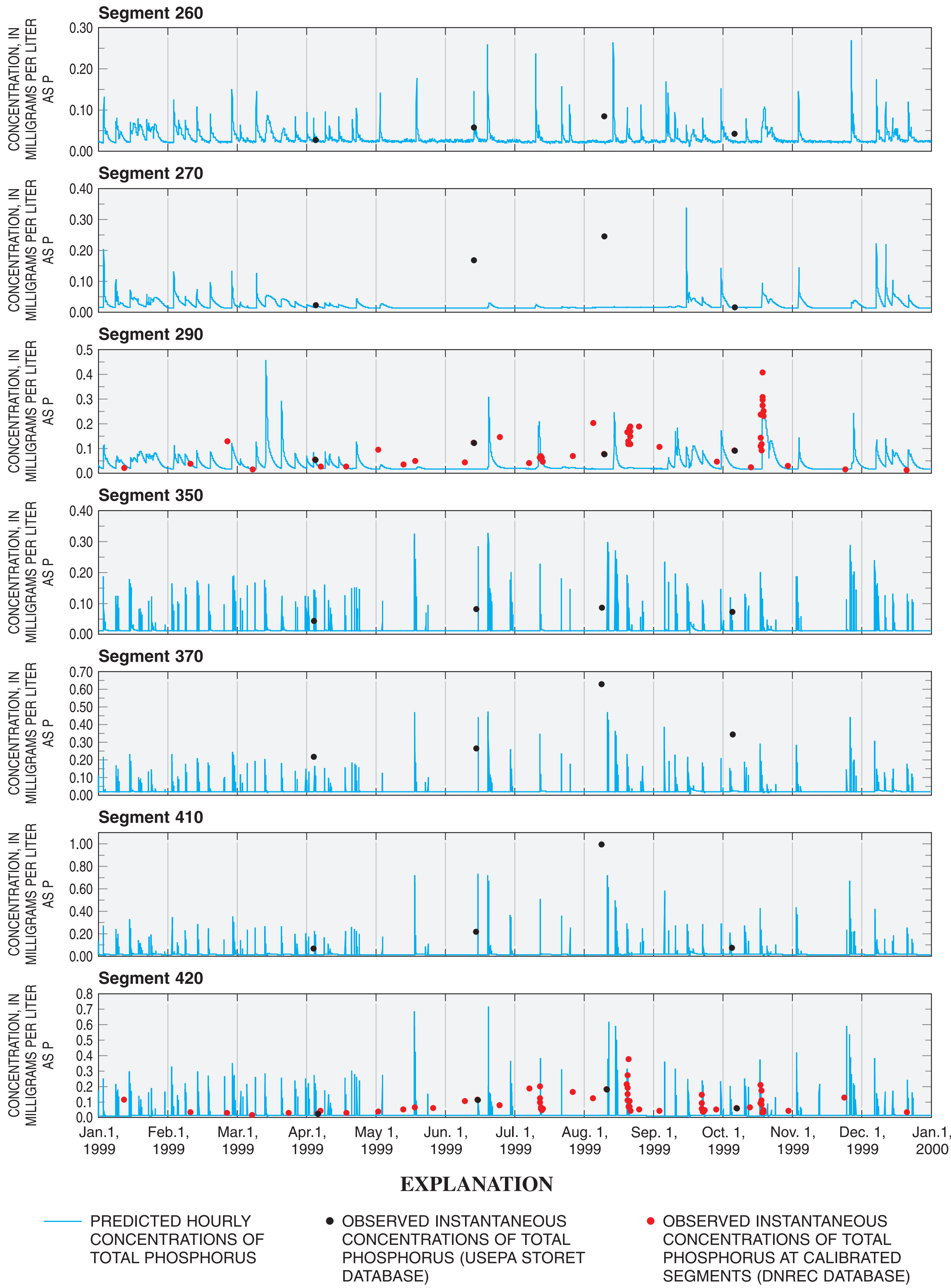

Figure 9. Simulated hourly total phosphorus concentrations and measured instantaneous values for the nearest calibrated basin for the Delaware Inland Bays watershed (segment source of parameter values), and U.S. Environmental Protection Agency's (USEPA) STORET database during 1999. [Delaware Department of Natural Resources and Environmental Control (DNREC)]. (See figure 3 for location of stream segments.)—Continued

Table 3. Predicted edge-of-stream loads and yields of total nitrogen (TN), total phosphorus (TP), and total suspended sediment (TSS) by model segment during water year 1999.

[All load values are in kilograms per year; all yield values are in kilograms per hectare per year–location of segments shown in figure 3; *, = calibrated segments]

Segment	Loads			Yields		
	TN	TP	TSS	TN	TP	TSS
010*	318	20.8	11,800	2.39	0.157	88.7
020	4,330	316	40,600	2.35	0.172	22.0
030*	6,300	86.4	104,000	3.89	0.053	64.4
040	3,790	156	14,900	1.61	0.066	6.31
050	2,940	139	13,600	1.32	0.062	6.10
060	2,450	194	23,400	1.19	0.094	11.4
070	3,860	61	3,980	2.87	0.045	2.96
080	1,940	37	2,530	2.63	0.050	3.41
090	814	55	5,630	2.00	0.135	13.8
100	3,540	184	16,100	1.82	0.095	8.30
110	746	49	5,940	1.48	0.097	11.8
120	13,200	490	42,200	4.15	0.157	13.2
130*	699	23.7	7,460	0.595	0.020	6.36
140	28,300	353	64,200	13.5	0.169	30.7
150	10,500	199	40,400	9.68	0.183	37.2
160	11,600	169	41,700	11.6	0.169	41.7
170	9,680	226	54,900	7.77	0.182	44.0
180	11,600	246	37,600	10.0	0.211	32.3
190	7,680	234	47,100	8.92	0.272	54.8
200	28,700	388	61,600	14.1	0.191	30.3
210	14,700	280	43,000	8.33	0.159	24.4
220	12,600	287	40,700	9.06	0.206	29.2
230	8,630	149	29,200	11.3	0.194	38.1
240	5,480	124	17,000	11.9	0.270	37.0
250	2,910	75	5,200	1.95	0.050	3.48
260	39,800	244	132,000	20.1	0.123	66.7
270	40,700	178	68,900	28.0	0.122	47.3
280	14,600	208	130,000	6.48	0.092	57.4
290	41,200	229	174,000	19.7	0.110	83.3
300	32,900	325	406,000	6.25	0.062	77.1
310*	14,200	263	33,100	15.8	0.293	36.8
320	8,310	223	19,800	4.28	0.115	10.2
330*	11,000	605	124,000	17.3	0.948	194
340	19,100	297	31,800	8.08	0.125	13.5
350	4,170	89	9,340	4.73	0.101	10.6
360	37,200	1,140	354,000	21.1	0.649	201
370	4,944	257	16,800	1.83	0.095	6.22
380	797	46	5,480	2.62	0.151	18.0
390	4,190	188	23,600	3.51	0.157	19.7
400	696	37	4,490	0.89	0.047	5.72
410	1,660	103	7,360	1.61	0.100	7.12
420	5,380	489	226,000	1.25	0.114	52.6
440	1,430	143	16,500	2.81	0.281	32.5
450*	13,900	520	89,000	7.76	0.290	49.6
470	2,800	111	51,100	2.33	0.092	42.6

between gaged and ungaged segments (Gutiérrez-Magness and Raffensperger, 2003). Although it is difficult to state that the new yields are better estimates of the actual values, the verification of the predicted model concentrations of TSS, TN, and TP with monitoring data from nearby sites (fig. 7, fig. 9), indicate that these estimates may provide better approximations of the annual yields (kilograms per hectare) under drought conditions. The recalculated and updated values by model segment are shown in the maps in Appendix A.

Summary and Conclusions

Rapid population increases, agriculture, and industrial practices have been identified as important sources of excessive nutrients and sediments in the Delaware Inland Bays watershed. A cooperative study was established in 2000 by the Delaware Department of Natural Resources and Environmental Control, the Delaware Geological Survey, and the U.S. Geological Survey for the development of the Delaware Inland Bays watershed model in order to estimate nutrient and sediment concentrations and loads in the watershed. The study was extended to evaluate the model predictions in ungaged segments and to ensure that the model developed in 2003 as a planning and management tool could accurately predict nutrient and sediment concentrations within the measured range of values in ungaged segments. The evaluation required analyses on the method of transferring parameter values from calibrated to uncalibrated model segments. The U.S. Geological Survey used a well-documented model, Hydrological Simulation Program–FORTRAN (HSPF) for the analyses. Water-quality data for streams within the Inland Bays watershed were retrieved from the U.S. Environmental Protection Agency's STORET database to supplement the Inland Bays Total Maximum Daily Loads database and used for the validation of model predictions in ungaged segments. The primary objective when comparing the predicted edge-of-stream concentrations at ungaged segments to the measured in-stream concentrations at the calibrated segments, or at streams within or near the ungaged model segments, was to guarantee that the model predictions were within the range of the observations, rather than to have a perfect match between the individual predicted and measured values.

The ungaged segments were grouped into five sets for the transfer of parameter values. For purposes of model validation, the monthly and annual water balances at the source segments were compared with the average of the monthly and annual water balances for the corresponding recipient segments. Higher streamflow was measured in the southern part of the watershed than in the northern part. The predicted annual water balances of the recipient segments using parameters from calibrated segments 010, 030, 310, and 450 were within 25 percent of the measured values. When using parameters from segment 130, considerable difference between the measured and predicted average annual streamflow for the recipient segments may be explained by the reduction of the parameter controlling deep percolation and by the parameters controlling evapotranspiration. This change to the parameter values was in response to the high predicted concentrations of ammonia and phosphate during the summer season, and due to zero predicted flow in the ungaged segments. The monthly water balances for the groups using parameters from segments 010, 030, 310, and 450 showed good agreement, with most predicted values within 35 percent of the measured values. Seasonality in the predicted edge-of-stream flow and the predicted streamflow was well represented in the model, although some overpredictions resulted during the summer season. This overprediction was also observed for the streamflow of the calibrated segments.

The highest total-suspended-solids concentrations were predicted in segments 300, 420, and 360, which coincide with areas of low permeability and the highest annual runoff: 507 millimeters per year, 341 millimeters per year, and 328 millimeters per year, respectively; all had high sediment concentrations associated with edge-of-stream storm runoff.

Temporal and spatial patterns in nutrient concentrations throughout the watershed indicate that the amount of animal waste in kilograms per hectare per year applied in the agricultural land use within each of the ungaged segments exerts a dominant control on the variations in concentrations and loads. For segments where the nutrient application for particular crops was above the recommended rate (120, 280, 300, 320, and 340), the predicted nutrient loads were higher than in segments where the recommended application in kilograms per hectare per year was not exceeded. Except for segment 120, located in the northern part of the Inland Bays watershed, the higher streamflow predicted in segments located in the southern area was also a factor in the higher predicted loads.

Time series of simulated hourly total nitrogen and phosphorus concentrations and measured instantaneous values indicate seasonality in the measured and simulated concentrations for total nitrogen, with the lowest values during the summer and the highest values during the winter months. Phosphorus concentrations were less seasonal than nitrogen concentrations. In general, total phosphorus concentrations during base flow 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 largely through ground water, whereas phosphorus is strongly associated with sediment, which washes off during precipitation events.

Acknowledgments

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Appendix A. Recalculated and Updated Yields by Model Segment

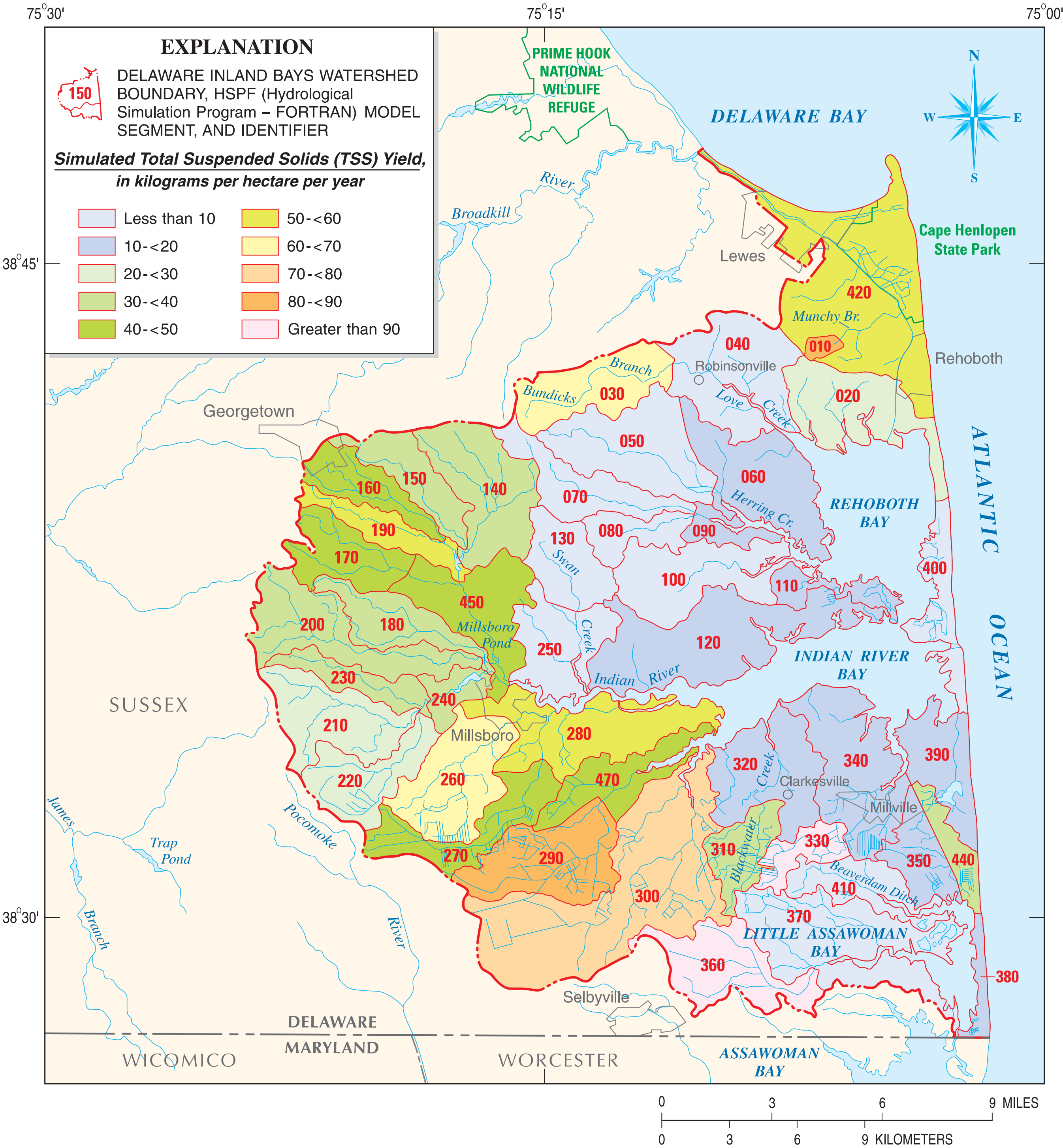

Figure A–1. Simulated total suspended solids yield during water year 1999 by model segment for the Delaware Inland Bays watershed model (modified from Gutiérrez-Magness and Raffensperger, 2003).

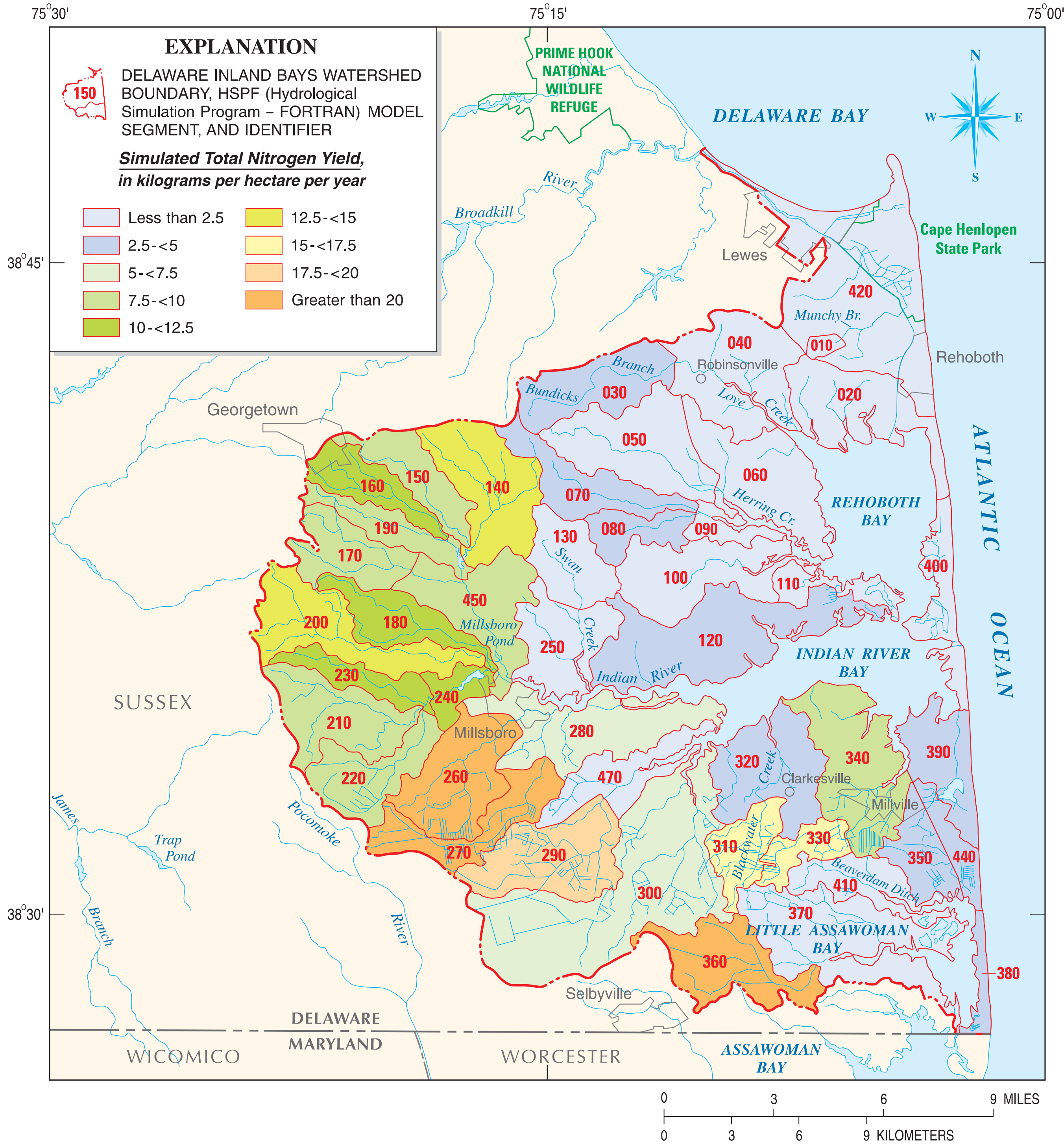

Figure A–2. Simulated total nitrogen yield during water year 1999 by model segment for the Delaware Inland Bays watershed model (modified from Gutiérrez-Magness and Raffensperger, 2003).

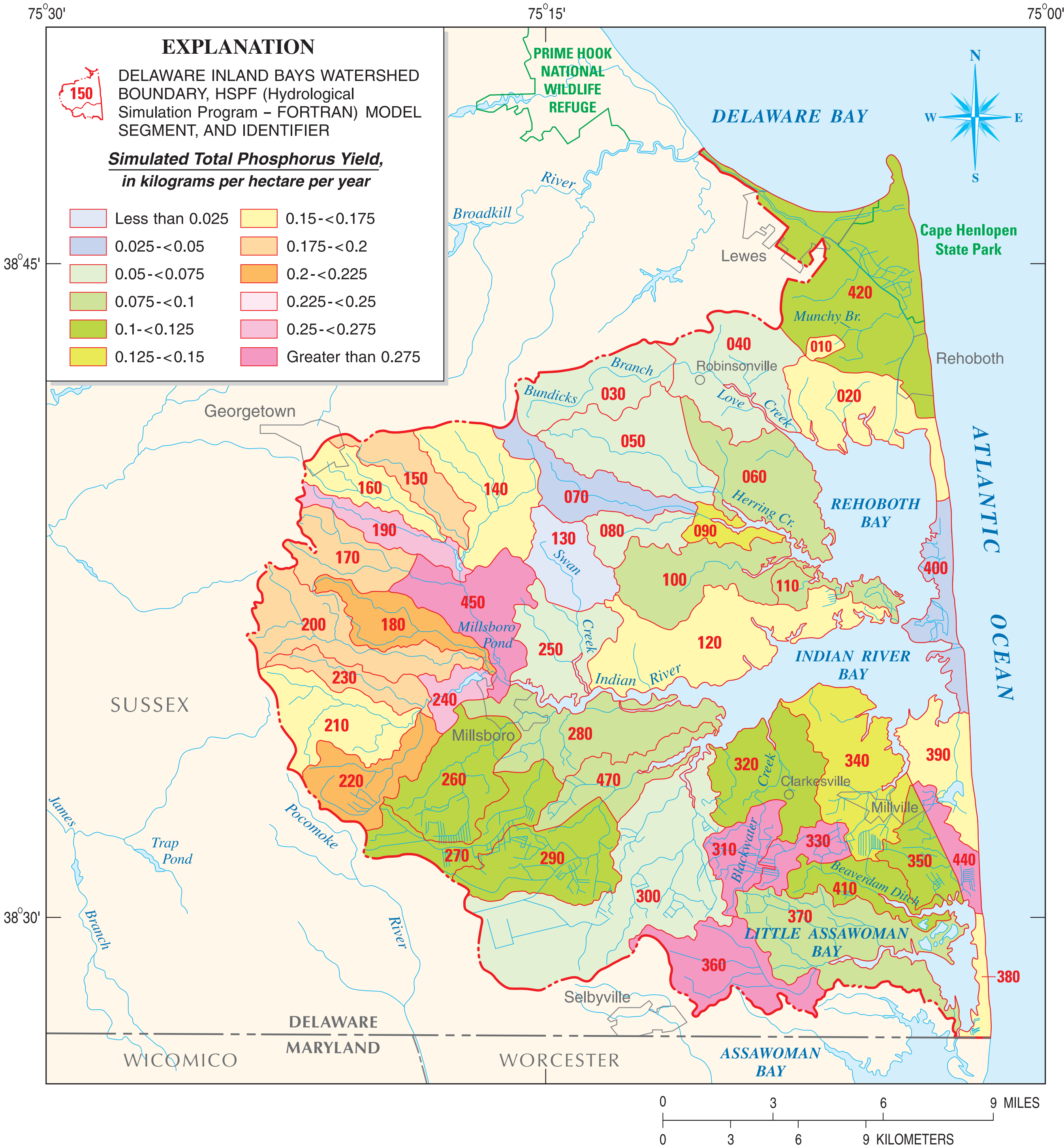

Figure A–3. Simulated total phosphorus yield during water year 1999 by model segment for the Delaware Inland Bays watershed model (modified from Gutiérrez-Magness and Raffensperger, 2003).

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