CROSS-MEDIA MODELS OF THE CHESAPEAKE BAY WATERSHED AND AIRSHED

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ABSTRACT: A continuous, deterministic watershed model of the Chesapeake Bay watershed, linked to an atmospheric deposition model is used to examine nutrient loads to the Chesapeake Bay under different management scenarios. The Hydrologic Simulation Program - Fortran, Version 11 simulation code is used at an hourly time-step for ten years of simulation in the watershed. The Regional Acid Deposition Model simulates management options in reducing atmospheric deposition of nitrogen. Nutrient loads are summed over daily periods and used for loading a simulation of the Chesapeake estuary employing the Chesapeake Bay Estuary Model Package. Averaged over the ten-year simulation, loads are compared for scenarios under 1985 conditions, forecasted conditions in the year 2000, and estimated conditions under a limit of technology scenario. Limit of technology loads are a 50%, 64%, and 42 % reduction from the 1985 loads in total nitrogen, total phosphorus, and total suspended solids, respectively. Urban loads, which include point source, on-site wastewater disposal systems, combined sewer overflows, and nonpoint source loads have the highest flux of nutrient loads to the Chesapeake, followed by crop land uses.

Keywords: *watershed model, airshed model, watershed management, water pollution control, water quality, Chesapeake Bay, HSPF*

INTRODUCTION

Cross-media models examine movement of material or energy among air, land, and water. Results from the integration of models simulating different media are used to elucidate complexities like eutrophication of coastal waters through atmospheric deposition, or to closely examine nutrient sources to a water body from an airshed and watershed. The cross-media models of the Chesapeake Bay consist of three major elements; the Regional Acid Deposition Model (RADM) of the Chesapeake

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airshed, the Chesapeake Bay Watershed Model (WSM), and the Chesapeake Bay Estuary Model Package (CBEMP) (Fig. 1). These models are linked since the state variable output from one model is used as the state variable input to another. For example, the nitrogen output from RADM affects the nitrogen input from atmospheric deposition to the WSM, which in turn simulates nitrogen loads to the CBEMP. The WSM transports the total nutrient load, including the contributions from atmospheric deposition with associated terrestrial and lotic transformations, to the tidal Chesapeake, the boundary of the WSM and CBEMP domains.

Physical Description

The Chesapeake Bay watershed covers portions of six mid-Atlantic States, including New York, Pennsylvania, West Virginia, Maryland, Delaware, and Virginia (Fig. 2). Land uses in 1990 in the 166,000 square kilometer watershed are estimated to be 57% forest, 16% cropland, 8% pasture, 18% urban or developed land, and 1% of land in rivers and lakes. Forests are the predominate land use in the Appalachian Highland region, placing the highest density of forest areas in the western, southwest, and northwest regions of the Chesapeake watershed. Agriculture is generally located on the Coastal Plain, in the Piedmont region, and in the valleys of the Appalachian Highlands and Ridge and Valley region. Urban and developed land use includes the southern portion of the Boston to Washington, D.C. megalopolis and is predominately located close to the Bay relative to other land uses. In particular, the metropolitan areas of Baltimore, Washington, and Richmond are found on the fall line between the Piedmont and Coastal Plain regions.

The Chesapeake Bay, like many East and Gulf Coast estuaries, is eutrophic. Excessive nutrient loading has increased the bottom area of anoxic and hypoxic bottom waters of the Bay 15 fold since 1950 (*Chesapeake Bay Program 1983*) and has caused significant declines in the area and density of submerged aquatic grasses since the 1960s and 1970s (Chesapeake Bay Program 1982).

MODEL STRUCTURE AND CALIBRATION

Airshed Model

The Regional Acid Deposition Model (RADM) is designed to provide estimates of nitrogen deposition resulting from changes in precursor emissions due to management actions or growth, and to predict the influence of source loads from one region on deposition in other regions (Chang et al. 1987). The model solves a series of conservation equations in the following form:

$$\partial C/\partial t = \nabla VC + \nabla (k_e \nabla C) + P_{chm} - L_{chm} + E + (\partial C/\partial t)_{cloud} + (\partial C/\partial t)_{dry}$$

where C = nitrogen species mixing ratio; V = three dimensional velocity vector at each grid point; k_e = eddy diffusivity; P_{chm} = chemical production of nitrogen species; L_{chm} = chemical loss of nitrogen species; E = nitrogen oxide, ammonia, and other oxidant precursor emission rate; $(\partial C/\partial t)_{cloud}$ = sub-grid cloud vertical transport, scavenging, and aqueous reactions; and $(\partial C/\partial t)_{dry}$ = dry deposition.

FIG. 1. Cross-Media Models of the Chesapeake Bay Airshed, Watershed, and Estuary

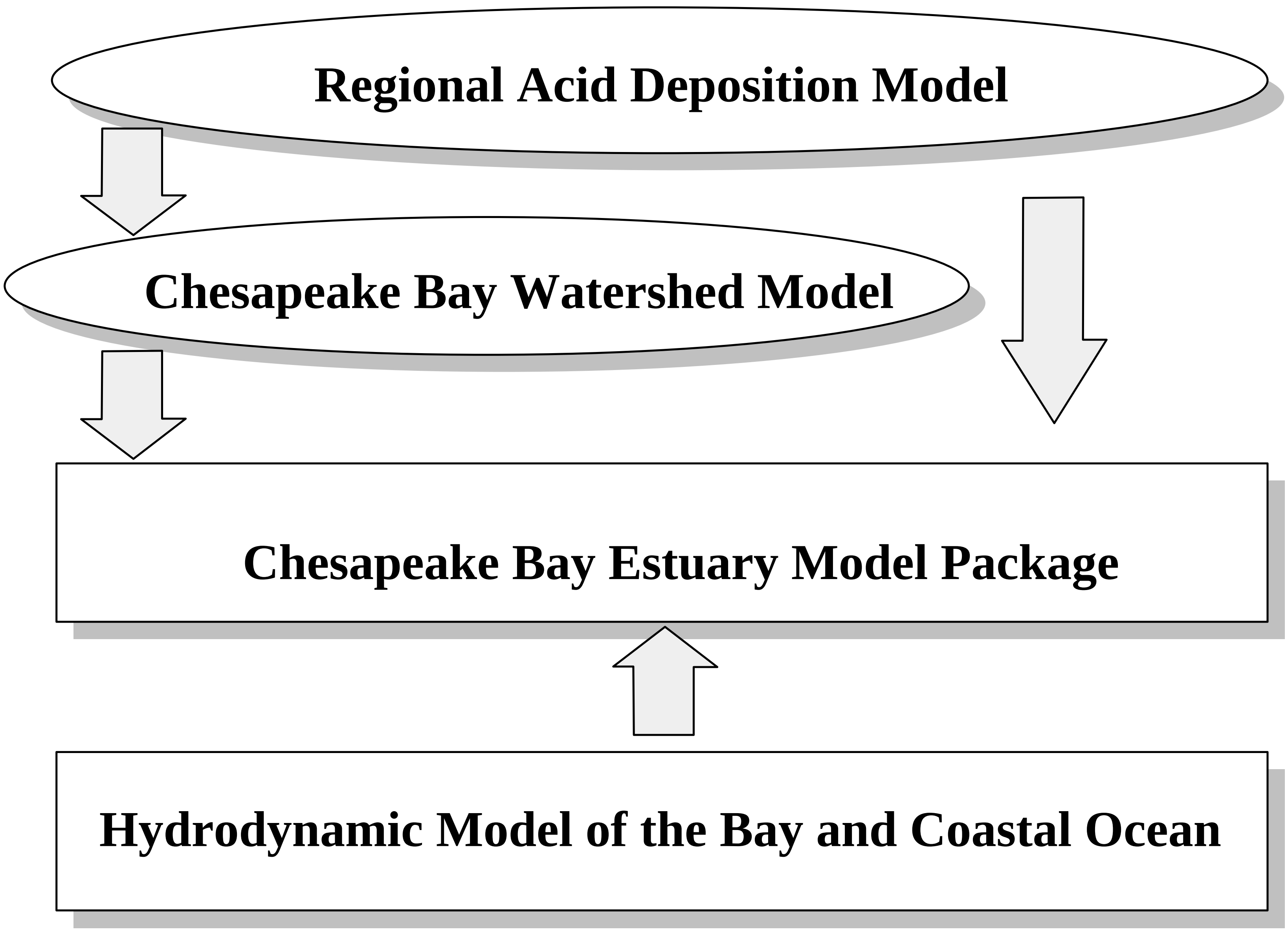
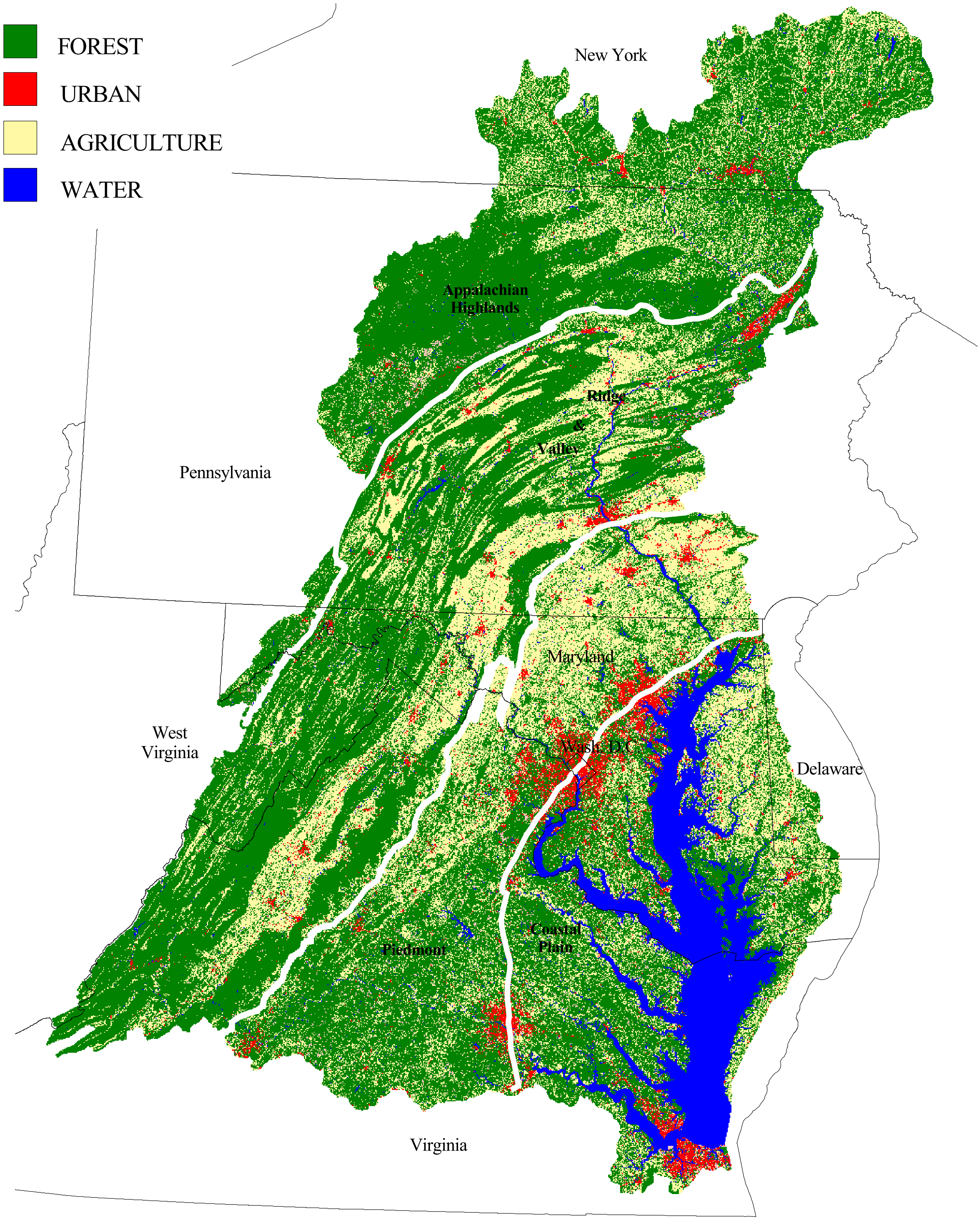


FIG. 2. Land Uses, Physiographic Provinces, and States of the Chesapeake Bay Watershed.



CBPO GIS Team: 11-30-99

Understanding and modeling nitrogen deposition requires consideration of a complex range of physical and chemical processes and their interactions, including 1) the emission of precursor chemicals that produce and regulate atmospheric deposition of nitrogen, 2) meteorological processes, including clouds, that transport and mix emitted nitrogen deposition precursors and the depositing nitrogen species, 3) physical and chemical transformations of nitrogen deposition precursors, and 4) meteorological factors and surface feature properties that lead to nitrogen deposition.

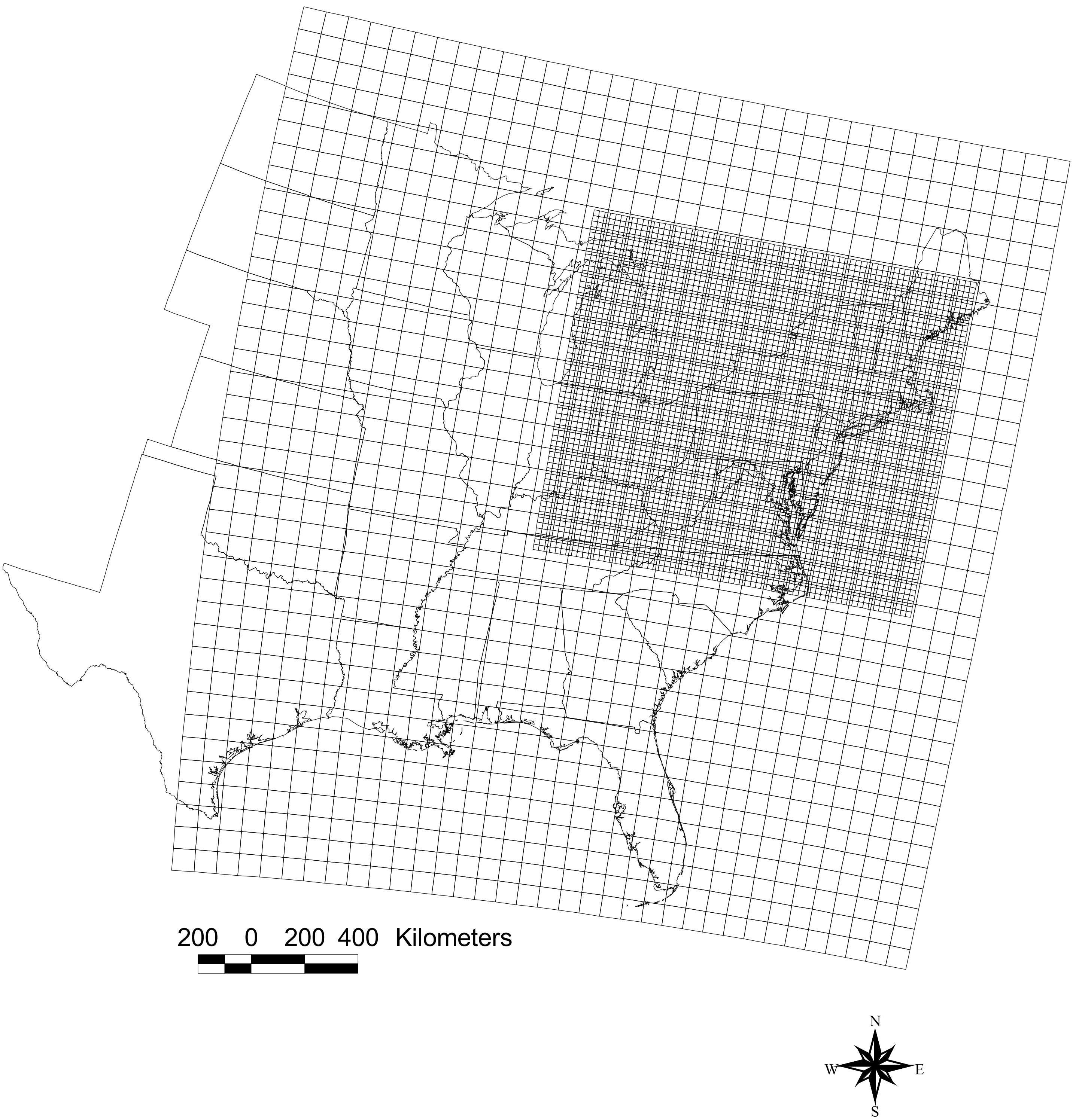
The RADM is a Eulerian model in which the concentrations of gaseous and particulate species are calculated for specific fixed positions in space (grid cells) as a function of time. The concentrations of nitrogen species in a grid cell at a specific time are determined by the emission input rates as well as three-dimensional advective transport, dry deposition rates, turbulent transport, chemical transformations, scavenging, and precipitation.

The version of RADM described in this paper, RADM 2.61, encompasses a geographic domain of 2,800 by 3,040 km (Dennis 1996) (Fig. 3). Coverage in the eastern U.S. is from longitudes of about central Texas to Bermuda and latitudes from south of James Bay, Canada to Florida, inclusive. Grid cells are 80 km by 80 km with 15 vertically layered cells logarithmically placed from ground level to the top of the troposphere, an altitude of 16 km. The total number of cells in the model domain is 19,950 (Chang et al. 1990). Over the regions of the mid-Atlantic states and the Chesapeake Bay watershed, the RADM contains a finer grid of 20 by 20 km cells nested into the larger grid, allowing finer spatial distribution of nitrogen deposition.

The chemistry that is simulated by the model consists of 140 reactions among 60 species, 40 of which are organic compounds. Photolysis and oxidant photochemistry is included in the simulation as are aqueous phase reactions which occur in clouds. Emissions are input to a completely mixed grid cell on an hourly time step. Emissions include nitrogen oxides from anthropogenic fuel combustion, soil biological processes, and ammonia. Simulation is with dynamically determined time steps of seconds to minutes and model output is on an hourly basis. Forty one of the longer-lived chemical species are transported between model cells. Hourly wet and dry deposition values are calculated for each surface cell. The key nitrogen species that are simulated include: 1) ambient concentrations of nitric oxide (NO), nitrogen dioxide (NO_2), nitric acid (HNO_3), ammonia (NH_3), and peroxyacetylnitrate (PAN); 2) wet deposition components of nitrate (NO_3^-), nitric acid, and ammonia; and 3) dry deposition components of nitric acid and nitrogen dioxide.

Meteorological fields used for advective transport and meteorological conditions for RADM chemistry are from the Pennsylvania State University National Center for Atmospheric Research Mesoscale Model (MM4). The MM4 is a weather model used to recreate detailed meteorology. In these simulations, MM4 provides RADM with a total of 30 five-day simulations representing an annual average meteorology and atmospheric deposition pattern (Dennis et al. 1990; Brook et al. 1995a,b).

FIG. 3. RADM Domain Grid and Fine Scale Nested Grid for the Chesapeake Bay Watershed



Atmospheric Deposition Loads

While RADM provides estimates of atmospheric deposition due to growth or management of atmospheric emissions, a base data set of atmospheric deposition is needed to provide a continuous ten-year time series of daily atmospheric deposition loads to the WSM and CBEMP. A base data set of daily inputs of wet deposition of nitrate and ammonia is developed through a regression model using 8 years of National Atmospheric Deposition Program (NADP) data for 15 stations in the Chesapeake watershed area. The use of a base data set allows for daily estimates of wet deposition loads in the ten-year simulation of the WSM, which are modified by RADM for specific scenarios that account for reductions in atmospheric deposition. The regression is based on precipitation amounts, the month of the year, and latitude.

Concern over the weekly sampling protocol of NADP and possible difficulties in nitrogen speciation led to a screening procedure to eliminate all samples except those which represented rainfall events in the last 24 hours before the sample was analyzed. Screening reduced the sample pool from approximately 5,000 data observations to 265. Using these data, the following regressions are developed:

$$[NO_3] = 0.226 * e^{(-0.3852 * \ln(ppn) - 0.0037 * M**2 + 0.744 * L - 1.289)}$$

$$[NH_4] = 0.7765 * e^{(-0.3549 * \ln(ppn) + 0.3966 * M - 0.0337 * M**2 - 1.226)}$$

where [ ] = concentration in mg/l as N; ppn = precipitation in mm; M = month expressed as an integer; and L = latitude of the centroid of the precipitation segments in decimal degrees.

The concentration calculated by the regression is applied to the volume of precipitation, calculated for each model segment through the Thiessen polygon method, to develop a daily load in kg/ha-day for wet nitrate and ammonia deposition. Table 1 compares annual regression calculations of atmospheric deposition loads for wet nitrate and ammonia deposition to the NADP observed data (Valigura et al. 1996).

As few observations of dry nitrate deposition exist, ratios of wet to dry nitrate calculated by the RADM model are used to determine the dry flux. This ratio is representative of long-term meteorological averages. The RADM ratios of wet/dry nitrate range from 1.18 to 0.84 among WSM segments, with higher ratios generally occurring in segments in the Appalachian Highlands, possibly due to orographic precipitation. For each WSM segment, the RADM wet to dry ratio is applied to the long-term nitrate wet deposition record to develop a constant daily dry deposition rate. Analysis of CASTNet data shows that the inter-annual variability of dry deposition is relatively small. In tidal waters of the Bay, an over-water monitoring site on Smith Island is used. Dry nitrate deposition at this site is about 0.3 of the wet deposition, and all deposition rates to tidal waters are set at this flux.

TABLE 1. Observed Versus Calculated Nitrogen Species Yearly Deposition

NADP Station (1)	NO_3 NADP Observed (kg/ha-yr) (2)	NO_3 Regression Calculated (kg/ha-yr) (3)	NH_4 NADP Observed (kg/ha-yr) (4)	NH_4 Regression Calculated (kg/ha-yr) (5)
Penn State, PA	4.06	4.15	1.95	2.18
Leading Ridge, PA	4.55	4.29	2.23	2.27
Milford, PA	4.34	4.50	1.85	2.28
White Rock, MD	3.70	3.53	2.05	2.03
Wye, MD	3.22	3.31	1.91	1.98
Charlottesville, VA	3.53	3.29	1.98	2.16
Chautauqua, NY	4.29	4.15	2.56	1.92
Jasper, NY	2.83	3.81	1.55	1.86
Babcock State Park, WV	3.26	4.06	1.73	2.59
Parsons, WV	4.62	4.66	2.28	2.73
Lewiston, NC	2.35	3.03	1.56	2.30
Finely Farms, NC	2.43	2.77	2.35	2.14

Atmospheric loads of inorganic phosphate, organic phosphate, and organic nitrogen are obtained from two state-operated atmospheric stations in Maryland. An aeolian source is assumed for phosphorus and organic nitrogen atmospheric inputs. Phosphorus and organic nitrogen atmospheric loads are simulated as a flux only to water surfaces because aeolian inputs and outputs are assumed to be in balance on land surfaces.

When used for scenarios which have reduced emissions and subsequent deposition in the Chesapeake watershed, RADM information on nitrogen emission reductions is applied to the WSM through a proportional method. The relative seasonal percent change in the RADM scenario deposition, compared to the RADM reference deposition, is calculated for each RADM surface 20 km x 20 km cell, and this factor is applied to the WSM nitrogen deposition input. That is, if the RADM simulates a 50% reduction in atmospheric deposition to a WSM segment, the WSM will apply a 50% reduction in nitrogen deposition derived from the regression of NADP observed data.

Watershed Model

The WSM has been in continuous operation at the Chesapeake Bay Program since 1982 and has had many upgrades and refinements since that time. The WSM described in this paper is application Phase 4.2, based on the Hydrologic Simulation Program - Fortran (HSPF) Version 11 (Bicknell, et al.1996). HSPF is a widely used public domain model supported by the U.S. Environmental

Protection Agency, U.S. Geological Survey, and U.S. Army Corps of Engineers.

The WSM calculates nutrient and sediment loads delivered to the Chesapeake Bay from all areas of the watershed (Donigian et al. 1994; Linker et al. 1996; Linker 1996; Thomann et al. 1994). Land uses of cropland, pasture, urban areas, and forests are simulated on an hourly time step tracing the fate and transport of input nutrient loads from atmospheric deposition, fertilizers, animal manures, and point sources. The ultimate fate of input nutrients is simulated so that they are either incorporated into crop or forest plant material, incorporated into soil, or discharged to a river and the Bay. Nitrogen fates include volatilization into the atmosphere and denitrification. [Sediment is simulated as eroded material washed off land surfaces and transported to the tidal Bay.] Scenarios are run for ten years (1985 to 1994) on a one hour time step, and results are aggregated into daily loads and flows to be used as input to the CBEMP or into ten-year average loads for comparison among scenarios.

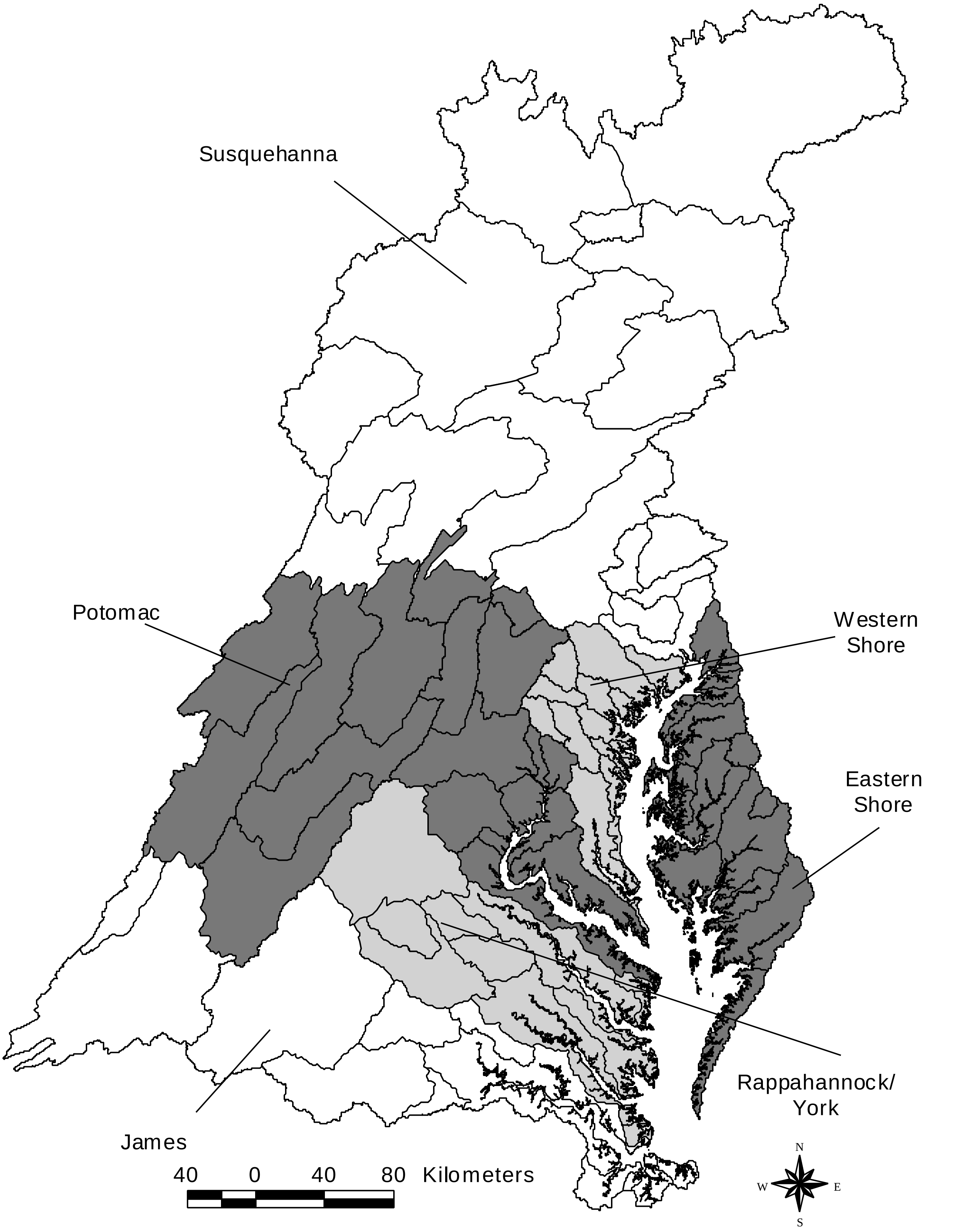
To simulate the delivery of nutrients and sediment to the Bay, the watershed is divided into 89 major model segments, with an average segment area of 187,000 hectares (Fig. 4). Segmentation partitions the watershed into regions of similar characteristics based on three tiers of criteria. The first criterion is the segmentation of similar geographic and topographic areas along hydrologic boundaries. These areas are further delineated in terms of soil type, soil moisture holding capacity, infiltration rates, and uniformity of slope. The second criterion is that bankful channel travel time of each segment is about 24-72 hours (Hartigan 1983). The third criterion used to further delineate segments is based on features of the river reach such as the location of reservoirs or monitoring stations.

Model segments are located so that segment outlets are as close as possible to a monitoring station. Water quality and discharge data are obtained from Federal and state agencies, universities, and other organizations that collect information at multiple and single land use sites (Langland et al. 1995). At the interface of the WSM and CBEMP domains, model segments are further divided into 259 subsegments to deliver flow, nutrient, and sediment loads to appropriate areas of the tidal waters.

Nutrient and sediment loads from the following nonpoint sources are simulated: conventional-tilled cropland, conservation-tilled cropland, cropland in hay, pasture, pervious urban land, impervious urban land, forest, animal waste areas, and atmospheric deposition directly to water surfaces. Sediment from all pervious land surfaces is simulated using an empirically-based module (SEDMNT) which represents sediment export as a function of the amount of detached sediment and the runoff intensity. HSPF 11 allows two types of nutrient export simulation from pervious land. The AGCHEM group of subroutines simulates nutrient cycling and export mechanistically, using storages of nutrients in the soil and plant mass and parameters to govern movement between the storages. The PQUAL group of subroutines uses an empirically-based approach, with potency factors for surface runoff and monthly specified concentrations in the subsurface.

Nitrogen cycling is simulated in forest using recent research of forest dynamics included in the AGCHEM subroutines for HSPF 11 (Hunsaker 1994). Forest phosphorus is simulated using PQUAL. Crops are simulated using a yield-based nutrient uptake AGCHEM algorithm for both nitrogen and phosphorus. This method allows for the direct simulation of nutrient management practices. Pasture

FIG. 4. Major Basins of the Chesapeake Bay Watershed with Watershed Model Segments



and pervious urban use AGCHEM for nitrogen simulation and PQUAL for phosphorus. Nutrient export from animal waste areas are simulated as a concentration applied to the calculated runoff. Impervious urban exports depend on nutrient storage that is incremented by a daily accumulation factor equal to atmospheric deposition. This storage is then washed off as a function of the rainfall intensity.

HSPF is a lumped-parameter model and each land use is simulated as an average for the entire segment. For example, conventional-tilled cropland is simulated as an average crop rotation of corn, soybeans, and small grains in a segment with an average model segment input of fertilizer and manure loads, and with average slope, soil conditions, and so on.

A consistent land use data base is compiled for the entire Chesapeake basin using a LANSAT-derived GIS land use as a base (U.S. EPA 1994). Detailed information on agricultural lands is obtained from the U.S. Census Bureau series, Census of Agriculture for 1982, 1987, and 1992 (Volume 1, Geographic Area Series) published for each state. Tillage information on a county level is obtained for the conventional and conservation cropland distribution from the Conservation Technology Information Center (CTIC) (Palace et al. 1998). State agricultural engineers provide fertilizer and manure application rates and timing of applications as well as information on crop rotations, and the timing of field operations.

Soil characteristics for nutrient interaction are obtained from the Soils-5 data base. The USGS Land Use and Land Cover System (USGS LU/LC, Level II) is used to differentiate urban land into five urban subcategories: residential, commercial, industrial, transportation, and institutional. Each urban subcategory is associated with a level of imperviousness. Other sources used to generate the land use data base are Soil Interpretations Records (SCS-SOI-5 data file (1984), National Resources Inventory (NRI) (1984), Forest Statistics for New York (1980), Forest Statistics for Pennsylvania (1980), Forest Resources of West Virginia (1978), and Virginia's Timber (1978).

Information on land slope and soil fines is provided by the NRI data base. Data concerning hydrologic characteristics of soils, such a percolation and reserve capacity, are obtained primarily from the Soil Interpretation Records. Delivery of sediment from each land use is calibrated to the NRI estimates of annual edge-of-field sediment loads calculated by the USLE (Universal Soil Loss Equation).

Precipitation is the primary forcing function in the WSM and therefore, great care is taken in developing this data base. For the 12 years of hourly time series input data, 147 precipitation stations are used, of which 88 are hourly records and 59 are daily records of rainfall. Typically, about six stations are used to develop the precipitation record for a model segment using the Thiessen polygon method for spatial distribution. The average daily precipitation rates are formed from all hourly and daily rainfall gages associated with a model segment. Then the total average daily precipitation rate is converted to an hourly record by choosing, for each day, the hourly gage closest in volume with the day’s total average volume (Wang et al. 1997). Temperature, solar radiation, wind speed, snow pack, and dewpoint temperature data are from seven primary meteorological stations in the watershed. Three back-up meteorological stations are used in cases when data is missing from the primary stations

(Wang et al. 1997).

Each WSM river reach is simulated as completely mixed waters of a fifth to seventh order river with all simulated land uses considered to be in direct hydrologic connection. Of the 44 reaches simulated, the average length is 170 kilometers, the average drainage area is 1900 square kilometers, and the average time of travel is one day. Seven of the reaches are impounded by reservoirs. One of the reservoirs, Conowingo (model segment 140), is used for power generation and is simulated with specific spill and release rules.

For the Phase 4.2 WSM, the period of 1984 through 1995 is used as the calibration time period. Previously, for version 4.0, calibration was on the 1984 to 1992 period and verification was performed on the period 1993 through 1995, without adjustment of the earlier 1984 -1992 calibration. Agreement between the WSM simulation and observed 1984-1992 data of the calibration period was compared with the agreement between the WSM and observed data for the 1992-1995 verification period with the finding of no significant difference in model accuracy (Wang et al. in preparation). For purposes of comparison, all scenarios described in this paper use a consistent average Chesapeake Bay watershed hydrology defined as ten years of the simulation, 1985-1994. The use of this average hydrology allows a mix of wet, dry, and average hydrology years throughout the basin.

Land Use Loadings

All simulated land uses receive nitrogen inputs from atmospheric deposition. Other inputs include fertilizer and manures to cropland and hay land, and manure inputs to pasture. The urban simulation includes inputs of fertilizer and is associated with loads from point sources, on-site waste disposal systems (OSWDS), and combined sewer overflows (CSO). Fig. 5 describes the quartile ranges of atmospheric, fertilizer and manure loads for nitrogen used for the different land use simulations. Fig. 6 shows the phosphorus inputs for fertilizer, manure, and mineralization for the various land uses. Development of these input nitrogen and phosphorus loads is described below. The simulation of nitrogen is a complete mass balance for all land uses, but the phosphorus load simulation uses a more simplified application of loading factors for pasture, urban, and forest land uses.

Conventional tillage and conservation tillage cropland

The approach used for the calibration of cropland is to simulate, in a consistent manner, the growth and nutrient uptake of estimated crop types, taking into account drought, heat stress, and the growing season and using estimated nutrient inputs. Nutrient inputs to conventional tillage and conservation tillage cropland are from fertilizers, manure, and atmospheric deposition. Fertilizers and manures are applied at specific times and usually correspond with tillage and harvest operations.

Crop types and insight into crop rotations are determined by the record of the Agricultural Census which provides this information on a county level. Rates of fertilizer and manure inputs for each crop type are estimated by personnel in the state agriculture departments and the county Natural Resource Conservation Service (NRCS) offices. Agriculture Census records are used from 1982, 1987, 1992 or 1997 with other annual values interpolated between the years of record. The assessment of manure

FIG. 5. Quartile Ranges and Extremes of Nitrogen Inputs to the WSM from Atmospheric Deposition and Fertilizer and Manure Application

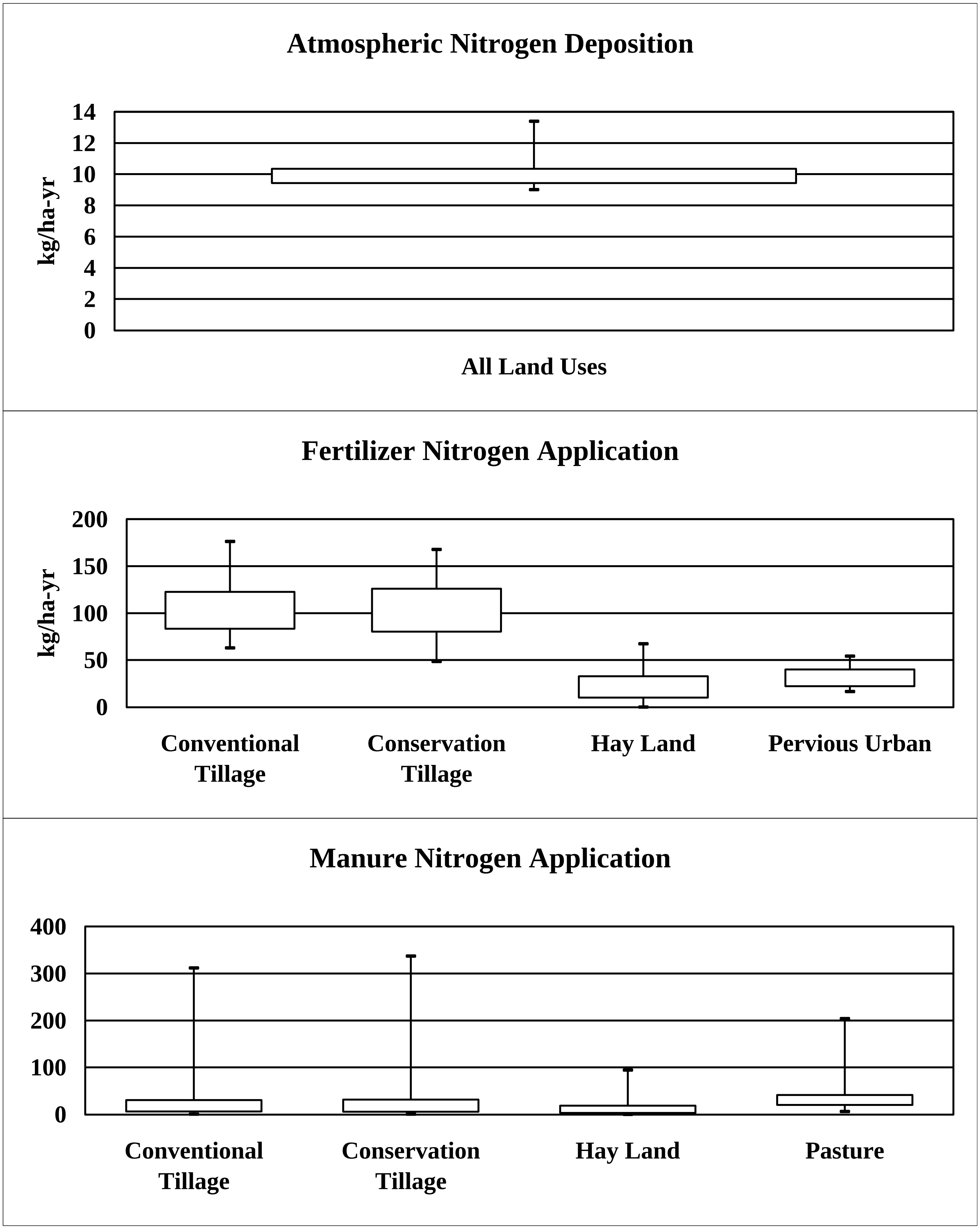
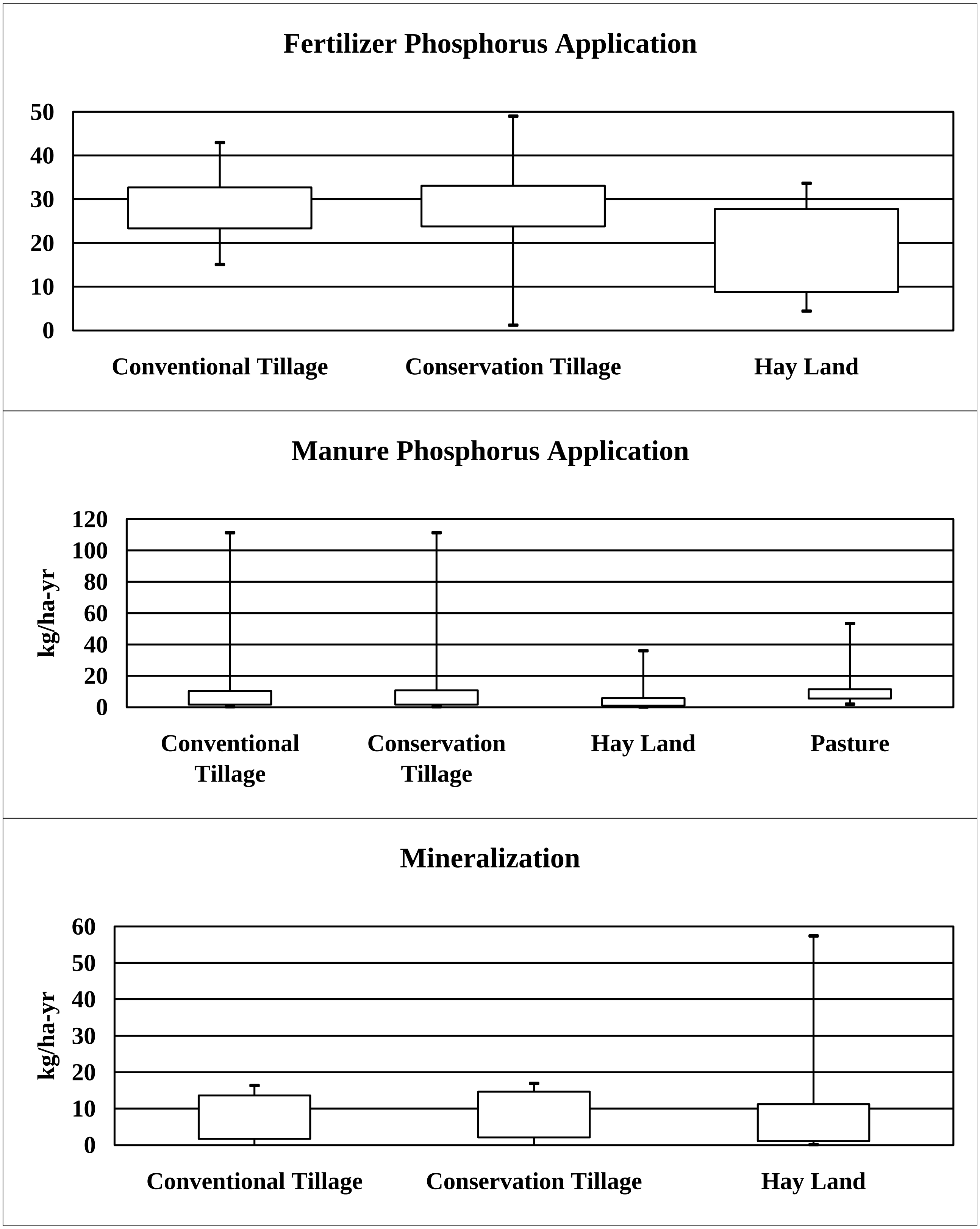


FIG. 6. Quartile Ranges and Extremes of Phosphorus Inputs to the WSM from Fertilizer and Manure Application and Mineralization



loads applied to cropland is determined by a mass balance of manure loads developed through the agricultural census of animal populations and the predominant manure handling practices (Palace et al. 1998). Wet and dry atmospheric deposition loads are input as a daily time series. For an average hectare of conventional or conservation cropland, the nitrogen loading rate for fertilizer, manure, and atmospheric deposition is 102.4 kg/ha-yr, 30.4 kg/ha-yr, and 10.0 kg/ha-yr, respectively. For phosphorus the average loading rate is 28.1 kg/ha-yr for fertilizer and 9.8 kg/ha-yr for manure.

Figure 7 shows average simulated cropland nitrogen dynamics. The primary fate of nitrogen and phosphorus applied to cropland is uptake and harvest of crops, at 116.0 kg/ha-yr and 27.9 kg/hr-yr, respectively. Export to rivers accounts for 23.8 kg/ha-yr nitrogen and 2.1 kg/ha-yr for phosphorus on average. The remainder is attenuated in low order streams or is accounted for through changes in soil storage such as mineralization or in the case of nitrogen, loss through volatilization or denitrification.

Hay land

Cropland in hay is a major land use in the Chesapeake watershed. Inputs to hay land are primarily from fertilizers. In regions of high animal populations, manure loads are also applied to hay land. Hay cropland is calibrated as described above for conventional and conservation tilled cropland. Average nutrient dynamics for cropland in hay simulated in the WSM are depicted in Figure 8. Mean nitrogen input rates of fertilizer, manure, and atmospheric deposition are 19.1 kg/ha-yr, 13.0 kg/ha-yr, and 10.0 kg/ha-yr, respectively. Phosphorus inputs to hay land are 16.8 kg/ha-yr for fertilizer and 4.4 kg/ha-yr for manure. Crop uptake and harvest account for 53.1 kg/ha-yr for nitrogen and 14.3 kg/ha-yr for phosphorus while export to rivers is 12.0 kg/ha-yr and 1.1 kg/ha-yr for nitrogen and phosphorus, respectively.

The negative value for changes in hay land soil storage (Fig. 8) is due to two factors. Missing from the simulation is an accounting of nitrogen fixation by leguminous hay. In addition, hay is normally part of a crop rotation and receives some of its input from excess nitrogen left over from the previous crop. Since hay is simulated as a separate land use, this excess nitrogen is provided in the model by mineralization of stored organic nitrogen and subsequent annual replenishing of the organic stores.

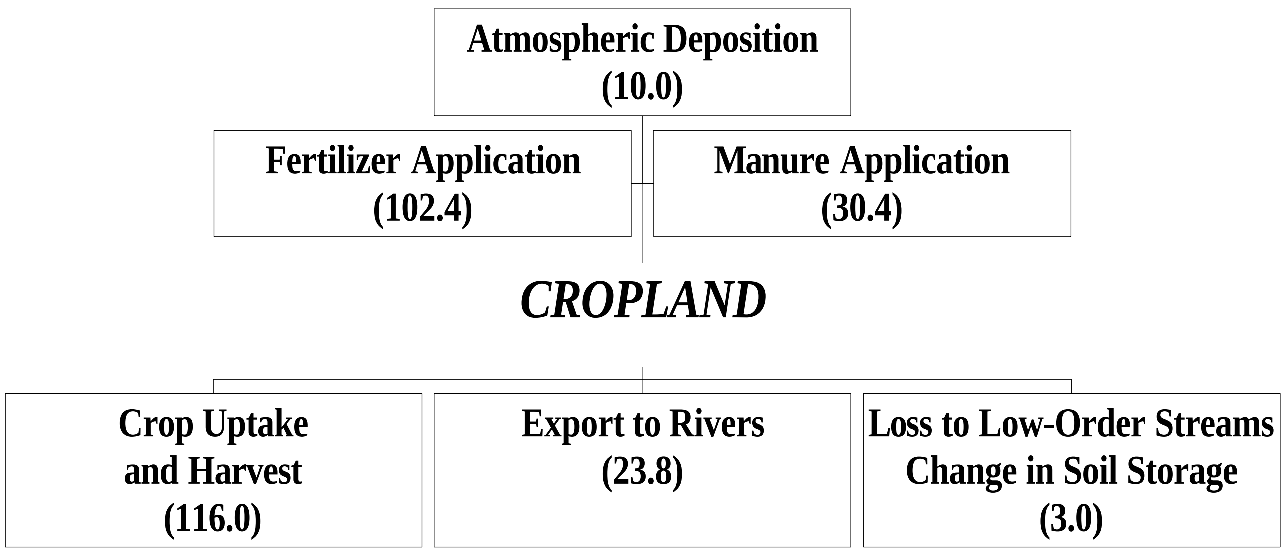
Pasture

Inputs to pasture are from manure of pastured animals and atmospheric deposition. Manures are applied daily in the pasture simulation on the basis of the number of pastured animals as estimated from the Agricultural Census and an estimate of the portion of time each animal type spends on pasture (Palace et al. 1998). A consistent nutrient uptake rate for pasture grass is applied throughout the watershed.

Average nitrogen dynamics for pasture simulated in the WSM are shown in Figure 9. Annual average input rates of nitrogen in manure and atmospheric deposition are 37.0 kg/ha-yr and 10.0 kg/ha-yr respectively. Phosphorus loads to pasture from manure are estimated to be 10.1 kg/ha-yr. Grass uptake and harvest, presumably by pastured animals, accounts for the greatest portion of the input nitrogen fate. Transport to rivers accounts for 9.3 kg/ha-yr of the nitrogen load and 0.4 kg/ha-yr of the phosphorus load.

FIG. 7. Cropland Total Nitrogen and Total Phosphorus Mass Balance (kg/ha-yr)

Nitrogen



Phosphorus

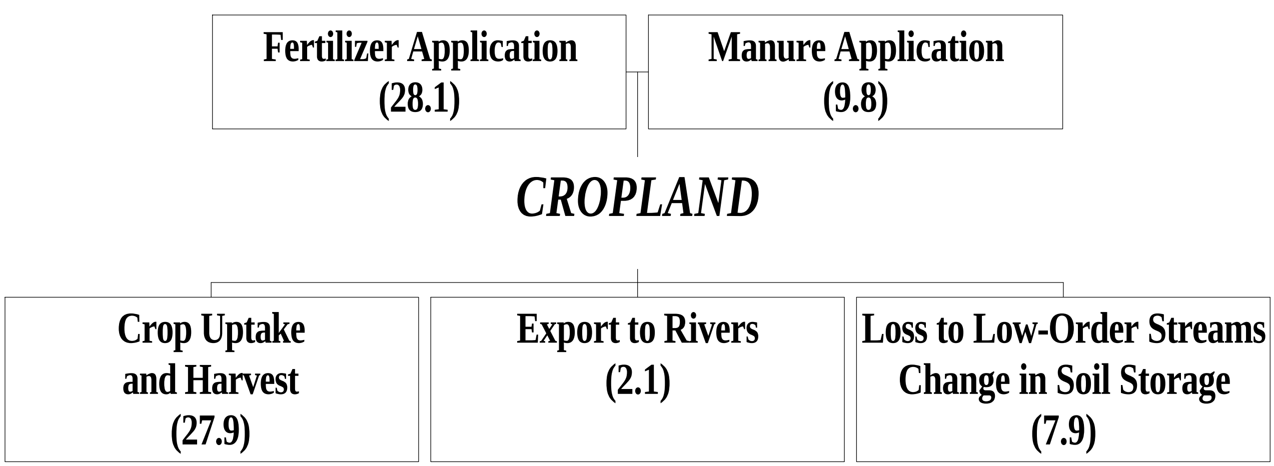
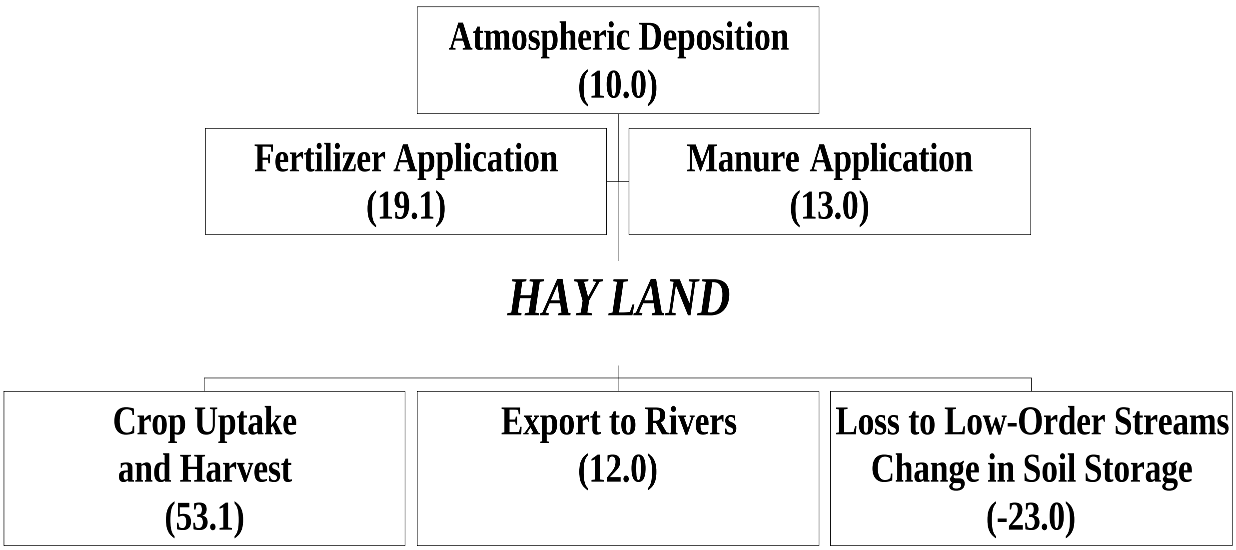


FIG. 8. Hay Land Total Nitrogen and Total Phosphorus Mass Balance (kg/ha-yr)

Nitrogen



Phosphorus

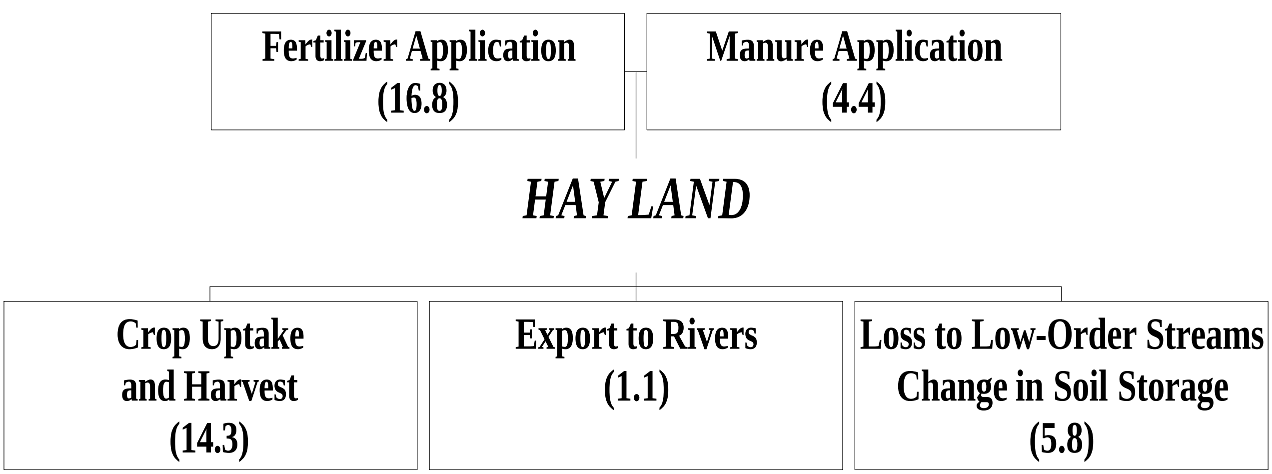


FIG. 9. Pasture Total Nitrogen and Total Phosphorus Mass Balance (kg/ha-yr)

Nitrogen

Atmospheric Deposition
(10.0)

Manure from
Pastured Animals
(37.0)

PASTURE

Pasture Grass Uptake and Animal Harvest
Loss to Low-Order Streams
Change in Soil Storage
(37.7)

Export to Rivers
(9.3)

Phosphorus

Manure from
Pastured Animals
(10.1)

PASTURE

Pasture Grass Uptake and Animal Harvest
Loss to Low-Order Streams
Change in Soil Storage
(9.7)

Export to Rivers
(0.4)

Forest

In the WSM simulation, nitrogen inputs to forests are assumed to be from atmospheric deposition only. Nitrogen fixation can also contribute nitrogen to forest land through certain species of trees and from nonsymbiotic nitrogen fixation, but these loads are not considered in the model. Nonsymbiotic nitrogen fixation in temperate forests may range between 1 to 6 kg/ha-yr. Denitrification is an important process in forests having poorly drained soils, but in forests with well drained soils, the denitrification rate may range from 0.2 to 2.1 kg/ha-yr to as high as 3 to 6 kg/ha-yr in clear-cut forests. Given the spatial heterogeneity of these two processes and their relatively equal rates, nitrogen fixation and denitrification are not explicitly included in the WSM simulation of forests (Hunsacker et al. 1994).

Calibration of forest is achieved through the parameterization of the HSPF forest module as suggested by Hunsacker (1994) and by assuming that forests with the highest inputs of atmospheric nitrogen loads export the highest nitrogen load. Export nitrogen loads from forest are estimated to be 3.4 kg/ha-yr and 0.06 kg/ha-yr for phosphorus loads. Forest average nitrogen dynamics simulated in the WSM are depicted in Figure 10. The use of PQUAL to simulate forest phosphorus precludes estimating the phosphorus mass balance.

Urban land

Urban land in the WSM includes anthropogenically altered landscapes that are not forest or agricultural land. Urban land includes all structures (including farm structures), roads, railroads, airports, transmission right-of-ways, communication facilities, undeveloped urban land, etc. Inputs to urban lands include fertilizers and atmospheric deposition. Urban nonpoint source loads are calibrated, based on the level of imperviousness, to expected urban loads determined by a regression on the National Urban Runoff Program (NURP) data as described by Schueler (1987).

Loads from point sources, CSOs, and OSWDS are associated with urban land and are input directly to the river reach. Point source inputs from municipal and industrial sources are developed from state National Pollution Discharge Elimination System (NPDES) records. If no state NPDES data are available, state and year-specific default data are calculated for each missing parameter and annual estimates of load are based on flow from the wastewater treatment plant.

Several cities in the watershed have a sewer system with CSOs, including Washington, D.C., Richmond, VA, and Harrisburg, PA. Estimates of the average annual discharge from these CSOs are only available for Washington, D.C. and the annual discharge is evenly distributed over the simulation period. Detailed information on point source and CSO loads in the Chesapeake Bay watershed can be found in Chesapeake Bay Watershed Model Application & Calculation of Nutrient & Sediment Loadings - Phase IV Chesapeake Bay Watershed Model - Appendix F: Point Source Loadings (Wiedeman and Cosgrove 1998).

Loads from OSWDS are compiled using census data and methodology suggested in Maizel et al. (1995). On-site Waste Disposal Systems are simulated as a nitrate load discharged to the river. Phosphorus loads are assumed to be entirely attenuated by OSWDS. The OSWDS loads are determined through an assessment of the census records of waste disposal systems associated with

FIG. 10. Forest Total Nitrogen Mass Balance (kg/ha-yr)

Nitrogen

Atmospheric Deposition
(10.0)

FOREST

Forest Uptake and Harvest Change in Soil Storage (6.6)	Export to Rivers (3.4)

households. Standard engineering assumptions of per capita nitrogen waste and standard attenuation of nitrogen in the septic systems are applied. Overall, the assumption of a load of 4.0 kg/person-year is used at the edge of the OSWDS field, all in the form of nitrate. Attenuation through groundwater and through smaller order streams until discharged to a fifth or larger order stream is assumed to be 60%. Total OSWDS loads delivered to the edge-of-stream are 5.9 millions of kilograms of nitrogen (Palace et al. 1998).

Impervious urban land is simulated as an impermeable surface which accumulates nitrate daily from dry atmospheric deposition and periodically receives wet deposition loads when both the wet deposition and the accumulated dry deposition are washed off. The wash-off of the accumulated nitrogen occurs after the satisfaction of surface interception, and occurs at a rate proportional to the overland flow. During periods of no rain, nitrate dry deposition is subject to a decay rate which allows atmospheric dry deposition to only build up to an arbitrary maximum accumulation of twenty times the daily dry deposition load. Dry deposition of phosphorus and organic nutrients on impervious urban surfaces are simulated in a similar manner.

Pervious urban land is simulated with an AGCHEM module for nitrogen which incorporates a first order uptake rate for turf. The empirically-based PQUAL group of subroutines is used to simulate phosphorus in pervious urban land.

Overall, WSM dischargers from urban land include point sources, CSOs, OSWDS, and both pervious and impervious nonpoint sources. Combined, these areas account for a total nitrogen export of 28.6 kg/ha-yr based on ten-year average hydrology. The urban yield for total phosphorus is 2.4 kg/ha-yr. Figure 11 shows the percentage of the total annual urban load from individual sources for both nitrogen and phosphorus. Point sources, which include CSOs, account for 51% of the annual urban nitrogen load and 75% of the phosphorus load.

Animal waste areas

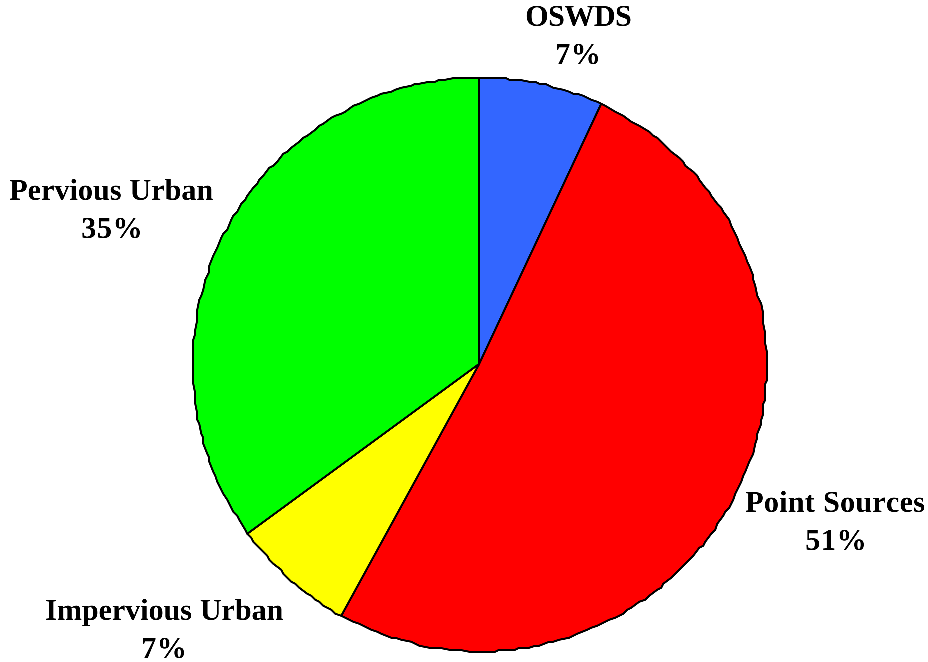
Simulated animal waste areas are areas of concentrated manures that are susceptible to runoff. These tracts include loafing areas, feed lots and manure piles. Animal waste areas are simulated as an impervious surface. The extent of animal waste area in each model segment is determined by the Agricultural Census estimate of animal numbers and types, and estimates of agricultural practices as described in Palace et al. (1998).

Comparison To Land Use Yield Data

A comparison is made between average annual nutrient export calculated by the WSM by land use type and observed nutrient export data synthesized by Beaulac and Reckhow (1982). Figure 12 compares observed and simulated data for total phosphorus where the boxes represent the 25th and 75th quartile ranges and whiskers show minimum and maximum values in the data set. Overall, the simulation shows good agreement with the observed phosphorus export ranges. Figure 13 makes similar comparisons for total nitrogen exports by land use. For cropland, hay land, pasture, and urban land, the model quartile ranges are higher than the observed ranges, perhaps due to modeling both

FIG. 11. Percentage of Total Annual Nitrogen and Phosphorus Load from Urban Sources

Total Nitrogen
(Average Urban Load = 28.6 kg/ha-yr)



Total Phosphorus
(Average Urban Load = 2.4 kg/ha-yr)

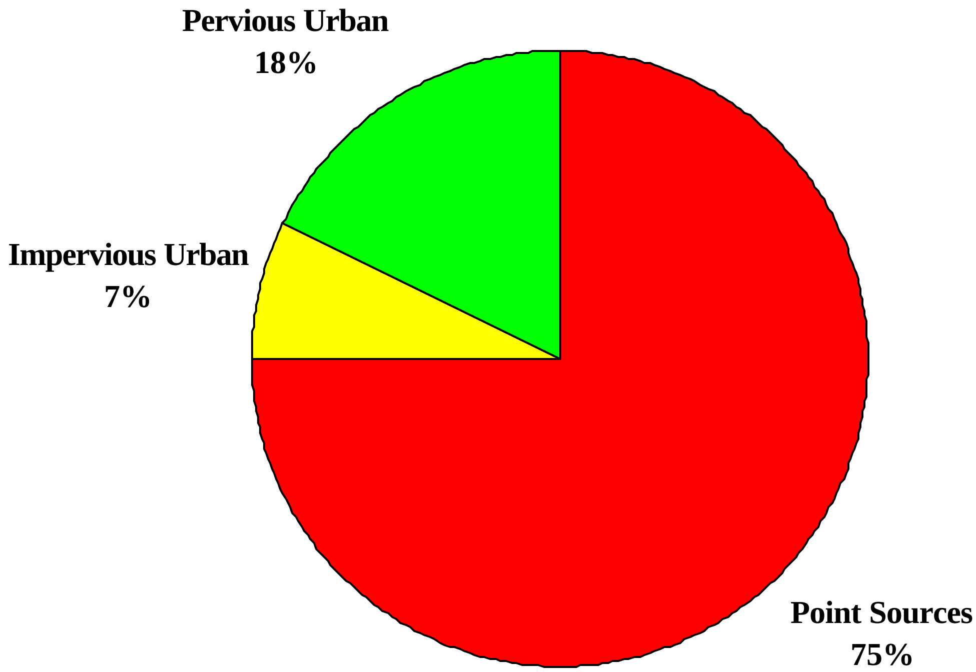


FIG. 12. Simulated Versus Observed Phosphorus Export By Land Use

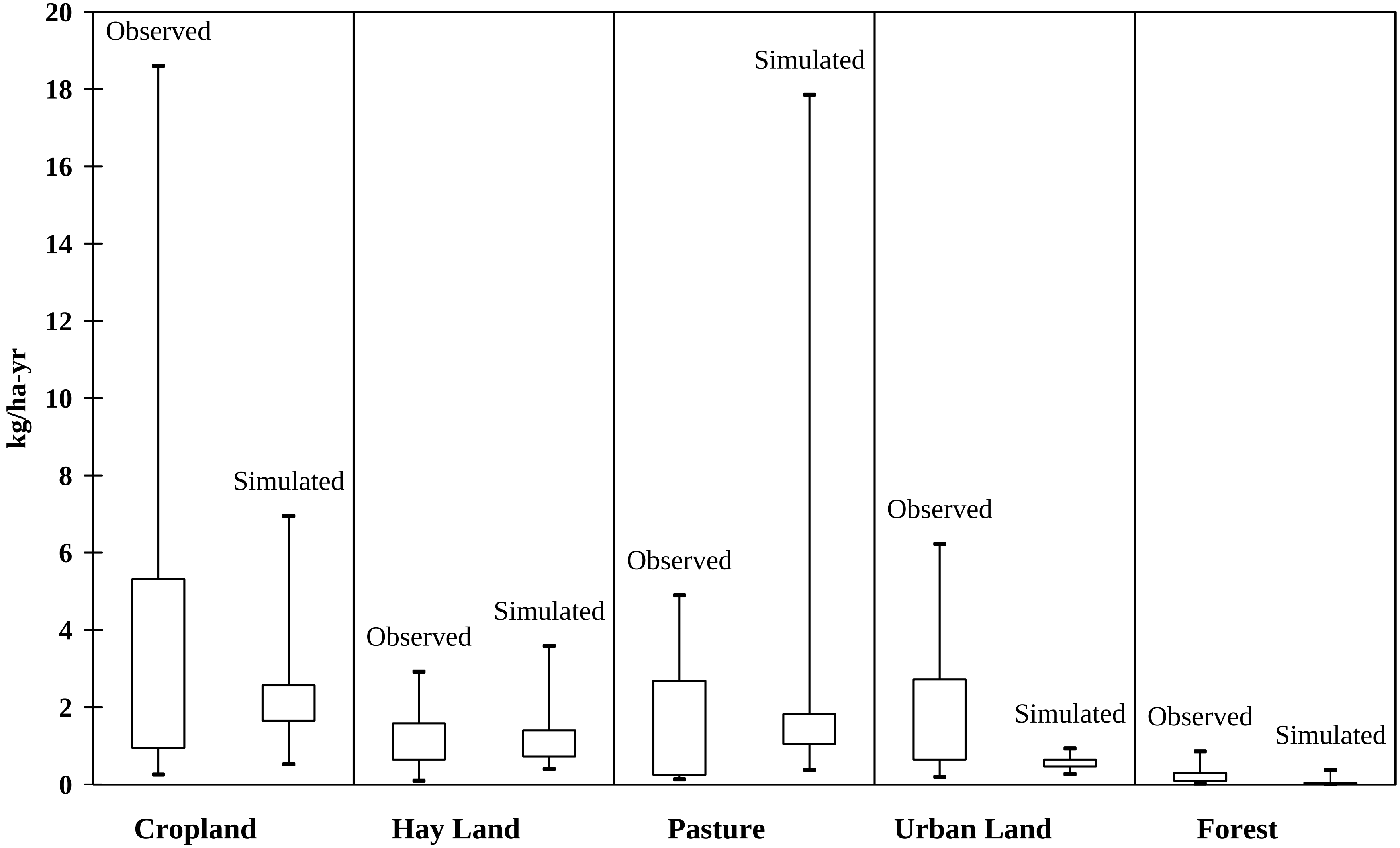
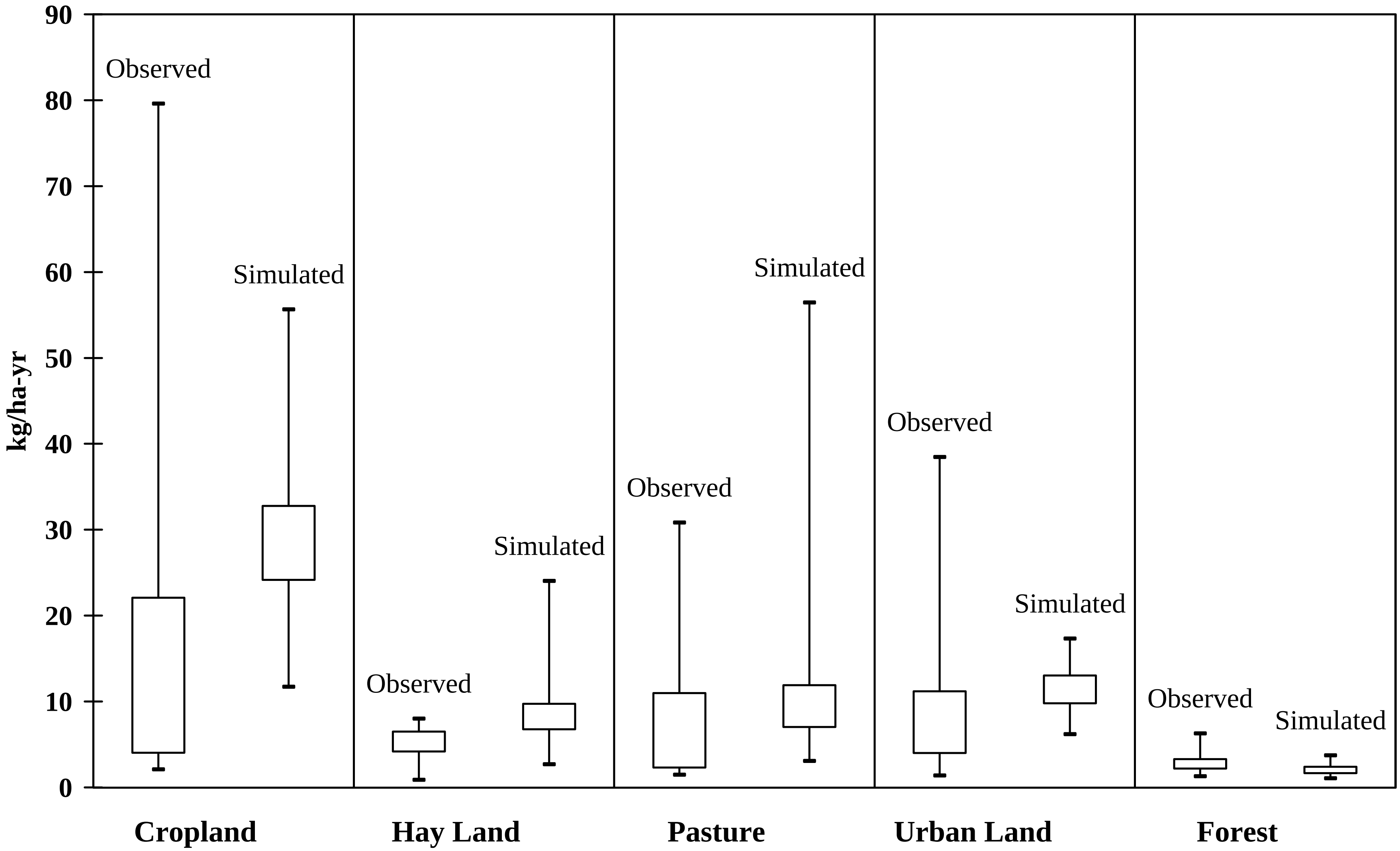


FIG. 13. Simulated Versus Observed Nitrogen Export By Land Use



surface and subsurface fluxes in the simulation while observed data in the studies were mostly surface fluxes. Extremes in the WSM range of loads are primarily due to extremes in nutrient inputs. For example, the high nutrient loads on pasture are associated with high stocking rates in some model segments as described by the Agricultural Census. Likewise, high loads in cropland are due to high nitrogen loads from fertilizers, manure, or both.

Reach Simulation And Calibration

The riverine simulation includes the HSPF modules simulating sediment transport, oxygen transformations such as reaeration and benthal sediment oxygen demand, ammonification, nitrification and other first order microbially-mediated nutrient transformations, and the simulation of periphyton and phytoplankton. For areas close to the Bay with a time of travel less than one day, a river reach is not simulated and terrestrial nutrient and sediment loads are directly loaded to the tidal estuary.

Examples of the WSM calibration for flow and nutrient concentrations are shown in Figures 14-16. Figure 14a compares observed and simulated flow data for a ten-year period from 1984 through 1994 for the Susquehanna River, the greatest source of flow to the Chesapeake Bay. The comparison is made to observed data from a monitoring site at Conowingo Dam. Figure 14b is a frequency distribution of paired simulated and observed flow data for the Susquehanna. This plot is useful for examining the differences between the observed and simulated flows with respect to flow magnitude and frequency of occurrence. Generally, calibration is best in the central area of the data and calibration performance is least in the tails.

Figure 15a shows observed and simulated total nitrogen concentrations in the Potomac River at Chain Bridge for the eleven-year period. The Potomac is second only to the Susquehanna in the delivery of nitrogen loads to the Chesapeake and Chain Bridge is at the fall line of the tributary . Nitrate comprises the greatest part of total nitrogen and is highly seasonal with nitrate concentrations generally highest in winter and lowest in summer. Figure 15b is the frequency distribution of paired simulated and observed nitrogen concentration data for this site showing very good agreement between the model and monitoring values including extreme concentrations.

Figure 16a is a plot of modeled and monitoring data for total phosphorus concentrations for the Patuxent River near Bowie, MD. The Patuxent basin is the most urbanized of the major Chesapeake Bay basins. The water quality time series reflects the urban, hydrologically “flashy” character of the basin where water quality is dominated by point source discharges. Changes in point source discharges over the simulation period, including the phosphorus detergent ban in January, 1986, have resulted in large step-wise changes in water quality in both the observed and simulated data, as seen in the decline in phosphorus concentrations (Fig. 16a). Figure 16b is the frequency distribution of paired simulated and observed total phosphorus concentration data at this gaged site on the Patuxent. Complete calibration information for hydrology and water quality constituents for the major basins can be found in Chesapeake Bay Watershed Model Application & Calculation of Nutrient & Sediment Loadings - Phase IV Chesapeake Bay Watershed Model - Appendix A: Model Hydrology Calibration Results (Greene and Linker 1998) and Appendix B: Water Quality Calibration Results (Linker et al. 1998).

FIG. 14a. Susquehanna River at Conowingo Dam Observed and Simulated Flow

(*=Observed, -=Simulated)

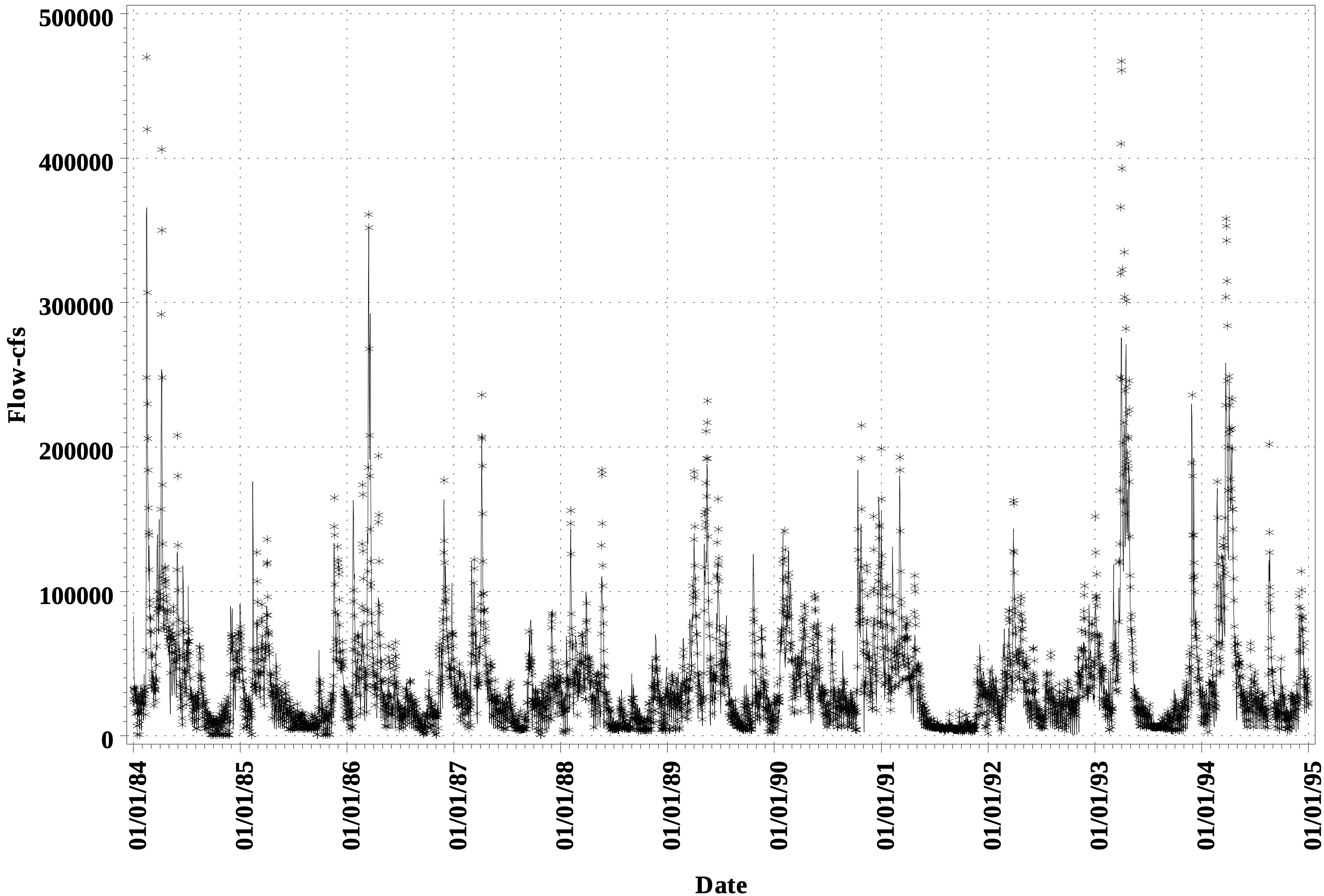


FIG. 14b. Susquehanna River at Conowingo Dam Paired Frequency Distribution.
(Observed and Simulated Flow)

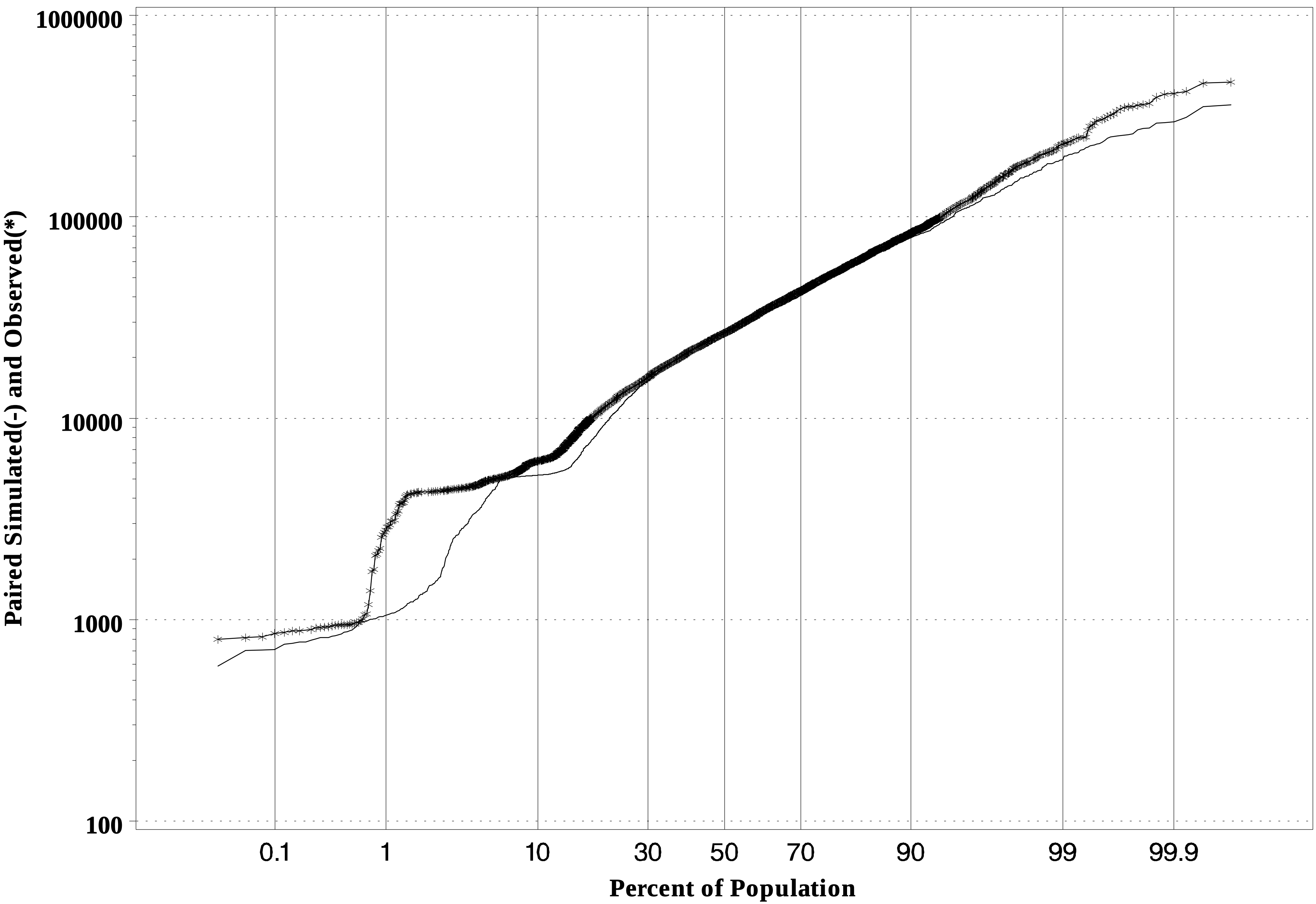


FIG. 15a. Potomac River at Chain Bridge Observed and Simulated Total Nitrogen Concentration

(*=Observed, -=Simulated)

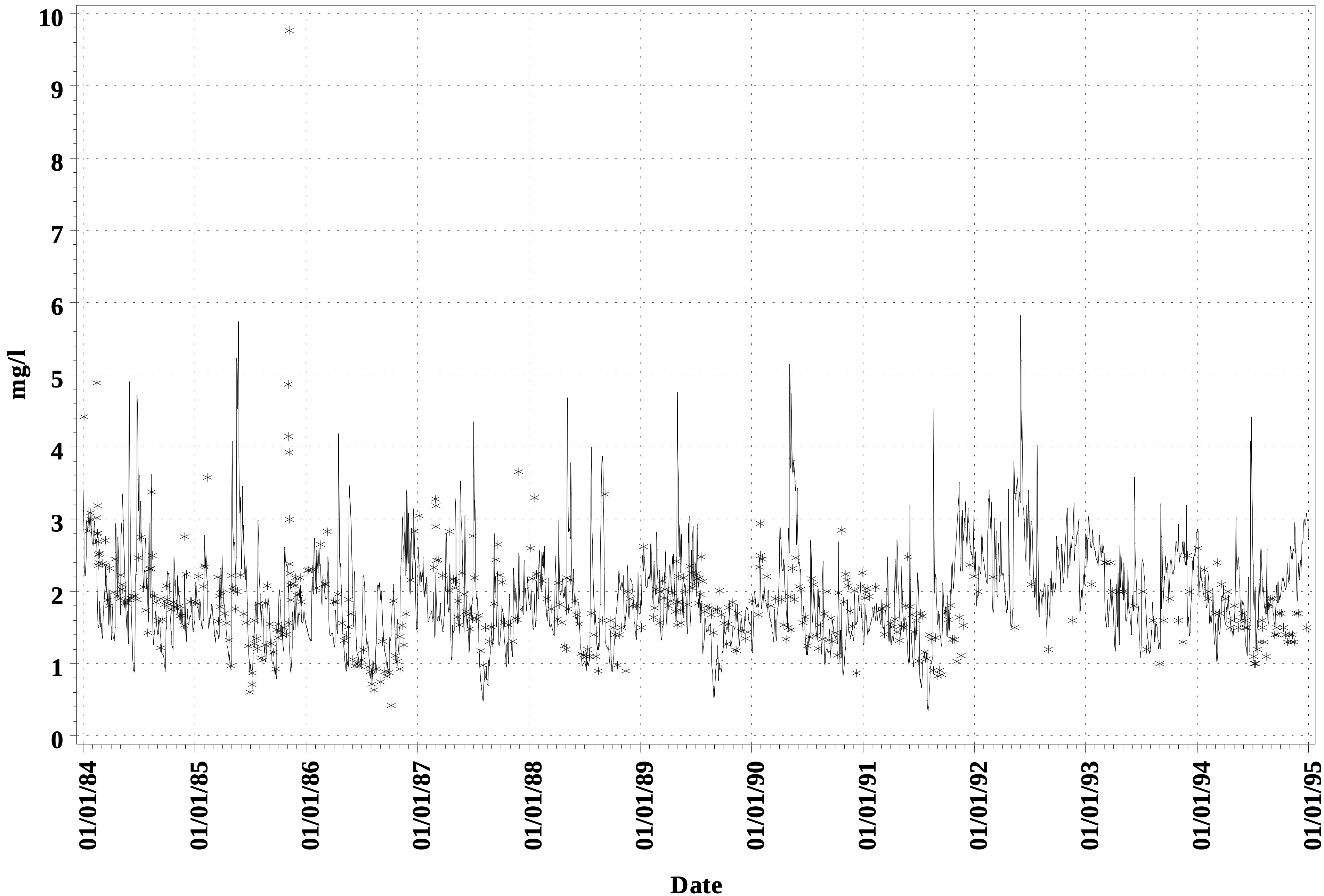


FIG. 15b. Potomac River at Chain Bridge Paired Frequency Distribution
(Observed and Simulated Total Nitrogen Concentration)

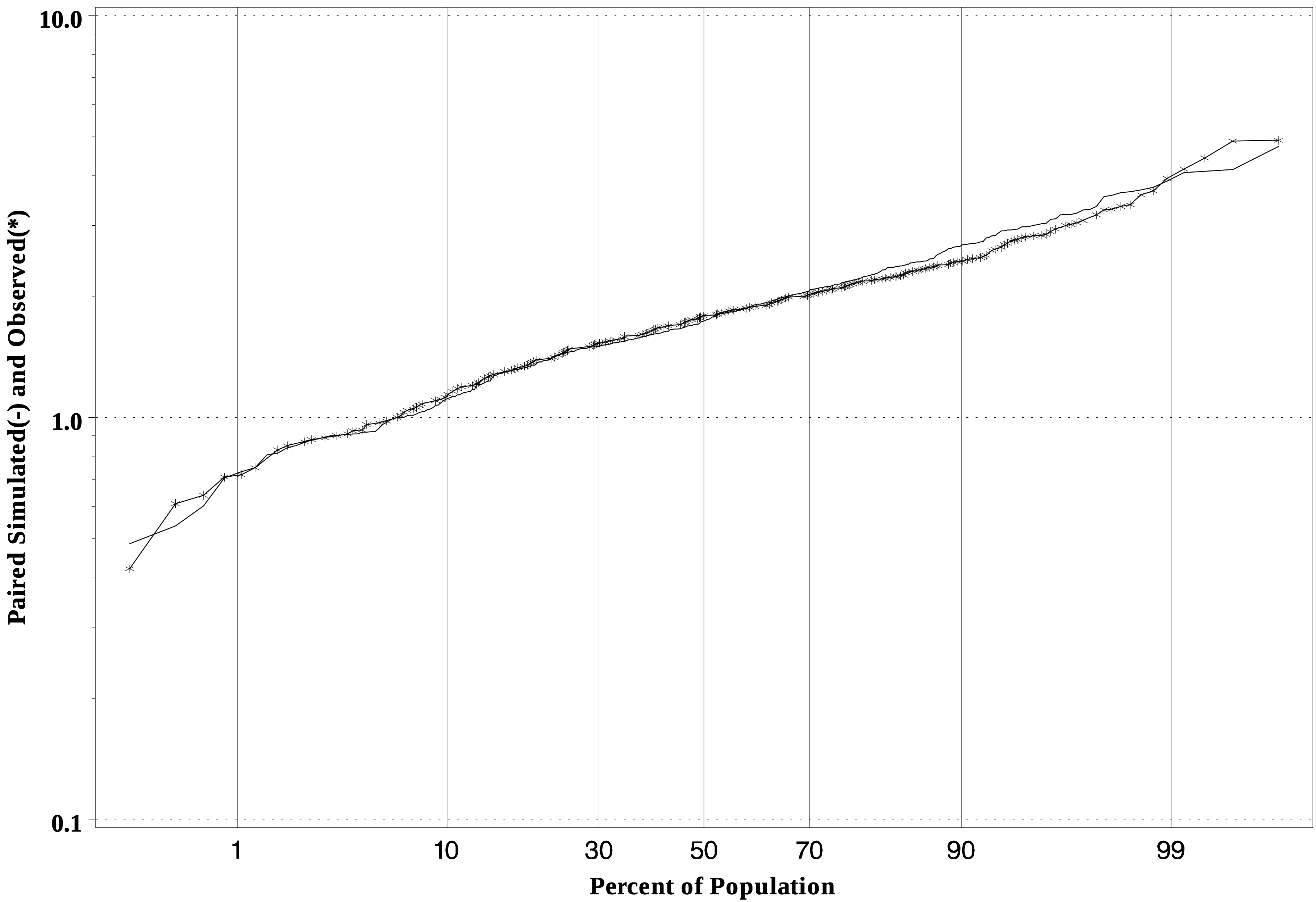


FIG. 16a. Patuxent River near Bowie, MD Observed and Simulated Total Phosphorus Concentration

(*=Observed, -=Simulated)

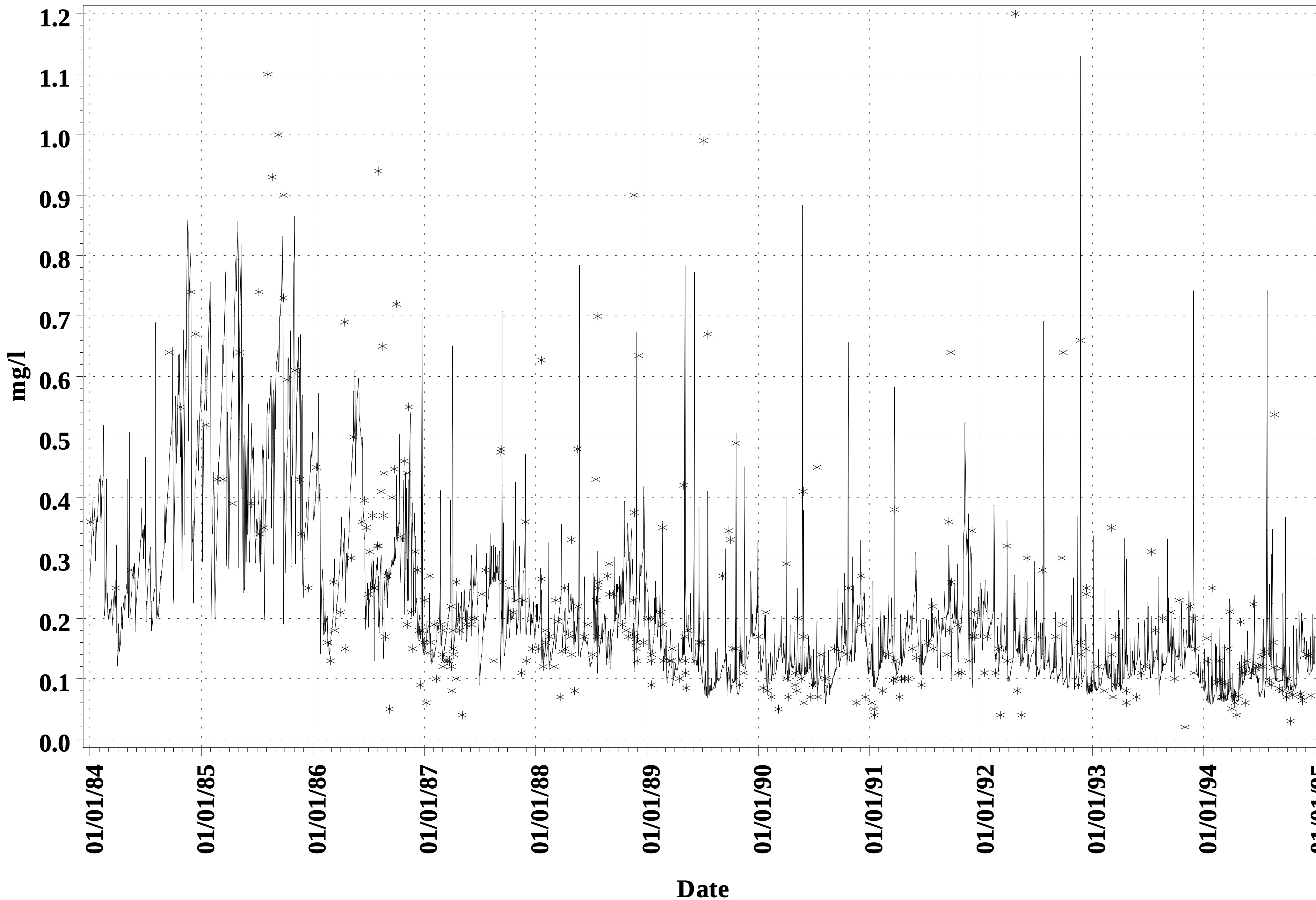
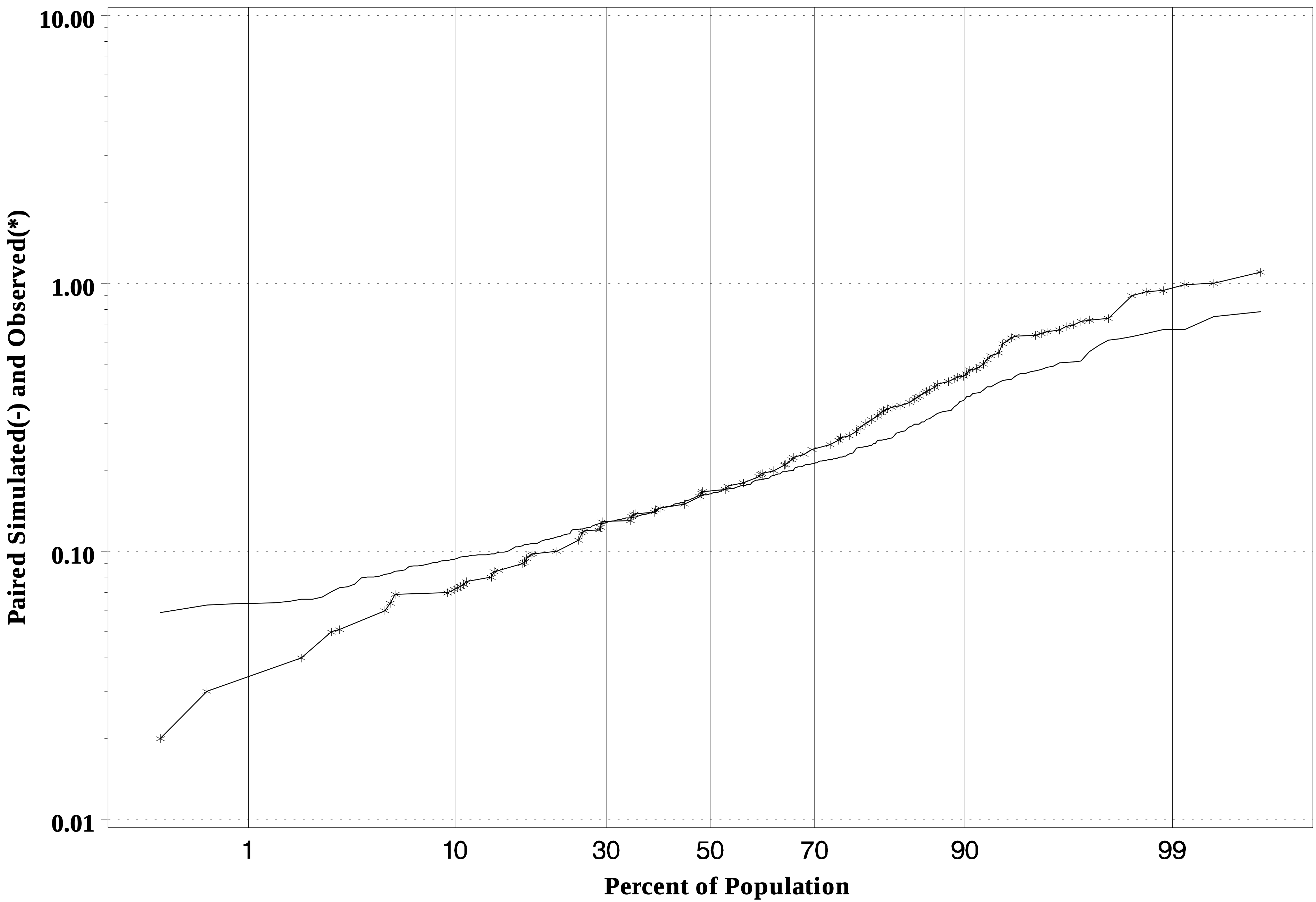


FIG. 16b. Patuxent River near Bowie, MD Paired Frequency Distribution
(Observed and Simulated Total Phosphorus Concentration)



RESULTS

A key Chesapeake Bay Program goal is a 40% reduction of the 1985 controllable nitrogen and phosphorus loads by 2000 from point and nonpoint source nutrient loads from the Bay Program signatory states of Pennsylvania, Maryland, Virginia, and the District of Columbia. The 1985 year is chosen as the reference year because hydrologic conditions were normal that year and it was the first relatively complete year of basin monitoring in the watershed and tidal waters. Controllable loads are defined as the total point source loads from the states signatory to the Bay Agreement, as well as nonpoint source loads greater than the loads estimated from an all-forested watershed condition. Nutrient loads from states within the basin, but not signatory to the load reduction agreement (New York, Delaware, West Virginia), are not considered controllable by the Bay Agreement.

For all nutrient and sediment reduction scenarios, the WSM is run for ten years of simulation, representing 1985 to 1994. This provides a consistent ten-year hydrology, including wet, dry, and average periods of flow in each basin. The 1985 Reference Scenario employs land uses back-projected from 1990 Environmental Monitoring and Assessment Program (EMAP) satellite information. Urban land use is further divided from GIRAS data into herbaceous and forest categories. The EMAP herbaceous category is reclassified according to Agricultural Census land use designations and land use acreage for the 1985 Reference Scenarios is interpolated from the 1982 and 1987 surveys.

Septic system loads and animal waste loads are estimated for 1985 using watershed human and animal population estimates. Point source loads and Best Management Practices (BMPs), used to control nonpoint source loads, are at 1985 levels. Atmospheric deposition loads are input on a daily basis for wet deposition of nitrate and ammonia over the 1985-1994 period, based on a regression of National Atmospheric Deposition Program (NADP) data. The 1985 Reference Scenario establishes a baseline to which other scenarios are compared in a period just prior to major implementation efforts by the Chesapeake Bay Program to reduce nutrient loads.

Based on the 1985 reference year, the 40% reduction goal is quantified as a reduction of 27.8 million kilograms of nitrogen and 2.5 million kilograms of phosphorus. These load reductions are determined by Phase 4.1 of the WSM with a ten-year average hydrology. Chesapeake basins in the upper Bay (Fig. 4) are expected to reduce nutrient loads by the year 2000, and the lower basins of the Rappahannock/York, James, and Virginia Eastern Shore will reduce nutrient loads by 2010. After the 40% controllable load reduction allocation for each basin is met, the allocations will become a cap not to be exceeded despite increased loads from population and growth.

Other key scenarios are the 2000 Progress Scenario, which tracks recent progress toward the year 2000 goal, the Tributary Strategy Scenario, which simulates the loads to the Bay once the Bay Agreement Goal is achieved, and the Limit of Technology (LOT) Scenario, which examines the extremes of nutrient and sediment reductions. Atmospheric deposition loads are set to base levels for the 1985 Reference, 2000 Progress, and Tributary Strategy scenarios.

The LOT Scenario represents the upper boundary of what can be achieved in nutrient reductions with current technology given greatly expanded resources and complete land owner cooperation. Nutrient and sediment control assumptions are based on a “do everything, everywhere” scheme using current available technologies. Land use coverage, human population, and animal livestock population for the year 2000 are assumed.

Agricultural land under the LOT Scenario has Soil and Water Quality Conservation Plans (SWQCP) on all cropland acres (conventional tillage, conservation tillage, and hay land), an 85% reduction efficiency for all manure loads, grazing land protection practices on all pasture lands, and nutrient management practices implemented everywhere. Agricultural practices such as cover crops are on 100% of Coastal and Piedmont physiographic regions south of the Potomac River and on 20% of the Piedmont physiographic region of the Potomac River and watershed areas north of the Potomac. These cover crop nutrient reductions account for an edge-of-stream nutrient reduction of 43% for total nitrogen, and 15% for both total phosphorous and total suspended solids.

Limit Of Technology land use conversions within the WSM include the retirement of highly erodible land (HEL) by converting 2% of all conventional tilled, conservation tilled, and hayland acreage to pasture. Highly erodible acreage converted to pasture is assumed to be maintained as an unfertilized, unharvested, permanent grass. Seventy five percent of all tilled acreage is converted to conservation tillage in this scenario.

Forest conservation and tree planting land use conversions include simulating the nutrient reduction effects from the implementation of forest/grass buffers on all conventional and conservation tilled cropland and hayland adjacent to streams. Establishment of forest buffers on 50% of the stream miles associated with pervious urban acres is assumed. Buffered stream acres are assumed to be distributed among land uses in the same proportion as the total land use in each WSM segment. Out of the total buffered stream acres, all acres that correspond to cropland and half of those corresponding to pervious urban are considered buffered. All pasture is protected through stream bank fencing, a form of grass or forest buffer, and manure is considered controllable by other methods in the LOT Scenario.

Urban LOT Scenario controls include stormwater management BMPs incorporated by applying nutrient reduction percentages to nutrient loads from pervious and impervious land areas. These reductions apply to the nutrient and suspended sediment load from land acres affected by stormwater management BMPs. An overall assumption for all types of stormwater management systems simulated within the WSM, is that nutrient reduction efficiencies are 27%, 47%, and 47% for total nitrogen, total phosphorous, and total suspended solids, respectively. Urban stormwater management is assumed to be applied to 50% of the urban land.

As part of the LOT Scenario, septic system connections that will be made as part of the tributary strategies are assumed to have an 80 % total nitrogen reduction. Denitrification in septic systems is assumed to be installed on all septic systems installed after 1996. A sand mound system with effluent recirculation is assumed with a nitrogen load reduction of 50%.

Also for LOT, nutrient management is assumed to occur on 100% of pervious urban acres. Urban erosion and sediment (E&S) controls are implemented at Tributary Strategy levels. Erosion and sediment controls include sediment ponds and silt fencing, and are applied to urban construction sites. The WSM assumes that some portion of the urban land use is in a transitory construction phase at all times. Erosion and sediment controls primarily protect off-site areas from suspended sediment runoff and nutrient pollution. Incorporation of erosion and suspended sediment controls result in the reduction of suspended sediment and nutrients from pervious urban land. Erosion and sediment controls are estimated to reduce nutrient loads from urban acres by 33% for total nitrogen and 50% for both total phosphorus and sediment at the edge of stream.

Limit of Technology point source reductions are based on a “do stringent point source reductions everywhere” scheme using current available technologies. Point source concentrations of 3.0 mg/l TN and 0.075 mg/l TP are applied to the estimated 2000 point source flows.

Reductions in atmospherically deposited nitrogen are based on the highest levels of current controls applied on an annual basis, along with a High Enhanced Inspection and Maintenance program (High EI/M) throughout the entire domain of RADM (eastern U.S.). Annual Phase II levels of control on all stationary sources in the RADM domain are also applied, resulting in emissions of no more than 0.15 lb/mm Btu. Mobile source controls include the National Low Emission Vehicle (NLEV) Program.

Comparison of loads among the scenarios for six major Chesapeake basins including the Susquehanna, Potomac, Patuxent/Western Shore MD, Rappahannock/York, James, and Eastern Shore are shown in Figures 17 and 18 for total nitrogen and total phosphorus, respectively. As estimated by the WSM, all basins show progress between 1985 and year 2000 in the reduction of nitrogen loads, particularly those basins dominated by point source loads such as the Patuxent/Western Shore MD. Limit of Technology loads are considerably below Tributary Strategy loads indicating that the tributary strategy reductions are, in all cases, achievable. Phosphorus loads show even greater declines since phosphorus is more amenable to control for both point and nonpoint sources.

CONCLUSIONS

Refinements to the RADM, WSM, and CBEMP are continuing. Motivations for these refinements are 1) increased complexity in maintaining the nutrient reduction cap due to increased growth in the region, 2) expanded public expectation for water quality and living resource improvements, 3) advances in the state of scientific knowledge, 4) demands for greater accountability from government and other institutions, 5) reductions in aggregate risks, and 6) movement toward transparent decision-making in an expanded, open, decision-making process. Because of greater processing speeds and better tools for computers, it is possible to improve the model applications.

Chesapeake Bay airshed and watershed models focus on quantifiable outcomes such as reductions in estimated nutrient and sediment loads resulting from integrated point source, nonpoint source, and air emission management actions, rather than a pollutant reduction strategy based on a single media. For decision-makers in the Chesapeake Bay Program, model results are choices to be examined, analyzed,

FIG. 17. Total Annual Nitrogen Load by Scenario for Six Major Chesapeake Bay Basins

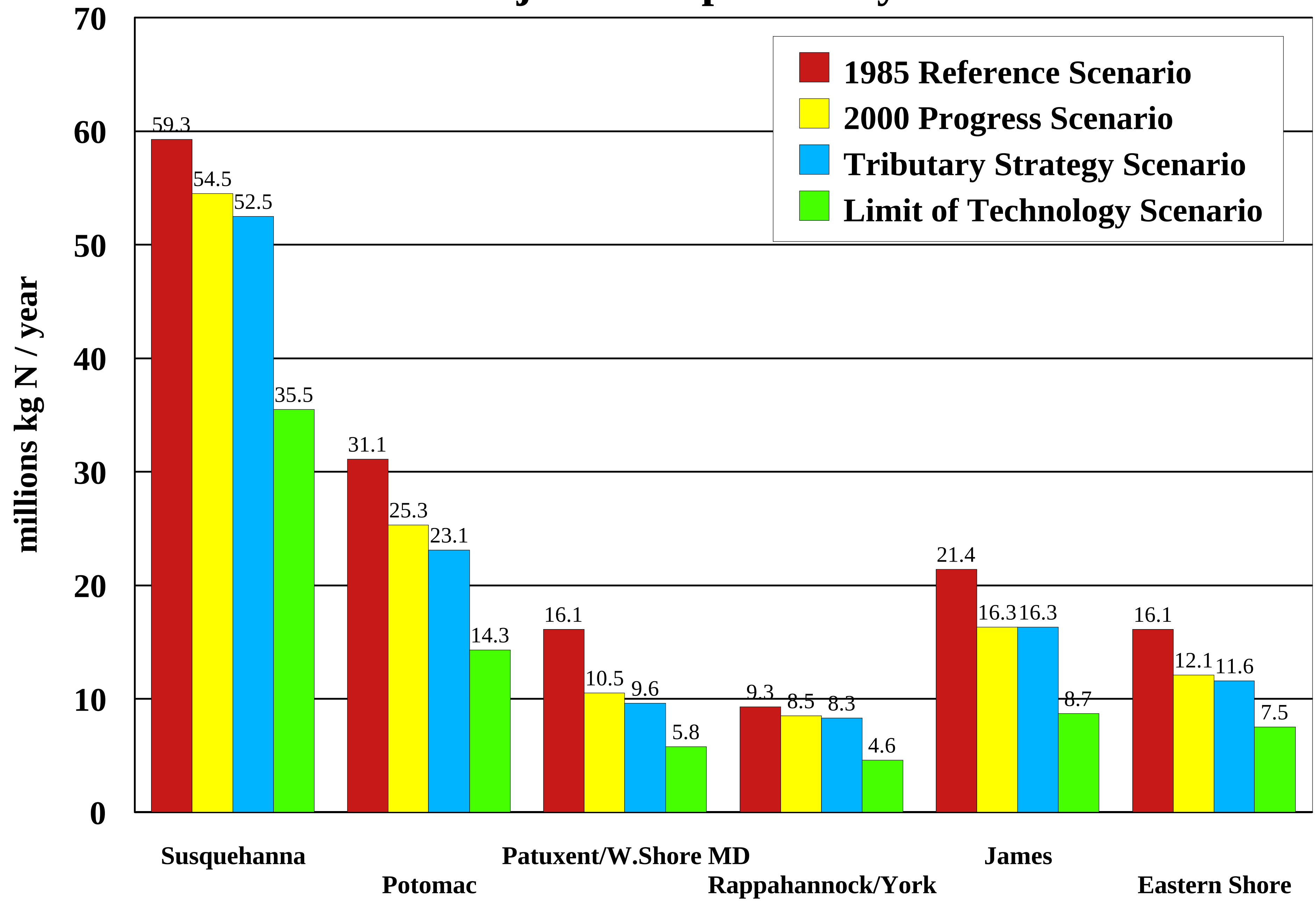
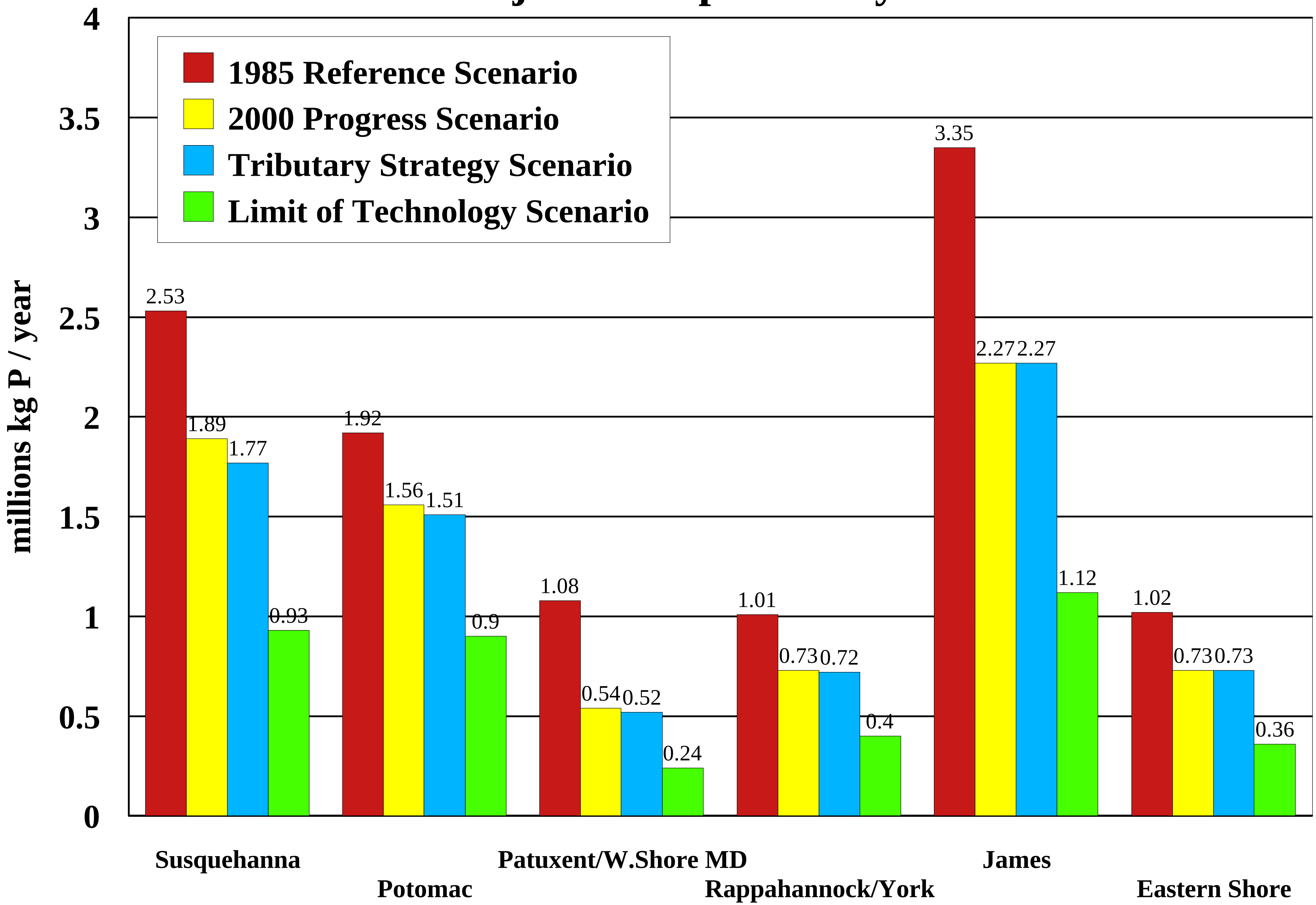


FIG. 18. Total Annual Phosphorus Load by Scenario for Six Major Chesapeake Bay Basins



and further developed through an iterative process with the model practitioners. Ultimately, decision-makers must choose. The criteria applied to the ultimate decision set are outcomes directed at nutrient reductions that are equitable, achievable, cost effective, and protective of the environment.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

C	=	nitrogen species mixing ratio;
E	=	nitrogen oxide or ammonia emission rate;
k_e	=	eddy diffusivity;
L	=	latitude of the centroid of the precipitation segments;
L_{chm}	=	chemical loss of nitrogen species;
M	=	month, expressed as an integer;
P_{chm}	=	chemical production of nitrogen species;
ppn	=	precipitation, in mm; and
V	=	three dimensional velocity vector at each grid point.

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Linker, L.C., G.W. Shenk, R.L. Dennis, and J.L. Sweeney. 1999. Cross-Media Models for the Chesapeake Bay Watershed and Airshed November, 1999. Chesapeake Bay Program Office, Annapolis, MD. *http://www.chesapeakebay.net/modsc.htm* - *Publications Tab.* Date Retrieved: *retrieval date*