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1.1.1 Phase 5.3 Watershed Model Overview

Excessive nutrients in the Chesapeake Bay and its tidal tributaries promote a number of undesirable water quality conditions such as excessive algal growth, low dissolved oxygen, and reduced water clarity.

To simulate the Chesapeake Bay watershed, the river flows, and associated transport and fate of nutrients and sediment that contribute to Chesapeake Bay water quality degradation, the Chesapeake Bay Community Phase 5.3 Watershed Model was developed. The Phase 5.3 Model, in conjunction with models of the Chesapeake airshed and estuary, provides estimates of management actions needed to protect water quality and restore living resources in the Chesapeake.

The Phase 5.3 Model is the most recent of a series of increasingly refined versions of the Chesapeake Bay Watershed Model. Different versions of this model have been operational for more than two decades. Phase 5.3 has an expanded model domain compared to the previous versions. Economies of scale and additional state resources allowed for the expansion of the Watershed Model to cover the entire states of Virginia, Maryland, and Delaware. That provides for statewide consistency of water quality analysis and total maximum daily load (TMDL) development, as well as consistency of local TMDLs with the large-scale, regional TMDL of the Chesapeake Bay. Figure 1.1 shows the Chesapeake Bay watershed and the expanded study domain.

1.1.2 Introduction to the Chesapeake Bay Watershed

The Chesapeake Bay’s 64,000-square-mile watershed includes parts of New York, Pennsylvania, West Virginia, Delaware, Maryland, Virginia, and the entire District of Columbia (Figure 1.1). Throughout the Chesapeake Bay watershed are more than 100,000 streams and rivers that eventually flow into the Bay (USEPA 2003a). Runoff and groundwater from the watershed flow into an estuary with a surface area of 4,500 square miles, resulting in a land-to-water ratio of 14 to 1. That ratio is a key factor in explaining the significant influence the watershed has on Chesapeake Bay water quality. The nine major basins of the Chesapeake Bay watershed are the Susquehanna, Potomac, Patuxent, Rappahannock, York, and James rivers and the Maryland Western Shore, Maryland Eastern Shore, and the Virginia Eastern Shore.

The Chesapeake Bay watershed is almost entirely within the Appalachian, Ridge and Valley, Piedmont, and Atlantic Coastal Plain geologic provinces. The Atlantic Coastal

Plain is a flat, lowland area with a maximum elevation of about 300 feet. The Coastal Plain extends from the edge of the continental shelf, east to a fall line that ranges from 15 to 90 miles west of the Chesapeake Bay. The fall line forms the boundary between the Piedmont Plateau and the Coastal Plain. Waterfalls and rapids clearly mark the line, which is marked by the Bay watershed cities of Baltimore, Washington, D.C., Fredericksburg, and Richmond. Those cities developed along the fall line taking advantage of both the potential water power generated by the falls and tidewater shipping. The confluence of geography and history placed the largest population centers in the watershed, including Baltimore, Washington, D.C., and Richmond, directly on the Chesapeake tidewater. The Eastern Shore is entirely within the Coastal Plain.

The Piedmont Plateau extends from the fall line in the east to the Ridge and Valley province in the west. The Patuxent, Rappahannock, and York River basins span the Piedmont and Coastal Plain (Figure 1.2). The Susquehanna, Potomac, and James rivers span the Ridge and Valley region through a series of water gaps with some rivers, such as the Shenandoah, lying entirely within the Ridge and Valley province.

The Appalachian province covers the western and northern part of the watershed. Water from this province flows to the Chesapeake Bay through the upper reaches of the Susquehanna, Potomac, and James rivers. The Susquehanna is the largest river, followed by the Potomac and James rivers. The current land use in the watershed is about 65 percent forest or wooded, 24 percent agriculture, and 11 percent developed land (buildings, roads, and so on, in urban, suburban, and rural areas). Nearly 17 million people live in the Chesapeake Bay watershed, and the population by 2030 is estimated to increase to about 30 million.

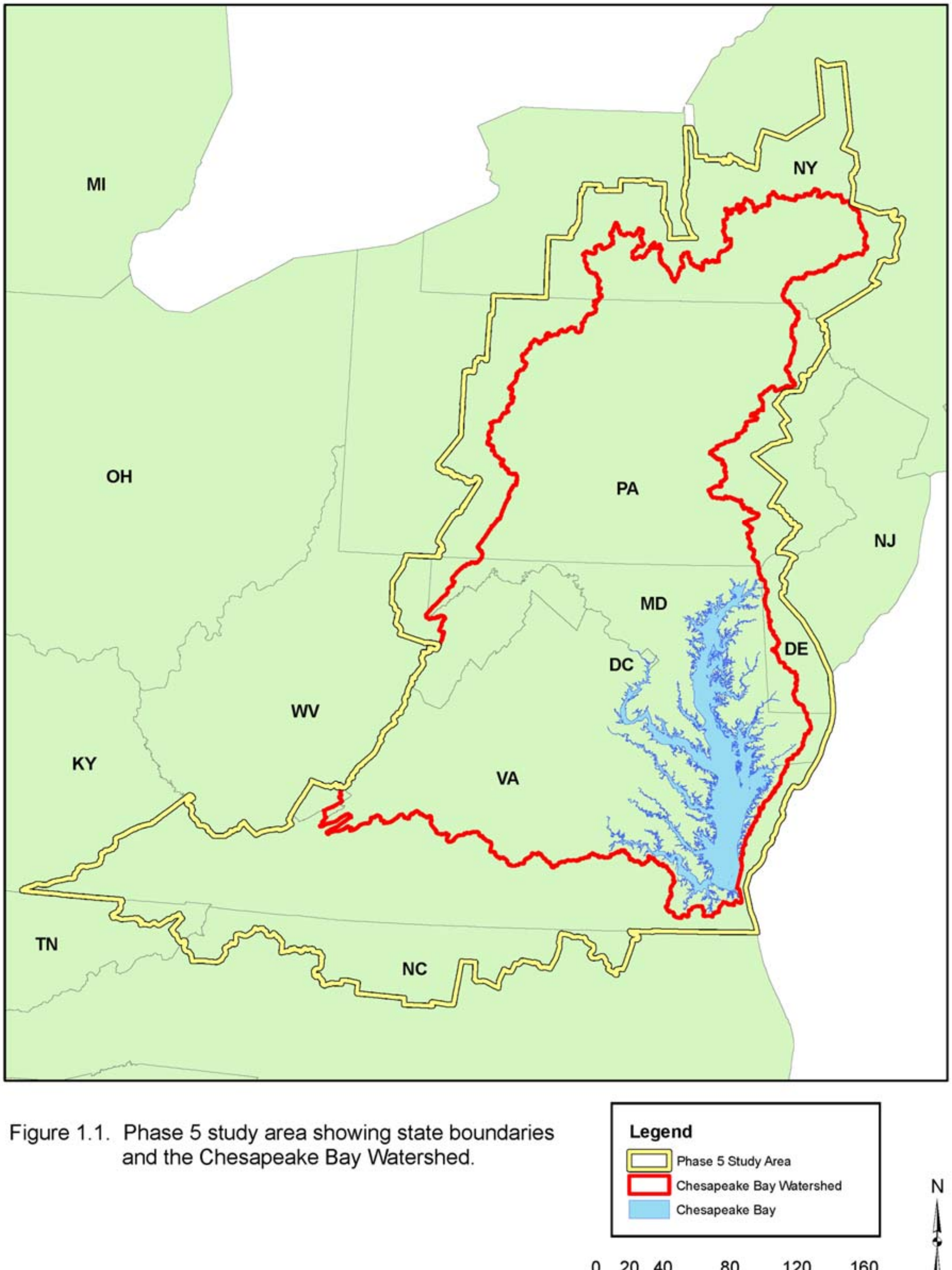
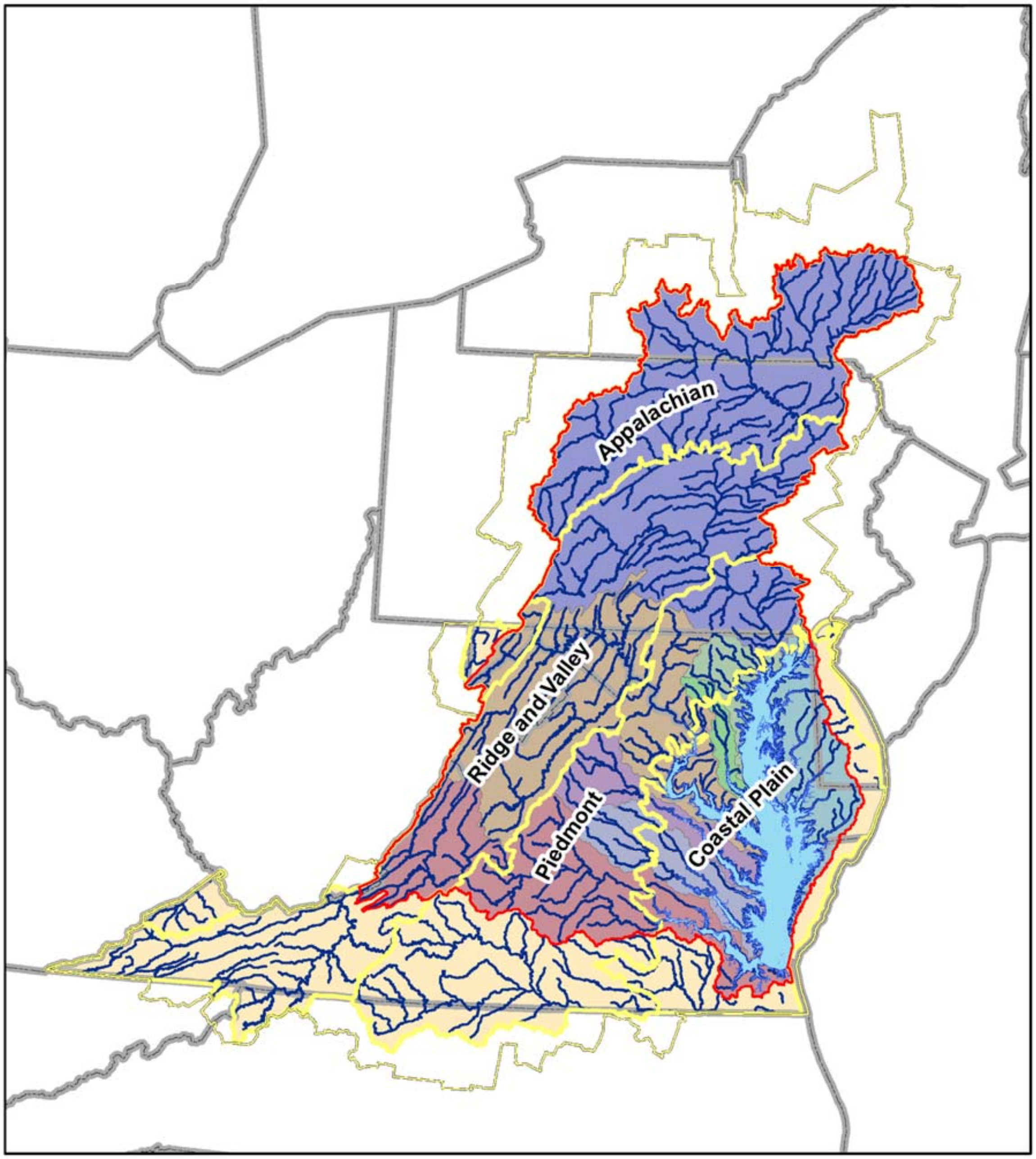


Figure 1.1. Phase 5 study area showing state boundaries and the Chesapeake Bay Watershed.



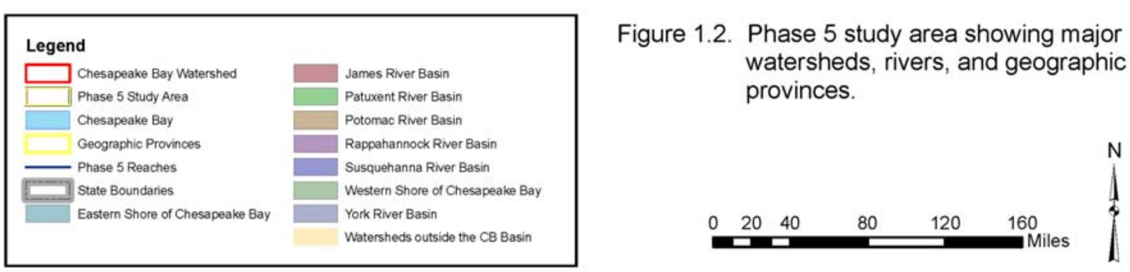


Figure 1.2. Phase 5 study area showing major watersheds, rivers, and geographic provinces.

The Chesapeake Bay Community Phase 5.3 Watershed Model was developed to simulate the Chesapeake watershed, the river flows, and associated transport and fate of nutrients and sediment. The Phase 5.3 Model, in conjunction with models of the Chesapeake airshed and estuary, provides estimates of management actions needed to protect water quality and restore living resources in the Chesapeake.

The major river basins of the Phase 5.3 Model domain are shown in Figure 1.3a. Mean annual flow estimates for the major rivers in the Chesapeake Bay watershed for the period of record are shown in Figure 1.3b. The flow time series for the major rivers for the entire Phase 5.3 simulation period (1985–2005) is shown in Figures 1.3c–g. Flow in the rivers typically varies by an order of magnitude between the extreme high storm and summer low flows. Figure 1.4 shows the distribution and pattern of major land uses in the Phase 5.3 study area.

1.1.3 Introduction to Chesapeake Bay Water Quality Criteria

To achieve and maintain water quality conditions necessary to protect aquatic living resources of the Chesapeake Bay and its tidal tributaries, the Chesapeake Bay Program (CBP) developed water quality criteria for dissolved oxygen, clarity, and chlorophyll (USEPA 2003b). Those published criteria, along with criteria attainment assessment procedures and refined tidal water designated uses (USEPA 2003a) were adopted by Maryland, Virginia, Delaware, and the District of Columbia into their state water quality standards and regulations to address nutrient and sediment-based pollution in the Chesapeake Bay and its tidal tributaries. The Chesapeake Bay water quality standards, based on dissolved oxygen, water clarity, and chlorophyll *a*, are an integrated set of criteria that provide the basis for defining the water quality conditions necessary to protect Chesapeake Bay tidal waters.

1.1.4 The Chesapeake Nutrient and Sediment Cap Load Allocations

The criteria define the water quality conditions necessary to protect Chesapeake Bay aquatic living resources from impairments due to nutrient and sediment over-enrichment (USEPA 2003b; Koroncai et al. 2003). Reductions in the nutrient and sediment loads in the watershed are necessary to achieve and maintain the water quality criteria (Koroncai et al. 2003).

1.1.4.1 The 2003 Nutrient Cap Load Allocations

Excessive nutrients in the Chesapeake Bay and its tidal tributaries promote a number of undesirable water quality conditions such as excessive algal growth, low dissolved oxygen, and reduced water clarity. The effect of nutrient loads on water quality and living

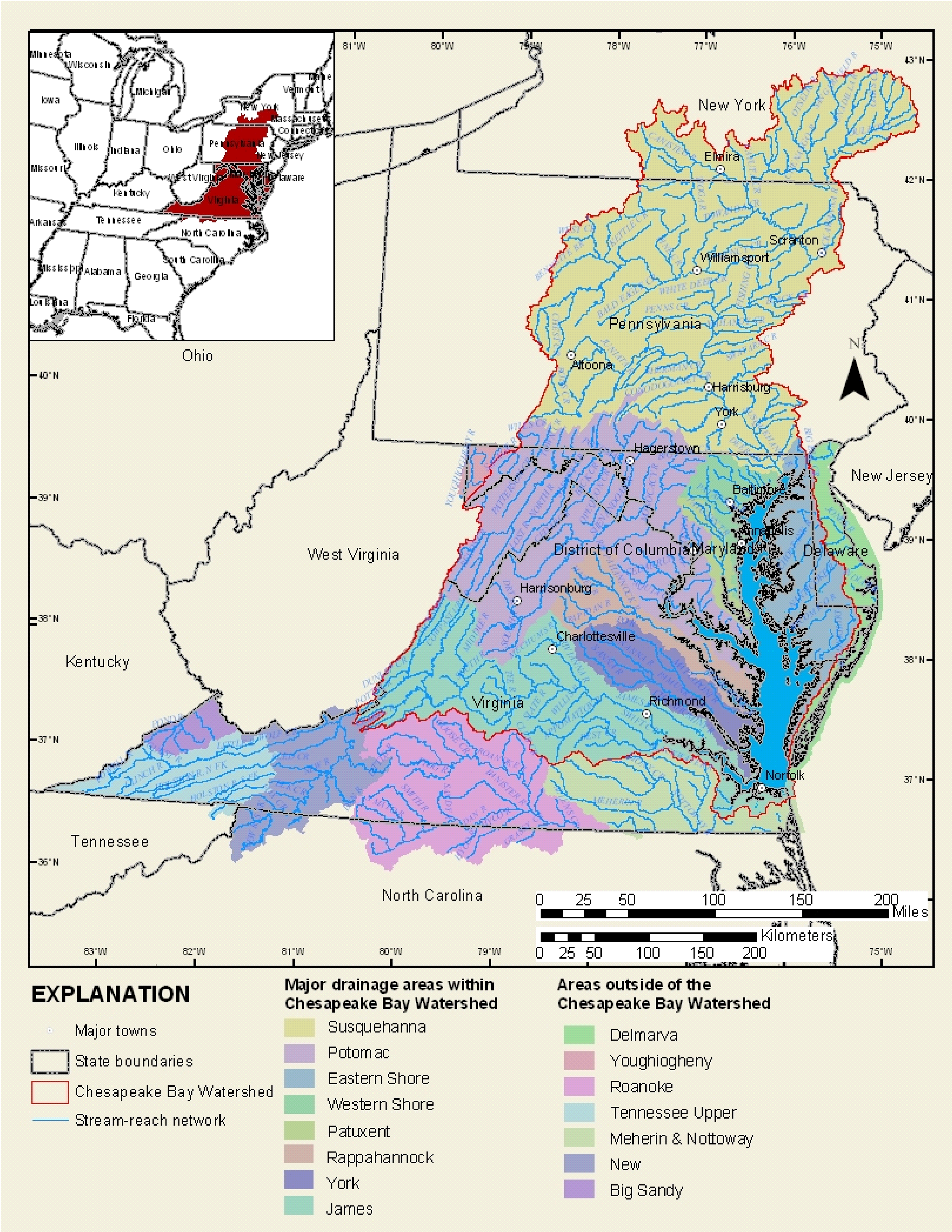


Figure 1.3a. The Phase 5.3 Model domain showing major river basins.

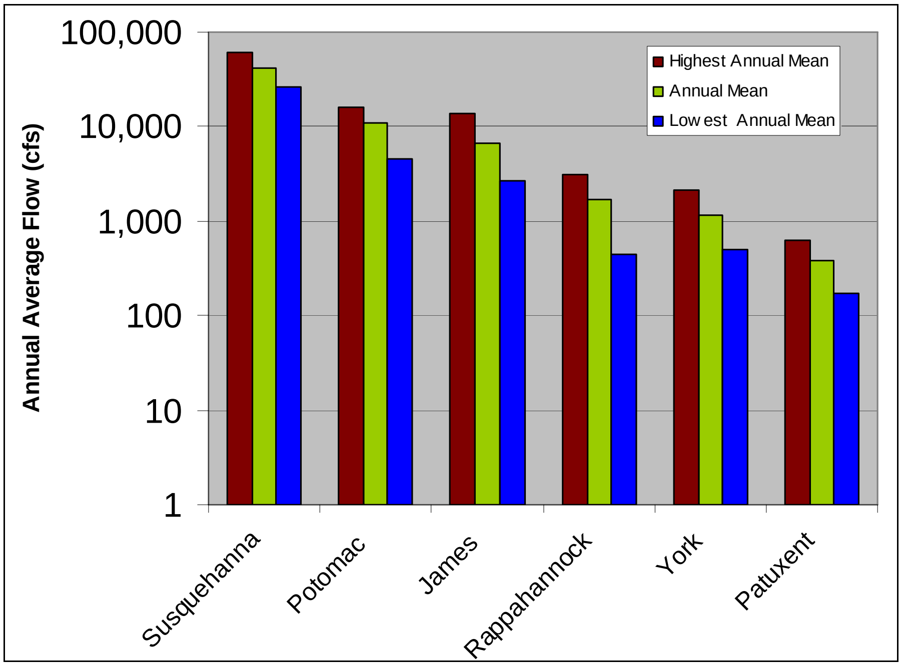


Figure 1.3b. Major river mean annual flow (cfs), and the highest and lowest annual mean flow for the period of record of basin flow gages closest to the head of tide.

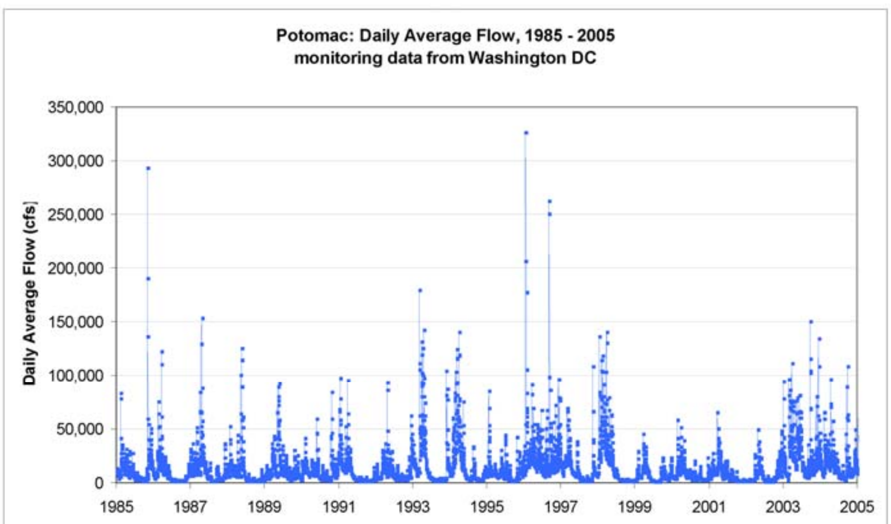


Figure 1.3c. Daily observed flows for the Potomac for 1985 to 2005.

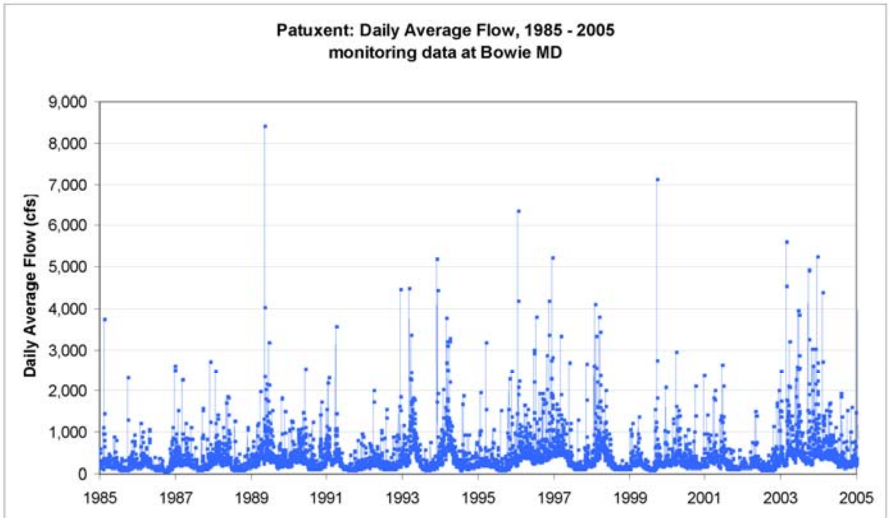


Figure 1.3d. Daily observed flows for the Patuxent for 1985 to 2005.

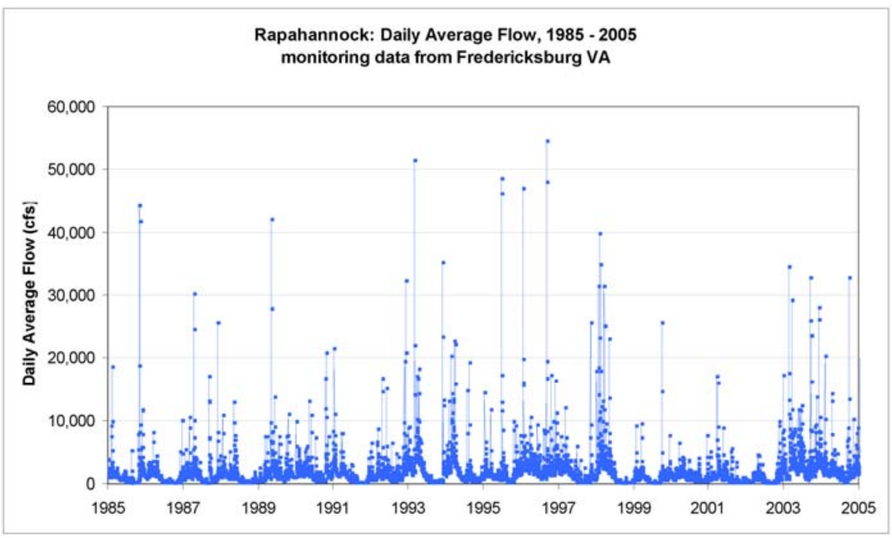


Figure 1.3e. Daily observed flows for the Rappahannock for 1985 to 2005.

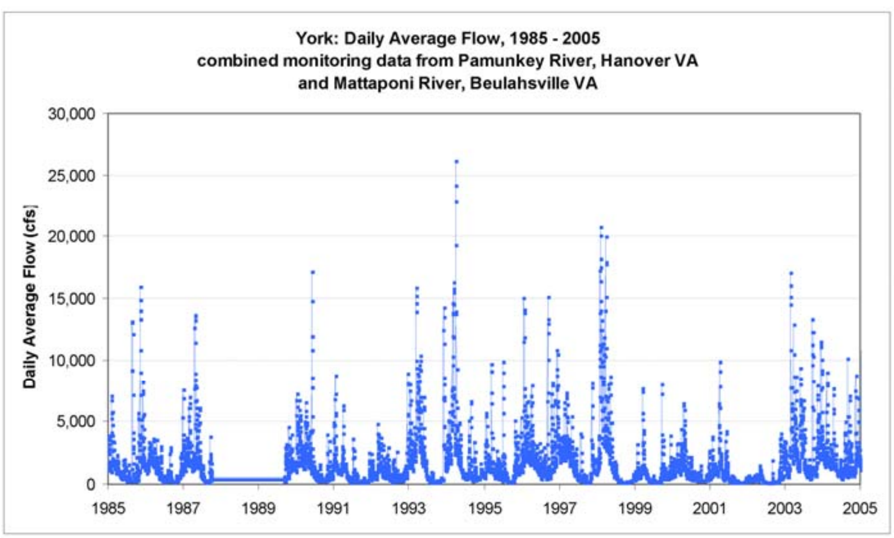


Figure 1.3f. Daily observed flows for the, York for 1985 to 2005 (Period of missing data in 1987-1989).

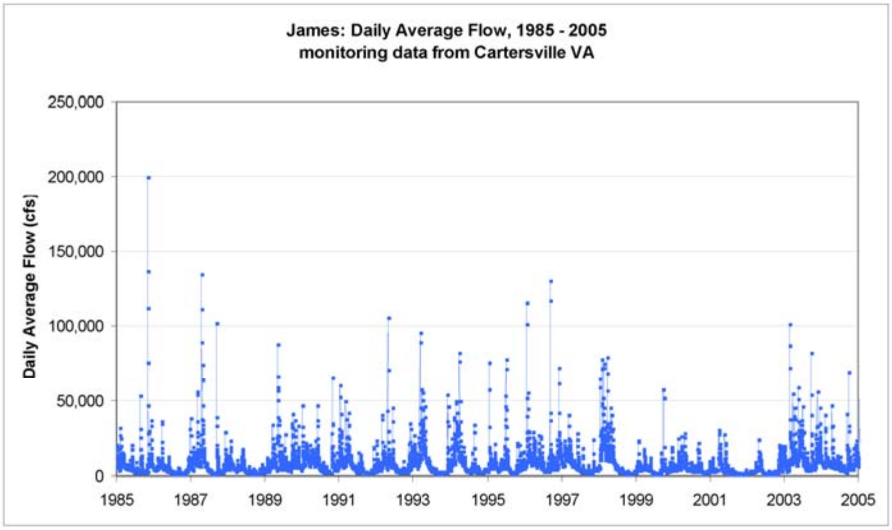


Figure 1.3g. Daily observed flows for the James for 1985 to 2005.

resources tends to vary considerably by season and region. Low dissolved oxygen problems tend to be more pronounced in the deeper parts of the upper-Bay region during the summer months. The allocations for nutrients were developed primarily to address that problem and the related problem of sieches, or periodic oscillations of hypoxic bottom waters, into the surface waters of the Chesapeake. In addition, reductions of nutrient and sediment loads contribute to the restoration of the Chesapeake's underwater grasses.

As a result, in the 2003 Allocations, New York, Pennsylvania, Maryland, Delaware, Virginia, West Virginia, the District of Columbia, and the U.S. Environmental Protection Agency (EPA) agreed to cap average annual nitrogen loads delivered to the Bay's tidal waters at 175 million pounds and average annual phosphorus loads at 12.8 million pounds (Koroncai et al. 2003).

The CBP partners, consisting of the above states, the District of Columbia, and the federal government, agreed to those load reductions on the basis of the Chesapeake Bay Water Quality Model (Cerco and Noel 2004). The Water Quality Model projected nutrient load reductions required to attain published Bay dissolved oxygen criteria applied to the refined tidal water designated uses. The model projected that such load reductions would significantly reduce the persistent summer anoxic conditions in the deep, bottom waters of the Chesapeake Bay and restore suitable habitat quality conditions throughout the tidal tributaries (Koroncai et al. 2003). Furthermore, the reductions are projected to curtail excessive, sometimes harmful, algae conditions (measured as chlorophyll *a*) throughout the Chesapeake Bay and its tidal tributaries.

The Phase 5.3 Model is designed to further the development of management plans under the Chesapeake TMDL to ensure water quality standards for dissolved oxygen and chlorophyll are achieved and fully maintained as required by the Chesapeake TMDL under future conditions of land use and population growth. As discussed in Section 12, the Chesapeake TMDL Allocations of 2010 were entirely consistent with the loads found to achieve water quality standards in 2003.

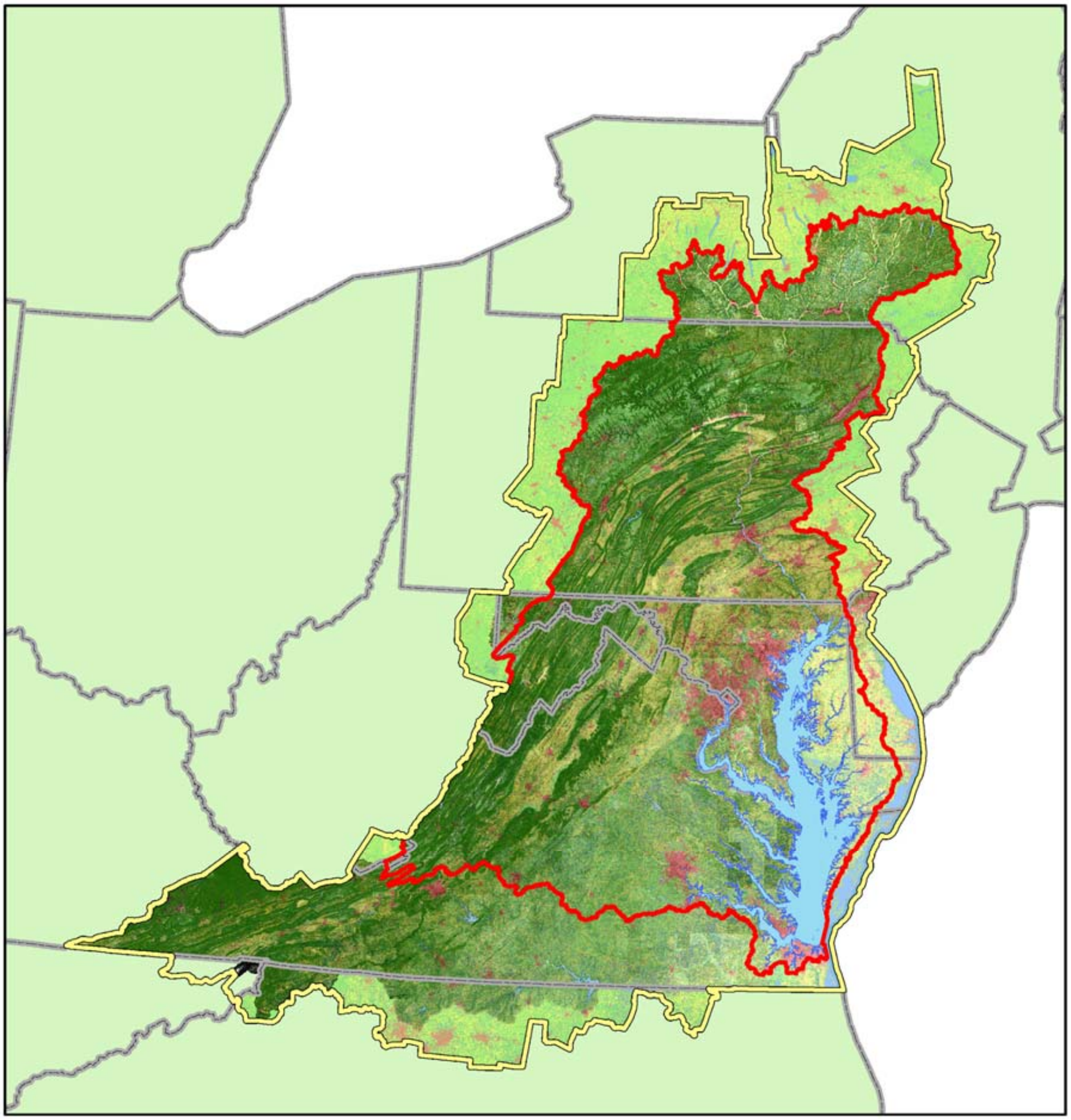


Figure 1.4. Phase 5 study area showing states in the watershed and major land uses.

1.1.4.2 Sediment Cap Load Allocations

Sediments suspended in the water column reduce the amount of light available to support healthy and extensive submerged aquatic vegetation (SAV) or underwater grass communities (USEPA 2000). The relative contribution of suspended sediment and algae that cause poor light conditions varies with location in the Bay tidal waters. The CBP partners agreed that a primary reason for reducing sediment loads to the Bay tidal waters is to provide suitable, shallow-water habitat for restoring SAV. As a result, the cap load allocations for sediments were linked to the recommended water clarity criteria, and a new SAV restoration goal of 185,000 acres was set in recognition that sediment load reductions are essential to SAV restoration.

Unlike nutrients, where loads from virtually the entire Chesapeake Bay watershed affect mainstem Chesapeake Bay water quality, impacts from sediments are predominantly localized. For this reason, local, segment-specific SAV acreage goals have been established, and the sediment cap load allocations are aimed at achieving those restoration goals. The CBP partners recognize that the understanding of sediment sources and their impact on the Chesapeake Bay in 2003 was incomplete. Consequently, the 2003 sediment cap load allocations were focused on land-based sediment cap loads by major tributary basin.

Research, monitoring, and modeling of sediment sources and transport have made significant strides forward and by the completion of the 2010 TMDL, sufficient information was available to establish a sediment allocation, along with the nutrient allocation foe achievement of the clarity/SAV water quality standard.

The Phase 5.3 Model expands our sediment simulation ability in the watershed by adding key landuses like construction, mining, and forest harvest land uses. In addition, the simulation period and spatial scale have been extended to allow sediment calibration stations to increase by about an order of magnitude compared to pervious watershed model versions.

1.2 Watershed Model Background

1.2.1 Trends in Chesapeake Bay Modeling

The Phase 5.3 Model is the most recent of a series of increasingly refined versions of the Chesapeake Bay Watershed Model. Different versions of the model have been operational for more than two decades. Since the first version in 1982, the trends in development of the Watershed Model are (1) greater segmentation, (2) longer simulation periods, (3) greater simulation detail, particularly mechanistic detail increasingly oriented to first principals, (4) greater reliance on web-based distribution of model results and documentation, and (5) application of open source, public domain, community modeling where model code, preprocessors, and postprocessors are distributed via a Web server to the professional community.

1.2.2 History of the Chesapeake Watershed Model

The Chesapeake Bay Watershed Model has been in continuous operation at the CBP since 1982 and has had many upgrades and refinements (Linker et al. 2002). The first version of the model was proprietary software that simulated 64 model segments with a 2-year (1974–1975) calibration period, a 3-year application period (1966, 1974, and 1975), and a 3-year verification period (1976–1978) (Hartigan 1983). Five land uses were simulated including forest, urban, pasture, and cropland under high and low tillage. The major product of this application was the estimation of nonpoint source and point source loads for each major basin (USEPA 1983) and the demonstration of the relative importance of controlling nonpoint and point source loads in the Chesapeake Bay.

Watershed Model Phase 1

The next version of the Watershed Model, called Phase 1, was completed in 1985 with the primary purpose of converting the Watershed Model to the Hydrologic Simulation Program—Fortran (HSPF) public domain code, on which it runs (Bicknell et al. 1997; 2001; Donigian et al. 1984; Johanson et al. 1980). This phase of the model was linked to a steady-state model of the estuary to estimate the water quality benefits of a nutrient load reduction of 40 percent of the controllable loads, which were defined as the loads greater than an all forested condition (Thomann et al. 1994). The linked models were limited and simulated only the average nutrient loads and dissolved oxygen conditions of the summer months. The Phase 1 Watershed Model provided only the estimates of the coastal plain nonpoint source loads, with the balance of the nutrient loads coming from simple fall line loading estimates. The Phase 1 model also characterized the relative portion of the point and nonpoint load sources of the major basins (USEPA 1983). The estimates of these models became part of the basis for the landmark *1987 Chesapeake Bay Agreement*, which set a 40 percent nutrient-reduction goal by the year 2000 (Chesapeake Executive Council 1987).

Watershed Model Phase 2

Phase 2 of the model development increased the simulation period to 4 years (1984–1987) with time steps of one hour and added land uses to simulate areas of concentrated manures, like feedlots and atmospheric deposition to water surfaces (Donigian et al. 1994). This version was completed in 1992 and used linkages to the Regional Acid Deposition Model (RADM) in developing atmospheric deposition of nitrogen scenarios (Dennis 1996). The Phase 2 Watershed Model was fully linked to a three-dimensional, time-varying model of the estuary (Cerco and Cole 1994). Using those two linked models, the nitrogen and phosphorus load reductions needed to achieve the *1987 Chesapeake Bay Agreement* nutrient reduction goals were established (Thomann et al. 1994).

Watershed Model Phase 4.3

Subsequent model phases expanded simulation periods, segmentation, and mechanistic detail in land use and best management practices (BMPs) simulation (Linker et al. 2002). These interim model phases led to the development and application of the Phase 4.3

Model, which was applied in the establishment of the 2003 Allocations (Koroncai et al. 2003).

The Phase 4.3 version simulated a period of 14 years (1984–1997) using 94 model segments with nine land uses (Figure 1.5). Phase 4.3 was based on a slightly modified version of HSPF release 11.1 (Bicknell et al. 1997; 2001; Donigian et al. 1984; Johanson et al. 1980).

The Phase 4.3 Watershed Model allowed for the integrated simulation of land and soil contaminant runoff processes with in-stream hydraulic and sediment-chemical interactions. The model took into account watershed land uses with associated application of fertilizers and animal manure; loads from point sources, atmospheric deposition, onsite wastewater management systems; and BMP reduction factors and delivery factors (Linker et al. 2000). Land uses, including cropland, pasture, urban areas, and forests, were simulated on an hourly time step.

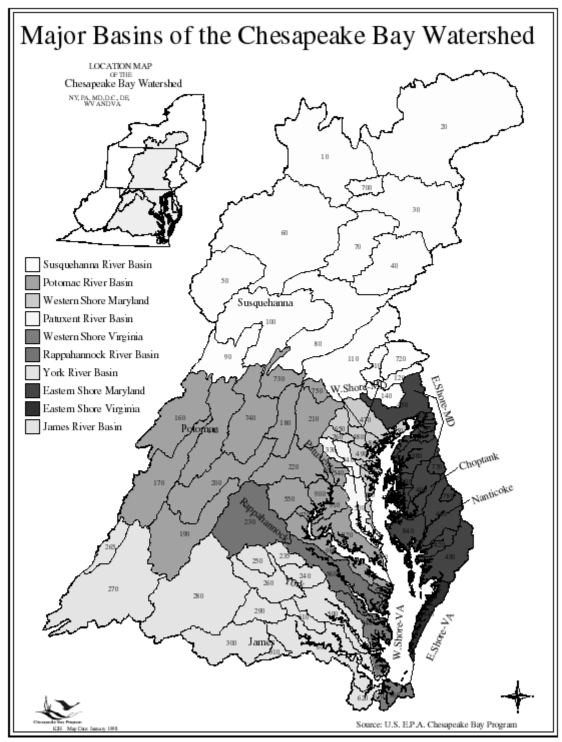


Figure 1.5a. Phase 4.3 segmentation.

The Phase 4.3 Watershed Model simulated an overall mass balance of nitrogen and phosphorus in the basin, so that the ultimate fate of the input nutrients might be incorporation into crop or forest plant material, incorporation into soil, or loss from the watershed and subsequent delivery to the Bay through river runoff (Donigian et al. 1994; Linker et al. 1996; Linker 1996). Nitrogen fates included volatilization to the atmosphere and denitrification as shown in Figure 1.5b. Sediment was simulated both as eroded material washed off land surfaces and as riverine processes of sediment accumulation and erosion. The model was run on a one-hour time step. Watershed Model results, in the form of daily flows and nutrient and sediment loads, were used as input to the Chesapeake Bay Estuary Model for developing the 2003 Allocation.

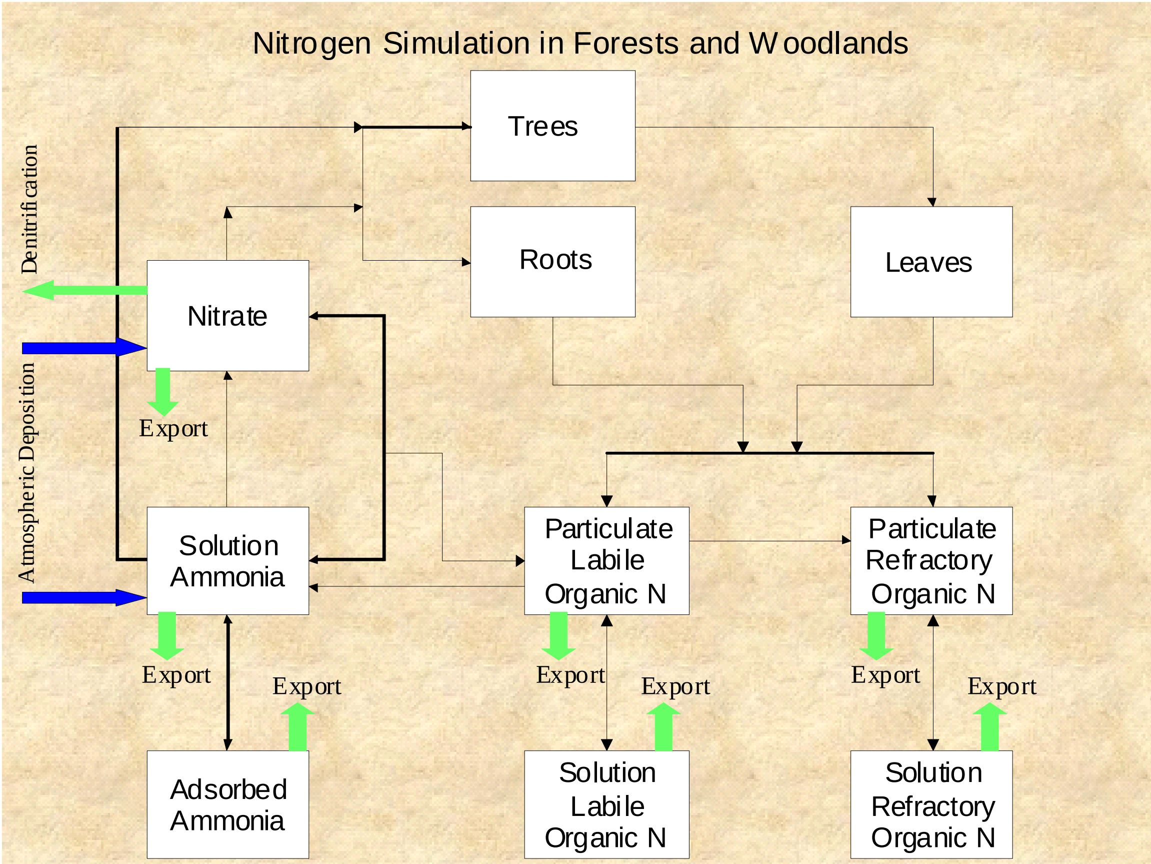


Figure 1.5b. The structure of nitrogen simulation in forests and woodlands. The only simulated nitrogen input is atmospheric deposition, shown here in blue, and the only losses are denitrification and the various exports of the different nitrogen chemical species. The major fate of nitrogen in forests and woodlands is plant uptake, and about two tons of organic nitrogen are typically observed in an acre of forest soil. This reservoir of organic nitrogen in plants and soil is also represented in the Phase 5.3 model.

The Phase 4.3 scenario results were typically reported at the basin level and for 10-year-average annual loads. The use of this average annual load allows for a typical mix of wet, dry, and average hydrology years throughout the basin.

Sediment from all pervious land surfaces was simulated using an empirically based module, which represented sediment export as a function of the amount of detached sediment and runoff intensity. Information on land slope and estimated erosion rates were provided by the National Resources Institute (NRI) database. Delivery of sediment from each land use was calibrated to the NRI estimates of annual, edge-of-field sediment loads as calculated by the Universal Soil Loss Equation (USLE). Riverine sediment processes of aggradation and erosion were also simulated.

Point source data for the simulation period were obtained from the National Pollutant Discharge Elimination System (NPDES). If no state NPDES data were available, state and year-specific default data were calculated for each missing parameter, and annual estimates of load are based on flow from the wastewater treatment plant. Septic system loads were also included in the Phase 4.3 Watershed Model simulation. Septic system data were compiled using census figures and methodology suggested in Maizel et al. (1995).

Each Phase 4.3 Watershed Model river reach was simulated as a completely mixed reach of about a fifth-order river, with all land uses considered to be in direct hydrologic connection, i.e., there were no intervening lower-order river reaches simulated between the simulated land uses and the simulated river reach. Of the 44 reaches simulated, the average length is 170 kilometers (km), the average drainage area was 1,900 square km, and the average time of travel was one day.

1.3 Phase 5.3 Overview

Over the past two decades, the Watershed Model refinements have tended toward increased segmentation, longer simulation periods, and greater land use and BMP mechanistic detail. That trend continues in Phase 5.3, which increases segmentation to about a thousand model segments (Figure 1.6) with an average segment size of about 66 square miles, as discussed in detail in Section 3. That allows greater application of existing calibration stations, of which 237 are used for the calibration of hydrology—an increase of an order of magnitude compared to the Chesapeake watershed stations used for Phase 4.3 (Figures 1.7a–c). Increased river-reach segmentation resulted in a 12-fold increase in monitoring stations compared to Phase 4.3, and improved characterization of spatial variation of the river reaches (within the limitations of the completely mixed reaches of the HSPF code).

In Phase 5.3, the model simulation period is expanded to 2005 to take advantage of recent and expanded monitoring. The expansion of model simulation to a 21-year period requires a change in the treatment of land use in model calibration. While Phase 4.3 and all previous versions had a constant land use, Phase 5.3 allows a time series of land use input data to change annually over the 1985 to 2005 simulation period.

Phase 5.3 has greater mechanistic detail including an expansion of land uses to 13 types of cropland, 2 types of woodland, 3 types of pasture, 4 types of urban land, and other special land uses such as surface mines and construction land uses, as discussed in Section 4. Section 5 covers the accounting of inputs of manures, fertilizers, and atmospheric deposition of nutrients on an annual time series, using a mass balance of Agricultural Census animal populations, crops, records of fertilizer sales, and other data sources. BMPs covered in Section 6 change annually, have refined nutrient and sediment reduction efficiencies, and vary their efficiency on the basis of storm size. Other sections in this report cover point sources (Section 7), the simulation of hydrology (Section 8), and sediment (Section 9). Land and riverine nutrient simulations are covered in Sections 9 and 10, respectively.

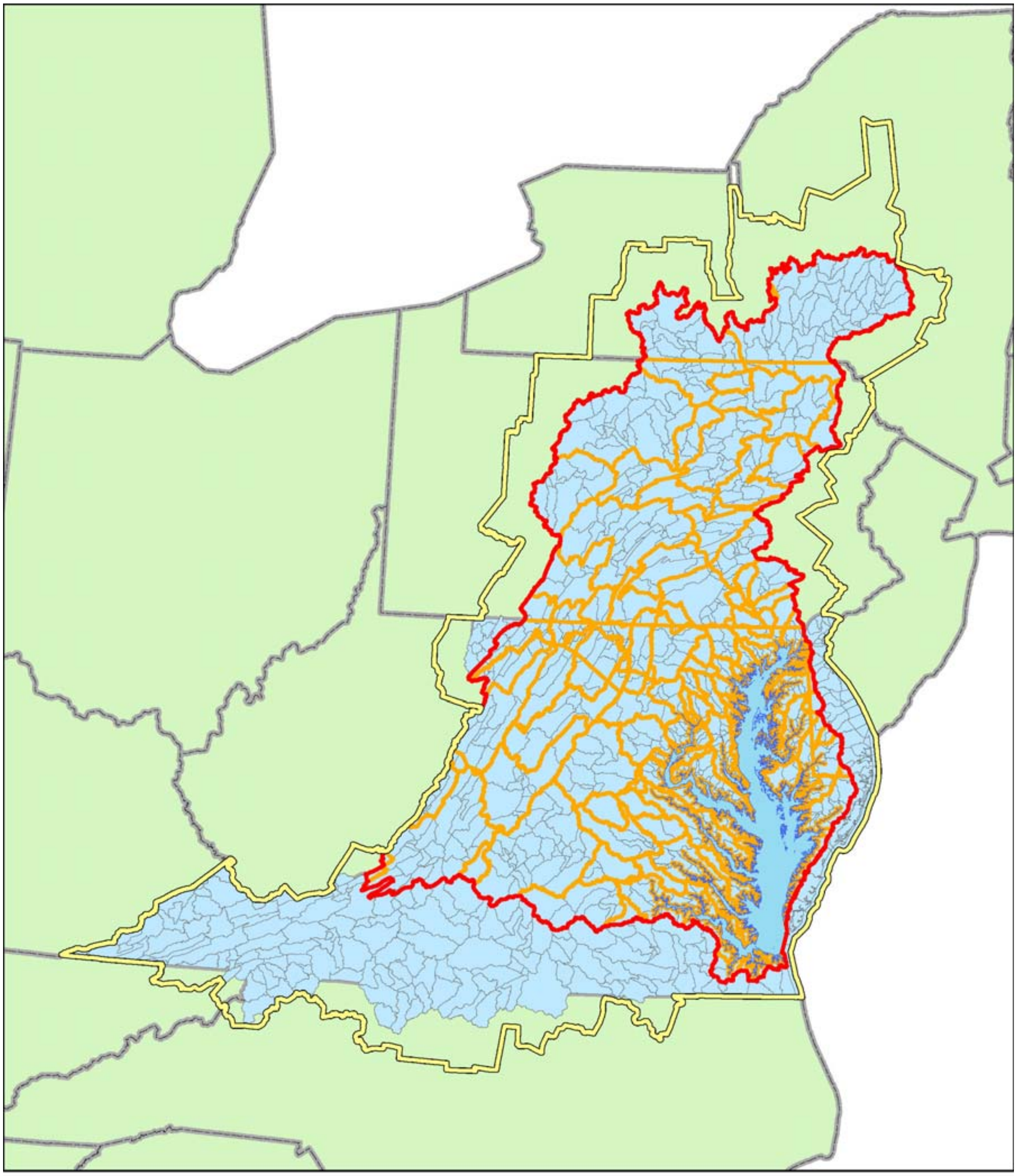


Figure 1.6. Phase 5 domain and segmentation compared to Phase 4.3.

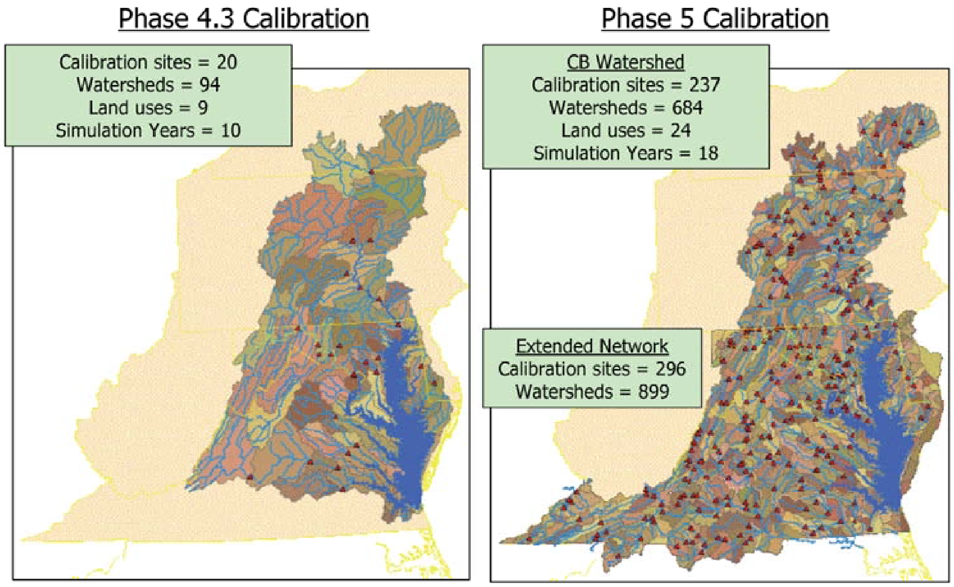
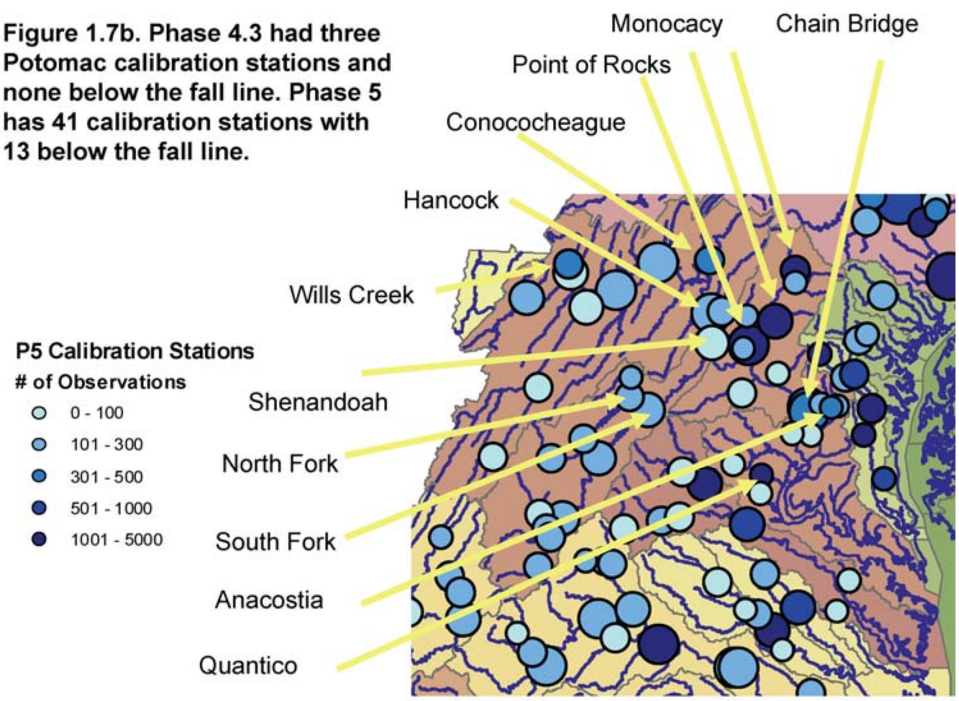


Figure 1.7a. Comparison of Phase 4.3 and Phase 5 calibration stations.

Figure 1.7b. Phase 4.3 had three Potomac calibration stations and none below the fall line. Phase 5 has 41 calibration stations with 13 below the fall line.



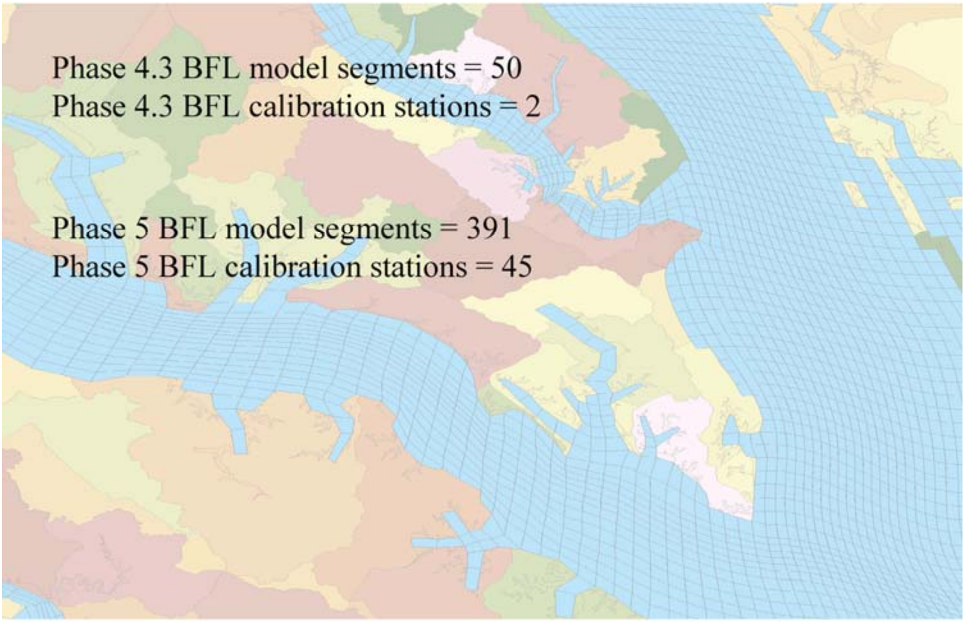


Figure 1.7c. Phase 5 Below Fall Line Model Segments at the Mouths of the Patuxent and Potomac Rivers.

1.4 Statewide Coverage of Virginia, Maryland, and Delaware

The Phase 5.3 Watershed Model was extended to cover the entire states of Virginia, Maryland and Delaware. Although that expands the Phase 5.3 domain beyond the Chesapeake watershed boundaries, the advantages of providing the potential for a consistent water quality assessment for an entire state are significant. Only small portions of four counties in Maryland and Delaware are outside the Chesapeake Bay watershed, so the extension of the Phase 5.3 simulation to cover those areas was trivial. Virginia provided additional funding specifically to extend of the model to cover all the watersheds of Virginia and portions of North Carolina and Tennessee that drain into Virginia.

1.5 Community Model Approach

A community model consists of open source, public domain programs of model code, preprocessors, postprocessors, and input data that are freely distributed often over the Web. In the case of the Phase 5.3 community model operating system, Linux is also open source. Model input data, such as the precipitation fields, point source discharges, atmospheric deposition, and land use are made freely available in a data-sharing approach.

Phase 4.3 was the first Chesapeake Bay Watershed Model distributed as a community model, and the approach was expanded in Phase 5.3. Typical Phase 5.3 users are TMDL model developers and watershed researchers. The Phase 5.3 Model is specifically designed as a community model that can be used in a direct, *as-is* application or can be used as a point of departure for more detailed, small-scale models. The data sharing and the modularity of Phase 5.3 are intended to encourage the efficient use of Phase 5.3 data, or particular model elements, in other independent analyses or models of the watershed.

The use of the community model approach has been adopted and expanded by some state environmental agencies that plan to use the Phase 5.3 Model in a *nested* TMDL approach. That allows better coordination between the small-scale TMDL models in the watershed and the river basin-scale nutrients and sediment reductions needed to achieve the Bay's water quality standards. Overall, the nested approach should be a more effective, cost-efficient, and equitable approach to developing TMDLs.

Details of the Phase 5.3 community model are in Section 13. Model code, input data, and all supporting material for the Phase 5.3 community model are at http://ches.communitymodeling.org/models/CBPhase5/index.php

1.6 Linkage to the Airshed and Estuarine Models

1.6.1 Introduction to Airshed and Estuarine Model Linkage

The Watershed Model is linked to two other models that, together, form a simulation system sufficient for attainment analysis of the Chesapeake Bay water quality standards of dissolved oxygen, clarity/SAV, and chlorophyll for the Chesapeake TMDL (Linker et al. 2008). The two models are the Airshed Model and the Water Quality and Sediment Transport Model (WQSTM).

The Airshed Model, like the Phase 5.3 Watershed Model, is a loading model. As discussed in detail in Section 5, the Airshed Model provides atmospheric deposition loads of nitrogen to the watershed lands and waterbodies simulated by the Phase 5.3 Model and to the tidal Bay and adjacent coastal ocean.

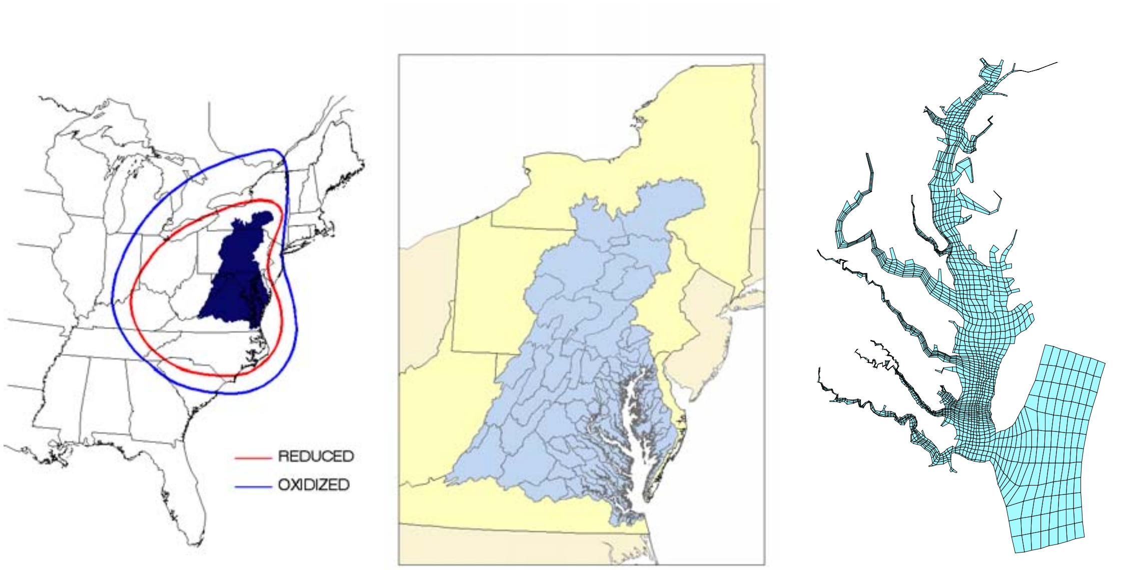
Taking the nutrient loads from the Airshed Model and the nutrient and sediment loads from the Watershed Model, the Chesapeake Bay WQSTM is the decision model used to assess water quality and living resource responses and the degree of water quality standard achievement to the nutrient and sediment input loads. Together, this triad of models forms the Chesapeake Bay Model Package (CBMP).

The CBMP includes other linked or coupled models (Figures 1.8a–b). A hydrodynamic model simulates the hourly temperatures and movement of water in the Bay. The WQSTM simulates the water and habitat quality response to nutrient and sediment loads including the simulation of sediment diagenesis, benthos, and SAV. Loads are inputs from the Watershed Model, from direct atmospheric deposition to the surface of the Bay, and estimated loads from the ocean boundary. The model package is applied in one continuous simulation period (1985–2005) to model transport, eutrophication processes, and sediment-water interactions under various management scenarios designed to analyze the water quality and living resource responses to load reductions at all points in the Bay.

The details of developing the hydrodynamic and water quality models and their calibration and sensitivity are presented in Cerco and Cole (1994), Wang and Johnson

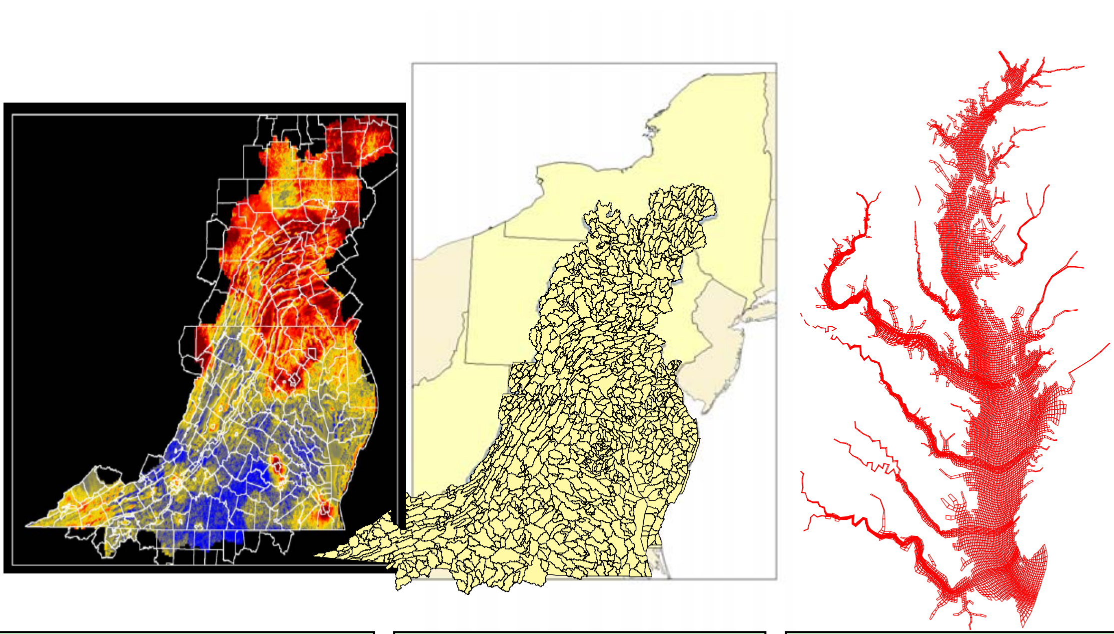
(2000), Cerco and Meyers (2000), Cerco (2000), Cerco and Moore (2001), and Cerco and Noel (2004).

Like the Watershed Model, the WQSTM has had several versions and originated from simpler simulation systems. The first estuary model of the Chesapeake Bay, completed in 1987, was a steady-state, three-dimensional simulation of the summer average period of 1965, 1984, and 1985 (USEPA 1987). Increasingly sophisticated models followed expanding spatial detail, simulation periods, and from water quality to key living resources such as SAV and key filter feeders such as oysters (Cerco and Cole 1994; Cerco and Meyers 2000; Cerco and Noel 2004).



Nitrate and ammonia deposition from improved <u>Daily Nitrate and Ammonium Concentration Models</u> using 35 monitoring stations over 18 simulation years. Adjustments to deposition from <u>Models-3/Community Multi-scale Air Quality (CMAQ) Modeling System</u>	<u>Phase 5 Watershed Model</u> Year-to-year changes in land use and BMPs; 899 segments; 24 land uses; 296 calibration stations; 18 simulation years; sophisticated calibration procedures; calibration demonstrably better in quality and scale	<u>Chesapeake Bay Estuary Model</u> Detailed sediment input; Wave model for resuspension, Full sediment transport; Filter feeder simulation; Simulation of Potomac algal blooms; 54,000 model cells; 18 simulation years

Figure 1.8a. Overview of CBMP application during Phase 4.3 application.



Nitrate and ammonia deposition from improved Daily Nitrate and Ammonium Concentration Models using 35 monitoring stations over 18 simulation years.
Adjustments to deposition from Models-3/Community Multi-scale Air Quality (CMAQ) Modeling System

Phase 5 Watershed Model
Year-to-year changes in land use and BMPs; 899 segments; 24 land uses; 296 calibration stations; 18 simulation years; sophisticated calibration procedures; calibration demonstrably better in quality and scale

Chesapeake Bay Estuary Model
Detailed sediment input; Wave model for resuspension, Full sediment transport; Filter feeder simulation; Simulation of Potomac algal blooms; 54,000 model cells; 18 simulation years

Figure 1.8b. Overview of CBMP application during Phase 5.3 application.

The previous phase of estuary model development had segmentation of about 13,000 cells as shown in Figure 1.9 (Cerco and Meyers 2000). This was the model used with the Phase 4.3 Watershed Model to develop the Chesapeake Bay basin nutrient and sediment cap load allocations of 2003 (Koroncai et al. 2003).

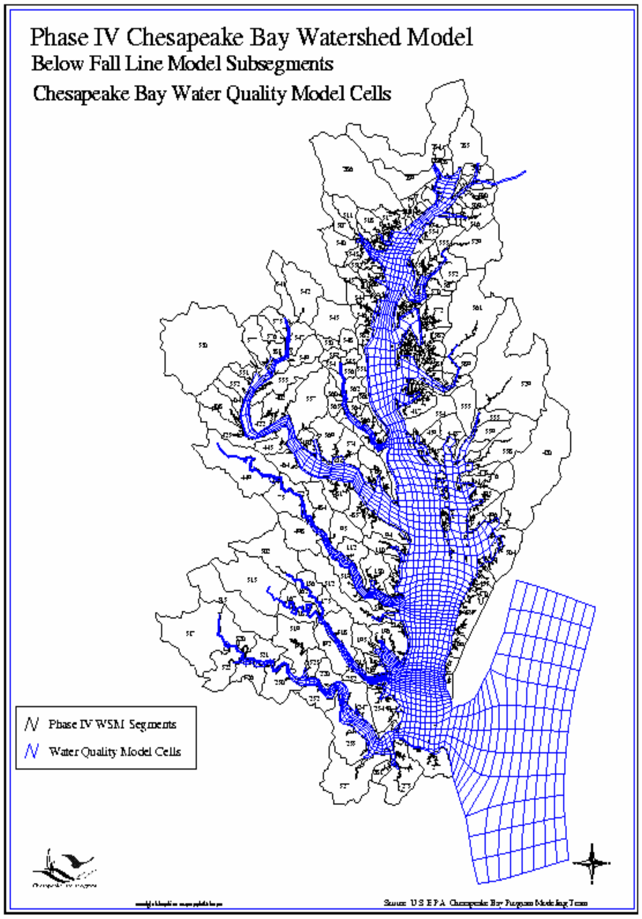


Figure 1.9. Water Quality Model grid.

1.6.2 Chesapeake Bay Water Quality and Sediment Transport Model

The central issues of the WQSTM simulation are the computations of algal biomass, dissolved oxygen, and water clarity. To compute algae and dissolved oxygen, a suite of 24 model state variables is used (Table 1.1).

The WQSTM treats each cell as a control volume, which exchanges material with its adjacent cells. The WQSTM solves, for each volume and for each state variable, a three-dimensional conservation of mass equation (Cerco and Cole 1994). The details of the kinetics portion of the mass-conservation equation for each state variable are described in Cerco and Cole (1994) and Cerco and Noel (2004). The processes and phenomena relevant to the water quality model simulation include (1) bottom-water hypoxia, (2) the spring phytoplankton bloom, (3) nutrient limitations, (4) sediment-water interactions, and (5) nitrogen and phosphorus budgets.

Table 1-1. WQSTM state variables.

Temperature	Dissolved organic nitrogen
Salinity	Labile particulate organic nitrogen
Inorganic suspended solids	Refractory particulate organic nitrogen
Diatoms	Total phosphate
Cyanobacteria (blue-green algae)	Dissolved organic phosphorus
Other phytoplankton	Labile particulate organic phosphorus
Dissolved organic carbon	Refractory particulate organic phosphorus
Labile particulate organic carbon	Dissolved oxygen
Refractory particulate organic carbon	Chemical oxygen demand
Ammonium	Dissolved silica
Nitrate	Particulate biogenic silica
Microzooplankton	Mesozooplankton

Source: Cerco and Noel 2004.

Over seasonal time scales, sediments are a significant source of dissolved nutrients to the overlying water column. The role of sediments in the system-wide nutrient budget is especially important in summer when seasonal low flows diminish riverine nutrient input, sediment oxygen increases with warmer temperatures, and low dissolved oxygen causes large fluxes of ammonia and phosphate from the sediment. The WQSTM is coupled directly to a predictive benthic-sediment model (DiToro and Fitzpatrick 1993). The two models interact at each time step with the WQSTM delivering settled organic material to the sediment bed and the benthic-sediment model calculating the flux of oxygen and nutrients to the water column.

1.6.3 Modeling Living Resources

The ultimate aim of eutrophication modeling is to preserve living resources. Usually, the modeling process involves simulating living resource parameters such as dissolved oxygen. Computed values are compared to living resource standards, and a projection is made whether simulated conditions are beneficial to the resources of interest (e.g., fish, oysters).

SAV is an important living resource because it provides habitat for biota of economic importance and helps support the estuarine food chain. Establishing healthy SAV acres is also directly tied to the clarity water quality standard. The WQSTM’s direct simulation of SAV accounts for the relationships among grass production, light, and nutrient availability, allowing for a measurement of the response of SAV to reductions in nutrient and sediment loads. A thin ribbon of model cells following the 2-meter contour is used to depict the littoral zone for SAV growth. The SAV component of the model builds on the concepts established by Madden and Kemp (1996) and Wetzel and Neckles (1986).

Three state variables are modeled for SAV: shoots, (above-ground biomass), roots (below-ground biomass), and epiphytes (attached growth to leaves). In addition, the estuary model incorporates three dominant SAV communities based largely on salinity regimes (Moore et al. 1999). Within each community, a target species is selected: eelgrass *(Zostera marina*) for high salinity, widgeon grass (*Ruppia maritima)* for moderate salinity, and wild celery (*Vallisneria americana)* for tidal fresh. Because SAV production in the Bay and tributaries is largely determined by light availability (Orth and Moore 1984; Kemp et al. 1983), a predictive representation of light attenuation is needed. The computation of light attenuation requires the addition of fixed solids, or suspended sediment, to the list of model state variables.

In addition to simulating SAV as a living resource, the model simulates three phytoplankton groups (diatoms, greens, and blue-greens) and separates zooplankton into two size classes for modeling purposes: microzooplankton (44–201 microns) and mesozooplankton (> 201 microns). Zooplankton are selected as a parameter because they are a valuable food source for finfish and to improve the computation of phytoplankton since zooplankton feed on phytoplankton, detritus, and each other.

Benthos, or bottom-dwelling organisms, are included in the model because they are an important food source for crabs, finfish, and other economically significant biota and because they can exert a substantial influence on water quality through their filtering of overlying water (Cohen 1984; Newell 1988). Within the estuary model, benthos are divided into deposit feeders and filter feeders.

1.6.4 Linkage of Phase 5.3 and the Water Quality Sediment Transport Model

The WQSTM processes nutrient and sediment loads delivered from the Phase 5.3 Watershed Model and nutrient atmospheric deposition to tidal surface waters from the Community Multiscale Air Quality (CMAQ) airshed model. In addition, the model incorporates loads from the ocean interface and from the linked-bottom sediments model. The simulation of estuarine hydrology and water and habitat quality parameters and processes occurs on 15-minute time steps with output generated every 10 days. The entire simulation period is 21 years (1985–2005). Seasonal averages for all water and habitat quality parameters are calculated for each year in the period. Estuary model results from management scenarios, designed to determine the impact of reduced nutrient and sediment loads, are often reported as a yearly or seasonal averages of a 10-year simulation of 1991 to 2000.

The Sassafras River is used here as an example of the Phase 5.3–WQSTM linkage. The Sassafras River basin consists of four Phase 5.3 segments roughly equivalent to federal Hydrologic Unit Code (HUC) 11 delineations (Figure 1.10). The Phase 5.3 river segments are, from east to west, 3363, 3360, 3362, and 3361. Also shown are the three counties in the Sassafras watershed; Kent County, Maryland (A24029); Cecil County, Maryland (A24015); and New Castle County, Delaware (A10003). Shown are the Phase 5.3 county-segments that simulate the land use loads, the Phase 5.3 river-segments, and the cells of WQSTM with the edge cells of the WQSTM highlighted in yellow. The county-river-segments are the intersection of the county-segments and the river-segments. The Sassafras River basin consists of nine county-river segments, as marked by the nine segment numbers, with reference to their corresponding counties, in Figure 1.10. The county-river segments are loading 20 WQSTM edge cells, as listed in Table 1.2, also shown in Figure 1.10.

The load from a county-segment is split for its contacting edge cells, proportionally to the sub-drainage areas of the cells, which are estimated from the Digital Elevation Model (DEM) map. For example, the county-segment A24029-3362 allocates 20, 30, and 50 percent of the loads to cells 144244, 145244, and 146244, respectively (Table 1.2). Some cells can receive loads from more than one county-segment. For example, cell 145244 receives 30 percent load of county-segment A24029-3362 and 40 percent load of county-segment A24015-3362, as indicated by the number 2 in the column of sources (Table 1.2). The total *sum of percent* equals 900 percent, indicating that the loads from the nine county-segments are entirely allocated onto the 20 cells.

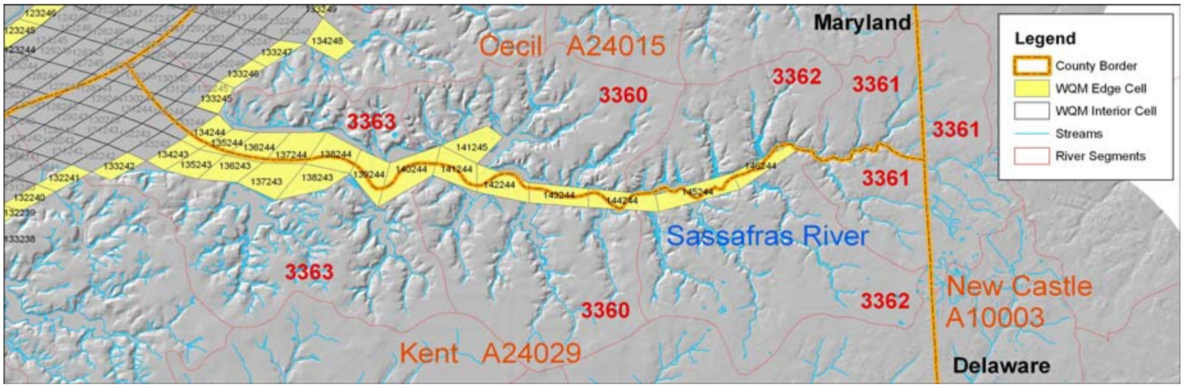


Figure 1.10. County-river segments of the Sassafras River basin and edge cells of the WQSTM.

Table 1-2. Example of allocating loads from county-segments of the Watershed Model

		County-segment			County-segment			County-segment			County-segment			County-segment		
Cell #	Sources	%	County	Seg	%	County	Seg	%	County	Seg	%	County	Seg	%	County	Seg
133242	1	5.0	A24029	3363												
134243	1	5.0	A24029	3363												
134244	1				12.5	A24015	3363									
135243	1	5.0	A24029	3363												
135244	1				12.5	A24015	3363									
136243	1	5.0	A24029	3363												
136244	1				12.5	A24015	3363									
137243	1	40.0	A24029	3363												
137244	1				12.5	A24015	3363									
138243	1	5.0	A24029	3363												
138244	1				12.5	A24015	3363									
139244	2	20.0	A24029	3363	25.0	A24015	3363									
140244	4	15.0	A24029	3363	12.5	A24015	3363	4.167	A24015	3360	3.125	A24029	3360			
141244	1										21.875	A24029	3360			
141245	1							62.50	A24015	3360						
142244	2							4.167	A24015	3360	50.000	A24029	3360			
143244	2							25.00	A24015	3360	21.875	A24029	3360			
144244	4	20.0	A24029	3362	10.0	A24015	3362	4.167	A24015	3360	3.125	A24029	3360			
145244	2	30.0	A24029	3362	40.0	A24015	3362									
146244	5	50.0	A24029	3362	50.0	A24015	3362	100.0	A10003	3361	100.00	A24015	3361	100.0	A24029	3361
	sum of %	200.0			200.0			200.0			200.0			100.0		

1.6.5 Airshed Model

The Airshed Model is a combination of two models—a regression model of atmospheric wet deposition and a fully developed air simulation of the North America continent called the CMAQ Model (USEPA 1999). The Airshed Model, like the other models of the CBMP, has gone through a series of refinements with increasingly sophisticated regression and air quality models applied over time (Linker et al. 2000).

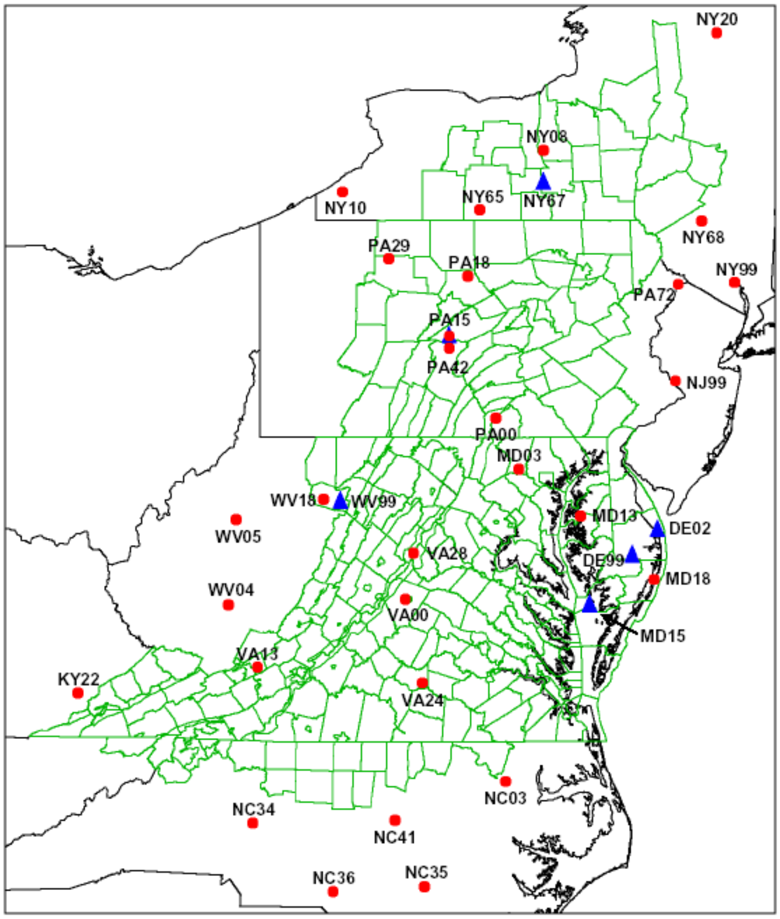


Figure 1.11. Atmospheric deposition monitoring stations used in the airshed regression model.

The regression model uses 15 National Atmospheric Deposition Program (NADP) monitoring stations and 6 AirMoN stations (Figure 1.11) to form a regression of wetfall deposition in the entire Phase 5.3 Model domain over the entire simulation period (Grimm and Lynch 2004). For each day of rain, a regression—using rainfall, land use, and local emission levels of ammonia and nitrous oxides—estimates wetfall atmospheric deposition.

Dryfall deposition is continuous, and the CMAQ model estimates it daily. The CMAQ model is run on a 36-km grid covering the North American continent simulating boundary conditions with a refined 12-km grid for the entire Phase 5.3 study area (Figure 1.12). In scenario mode, CMAQ also provides estimates of nitrogen deposition resulting from changes in emissions from utility, mobile, and industrial sources due to management actions or growth. The base deposition that a regression determines is adjusted by a reduction ratio deposition determined by CMAQ.

Figure 1.12. The 12-km CMAQ model grid over the Chesapeake Bay basin used for Phase 5.3 MModel applications.

1.7 Overview of Key Phase 5.3 Scenarios

Several key scenarios were used to assess the achievement and maintenance of the Chesapeake water quality standards for dissolved oxygen, chlorophyll, and clarity (EPA, 2003a; EPA, 2003b). One key scenario was the 2010 Tributary Strategy Scenario, which encompassed the estimated 2010 management conditions, land use, and human and animal populations under conditions of the 2003 Allocation's tributary strategies. Other key scenarios included a 2010 No-Action Scenario and an E3 Scenario which together formed the basis for the 2010 TMDL Allocation (Figure 1.13). Scenarios were also developed to represent key Chesapeake Bay Program years of like the 1985 Scenario, corresponding to a period of highest nutrient and sediment loads to the Bay, and the 2009 Scenario representing current conditions. The lowest loads to the Bay were simulated by the All Forest Scenario which estimated the nutrient and sediment loads under an all forested condition in the watershed. Section 12 describes in detail the development of these scenarios and their estimated loads

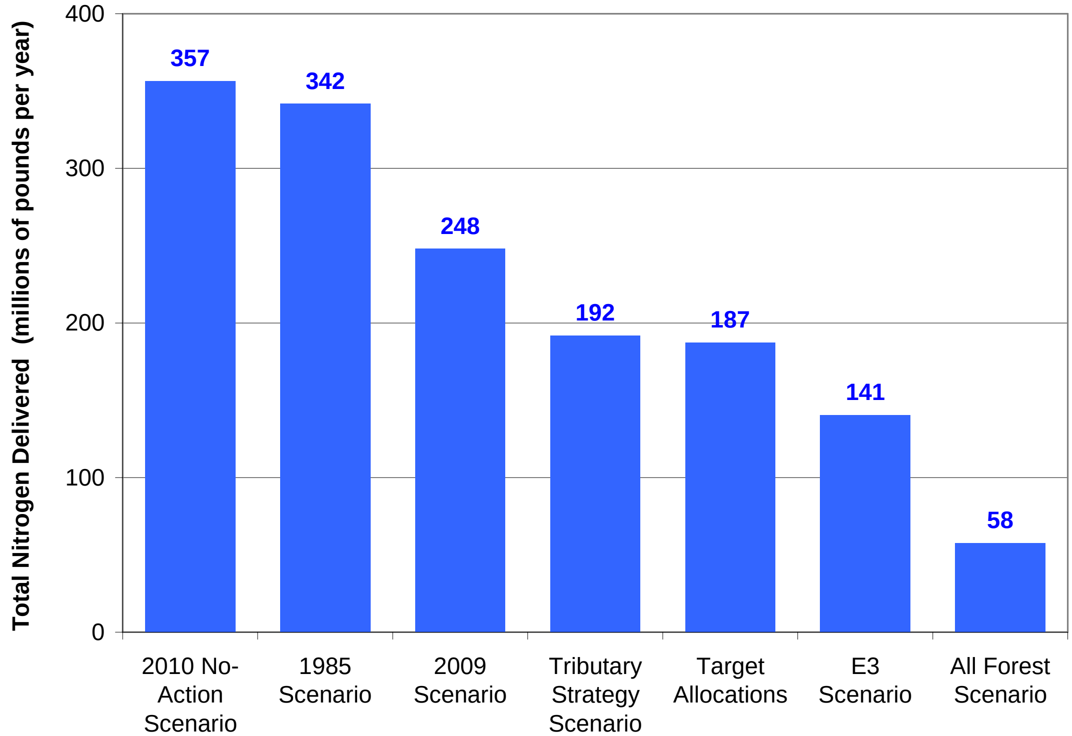


Figure 1.13. Nitrogen loads delivered to the Bay for the key scenarios (in million pounds per year).

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