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# DEVELOPMENT AND APPLICATION OF THE 2010 CHESAPEAKE BAY WATERSHED TOTAL MAXIMUM DAILY LOAD MODEL[1]

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ABSTRACT: The Phase 5.3 Watershed Model simulates the Chesapeake watershed land use, river flows, and the associated transport and fate of nutrient and sediment loads to the Chesapeake Bay. The Phase 5.3 Model is the most recent of a series of increasingly refined versions of a model that have been operational for more than two decades. 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, achieve Chesapeake water quality standards, and restore living resources. The Phase 5.3 Watershed Model tracks nutrient and sediment load estimates of the entire 166,000 km$^2$ watershed, including loads from all six watershed states. The creation of software systems, input datasets, and calibration methods were important aspects of the model development process. A community model approach was taken with model development and application, and the model was developed by a broad coalition of model practitioners including environmental engineers, scientists, and environmental managers. Among the users of the Phase 5.3 Model are the Chesapeake watershed states and local governments, consultants, river basin commissions, and universities. Development and application of the model are described, as well as key scenarios ranging from high nutrient and sediment load conditions if no management actions were taken in the watershed, to low load estimates of an all-forested condition.

(KEY TERMS: best management practices (BMPs); Chesapeake Bay; total maximum daily load (TMDL); Chesapeake TMDL; integrated environmental models; Watershed Model, Phase 5.3; HSPF; watershed nutrient loads; watershed sediment loads; watershed management.)

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## INTRODUCTION

The Chesapeake's 166,000 km$^2$ watershed includes parts of New York, Pennsylvania, West Virginia, Delaware, Maryland, Virginia, and the entire District of Columbia (Figure 1). The Chesapeake watershed spans the Appalachian, Ridge and Valley, Piedmont, and Atlantic Coastal Plain geologic provinces in the Mid-Atlantic region. The Atlantic Coastal Plain is a flat, lowland area with a maximum elevation of about 90 m. The Coastal Plain extends from the edge of the continental shelf, east to a fall line that ranges from 25 to 145 km west of the Chesapeake Bay. The fall line forms the boundary between the Piedmont Plateau and the Coastal Plain and is marked by a rapid drop in elevation with waterfalls and rapids, as well as the Bay watershed cities of Baltimore, Washington,

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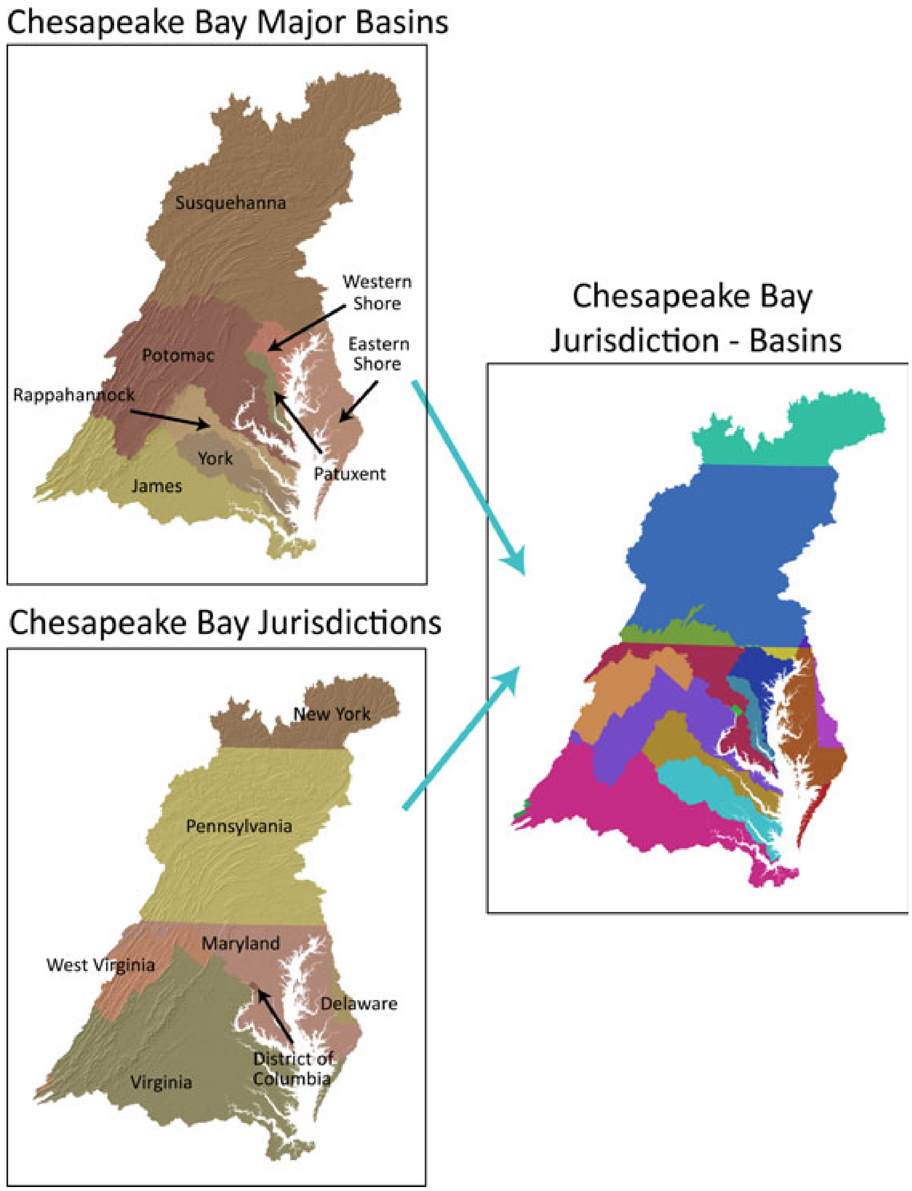


FIGURE 1. Location of the Chesapeake Bay Watershed.

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 opportunities for 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 tidal waters. 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. Both the Piedmont and the Coastal Plain are regions of considerable agricultural activity. The Ridge and Valley and the Appalachian provinces cover the western and northern part of the watershed and are typically characterized by forested mountain slopes and agricultural land uses in the valleys. The current land use in the watershed is about 65% forest or wooded, 24% agriculture, and 11% developed land (buildings, roads, and so on, in urban, suburban, and rural areas) (USEPA, 2010d). Nearly 17 million people live in the Chesapeake Bay watershed.

The tidal waters of the Chesapeake are impaired by high loads of nutrients and sediment from the watershed (Kemp *et al.*, 1992, 2004, 2005; Boynton *et al.*, 1995; Boynton and Kemp, 2008) and the Chesapeake total maximum daily load (TMDL) allocation is designed to reduce nutrient and sediment loads from the watershed to achieve dissolved oxygen, chlorophyll, and clarity water quality standards in the tidal Bay (USEPA, 2010a; Linker *et al.*, this issue).

To develop the TMDL allocation and to simulate the flows and nutrient and sediment loads in the watershed, the open source, public domain Phase 5.3 Community Watershed Model was developed and is freely distributed through web sites of the EPA Chesapeake Bay Program Office and the Chesapeake Bay Community Model Program (http://www.chesapeakebay.net/phase5.htm and http://ches.communitymodeling.org/models/CBPhase5/index.php).

*Community Model Approach*

Phase 5.3 is based on Hydrologic Simulation Program — Fortran (HSPF) which is a widely used watershed model in continual development through support by several federal agencies (Donigian *et al.*, 1995a, b; Bicknell *et al.*, 1997, 2001). HSPF is a continuous, physically based, lumped-parameter model that simulates hydrology, sediment, and water quality constituents in the soil and in streams. The model uses meteorological information, land surface characteristics, application data, and management practices to simulate the processes that occur in a watershed. The result of the simulation is a multidecade time series of flow, and nutrient and sediment loads at any segment in the watershed. An HSPF model is typically calibrated to observed flow and water quality data measured at river segment outlets.

The Phase 5.3 application of HSPF has been developed by a broad coalition of model practitioners, environmental engineers, scientists, and environmental managers. The Chesapeake Bay Program, principally through its modeling and nutrient work groups, provided technical guidance and review of the Phase 5.3 Model development and application. Among the users of the Phase 5.3 Community Watershed Model are Chesapeake Bay watershed states and local governments, which use the Phase 5.3 Model as a starting point for small-scale TMDL and other pollutant load modeling. Using the same model for local TMDL development that already provides guidance to the regional Chesapeake TMDL has obvious advantages of efficiency and consistency. For three states, Virginia, Maryland, and Delaware, the Phase 5.3 Model domain was extended beyond the Chesapeake watershed boundary, shown in red in Figure 1, to provide, to the fullest extent possible, consistent state-wide coverage for both the Chesapeake TMDL and local TMDLs. Other community model users include consultants, river basin commissions, and universities that can use the Phase 5.3 analysis capability in studies of watersheds, water supply, and climate change.

The Phase 5.3 Model code, documentation, calibration data, data libraries, list servers, the Model Operations Manual, model scenario output, and more can be found on the links above. These websites are dynamic and are intended to be responsive to user needs. As Phase 5.3 Model development and application expand, the information on these websites will continue to be updated (Shenk *et al.*, 2012).

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) finer segmentation, (2) longer simulation periods, (3) greater simulation detail, particularly simulation of the nitrogen and phosphorus cycle in more detail, (4) more complexity in the development of nutrient input data such as fertilizer, manure, and atmospheric deposition, (5) greater reliance on web-based distribution of model results and documentation, and (6) application of open source, public domain, community modeling where model code, preprocessors, and postprocessors are distributed via web servers to the professional community (Linker *et al.*, 2008; Shenk *et al.*, 2012).

*Model Development History*

The Chesapeake Watershed Model has been in continuous operation since 1982 and has had many upgrades and refinements (Linker *et al.*, 2002). The first version of the model utilized proprietary software and simulated 64 model segments with a two-year (1974-1975) calibration period, a three-year application period (1966, 1974, and 1975), and a three-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.

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 HSPF public domain code, on which it now runs (Johanson *et al.*, 1980; Donigian *et al.*, 1984; Bicknell *et al.*, 1997, 2001). 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 in 40% of the controllable loads, which were defined as the loads greater than those produced by an all-forested condition (Thomann *et al.*, 1994).

Phase 2 of the model development increased the simulation period to four years (1984-1987) with time steps of 1 h, and added land uses to simulate areas of concentrated loads like feedlots, as well as atmospheric deposition to water surfaces (Donigian *et al.*, 1994). This version was completed in 1992 and used linkages to the Regional Acid Deposition Model in developing scenarios of atmospheric deposition of nitrogen (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).

Subsequent model phases expanded simulation periods, segmentation, and mechanistic detail in land use and best management practice (BMP) 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. Phase 4.3 was based on a slightly modified version of HSPF release 11.1 (Johanson *et al.*, 1980; Donigian *et al.*, 1984; Bicknell *et al.*, 1997, 2001).

In Phase 5.3, the Watershed Model has increased in complexity, commensurate with the increased management challenges associated with the Chesapeake Bay TMDL. The model simulation period was expanded from 1984 to 2005 to take advantage of recent and expanded monitoring data. The expansion of model simulation to a 22-year period required a change in the treatment of land use in model calibration. Whereas Phase 4.3 and all previous versions had a constant land use, Phase 5.3 allowed a time series of land use input data to change annually over the 1984-2005 simulation period (Shenk *et al.*, 2012). Segmentation and the number of monitoring stations used for calibration increased by about an order of magnitude compared to Phase 4.3 (USEPA, 2010c). 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. The increased complexity of Phase 5.3 posed challenges in efficient model operation in the large-scale watershed, as well as in incorporating changes in management practices and land uses over time. To resolve these difficulties, ancillary software that enhances the existing HSPF model structure was developed (Shenk *et al.*, 2012).

In the Chesapeake TMDL application, the Phase 5.3 Model is used with Bay Program models of the airshed (Community Multiscale Air Quality Model — CMAQ) and tidal Bay water quality (Water Quality and Sediment Transport Model) (Linker *et al.*, 2008, this issue; Cerco *et al.*, 2010, this issue; Cerco and Noel, this issue).

## METHODS

Phase 5.3 Community Watershed Model simulates both land and river processes. Simulated river reaches receive flows, nutrients, and sediment from the land simulation and ultimately transport their loads to the Bay. The framework for the Phase 5.3 Community Watershed Model is based on jointly applying two types of segmentation to the model domain: (1) county-based *land segments,* and (2) *river segments*, which are the watersheds associated with the river reach network (Martucci *et al.*, 2006; USEPA, 2010c). Figure 2 illustrates the overlapping land segments and river segments for the example of Tioga County, Pennsylvania. The intersection of a land segment and a river segment is designated a land-river segment.

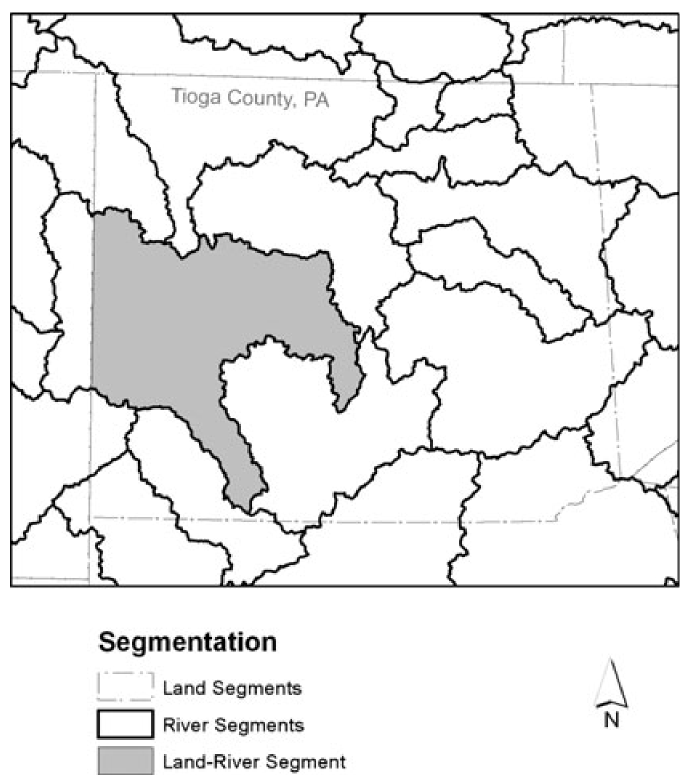


FIGURE 2. An Example of the Relation between Land Segments, River Segments, and Land River Segments in Tioga County, Pennsylvania.

*Model Segmentation*

In Phase 5.3, the Chesapeake watershed is represented as 309 land segments which are primarily defined by county boundaries because this is the finest scale available for key model inputs, such as manure loads and crop types obtained from Agricultural Census data (U.S. Census Bureau, Economics and Statistics Administration, 1982, 1987, 1992, 1997, 2002, 2007). Surface and subsurface flows, sediment, and water quality constituents from the land segments are discharged to river segments representing a river reach, a lake or reservoir, or a watershed discharging directly to tidal waters.

The Phase 5.3 Model river segmentation has 1,063 river segments with an average area of about 170 $km^2$. At this scale, 287 of the river segments had available streamflow observations that were representative of the simulated river in that segment. This number was more than an order of magnitude increase compared to the 20 stations used for calibration of the previous Phase 4.3 version (USEPA, 2010c). The increased segmentation of Phase 5.3 improves characterization of spatial variation within the limitations of the "lumped-parameter" HSPF model. The hydraulic and water quality processes that occur in the river channel network are simulated as completely mixed reaches, and increasing the number of reaches increases the longitudinal variation.

*Land Use and Management Practices*

The Phase 5.3 Model expands land use types to 26. Each land use is simulated on an hourly time step tracing the fate and transport of input nutrient loads from atmospheric deposition, fertilizer, and animal manure. Each land use is simulated as a single unit area in each segment, and the single unit area, such as a hectare is then multiplied by the hectares of each land use draining to each river segment (USEPA, 2010d).

Coincident with the development of Phase 5.3 was the development of an online decision-support tool known as Scenario Builder (USEPA, 2010e). Scenario Builder is used to generate calibration and scenario data for the Phase 5.3 Model. Combined with the Phase 5.3 Model, the tool provides rapid scenario development and application. Scenario Builder allows state and local governments and watershed organizations to translate land use decisions such as zoning, permit approvals, and BMP implementation into changes in nitrogen, phosphorus, and sediment loads from a particular county or watershed. Scenario Builder is used by state and local governments for assessment and development of management plans to meet load allocations associated with the Chesapeake and local TMDLs.

The Scenario Builder tool utilizes input data from diverse sources, including the Agricultural Census, the Chesapeake Bay Program land use change model, the Chesapeake Bay Program point source database, the National Environmental Information Exchange Network, data on BMP effectiveness, and state-supplied nutrient use and BMP implementation data. The tool can process data at a variety of scales, including land-river segment, river segment, land segment, county, state and basin, tributary strategy basin or state.

Detailed information on Scenario Builder can be found at http://www.chesapeakebay.net/phase5.htm.

*Precipitation and Meteorology Inputs*

The foundation of any hydrological simulation is the input precipitation data. The Phase 5.3 Model uses hourly time series of precipitation over the 1984-2005 simulation period. Developing decades of hourly precipitation time series is a challenge as new precipitation monitoring stations became operative and older stations are discontinued. A precipitation model (Hay *et al.*, 1991, 2000, 2006) was used for generating the Phase 5.3 precipitation datasets to account for the changing spatial distribution of observed stations over the simulation period. Observed precipitation data are interpolated across the Phase 5.3 domain by fitting a multiple regression equation that relates the observed daily data to latitude, longitude, and elevation. In the case of the Phase 5.3 Model, the Chesapeake Bay basin was divided into six subregions, and a separate regression equation was fitted by month for each subregion. The intercept for each regression equation was allowed to vary on a daily basis to match local observed data. The fitted equations were then interpolated onto a 5-km grid and then averaged over land segments to estimate precipitation inputs. The resultant daily estimates were converted to hourly time series needed by the Phase 5.3 model using nearby available hourly observations that most closely matched the daily total. Temperature estimates were produced using a similar method (USEPA, 2010f).

The hourly meteorological data in the Phase 5.3 Watershed Model include air temperature, wind speed, and solar radiation. Air temperature is modeled from observations from numerous stations using a model similar to the precipitation model. Wind speed and solar radiation were compiled from observed meteorological data of daily average wind speed and daily cloud cover from sunrise to sunset taken at the seven primary meteorological stations including Binghamton, New York; Williamsport, Pennsylvania; Middletown/Harrisburg, Pennsylvania; Elkins, West Virginia; Dulles Airport, Virginia; Roanoke, Virginia; and Richmond, Virginia (USEPA, 2010f).

*Nutrient Inputs*

Nutrient inputs to the Chesapeake watershed model originate from manure, fertilizer, wastewater discharges, septic system loads, and atmospheric deposition. Manure loads are estimated over the 1984-2005 model simulation period from county-based animal inventories in the Agricultural Census (U.S. Census Bureau, Economics and Statistics Administration, 1982, 1987, 1992, 1997, 2002, 2007). Animal types and typical manure handling practices are accounted for in estimating the manure load available for application to the land and the estimated losses from volatilization (USEPA, 2010g).

Fertilizer application rates are determined from crop uptake rates guided by crop yields, as reported every five years in the Agricultural Census. Monthly application rates are specified in the land use inputs that represent starter, side-dress, and other fertilizer applications for the specific crop (USEPA, 2010g). It is assumed in the simulation that fertilizer is applied in a way that avoids harming crops. Nutrient over-application could cause lodging in grains or other harmful effects on plants. Where manure loads are insufficient to meet the application rates consistent with the estimated crop yield, fertilizer is applied. A further assumption is that farmers apply fertilizer in an economically rational manner and aim toward agronomically efficient application rates.

Wastewater nutrient loads are estimated for municipal and industrial discharges, combined sewer overflows, sanitary sewer overflows, and on-site wastewater disposal systems. The loads are estimated on a monthly basis for major wastewater facilities and on an annual basis for minor facilities based on the National Pollutant Discharge Elimination System records (USEPA, 2010h). As in the case of all the nutrient loads in the Phase 5.3 Model, the complete time series of information on point source discharges as applied in the Phase 5.3 river segments from 1985 to 2005 are in the Chesapeake Community Modeling Program's Phase 5.3 data library at: http://ches.communitymodeling.org/models/CBPhase5/datalibrary.php.

Loads of nitrogen from atmospheric deposition are estimated by a combination of a regression model of wet deposition (Grimm and Lynch, 2007), and a continental-scale air quality model of North America called the CMAQ for estimates of dry deposition (Dennis *et al.*, 2007; Hameedi *et al.*, 2007). The CMAQ Model also provides estimates of nitrogen deposition resulting from changes in emissions from utility, mobile, and industrial sources due to management actions or growth (Linker *et al.*, this issue).

*Land Use Target Load Calculation*

The start of the nutrient calibration process is development of land use-specific target loads for calibration of nutrient loads from each land use (USEPA, 2010i). The approach was to use all relevant literature values for a given land use to establish a median target calibration load for that land use. The median target load derived from the literature was assumed to be the exported load of a land which had a median input load for that land use as shown in Figure 3. To get the estimated load target for each land segment, the relative amounts of the input nutrients from fertilizer, manure, and atmospheric deposition of nitrogen for that land segment land use was determined. Then a slope of the change in export load to nutrient load inputs was established where the intercept with the *y*-axis corresponding to zero input loads was set at half the median land use export target value as shown in Figure 3. At a zero input load, a condition not actually seen for any land use in the watershed, the export target load would decrease to half that of the median because of the assumption that even under the condition of no new input loads the land would still discharge nitrogen at a decreased rate from groundwater and soil storage. This approach allowed for changes in application loads to cause an increase or decrease in nutrient exports. For a particular land use, it allows a land segment with high total input loads to have relatively high estimated nutrient targets and a land segment with

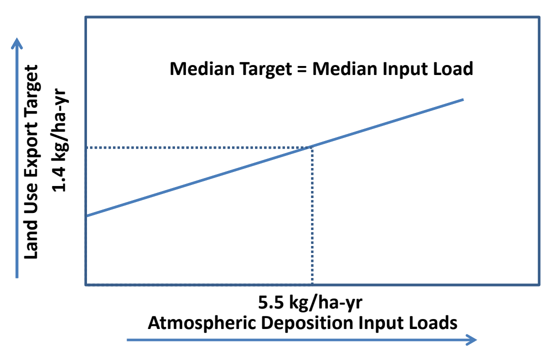


FIGURE 3. An Example of the Relationship between Input Nutrient Loads and Initial Export Target for Any Land Use. The nitrogen export target load for the forest, woodlots, and woodland land use is represented in this example. The observed range of input loads in this example is 2.9-12.4 kg/ha/yr.

relatively low loads to have a lower target. It should be noted that this method only established the initial calibration targets. Further adjustments were made during the calibration process. This method is not used for scenario analysis; rather the sensitivity to inputs is directly modeled. The approach and key assumptions are explained below for the example of the land use of forest, woodlots, and wooded.

The forest, woodlots, and wooded land use only receives atmospheric input (USEPA, 2010i). The median forest total nitrogen load exported to streams and rivers was found to be 1.4 kg/ha/yr, and the median atmospheric deposition in the Chesapeake watershed is 5.5 kg/ha/yr with a range from 2.9 to 12.4 kg/ha/yr for the 309 land segments of the Chesapeake watershed. It was also assumed that responses to changes in atmospheric deposition would be linear which is consistent with the literature under moderate levels of nitrogen loading to forest. At high levels of atmospheric deposition, nitrogen saturation occurs and the rate of export increases faster than the rate of deposition increase (Aber *et al.*, 1989, 2003; Hunsacker *et al.*, 1993; Stoddard, 1994; Goodale *et al.*, 2002).

Models involve choices, and the choices in setting the land use nutrient load calibration targets were made from a collection of observed values described in the literature which are always too few. More detailed local data for land use within each segment are always to be desired, though are rarely available. The aim of the calibration target loads was to represent broad watershed characteristics of the export of nutrient loads from each simulated land use. Table 1 gives the mean annual calibrated nitrogen and phosphorus loads for land uses in the 309 land segments. The range of the annual average export targets is set by the variation in input nutrient loads as described above. Note that Table 1 contains 16 land uses rather than 26 as described above. The additional 10 land uses in the final model are subclasses of those listed in Table 1. The developed classes are divided into high and low density and many of the agricultural classes have nutrient management subclasses with modified inputs of fertilizer and manure.

TABLE 1. Nitrogen and Phosphorus Calibration Targets in kg/ha/yr.

| Land Use | Nitrogen (kg/ha/yr) | Phosphorus (kg/ha/yr) |
|---|---|---|
| Forest, woodlots, and wooded | 3.4 | 0.1 |
| Hay — unfertilized | 6.7 | 0.4 |
| Pasture | 7.6 | 0.8 |
| Alfalfa | 9.2 | 0.8 |
| Hay — fertilized | 10 | 0.9 |
| Pervious developed | 14 | 0.7 |
| Impervious developed | 18 | 2.4 |
| Extractive | 21 | 3.9 |
| Harvested forest | 34 | 0.9 |
| Conventional till without manure | 39 | 2.8 |
| Conventional till receiving manure | 39 | 2.2 |
| Conservation till receiving manure | 39 | 1.7 |
| Construction | 42 | 7.8 |
| Degraded riparian pasture | 72 | 9.4 |
| Nursery | 404 | 95 |
| Animal feeding operations | 1,681 | 112 |

### *Enhanced Phase 5.3 Model Structure*

An enhanced HSPF model structure was developed for the Phase 5.3 Model to simulate the spatial segmentation that increased by an order of magnitude over the previous Phase 4.3 version (Linker *et al.*, 2008). The enhanced structure is useful for large model applications to administer the model efficiently and to simulate the effects of land use and management change through decadal timescales. The enhancement consists of two preprocessors called the Land UCI Generator (LUG) and the River UCI Generator (RUG), and an External Transfer Module (ETM). UCI refers to a User Control Input file which is the standard method of parameterizing an HSPF run. The LUG and RUG preprocessors were developed to automatically generate input files for land and river simulations and the ETM is a software system that links land simulation to river simulation with dynamic land use and management practice transfer functions (Shenk *et al.*, 2012).

Automated calibration techniques were applied in the hydrology, land, and river nutrient and sediment calibrations (USEPA, 2010i,j,k). The techniques were generally rule-based optimizations in which a parameter in the simulation is linked to a specific calibration metric or set of metrics. These calibration metrics were found heuristically through calibration experience, sensitivity tests, and trial and error. Automated calibration of HSPF and other watershed models is a growing practice as computing power increases (Lumb *et al.*, 1994; Flynn *et al.*, 1995; Doherty and Johnston, 2003).

## RESULTS

Seven key scenarios were used to assess the achievement and maintenance of the Chesapeake water quality standards for dissolved oxygen, chlorophyll, and clarity. 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 (Koroncai *et al.*, 2003). This is set in contrast to the 2010 Allocation Scenario, which represents the estimated loads under the Phase I Watershed Implementation Plans (WIPs) (USEPA, 2010a). Other key scenarios included a 2010 No-Action Scenario and an E3 Scenario which together formed the basis for the 2010 TMDL Allocation (USEPA, 2010b). Scenarios were also developed to represent key Chesapeake Bay Program years such as 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 (USEPA, 2010b).

### *No-Action Scenario*

The No-Action Scenario estimates nutrient and sediment loads under the conditions of no environmental point sources and nonpoint source controls using a 2010 land use and population (USEPA, 2010b). Major widespread management practices such as nutrient management and conservation tillage were eliminated in this scenario. Atmospheric deposition loads of nitrogen were set at estimated 1985 high load conditions. Wastewater point source load assumptions were assumed to be at a level of primary treatment only, with no phosphate detergent ban in place. Wastewater point source loads were assumed to be 25 mg/l total nitrogen and 6 mg/l total phosphorus concentrations and at 2010 flows. Figures 4-6 show the relative proportion of nutrient- and sediment-delivered loads for the 2010 No-Action Scenario. The No-Action Scenario is a *what-if* scenario of watershed conditions with minimal managed nutrient and Sediment controls on loads. It is used with the E3 Scenario to define *controllable* loads, the difference between No-Action and E3 loads. Controllable loads is a component of the methodology used to develop the 2010 TMDL Allocation loads needed to meet water quality standards (Linker *et al.*, this issue).

### *1985 Scenario*

The 1985 Scenario uses estimated 1985 land uses, animal populations, atmospheric deposition, and point source loads (USEPA, 2010b). The scenario's nutrient load estimates, along with the 2010 No-Action Scenario, have the highest delivered loads of nutrients and sediment to the Bay (Figures 4-6).

### *2009 Scenario*

The 2009 Scenario represents an estimate of current load levels and uses estimated 2009 land uses, animal populations, atmospheric deposition, and point source loads. The 2009 year was chosen for simulation as it was the most recent year for which

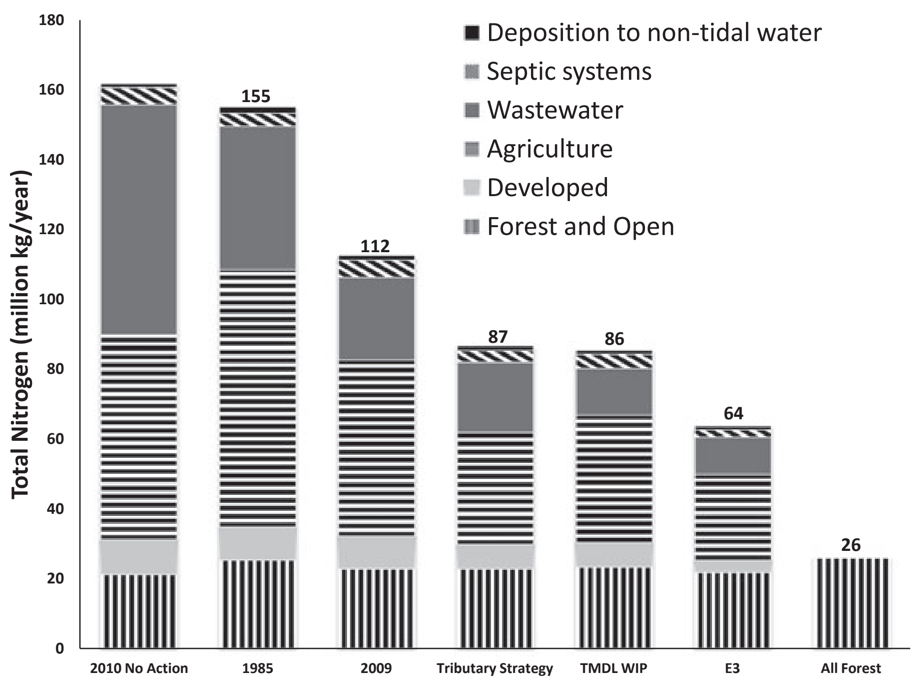


FIGURE 4. Estimated Total Nitrogen Loads from Key Scenarios in Million kg/yr. All loads are flow normalized.

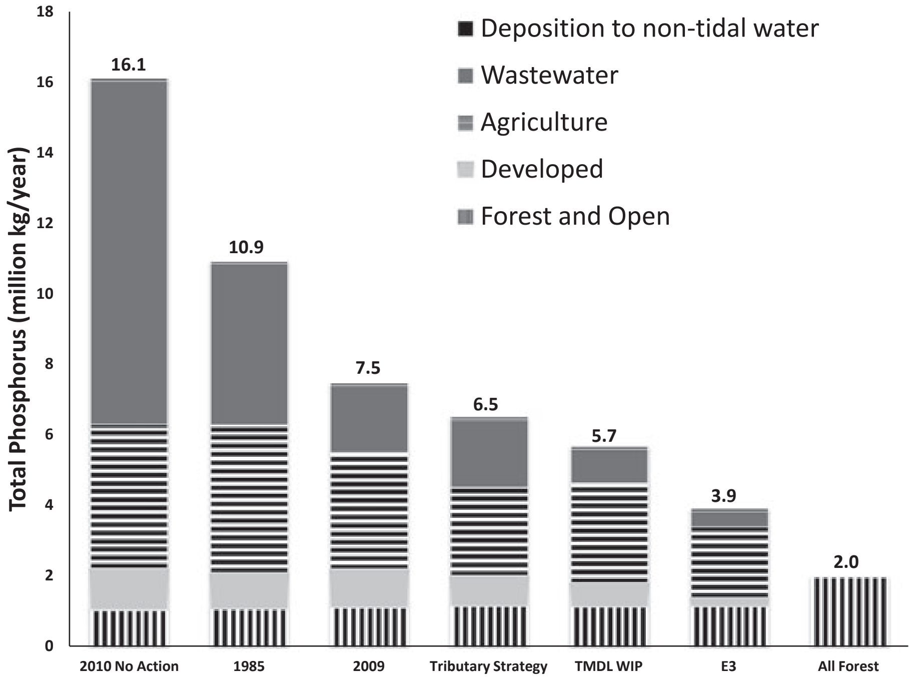


FIGURE 5. Estimated Total Phosphorus Loads from Key Scenarios in Million kg/yr. All loads are flow normalized.

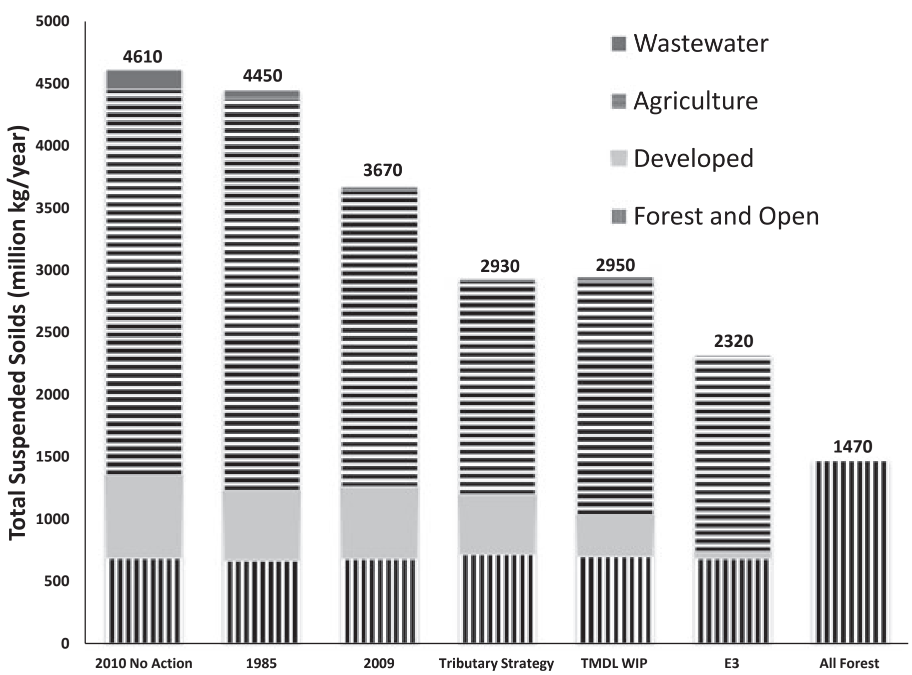


FIGURE 6. Estimated Total Sediment Loads from Key Scenarios in Million kg/yr. All loads are flow normalized.

complete input information was available during the 2010 TMDL assessment.

*2010 Tributary Strategy Scenario*

The 2010 Tributary Strategy Scenario estimates the nutrient and sediment loads of the jurisdictions' Tributary Strategies set as a result of the agreement on the 2003 Allocations. This scenario included an accounting for all the Tributary Strategy BMPs on a 2010 land use, and the 2010 estimated permitted loads for all the significant and nonsignificant wastewater dischargers. Nitrogen atmospheric deposition inputs were from estimated 2020 deposition loads and included the estimated State Implementation

Plans to reach 2020 air quality standards (Linker *et al.*, this issue).

*2010 TMDL WIP Scenario*

The 2010 TMDL Allocations were similar to the previous 2003 Allocation, and the strategies of point source and nonpoint source reductions to achieve both allocations were also similar on a Bay-wide basis. The six states and Washington, D.C. in the Chesapeake Bay Watershed developed WIPs designed to meet the TMDL Allocations. In these scenarios, the 2010 WIPs were run on 2010 land use. Atmospheric deposition loads were based on point source mobile and other emissions at a 2020 level of implementation.

*Everyone, Everywhere, Doing Everything (E3) Scenario*

The E3 Scenario is an estimate of applying management actions to the fullest possible extent. The E3 Scenario is a what-if scenario of watershed conditions with theoretical maximum levels of managed controls on load sources (Figures 4-6). There are no cost and few physical limitations to implementing BMPs for point and nonpoint sources in E3. It is used with the No-Action Scenario to define controllable loads, the difference between No-Action and E3 loads (USEPA, 2010a).

*All-Forest Scenario*

This scenario uses an all forest land use and current estimated atmospheric deposition loads for the 1991-2000 period and represents estimated loads with maximum reductions on the land including the elimination of fertilizer, point source, and manure loads. However, this scenario has loads greater than what would be estimated from a *pristine* scenario, which would have reduced input atmospheric deposition loads by approximately one order of magnitude, eliminated river reservoirs, and assumed a lower forest loading rate than that of modern forests and woodlands (USEPA, 2010b).

*Mass Balances of Major Land Use Types*

Mass balances of the annual average major inputs, outputs, uptake, and loss of nutrients were done for all the land uses and nitrogen mass balances are shown for three agricultural land uses in Figures 7-9. Major nitrogen inputs to land uses are from atmospheric deposition, fertilizer, and manure. Another major input of nitrogen comes from crops that are nitrogen-fixing legumes such as soybeans. Although nitrogen loads from legumes are not shown in Figures 7-9, annually legume crops add an estimated additional 32.5 million kilograms of nitrogen annually to agricultural lands in the watershed (USEPA, 2010i). The loss and fate of nitrogen in the landscape is represented in the model as loss from plant uptake, denitrification, soil storage, and export to rivers and streams. Similar plots and analysis can be formed for phosphorus.

*Cropland Nitrogen Mass Balance*

Cropland represented in Figure 7 includes all types of row crops in the Chesapeake watershed including conventional tillage and low or no tillage

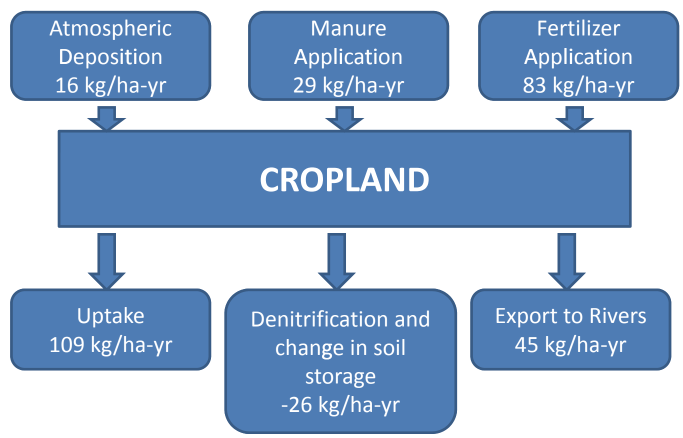


FIGURE 7. Average Mass Balance of Cropland Nitrogen over the Chesapeake Bay Watershed.

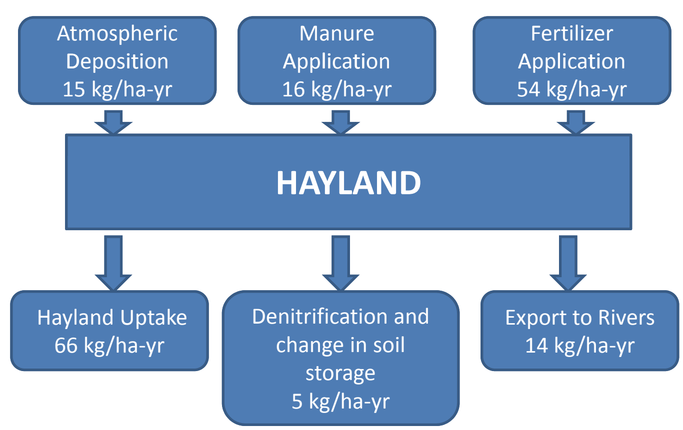


FIGURE 8. Average Mass Balance of Hay and Alfalfa Nitrogen over the Chesapeake Bay Watershed.

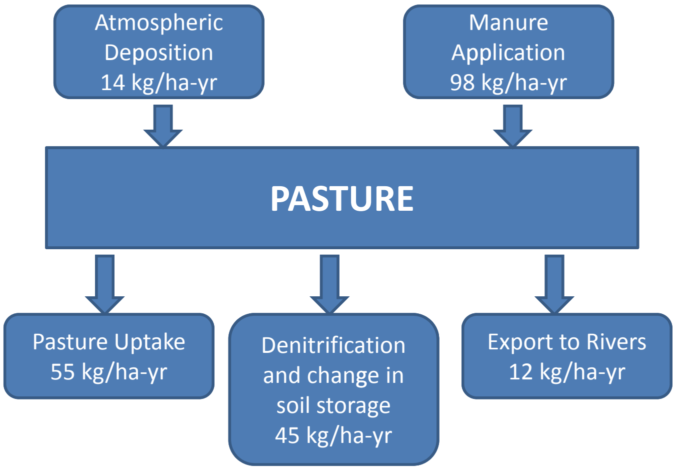


FIGURE 9. Average Mass Balance of Pasture Nitrogen over the Chesapeake Bay Watershed.

crops, as well as nutrient management croplands (USEPA, 2010d) and covers about 10% of the watershed area. The greatest areas of row crops in the Chesapeake watershed are in corn, soybeans, and small grains. Overall estimated annual average nitrogen inputs to Chesapeake row crops are 128 kg/ha/yr. The greatest of these is fertilizer which makes up 65% of the annual input nitrogen loads. Uptake, losses, and export from the row crops to rivers are 154 kg/ha/yr, and the greatest of the losses and sinks for nutrients on row crops and for agricultural lands are plant uptake and subsequent harvest of and removal of the crops for food or forage.

In the mass balance calculations of Figures 7-9, the fertilizer, manure, and atmospheric deposition inputs are calculated from all cropland land use types in the 309 land segments of the model. Likewise, the export and crop uptake values are model calculations from all cropland land uses in all land segments. The difference between inputs and outputs are the combined effects of denitrification, change in soil storage, and fixation. Where the balance of inputs and outputs is negative, fixation and any loss of soil nitrogen is simulated as greater than the sum of denitrification and any gain of soil nitrogen.

Also of note are the estimated atmospheric deposition loads in Figure 7 which are relatively higher for cropland than for hayland and pasture in Figures 8 and 9, respectively. This is due to the detailed spatial estimates of atmospheric deposition loads in the Chesapeake watershed (Linker *et al.*, this issue) and the predominant placement of row crops in the Eastern Shore and Piedmont regions including the Shenandoah Valley where atmospheric deposition loads are relatively high. Although atmospheric deposition loads are small on agricultural land uses compared to manure and fertilizer nitrogen loads, the rate of atmospheric loading is important because of its ubiquitous nature. Atmospheric deposition is one of the highest overall nitrogen input loads (Figure 10).

### *Hayland Nitrogen Mass Balance*

Hayland represented in Figure 8 includes all types of hay in the watershed (USEPA, 2010d). Hayland covers about 7% of the watershed. Similar to cropland, estimated annual average nitrogen inputs to hayland include fertilizer, manure, and atmospheric deposition which together total 85/ha/yr kilograms. The greatest input loads are from fertilizer. Nitrogen uptake by hayland is estimated to be 78% of the input loads, leaving an estimated annual average of 14 kg/ha/yr to be exported from the land to the rivers.

### *Pasture Nitrogen Mass Balance*

Pasture represented in Figure 9 includes all pasture land use types as well as nutrient management pasture lands (USEPA, 2010d) and, like hayland, covers about 7% of the watershed area. Nitrogen inputs to pasture are estimated to be solely from atmospheric deposition and manure, with the predominance of manure generated by pastured animals. Stocking rates on pasture are calculated from the agricultural Census of appropriate animal types on each land segment and the estimated available land in pasture (U.S. Census Bureau, Economics and Statistics Administration, 1982, 1987, 1992, 1997, 2002, 2007; USEPA, 2010i). Manure is applied to pasture according to the amount of pastured animals in a county land segment and the amount of time that animal type spends in the pasture. The amount of time that the animal does not spent in pasture, i.e., confinement, defines the amount of manure that is stored, and subsequently applied to cropland. Overall, an estimated 12 kg/ha/yr of nitrogen was estimated to be exported from pasture lands to rivers.

### *Watershed Trends in Nutrient Loads*

In the Phase 5.3 Model, the four key nonpoint source nutrient inputs are atmospheric deposition, manure inputs, fertilizer inputs, and wastewater from point sources and septic systems (USEPA, 2010i). The trends in those key inputs over the 2-decade simulation period vary as shown in Figure 10. Wastewater point source and atmospheric deposition loads are estimated on an annual basis and manure and fertilizer loads are estimated on a five-year basis from

Agricultural Census records (U.S. Census Bureau, Economics and Statistics Administration, 1982, 1987, 1992, 1997, 2002, 2007).

## DISCUSSION

As shown in Figures 4-6, implementing the TMDL WIPs is estimated to result in reductions from 1985 loading rates of 47% for nitrogen, 48% for phosphorus, and 33% reduction in sediment. Between 1985 and 2005, wet atmospheric deposition loads of nitrate have tended to decrease overall in the Chesapeake watershed and in the Phase 5.3 domain generally. Over that 21-year period, wet deposition nitrate loads decreased by about 30% (Figure 10) and are estimated to decrease further under Clean Air Act controls to about 61% of the 1985 loads by 2025 when all the Chesapeake Bay TMDL controls are scheduled to be in place (Linker *et al.*, this issue). Dissolved inorganic nitrogen (DIN) loads, which include both ammonia and nitrate wet and dry deposition, are estimated to be reduced from 1985 to 2025 by approximately 42%. The DIN reductions are less than the nitrate reductions because the nitrate loads are going down due to national controls on air emissions, whereas the ammonia emissions, primarily from agricultural manure are either at a constant load level or increasing slightly depending on location in the Chesapeake watershed.

Point source wastewater loads of nutrients also decreased over the 1985-2005 period (Figure 10) and

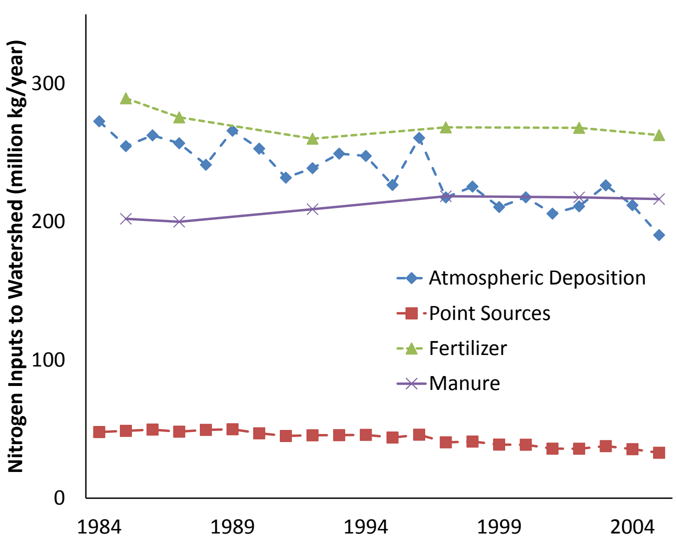


FIGURE 10. Time Series of Estimated Inputs of Total Nitrogen to the Chesapeake Bay Watershed from Atmospheric Deposition, Fertilizer, Manure, and Wastewater.

are estimated to have decreased by 57% for nitrogen and 69% for phosphorus compared to the 1985 loads when the TMDL WIPs are fully implemented. This is despite the observed increase in wastewater point source flows, because of increased population, throughout the Chesapeake watershed from 1985 to the present (USEPA, 2010h).

Based on the trend in Chesapeake loads between 1985 and 2005 shown in Figure 10, the greatest estimated nitrogen reductions are from the regulated sources of atmospheric deposition and wastewater. Likewise, wastewater is the greatest contributor to the phosphorus reductions over the same period.

In contrast, manure loads in the watershed are increasing and with the slight decrease in fertilizer input loads, the result is a relatively flat trend line in combined manure and fertilizer nitrogen loads to agricultural lands (Figure 10). This needs to be reconciled with the estimated load reductions from agricultural land uses shown in Figure 4. This can be done by observing that if agricultural products are grown more efficiently, making greater use of the nutrient inputs then greater crop yields can be achieved with the same input loads of nitrogen whereas associated exports of nitrogen to rivers would decrease.

The mass balance analysis provides insights into the nitrogen management importance of crop yields. As crop uptake is a large sink and loss term in agricultural lands, double or triple cropping, where practicable, is one way to reconcile the relatively steady combined fertilizer and manure nitrogen input loads with the decreases seen in scenario loads from agriculture between the 1985 and 2009 Scenarios. Decreases in nutrient loads are 31% for nitrogen and 21% for phosphorus estimated from agriculture in the 1985 and 2009 Scenarios (Figure 4). Increases in nutrient uptake diminish nutrient exports to streams and rivers given the same nutrient load inputs. Another approach to reach the same end is to increase crop yields for a given nutrient input. Monitoring observations at river basins that are predominantly agricultural are consistent with model findings that nutrient loads from agricultural lands are decreasing.

Innovative approaches for land use nutrient calibration targets in the 309 land segments were used in Phase 5.3 to allow adjustment over the range of literature values for the land use by the relative amount of input load applied. Automated calibration techniques and the LUG, RUG, and the ETM software allowed the incorporation of changes in land uses and management over time, and provided overall flexibility and parallel computing capabilities in the Chesapeake watershed simulation.

Separating land and river simulation into different model input files provided flexibility and parallel processing opportunities in model simulation. With the LUG, RUG, and ETM structure, each land use simulation for each land segment is completely independent of any other land or river simulation, and each river simulation is dependent on only the local land use type simulations and the upstream river simulations. This provides efficient model operations in the complex land-river and river-river logistics of a large-scale watershed simulation (Shenk *et al.*, 2012).

## SUMMARY AND CONCLUSIONS

The Chesapeake Bay TMDL is the largest, most complex TMDL in the United States, covering a 166,000 $km^2$ area across six states in the Mid-Atlantic region. The Phase 5.3 Community Watershed Model was used to develop equitable, cost-effective, and environmentally protective water quality management plans for nutrients and sediments in the watershed for each unique basin jurisdiction (Linker *et al.*, this issue).

The large scope and complexity of the Phase 5.3 Community Model gave rise to a number of innovations. The Phase 5.3 Community Model includes annually adjustable land uses over the 20 year simulation period, uniquely adjustable land use loads based on the level of input nutrients, automated calibration techniques, and a software system to efficiently apply large-scale parameter adjustments in a parallel computing environment.

The overall software system of adjustable land use loads and automated calibration techniques, as well as the LUG, RUG, and ETM computing approach provided the operational efficiency required in a large watershed simulation. For very large watershed applications, the advantages are as follows: (1) the approach more easily allows for large-scale parameter adjustments during calibration; (2) parallel computing operations become more convenient, the simulation can be arranged more efficiently, and run times decrease; (3) adding new land use types is easier, enabling the model simulation to be more conveniently expanded, particularly for management scenarios that investigate new and innovative land use practices; and (4) operational efficiencies allow a more complete representation of more land uses and finer segmentation in the river simulation.

Key scenarios, decadal trends in nutrient inputs, combined with a mass balance analysis provided insights into the changes in nutrient fates and transport in the watershed. From 1985 to the current time, the greatest reductions in nitrogen loads have come from the regulated sectors of nitrate atmospheric deposition and point source wastewater. Further reductions in point source wastewater and atmospheric deposition of nitrate, combined with greater agricultural efficiencies in nutrient utilization will be key drivers in the reductions from 1985 loading rates of 47% for nitrogen, 48% for phosphorus, and 33% reduction in sediment estimated when the WIPS are fully implemented in 2025.

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## LITERATURE CITED

Aber, J.D., C.L. Goodale, S.V. Ollinger, M.L. Smith, A.H. Magill, M.E. Martin, R.A. Hallett, and J.L. Stoddard, 2003. Is Nitrogen Deposition Altering the Nitrogen Status of Northern Forests? BioScience 53(4):375-389.

Aber, J.D., K.J. Nadelhoffer, P. Steudler, and J.M. Melillo, 1989. Nitrogen Saturation in Northern Forest Ecosystems. BioScience 39(6):378-386.

Bicknell, B.R., J.C. Imhoff, J.L. Kittle, Jr., A.S. Donigian, Jr., and R.C. Johanson, 1997. Hydrological Simulation Program — FORTRAN: User's Manual for Version 11. U.S. Environmental Protection Agency, Athens, Georgia.

Bicknell, B.R., J.C. Imhoff, J.L. Kittle, Jr., T.H. Jobes, and A.S. Donigian, Jr., 2001. Hydrologic Simulation Program — FORTRAN, HSPF Version 12 Users Manual. U.S. Environmental Protection Agency, Office of Research and Development/USGS Hydrologic Analysis Software Support Program, Athens, Georgia/Reston, Virginia.

Boynton, R.W., J.H. Garber, R. Summers, and W.M. Kemp, 1995. Inputs, Transformations, and Transport of Nitrogen and Phosphorus in Chesapeake Bay and Selected Tributaries. Estuaries 18(1B):285-314.

Boynton, W.R. and W.M. Kemp, 2008. Estuaries. *In:* Nitrogen in the Marine Environment (Second Edition), D.G. Capone, D.A. Bronk, M.R. Mulholland, and E.J. Carpenter (Editors). Elsevier Inc., Burlington, Massachusetts, pp. 809-856.

Cerco, C. and T. Cole, 1994. Three-Dimensional Eutrophication Model of Chesapeake Bay. Technical Report EL-94-4, U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, Mississippi.

Cerco, C.F., S.C. Kim, and M.R. Noel, 2010. The 2010 Chesapeake Bay Eutrophication Model. A Report to the US Environmental Protection Agency and to the US Army Corps of Engineer Baltimore District. US Army Engineer Research and Development

Center, Vicksburg, Maryland. http://www.chesapeakebay.net/publications/title/the_2010_chesapeake_bay_eutrophication_model1, *accessed* March 2012.

Cerco, C.F. and M.R. Noel, this issue. Twenty-One-Year Simulation of Chesapeake Bay Water Quality Using the CE-QUAL-ICM Eutrophication Model. Journal of the American Water Resources Association, doi: 10.1111/jawr.12107. EPA-903-R-13-011, CBP/TRS-317-13-10.

Cerco, C.F., M.R. Noel, and P. Wang, this issue. The Shallow-Water Component of the Chesapeake Bay Environmental Model Package. Journal of the American Water Resources Association, doi: 10.1111/jawr.12106. EPA-903-R-13-009, CBP/TRS-315-13-8.

Dennis, R.L., 1996. Absolute Nitrogen Deposition from Source Regions. Computer file prepared for U.S. Environmental Protection Agency, E.H. Pechan & Associates, Inc., Research Triangle Park, North Carolina.

Dennis, R.L., R. Haeuber, T. Blett, J. Cosby, C. Driscoll, J. Sickles, and J.M. Johnston, 2007. Sulfur and Nitrogen Deposition on Ecosystems in the United States. Environmental Management, December:12-17.

Doherty, J. and J.M. Johnston, 2003. Methodologies for Calibration and Predictive Analysis of a Watershed Model. Journal of the American Water Resources Association 39(2):251-265.

Donigian, Jr., A.S., B.R. Bicknell, and J.C. Imhoff, 1995a. Hydrologic Simulation Program — FORTRAN (HSPF). *In:* Computer Models of Watershed Hydrology, V.P. Singh (Editor). Water Resources Publications, Littleton, Colorado, pp. 395-442.

Donigian, Jr., A.S., B.R. Bicknell, A.S. Patwardhan, L.C. Linker, C.H. Chang, and R. Reynolds, 1994. Chesapeake Bay Program Watershed Model Application to Calculate Bay Nutrient Loadings. U.S. Environmental Protection Agency, Chesapeake Bay Program Office, Annapolis, Maryland.

Donigian, Jr., A.S., J.C. Imhoff, and R.B. Ambrose, Jr., 1995b. Modeling Watershed Water Quality. *In:* Environmental Hydrology, V.P. Singh (Editor). Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 377-426.

Donigian, Jr., A.S., J.C. Imhoff, B.R. Bicknell, and J.L. Kittle, Jr., 1984. Application Guide for Hydrological Simulation Program—Fortran (HSPF). EPA-600/3-84-065. U.S. Environmental Protection Agency, Environmental Research Laboratory, Athens, Georgia, 177 pp.

Flynn, K.M., P.R. Hummel, A.M. Lumb, and J.L. Kittle, Jr., 1995. User's Manual for ANNIE, Version 2, a Computer Program for Interactive Hydrologic Data Management. U.S. Geological Survey Water-Resources Investigations Report 95-4085, 211 pp. Reston, Virginia.

Goodale, C.L., K. Lajtha, K.J. Nadelhoffer, E.W. Boyer, and N.A. Jaworski, 2002. Forest Nitrogen Sinks in Large Eastern U.S. Watersheds: Estimates from Forest Inventory and an Ecosystem Model. Biogeochemistry 57(58):239-266.

Grimm, J.W. and J.A. Lynch, 2005. Improved Daily Precipitation Nitrate and Ammonium Concentration Models for the Chesapeake Bay Watershed. Environmental Pollution 135(2005):445-455.

Hameedi, J., H. Paerl, M. Kennish, and D. Whitall, 2007. Nitrogen Deposition in U.S. Coastal Bays and Estuaries. Environmental Managment, December:19-25.

Hartigan, J.P., 1983. Chesapeake Bay Basin Model. Prepared for the U.S. Environmental Protection Agency, Chesapeake Bay Program, Northern Virginia Planning District Commission, Annapolis, Maryland.

Hay, L.E., G.H. Leavesley, M.P. Clark, S.L. Markstrom, R.J. Viger, and M. Umemoto, 2006. Stepwise, Multiple Objective Calibration of a Hydrologic Model for a Snowmelt Dominated Basin. Journal of the American Water Resources Association 42(4):877-890.

Hay, L.E., G.J. McCabe, Jr., D.M. Wolcok, and M.A. Ayers, 1991. Simulation of Precipitation by Weather Type Analysis. Water Resources Research 27(4):493-501.

Hay, L.E., R.L. Wilby, and G.H. Leavesley, 2000. A Comparison of Delta Change and Downscale GCM Scenarios for Three Mountainous Basins in the United States. Journal of the American Water Resources Association 36(2):387-397.

Hunsacker, C.T., C.T. Garten, and P.J. Mulholland, 1993. Nitrogen Outputs from Forested Watershed in the Chesapeake Bay Drainage Basin. Oak Ridge National Laboratory, Environmental Sciences Division, Oak Ridge, Tennessee.

Johanson, R.C., J.D. Imhoff, and H.H. Davis, Jr., 1980. Users Manual for Hydrological Simulation Program — Fortran (HSPF). EPA-600/9-80-015, April 1980. Environmental Research Laboratory, Athens, Georgia.

Kemp, W.M., R.A. Batiuk, R. Bartleson, P. Bergstrom, V. Carter, C.L. Gallegos, W. Hunley, L. Karrh, E. Koch, J.M. Landwehr, K.A. Moore, L. Murray, M. Naylor, N.B. Rybicki, J.C. Stevenson, and D.J. Wilcox, 2004. Habitat Requirements for Submerged Aquatic Vegetation in Chesapeake Bay: Water Quality, Light Regime and Physical-Chemical Factors. Estuaries 27(3):363-377.

Kemp, W.M., W.R. Boynton, J.E. Adolf, D.F. Boesch, W.C. Boicourt, G. Brush, J.C. Cornwell, T.R. Fisher, P.M. Glibert, J.D. Hagy, L.W. Harding, E.D. Houde, D.G. Kimmel, W.D. Miller, R.I.E. Newell, M.R. Roman, E.M. Smith, and J.C. Stevenson, 2005. Eutrophication of Chesapeake Bay: Historical Trends and Ecological Interactions. Marine Ecology Progress Series 303:1-29.

Kemp, W.M., P.A. Sampou, J.H. Garber, J. Tuttle, and W.R. Boynton, 1992. Seasonal Depletion of Oxygen from Bottom Waters of Chesapeake Bay: Roles of Benthic and Planktonic Respiration and Physical Exchange Processes. Marine Ecology Progress Series 85:137-152.

Koroncai, R., L. Linker, J. Sweeney, and R. Batiuk, 2003. Setting and Allocating the Chesapeake Bay Basin Nutrient and Sediment Loads. U.S. Environmental Protection Agency, Chesapeake Bay Program Office, Annapolis, Maryland. http://www.chesapeakebay.net/pubs/doc-allocating-whole.pdf, *accessed* August 2007.

Linker, L.C., R. Dennis, G.W. Shenk, R.A. Batiuk, J. Grimm, and P. Wang, this issue. Computing Atmospheric Nutrient Loads to the Chesapeake Bay Watershed and Tidal Waters. Journal of the American Water Resources Association, doi: 10.1111/jawr.12112. EPA-903-R-13-008, CBP/TRS-314-13-7.

Linker, L.C., G.W. Shenk, P. Wang, and R. Batiuk, 2008. Integration of Modeling, Research, and Monitoring in the Chesapeake Bay Program. *In:* Management of Water Quality and Irrigation Techniques, J. Albiac and A. Dinar (Editors). Earthscan, London, United Kingdom, pp. 41-60.

Linker, L.C., G.W. Shenk, P. Wang, K.J. Hopkins, and S. Pokharel, 2002. A Short History of Chesapeake Bay Modeling and the Next Generation of Watershed and Estuarine Models. Proceedings of the Water Environment Federation, Watershed 2002. Water Environment Federation, Alexandria, Virginia, pp. 569-582.

Lumb, A.M., R.B. McCammon, and J.L. Kittle, Jr., 1994. Users Manual for an Expert System (HSPEXP) for Calibration of the Hydrological Simulation Program — Fortran. Water-Resources Investigations Report 94-4168, U.S. Geological Survey, Reston, Virginia. http://water.usgs.gov/software/HSPexp/code/doc/hspexp.pdf, *accessed* December 2011.

Martucci, S.K., J.L. Krstolic, J.P. Raffensperger, and K.J. Hopkins, 2006. Development of Land Segmentation, Stream-Reach Network, and Watersheds in Support of Hydrologic Simulation Program — Fortran (HSPF) Modeling, Chesapeake Bay Watershed, and Adjacent Parts of Maryland, Delaware, and Virginia. U.S. Geological Survey, Reston, Virginia.

Shenk, G.W., J. Wu, and L.C. Linker, 2012. An Enhanced HSPF Model Structure for Chesapeake Bay Watershed Simulation. Journal of Environmental Engineering 138(9) September 1, 2012.

Stoddard, J.L., Editor, 1994. Long-Term Changes in Watershed Retention of Nitrogen: Its Causes and Aquatic Consequences. *In:* Environmental Chemistry of Lakes and Reservoirs, L.A. Baker (Editor). ACS Advances in Chemistry Series No. 237. American Chemical Society, Washington, D.C., 83 pp.

Thomann, R.V., J.R. Collier, A. Butt, E. Casman, and L.C. Linker, 1994. Response of the Chesapeake Bay Water Quality Model to Loading Scenarios. CBP/TRS 101. U.S. EPA Chesapeake Bay Program Office, Annapolis, Maryland.

U.S. Census Bureau, Economics and Statistics Administration, 1982. U.S. Department of Commerce. 1982 Census of Agriculture. (Geographic Area Series 1C.) Government Printing Office, Washington, D.C.

U.S. Census Bureau, Economics and Statistics Administration, 1987. U.S. Department of Commerce. 1987 Census of Agriculture. (Geographic Area Series 1C.) Government Printing Office, Washington, D.C.

U.S. Census Bureau, Economics and Statistics Administration, 1992. U.S. Department of Commerce. 1992 Census of Agriculture. (Geographic Area Series 1C.) Government Printing Office, Washington, D.C.

U.S. Census Bureau, Economics and Statistics Administration, 1997. U.S. Department of Commerce. 1997 Census of Agriculture. (Geographic Area Series 1C.) Government Printing Office, Washington, D.C.

U.S. Census Bureau, Economics and Statistics Administration, 2002. U.S. Department of Commerce. 2002 Census of Agriculture. (Geographic Area Series 1C.) Government Printing Office, Washington, D.C.

U.S. Census Bureau, Economics and Statistics Administration, 2007. U.S. Department of Commerce. 2007 Census of Agriculture. (Geographic Area Series 1C.) Government Printing Office, Washington, D.C.

USEPA (U.S. Environmental Protection Agency), 1983. Chesapeake Bay: A Framework for Action. U.S. Environmental Protection Agency, Chesapeake Bay Program Office, Annapolis, Maryland.

USEPA (U.S. Environmental Protection Agency), 2010a. Chesapeake Bay Total Maximum Daily Load for Nitrogen, Phosphorus and Sediment. U.S. Environmental Protection Agency Chesapeake Bay Program Office, Annapolis, Maryland. http://www.epa.gov/reg3wapd/tmdl/ChesapeakeBay/tmdlexec.html, *accessed* February 2012.

USEPA (U.S. Environmental Protection Agency), 2010b. Chesapeake Bay Total Maximum Daily Load for Nitrogen, Phosphorus and Sediment Appendix J Key Chesapeake Bay TMDL Reference and Management Modeling Scenarios: Definitions and Descriptions. U.S. Environmental Protection Agency Chesapeake Bay Program Office, Annapolis, Maryland. http://www.epa.gov/reg3wapd/tmdl/ChesapeakeBay/tmdlexec.html, *accessed* February 2012.

USEPA (U.S. Environmental Protection Agency), 2010c. Chesapeake Bay Phase 5.3 Community Watershed Model: Section 3 Land and River Segmentation. EPA 903S10002 — CBP/TRS-303-10. U.S. Environmental Protection Agency, Chesapeake Bay Program Office, Annapolis, Maryland. December 2010. ftp://ftp.chesapeakebay.net/Modeling/P5Documentation/SECTION_3.pdf, *accessed* March 2012.

USEPA (U.S. Environmental Protection Agency), 2010d. Chesapeake Bay Phase 5.3 Community Watershed Model: Section 4 Land Use. EPA 903S10002 — CBP/TRS-303-10. U.S. Environmental Protection Agency, Chesapeake Bay Program Office, Annapolis, Maryland. December 2010. ftp://ftp.chesapeakebay.net/Modeling/P5Documentation/SECTION_4.pdf, *accessed* March 2012.

USEPA (U.S. Environmental Protection Agency), 2010e. Estimates of County-Level Nitrogen and Phosphorus Data for Use in Modeling Pollutant Reduction: Documentation for Scenario Builder Version 2.2. U.S. Environmental Protection Agency, Chesapeake Bay Program Office, Annapolis, Maryland. December 2010. ftp://ftp.chesapeakebay.net/modeling/P5Documentation/SB_V22_Final_12_31_2010.pdf, *accessed* March 2012.

USEPA (U.S. Environmental Protection Agency), 2010f. Chesapeake Bay Phase 5.3 Community Watershed Model: Section 2 Meteorology and Precipitation. EPA 903S10002 — CBP/TRS-303-10. U.S. Environmental Protection Agency, Chesapeake Bay Program Office, Annapolis, Maryland. December 2010. ftp://ftp.chesapeakebay.net/Modeling/P5Documentation/SECTION_2.pdf, *accessed* March 2012.

USEPA (U.S. Environmental Protection Agency), 2010g. Chesapeake Bay Phase 5.3 Community Watershed Model: Section 5 Nonpoint Source Nutrient Inputs. EPA 903S10002 — CBP/TRS-303-10. U.S. Environmental Protection Agency, Chesapeake Bay Program Office, Annapolis, Maryland. December 2010. ftp://ftp.chesapeakebay.net/Modeling/P5Documentation/SECTION_5.pdf, *accessed* March 2012.

USEPA (U.S. Environmental Protection Agency), 2010h. Chesapeake Bay Phase 5.3 Community Watershed Model: Section 7 Point Sources, Combined Sewer Overflows, Water Withdraws, and On-Site Waste Disposal Systems. EPA 903S10002 — CBP/TRS-303-10. U.S. Environmental Protection Agency, Chesapeake Bay Program Office, Annapolis, Maryland. December 2010. ftp://ftp.chesapeakebay.net/Modeling/P5Documentation/SECTION_7.pdf, *accessed* March 2012.

USEPA (U.S. Environmental Protection Agency), 2010i. Chesapeake Bay Phase 5.3 Community Watershed Model: Section 10 Nonpoint Source Nutrient Simulation. EPA 903S10002 — CBP/TRS-303-10. U.S. Environmental Protection Agency, Chesapeake Bay Program Office, Annapolis, Maryland. December 2010. ftp://ftp.chesapeakebay.net/Modeling/P5Documentation/SECTION_7.pdf, *accessed* March 2012.

USEPA (U.S. Environmental Protection Agency), 2010j. Chesapeake Bay Phase 5.3 Community Watershed Model: Section 8 Hydrology Simulation and Calibration. EPA 903S10002 — CBP/TRS-303-10. U.S. Environmental Protection Agency, Chesapeake Bay Program Office, Annapolis, Maryland. December 2010. ftp://ftp.chesapeakebay.net/Modeling/P5Documentation/SECTION_7.pdf, *accessed* March 2012.

USEPA (U.S. Environmental Protection Agency), 2010k. Chesapeake Bay Phase 5.3 Community Watershed Model: Section 11 Simulation and Calibration of Riverine Fate and Transport of Nutrients and Sediment. EPA 903S10002 — CBP/TRS-303-10. U.S. Environmental Protection Agency, Chesapeake Bay Program Office, Annapolis, Maryland. December 2010. ftp://ftp.chesapeakebay.net/Modeling/P5Documentation/SECTION_7.pdf, *accessed* March 2012.