4 Section 4: Sensitivity to Inputs

4.1 Introduction

Figure 4-1 shows the calculation of delivered loads for a land use in a land-river segment. With respect to the top line in the figure, Section 2 described the methodology for determining average loads by land use and Section 3 described the calculation of inputs. This Section deals with the sensitivity of loads to local inputs. **Sensitivity is defined as the change in export load per change in input load**.

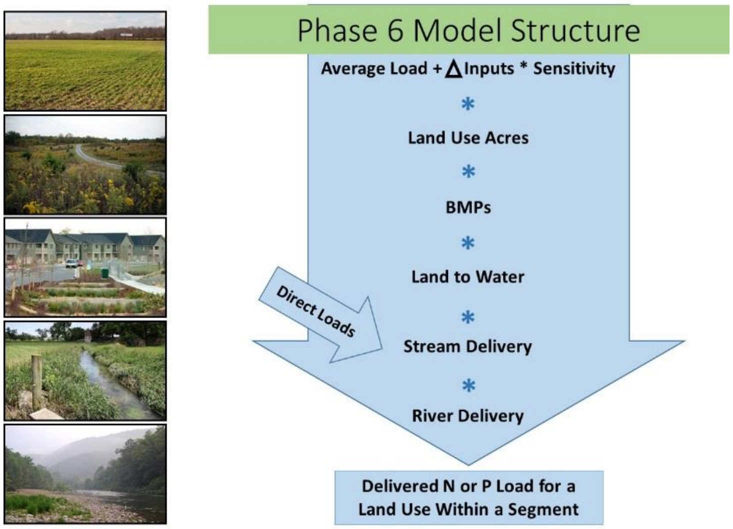


Figure 4-1: Phase 6 Model structure

The primary purpose of the Chesapeake Bay Program (CBP) partnership's watershed model since the early 1980s has been to determine the nutrient and sediment load reductions that result from management actions. Sensitivity is a major component of those estimations since it determines the effectiveness of input load reductions or decreases. The importance of the sensitivity component requires a careful look at the best available methods of simulation.

4.1.1 Definition of Sensitivity

Sensitivity analysis is the process of determining the rate of change in model load output with respect to changes in model inputs. Absolute sensitivity is the change in pounds exported per change in pound input. Absolute sensitivity is used in the model as shown in Figure 4-1. Relative sensitivity is the fractional change in load per fractional change in input. Relative sensitivity is used during the investigation of sensitivity to gain understanding about the most important inputs in determining export loads over the likely range of inputs. Equation 4-1 gives the formal definitions for absolute and relative sensitivity.

Equation 4-1: Definition of absolute sensitivity and relative sensitivity

$$Sa = \left(\frac{O_s - O_b}{I_s - I_b}\right)$$

$$Sr = \left(\frac{O_s - O_b}{I_s - I_b}\right)\frac{I_b}{O_b}$$

Where:

Sa is the absolute sensitivity
Sr is the relative sensitivity
O is the model output
I is the input to the model
The b and *s* subscripts represent the perturbed scenario and base condition respectively

Table 4-1 provides ranges for relative sensitivity that were considered when evaluating inputs with respect to their impact on exported loads. A slightly sensitive input parameter would only change outputs by 1 percent to 20 percent by setting that input parameter to zero, while an insensitive input parameter would change the output less than 1 percent.

Table 4-1: Relative sensitivity (Sr)

Relative Sensitivity (S_r)	
Insensitive	Sr $< \lvert 0.01 \rvert$
Slightly sensitive	$\lvert 0.01 \rvert \le$ Sr $< \lvert 0.20 \rvert$
Moderately sensitive	$\lvert 0.20 \rvert \le$ Sr $< \lvert 1.00 \rvert$
Sensitive	$\lvert 1.00 \rvert \le$ Sr $< \lvert 2.00 \rvert$
Extremely sensitive	Sr $\ge \lvert 2.00 \rvert$

4.2 Use of Multiple models

The CBP's Scientific and Technical Advisory Committee (STAC) (Weller et al. 2013) strongly recommended that the CBP implement multiple modeling strategies for all decision models. They found several strategies for implementing multiple models:

> *There are different ways to implement multiple models (multi-model ensembles, using other models to assess a decision model, modular community modeling, and model comparisons in pilot studies or testbed areas). The common principle is that findings are stronger when multiple lines of evidence, multiple data sets, or multiple algorithms agree.*

Following those recommendations, sensitivities were obtained from the analysis of multiple models. Four different watershed models developed for the Chesapeake Bay watershed were considered in this analysis. The models are listed here and discussed in sections immediately below:

- Chesapeake Bay Program's Phase 5.3.2 HSPF Watershed Model (USEPA 2010a)
- USGS's Spatially Referenced Regression on Watershed Attributes (SPARROW) model (Ator et al. 2011)
- USDA's Agricultural Policy Environmental Extender (APEX) model (USDA-NRCS 2013) (The APEX model was run for the Chesapeake region as part of the USDA-NRSC's Conservation Effects Assessment Program (CEAP) and is hereafter referred to as the CEAP model.)
- USDA's Annual Phosphorus Loss Estimator (APLE) model (Vadas 2014)

Phase 5.3.2, SPARROW, and CEAP were found to be in significant agreement for nitrogen sensitivity. For reasons discussed in following sections, the Modeling Workgroup directed the CBPO staff to directly estimate sensitivities from the Phase 5.3.2 model with SPARROW and CEAP in support. For phosphorus on agricultural land, the Modeling Workgroup found the APLE model to be a more appropriate simulation than Phase 5.3.2, CEAP, or SPARROW based on the STAC review of the Phase 5.3.2 Model (Staver et al. 2014) and the findings of a comprehensive APLE sensitivity analysis conducted by Chesapeake Bay Program modeling team. The 2014 STAC review of agricultural P dynamics in the CBP watershed model recommended very clearly that soil P be incorporated as a major driver of both sediment-associated and dissolved portions of load. They also explicitly mentioned the APLE model as one that incorporated the latest research. They noted that the incorporation of APLE had improved other models. The analyses and recommendations were presented and approved by the Modeling Workgroup on September 3, 2015.

4.2.1 Phase 5.3.2 Model

The CBP Phase 5.3.2 Watershed Model was used by the partnership in 2011 to set target loads consistent with the 2010 TMDL and has been used throughout the 2011-2017 period to evaluate progress toward implementation goals. The 2010 TMDL was based on the Phase 5.3 Watershed Model (USEPA 2010a). Differences between the Phase 5.3 and Phase 5.3.2 models were mostly in the handling of agricultural nutrient management and in a better representation of the amount of developed land. Land use types, simulation methods, calibration methods, and other specifications were substantially the same. The Phase 5.3.2 Model had 13 types of cropland, 3 type of pasture, 4 types of developed land, 2 types of natural land, and other specialty land uses such as nursery and feeding areas.

Phase 5.3.2 is an application of Hydrologic Simulation Program – Fortran (HSPF) (Bicknell et al. 2001). Land use nutrient export is simulated through three different modules within HSPF: Agricultural Chemical Simulation (AGCHEM), Pervious Quality Constituent (PQUAL), and Impervious Quality Constituent (IQUAL). The IQUAL module is a surface build-up and washoff simulation and hence has sensitivity to inputs built into it. PQUAL has a similar build-up and washoff component for the surface, but also has concentration coefficient models for subsurface loads. The PQUAL concentration coefficients are user-specified constants that are independent of inputs and thus have no simulated sensitivity. As a decision of the Modeling Workgroup, PQUAL concentration coefficients were assigned a sensitivity in Phase 5.3.2 such that reducing all inputs to zero would result an export of half the calibrated nutrient load from that land use. This is equivalent to a relative sensitivity of 0.5.

An uncertainty analysis was not performed on the Phase 5.3.2 Watershed Model. The Modeling Workgroup found the model to be appropriately calibrated to flow, nutrients, and sediments by graphically and numerically evaluating the spatial and temporal agreement of the Phase 5.3.2 to observed data and estimated loads statistically calculated from observed data.

The AGCHEM module is a detailed simulation of the nitrogen and phosphorus cycle, simulating plant uptake, mineralization, nitrification, denitrification, sorption, litter fall, and other processes. Inorganic and organic forms of each are tracked. AGCHEM accepts inputs of nitrogen and phosphorus from multiple sources including atmospheric deposition, manure, and inorganic fertilizer. A separate parameterization was developed for each land use and land segment as described in Section 10 of the Phase 5.3 documentation (USEPA 2010a-10). Summarized results from AGCHEM were used for Phase 6 nitrogen sensitivities.

4.2.2 Conservation Effects Assessment Program - CEAP

CEAP modeling provided estimates of the environmental benefits of the adoption of conservation practices on cropland. The U. S. Department of Agriculture's National Resource Conservation Service (NRCS) and Agricultural Research Service (ARS) have performed two rounds of modeling of the Chesapeake Bay watershed. The original Chesapeake study (USDA NRCS 2011) used acreage and other information collected by the National Resource Inventory (NRI) 2003 and a survey of farmers conducted by the National Agricultural Statistical Service (NASS) in 2003-2006. The second round of modeling (USDA NRCS 2013) was based on information from an NRI survey in 2007 and a NASS survey of farmers in 2011. Results of the second effort were considered with respect to sensitivity.

CEAP used a field-scale, daily time step model, the Agricultural Policy/Environmental eXtender (APEX), to model cropland (Williams *et al*. 2008). Based on the EPIC (Environmental Policy Impact Calculator) model, APEX has the capacity of simulating the impact of a wide variety of conservation practices, so the practices simulated were tailored to match the results of the NRI data and NASS surveys. APEX simulated farming practices include planting, tillage, irrigation, harvest, and nutrient application under different methods, timing, amounts, and sources. Biological and chemical processes are simulated in detail to estimate the effect of these practices on nutrient transport.

The model used by CEAP to simulate non-crop land uses and riverine transport is the Soil and Water Assessment Tool (SWAT) (Neitsch *et al*. 2011). A national SWAT model, developed at the eight-digit hydrologic unit (HUC) scale, formed the basis of the SWAT model of the Chesapeake Bay watershed. The national model is also referred to as HUMUS (Hydrologic Unit Model of the United States) (Arnold *et al*., 2004). Ten non-crop land uses are simulated, including pasture, urban land, and six kinds of forest or wetlands. Each land use is uniformly simulated within an eight-digit HUC. SWAT is a daily time-step model using the NRCS Curve Number method for hydrology and the Modified Universal Soil Loss Equation (MUSLE) for soil erosion. A process-based model simulates nutrient movement. The fate and transport of nutrient species in rivers is also simulated. For the purposes of the CEAP modeling, HUMUS was modified to integrate output from the APEX model with simulations of the other land uses at the 8-digit HUC watershed level.

SWAT is calibrated against expected annual water export per acre at the 8-digit HUC scale. Expected water exports were determined from stream flow contours developed by Gebert et al. (1987) from daily stream flow recorded USGS gaging stations, 1951-1980. The calibration of HUMUS used a 30-year calibration period (1960-1990) and a 16-year verification period. Calibration and uncertainty information were not included in the Chesapeake Bay report. Monthly and annual flows and annual nutrient loads were also compared, without further calibration, to observed values at five USGS gauges in the Chesapeake Bay watershed:

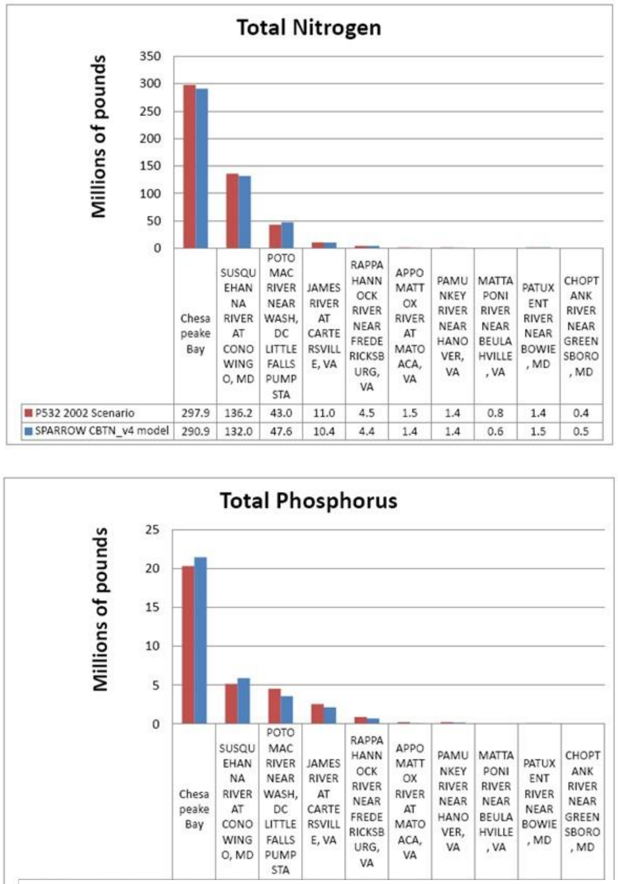
- The Susquehanna River at Danville, PA
- The Susquehanna River at Harrisburg, PA
- The Susquehanna River at Conowingo, MD
- The Potomac River at Little Falls, DC
- The James River at Cartersville, VA

CEAP modeling simulated four scenarios: (1) 2011 conservation conditions; (2) 2003-2006 conditions; (3) a “No Practices” scenario, in which no conservation practices were applied to cultivate cropland; and (4) a background scenario, in which a mixture of grass land and forest was substituted for cultivated cropland. The only differences among the scenarios are in the treatment of cropland. The simulation period was 52 years, 1960-2011.

Without access to the CEAP model, the CBPO modeling team was unable to directly determine sensitivities. To produce corroborating information for the other models, the CBPO modeling team calculated the ratio between output and all input sources for the No-Practice, 2003-2006, and 2011 scenarios.

4.2.3 Spatially Referenced Regression on Watershed Attributes - SPARROW

SPARROW is a spatially explicit watershed model that uses nonlinear regressions to quantify the relationship between observed nutrient fluxes in nontidal streams and inputs and factors that affect their overland and in-stream fate and transport. The SPARROW model has been used to provide empirical estimates of the source, fate, and transport of nutrients across the United States including the Chesapeake Bay Watershed (for example, Alexander et al. 2001). See Section 7 for a more detailed description of the SPARROW model structure.



	Chesa peake Bay	SUSQUEHANNA RIVER AT CONOWINGO, MD	POTOMAC RIVER NEAR WASH, DC LITTLE FALLS PUMP STA	JAMES RIVER AT CARTERSVILLE, VA	RAPPAHANNOCK RIVER NEAR FREDERICKSBURG, VA	APPOMATTOX RIVER AT MATOACA, VA	PAMUNKEY RIVER NEAR HANOVER, VA	MATTAPONI RIVER NEAR BEULAHVILLE, VA	PATUXENT RIVER NEAR BOWIE, MD	CHOPTANK RIVER NEAR GREENSBORO, MD
🟥 P532 2002 Scenario	297.9	136.2	43.0	11.0	4.5	1.5	1.4	0.8	1.4	0.4
🟦 SPARROW CBTN_v4 model	290.9	132.0	47.6	10.4	4.4	1.4	1.4	0.6	1.5	0.5

Figure 4-2: PHASE 5.3.2 and SPARROW nitrogen and phosphorus outputs at 9 USGS stations

Ator et al. (2011) simulated the fate, transport, and flux of nitrogen and phosphorus in the Chesapeake Bay Watershed using SPARROW, and the model parameters were estimated using mean annual conditions centered around 2002 in the Chesapeake Bay watershed. The NHDPlus segmentation and attributes developed by Wieczorek and LaMotte (2010a) were used in this study. The NHDPlus is a geospatial dataset that incorporates features of the National Hydrography Dataset (NHD) and the National Elevation Dataset (NED). The NHDPlus includes stream networks based on the 1:100,000-scale NHD. Inputs and outputs from this study were compared to a Phase 5.3.2 scenario run for a 10-year hydrology simulation period from 1991 to 2000 using a constant representational input data set for the year 2002.

SPARROW and Phase 5.3.2 have very similar manure distributions, but somewhat different atmospheric and fertilizer distributions and total input mass. They also differ in their approach to assess water quality.

SPARROW uses an estimated source-specific coefficient to interpret the proportion of the applied or deposited nutrient mass that is transported to streams as an average for the entire Chesapeake basin. These rates can be interpreted as sensitivities to inputs. The strength of SPARROW is that it is a regression approach that is based on observed data. A caveat is that these sensitivities are derived from spatial differences in application rates, rather than changes in application rate at a given location. The lack of an intercept in the estimated SPARROW equation indicates that these coefficients represent the load effect of the average applied amount, rather than the incremental load from an incremental input. Additionally, the manure sensitivity in SPARROW is based on the spatial differences in the amount of manure generated, not the amount actually applied to crops. As demonstrated in Section 3, there is a large difference between the amount of nutrients in generated manure and the amount of manure nutrients that are eventually applied, particularly for nitrogen.

4.2.4 Annual Phosphorus Loss Estimator - APLE

The STAC review of phosphorus dynamics in Phase 5.3.2 (Staver et al. 2014) identified soil phosphorus storage and dynamics as an important area for improvement in subsequent models. Because phosphorus tends to be sorbed to soils, in the short run the phosphorus content of the soils has a greater influence on phosphorus export rates than phosphorus application rates. The members of the STAC review committee recommended using the Annual Phosphorus Load Estimation (APLE) (Vadas, 2014) to improve the simulation of phosphorus losses. Vadas et al. 2009 discusses the validation of the APLE model, finding that field-scale measurements and model output for phosphorus loading rate in kilograms per hectare are in good agreement. The slope of a regression between measured and observed was either 0.98 or 1.04, depending on nutrient input type while the R^2 was greater than .8 in both cases.

APLE is a field scale model running on an annual time step. Figure 4-3 shows an overview of APLE's representation of field-scale phosphorus dynamics and APLE's mass balance on the two topsoil layers. The two topsoil layers receive inputs of phosphorus in fertilizer and manure. Incorporation of fertilizer and manure can also be represented. Phosphorus leaves the soil through four pathways: (1) crop uptake, (2) percolation to groundwater, (3) runoff, and (4) eroded sediment.

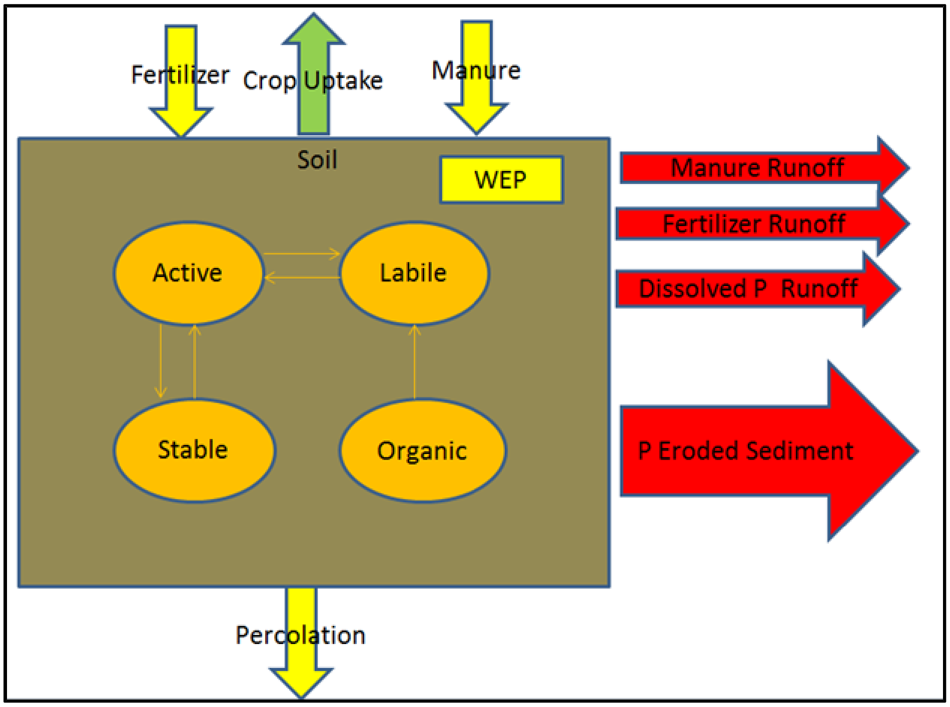


Figure 4-3: APLE Model Inputs, outputs, and state variables

Phosphorus in the soil is distributed among four pools: (1) labile phosphorus, (2) active phosphorus, (3) stable phosphorus, and (4) organic phosphorus. APLE also requires an input of the percentage of manure phosphorus that is water-extractable (WEP) and simulates the mineralization of non-WEP manure phosphorus to WEP. A portion of the phosphorus from manure is also added to the organic phosphorus pool. Partitioning among the soil phosphorus pools is a function of organic carbon concentration and percent clay in soil. Soil phosphorus pools are initialized by specifying the concentration of the Mehlich-3 soil test phosphorus. Labile phosphorus is set at one-half the Mehlich-3 value; the rest of the pools are set in equilibrium to the labile pool.

Phosphorus losses in erosion are taken from all soil phosphorus pools and include an enrichment factor which decreases with increasing erosion rates. APLE distinguishes phosphorus losses in runoff taken from the soil, manure, and fertilizer. Soil phosphorus losses come from the labile pool. Losses in manure come from WEP, while all of the phosphorus in fertilizer is vulnerable to runoff. For manure and fertilizer, runoff losses depend not only on the volume of runoff, but on the ratio of runoff to rainfall. The amount of percolation is a function of precipitation and soil depth, while phosphorus leached in percolation is a function of percent clay in the soil. Runoff, erosion, and precipitation are model inputs. For additional details on APLE phosphorus dynamics see Vadas (2014).

4.3 Nitrogen Sensitivities

4.3.1 Multiple Model Comparison

To the extent that multiple models agree, it increases the confidence in those models' predictions. The Phase 5.3.2 Model discussed above was compared for sensitivity to nutrient inputs using Equation 4-1. The sensitivities from Phase 5.3.2 were determined from direct testing of varying inputs to the model.

The APEX sensitivities were determined from tables presented in the CEAP report which gave inputs and outputs for cropland areas for No-Practice, 2006, and 2011 scenarios (USDA-NRCS, 2013). Ideally sensitivity is determined by an output response to a change in inputs. This information was not available for the APEX model and so the ratio between output and input was use for the comparison.

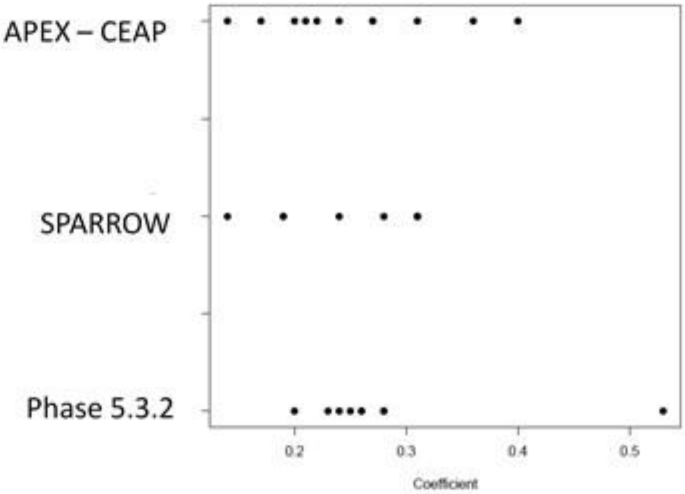


Figure 4-4: Overall model sensitivities of cropland to inorganic fertilizer inputs

As an empirical regression model, SPARROW helps to account for structural model uncertainty to the extent that the coefficients are in agreement with the sensitivities found from analysis of the process models. The caveats to interpreting the coefficients are noted in Section 4.2.3 above.

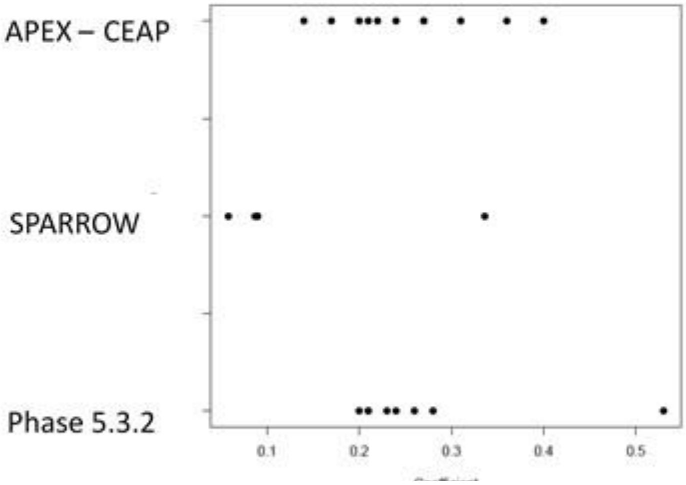


Figure 4-5: Overall model sensitivities of cropland to manure inputs

The sensitivities obtained from APEX, SPARROW, and Phase 5.3.2 models that represent the relationship between nitrogen predicted per acre loads and fertilizer and manure input loads for cropland are shown in Figure 4-4 and Figure 4-5. Variability in the APEX values is from scenarios and model versions. Variability in the SPARROW output is from model versions found in the literature (Preston and Brakebill (1999), Ator et al. (2011), Moore et al. (2011), and Preston et al. (2011)). Variability in the Phase 5.3.2 output is from different types of cropland land uses. Given the different sources of variability in the models, the comparison between them is not exact, however, Figure 4-4 and Figure 4-5 can be used to consider the range of responses of three different modeling structures under varying conditions. In general, there is considerable agreement between the three models, with the Phase 5.3.2 Model having a somewhat more constrained distribution near the means of the other two models. Given the overall agreement of the three models, the ability of the CBPO modeling team to access the Phase 5.3.2 Model, and the ability of the Phase 5.3.2 Model to directly estimate the nutrient sensitivity on land uses relevant to the Phase 6 simulation, the Modeling Workgroup determined that the sensitivities would be based on the Phase 5.3.2 Model.

An initial sensitivity analysis that was performed in 2013 is presented in Appendix 4A. The initial analysis used a limited number of existing scenarios and determined the sensitivities using linear multiple regression. This analysis was used to get a general understanding for how the AGCHEM module simulation was reacting to inputs. The Modeling Workgroup determined this initial work should be set aside in favor of a second sensitivity analysis that would be performed based on direct sensitivity test with manipulated inputs.

4.3.2 Sensitivity Tests with the Phase 5.3.2 Model

Starting with the 1997 No Action Scenario as a base, sensitivities were run by increasing and decreasing fertilizer, manure, atmospheric deposition, crop uptake, fixation, and crop cover. The increments were +60 percent, +30 percent, 0 percent, -30 percent, and -60 percent. Agricultural land uses were conventional till with manure, conventional till without manure, alfalfa, pasture, and hay without manure. The six developed land uses are regulated pervious, unregulated pervious, pervious in a combined sewer area, regulated impervious, unregulated impervious, and impervious in a combined sewer area. Natural land uses are represented by a land use known as wooded and open. See USEPA 2010a-04 for a detailed description of the land uses. The constituents tested were nitrate, ammonia, and organic nitrogen, which comprise total nitrogen. Sensitivity slopes were estimated though linear regression of load increment versus output increment for each combination of land segment, land use, input source, and constituent.

The median slope value across all land segments for each combination of land use, input source, and constituent was calculated to represent the average sensitivity to be used in the Phase 6 Model. The results were similar to the initial analysis detailed in Appendix 4A.

The Tables 4-2, 4-3, and 4-4 give the sensitivities to input for the Phase 5.3.2 land uses for the various input types. The units for all values are pounds export per pound input except for vegetative cover which is in units of pounds export. Vegetative cover is represented as a fraction of the area which is covered so that the range in input is zero to one.

Table 4-2: Absolute sensitivities of ammonia (NH_3) export to inputs

Phase 5.3.2 land use	Atmospheric Deposition	Fertilizer	Manure	Fixation	Crop Uptake	Vegetative Cover
Conventional Till with Manure	0.01	0.018	0.005	0.01	0	-0.012
Conventional Till without Manure	0.015	0.02	NA	0.015	0.001	-0.008
Hay without Manure	0.014	NA	NA	NA	0.0004	-0.002
Alfalfa	0.004	NA	0.003	NA	0.001	-0.001
Pasture	0.004	0.003	0.005	NA	NA	-0.004
Combined Sewer System Pervious Developed	0.008	0.008	NA	NA	0.004	-0.003
Regulated Pervious Developed	0.006	0.009	NA	NA	0.004	-0.003
Non-regulated Pervious Developed	0.006	0.008	NA	NA	0.0004	-0.004
Combined Sewer System Impervious Developed	0.193	NA	NA	NA	NA	NA
Regulated Impervious Developed	0.200	NA	NA	NA	NA	NA
Non-regulated Impervious Developed	0.199	NA	NA	NA	NA	NA
Wooded and Other	0.003	NA	NA	NA	NA	NA

Table 4-3: Absolute sensitivities of nitrate (NO_3) export to inputs

Phase 5.3.2 land use	Atmospheric Deposition	Fertilizer	Manure	Fixation	Crop Uptake	Vegetative Cover
Conventional Till with Manure	0.226	0.19	0.067	0.19	-0.057	0.012
Conventional Till without Manure	0.363	0.29	NA	0.34	-0.183	0.006
Hay without Manure	0.258	NA	NA	NA	0.00018	0
Alfalfa	0.212	NA	0.043	NA	0.011	0
Pasture	0.13	0.043	0.032	NA	NA	0

Combined Sewer System Pervious Developed	0.14	0.05	NA	NA	0.00018	0.001
Regulated Pervious Developed	0.117	0.05	NA	NA	0.00018	0.001
Non-regulated Pervious Developed	0.12	0.05	NA	NA	0.00018	0.001
Combined Sewer System Impervious Developed	0	NA	NA	NA	NA	NA
Regulated Impervious Developed	0	NA	NA	NA	NA	NA
Non-regulated Impervious Developed	0	NA	NA	NA	NA	NA
Wooded and Other	0.049	NA	NA	NA	NA	NA

Table 4-4: Absolute sensitivities of organic nitrogen export to inputs

Phase 5.3.2 land use	Atmospheric Deposition	Fertilizer	Manure	Fixation	Crop Uptake	Vegetative Cover
Conventional Till with Manure	0.083	0.073	0.104	0.101	0	-0.404
Conventional Till without Manure	0.009	0.009	NA	0.012	0.003	-0.24
Hay without Nutrients	0.004	NA	NA	NA	0.0001	-0.003
Alfalfa	NA	NA	0.004	NA	0.001	-0.264
Pasture	0.007	0.009	0.013	NA	NA	-0.536
Combined Sewer System Pervious Developed	0.012	0.015	NA	NA	0.0001	-0.378
Regulated Pervious Developed	0.012	0.015	NA	NA	0.0001	-0.378
Non-regulated Pervious Developed	0.012	0.014	NA	NA	0.0001	-0.378
Combined Sewer System Impervious Developed	0.417	NA	NA	NA	NA	NA
Regulated Impervious Developed	0.430	NA	NA	NA	NA	NA
Non-regulated Impervious Developed	0.435	NA	NA	NA	NA	NA
Wooded and Other	0.003	NA	NA	NA	NA	NA

4.4 Phosphorus Sensitivities

The APLE model discussed in Section 4.2.4 was found appropriate to simulate phosphorus based on both the STAC recommendation of Staver et al. (2014) and the findings of a comprehensive APLE sensitivity analysis conducted by the Chesapeake Bay Program modeling team. The recommendation of the Modeling Workgroup was to use APLE sensitivities in the Phase 6 simulation of phosphorus from agricultural land uses.

APLE was run to calculate sensitivities for a representative crop land use and a representative pasture land use. The Phase 6 inputs as described in Section 3 were not available at the time when the CBP partnership was determining the input sensitivities and so inputs from Phase 5.3.2 were used. These sensitivities were then transferred to Phase 6 land uses using the procedure discussed in Section 4.5. The conventional tillage with manure Phase 5.3.2 land use was used as the representative crop land use and the Phase 5.3.2 land use pasture was used as the representative pasture land use.

The rate of change in total phosphorus loss with respect to changes in model inputs was analyzed using land use inputs for conventional till with manure and pasture in every Phase 5.3.2 land segment. As with the nitrogen sensitivity, scenarios were run with increases and decreases of 30 percent and 60 percent for each parameter. APLE was tested for the sensitivity to the inputs of stormwater runoff, sediment washoff, fertilizer inputs, manure inputs, water extractable phosphorus, and soil storage. Stormflow is the combination of surface and interflow in the HSPF simulation in units of inches per year. Surface flow and interflow components combine to simulate stormflow in the hydrology calibration. Phosphorus sensitivity to stormflow is expressed in the units of pounds per inch. Sediment washoff in tons per acre is the value estimated at the edge-of-field as described in Section 2. Fertilizer, manure, and water extractable phosphorus inputs are as described in Section 3. Units for fertilizer, manure, and water extractable phosphorus are in pounds of phosphorus export per pound of phosphorus applied. Soil phosphorus storage is described in Section 3 and is in units of parts per million of Mehlich 3 phosphorus.

Each parameter was tested separately over the 30 and 60 percent change ranges for every land segment and land use. One test consisted of 2 separate APLE runs, one with the base input, and one with the percent change input. The output from both APLE runs was used to calculated sensitivity according to Equations (4-1). Thus, spatial variability and realistic parameter interactions were included in the sensitivity estimates. For all parameters, significant differences were found between crop land uses and pasture land uses, leading to the conclusion of a separate sensitivities: one for the crop type land uses (Table 4-5), and one for the pasture and hay type land uses (Table 4-6).

4.4.1 Agricultural Crop Sensitivities

Inputs for the Phase 5.3.2 land use conventional till with manure were used to test the sensitivity of APLE to the inputs described above. Chesapeake Bay watershed APLE model median and average sensitivity slopes of linear regression between phosphorus output and input change were calculated and are listed in Table 4-5. Median slopes were used for Phase 6 sensitivities. Figure 4-6 shows the distribution of all sensitivity slopes across all land uses and land segments in the Chesapeake Bay watershed.

Table 4-5: APLE model sensitivity slope of linear regression for crop land uses

Input	Input Unit	Average Slope	Median Slope	Median S_R	Relative Sensitivity
Soil P	ppm	0.017	0.015	0.696	Moderately sensitive
Sediment Washoff	ton/ac	0.181	0.168	0.633	Moderately sensitive
Stormflow	Inches	0.064	0.057	0.403	Moderately sensitive
Water Extractable P	lbs/acre	0.021	0.018	0.187	Slightly sensitive
Manure	lbs/acre	0.008	0.007	0.111	Slightly sensitive
Fertilizer	lbs/acre	0.005	0.004	0.068	Slightly sensitive
Uptake	lbs/acre	0.000	0.000	0.000	Insensitive

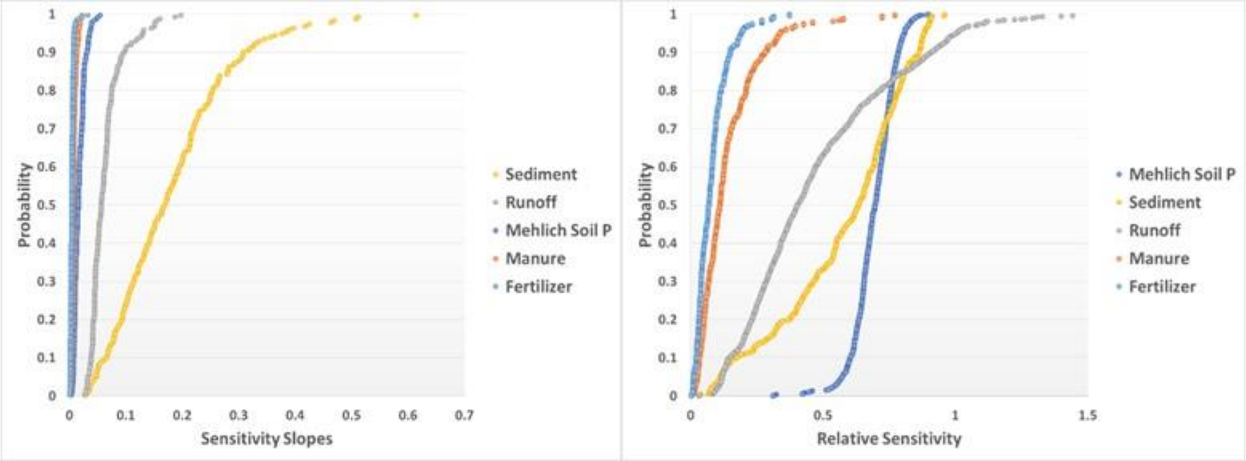


Figure 4-6: Cumulative distribution function of APLE model conventional till with manure absolute and relative sensitivity slopes in the CBW

From the relative sensitivity plot and the table of relative sensitivity, it is clear that APLE predicts that the phosphorus export load is most sensitive to the soil P storage (Mehlich Soil P) and the physical hydrologic parameters of stormflow and sediment washoff. Inputs of fertilizer and manure only have a slight effect on the output.

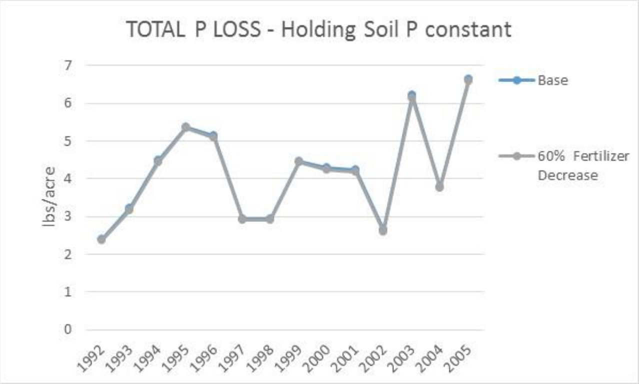


Figure 4-7: Constant soil P fertilizer test

Increased fertilizer and manure applications have the effect of increasing average soil storage so that the sensitivity to changes in inputs of fertilizer and manure would include the additional soil storage of phosphorus produced by those increases. To investigate this theory, APLE was run with resetting soil levels to the initial level at each annual time step. Figure 4-8 shows the results of this test. The conventional till with manure land use in Talbot County, Maryland was simulated holding soil P constant while decreasing fertilizer by 60 percent. Fertilizer is the dominant phosphorus load source to this land use in this county. APLE was found to have almost no sensitivity to fertilizer inputs independent of the effect of those inputs on soil P. Therefore, the final sensitivities do not include sensitivity to fertilizer and manure inputs, but only to soil P, stormflow, sediment washoff, and water extractable P. As discussed in Section 3, the soil P history is determined in part by the history of fertilizer and manure applications, and future scenarios consider the effect of fertilizer and manure applications on future soil P.

APLE is built on an extensive accumulation of literature, but additional evidence increases the confidence in its use in Phase 6. Figure 4-3 from Harmel et al. (2006) shows an empirical relationship between soil test P and annual P load. Picking values from the line and converting to pounds per acre gives a sensitivity of approximately 0.016, which is nearly identical to the value found by APLE.

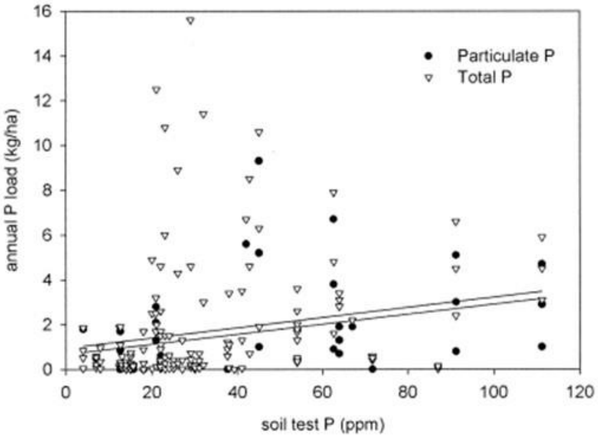


Figure 4-8: Soil test P versus Load (from Harmel et al. (2006))

4.4.2 Pasture land uses

The rate of change in total phosphorus loss with respect to changes in model inputs was analyzed for the pasture land use in every Phase 5.3.2 land segment. Chesapeake Bay watershed APLE model median and average sensitivity slopes of linear regression between phosphorus output and input change are listed in Table 4-6. Figure 4-9 shows the distribution of all sensitivity slopes across the Chesapeake Bay watershed.

The median slopes are very similar to crop median slopes however the relative sensitivities are much higher for the inputs due to the much lower loading rate of fertilizer and manure on pasture. The median slopes still predict about a 1 percent sensitivity which would not have a great effect on the nutrient export. For this reason, pasture sensitivities are also based solely on stormflow, sediment washoff, soil P storage, and water extractable phosphorus inputs. As with crops, pasture soil P in historical and future scenarios is determined in part by fertilizer and manure inputs. Pasture sensitivities for sediment washoff and stormflow were also applied to natural land uses.

Table 4-6: APLE model pasture sensitivity slope of linear regression.

Inputs	**Input Unit**	**Average Slope**	**Median Slope**	**Median S_R**	**Relative Sensitivity**
Stormflow	inches	0.187	0.121	0.947	Moderately sensitive
Manure	lbs/acre	0.018	0.017	0.523	Moderately sensitive
Soil P	ppm	0.009	0.007	0.429	Moderately sensitive
Direct Manure	lbs/acre	0.013	0.009	0.350	Moderately sensitive
Fertilizer	lbs/acre	0.010	0.009	0.346	Moderately sensitive
Water Extractable P (WEP)	lbs/acre	0.092	0.074	0.770	Moderately sensitive
Sediment Washoff	ton/ac	0.219	0.192	0.153	Slightly sensitive

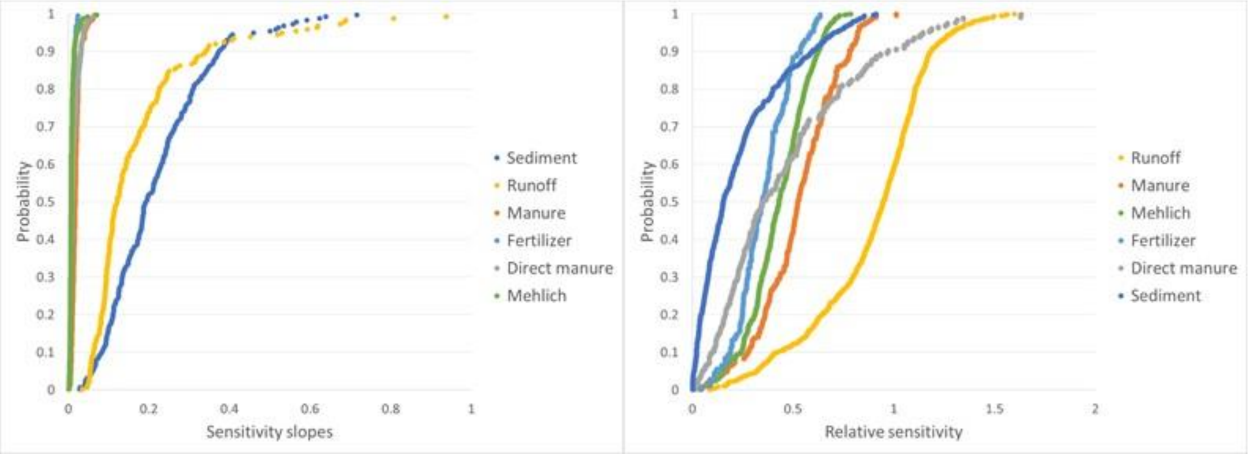


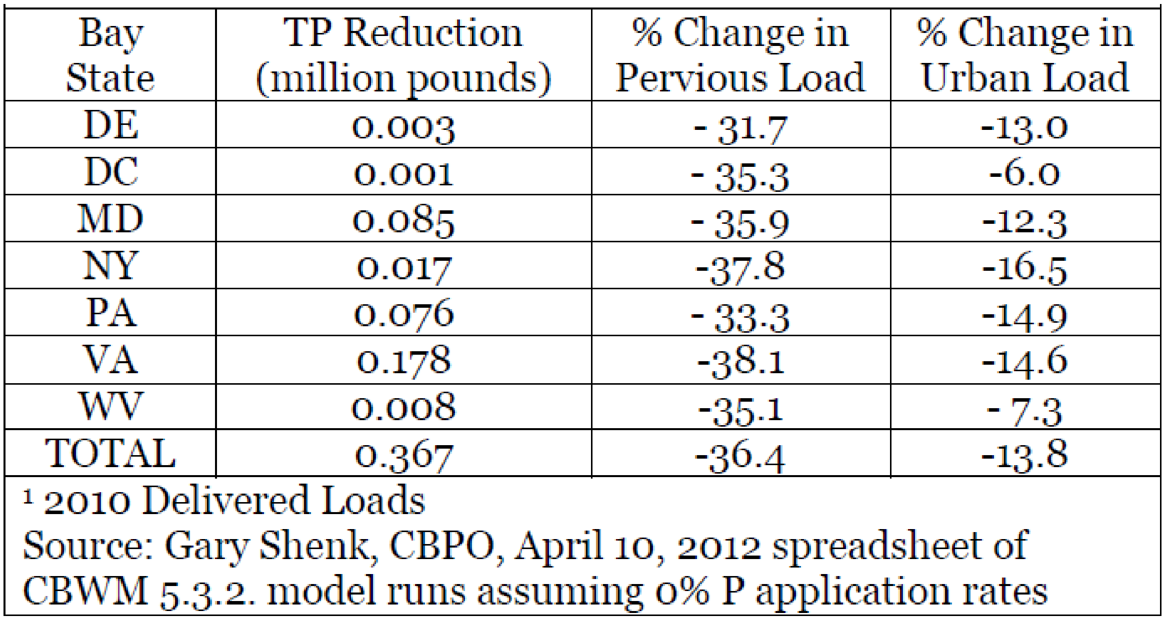
Figure 4-9: Cumulative distribution function of APLE model pasture absolute and relative sensitivity slopes

4.4.3 Phosphorus Sensitivities for Developed land

Phosphorus in developed land was simulated in Phase 5 using the PQUAL module, described above in Section 4.2.1. A Chesapeake Bay Program expert panel on urban nutrient management (Aveni et al. 2013) reviewed the Phase 5.3.2 simulation of phosphorus on developed land. They found that the phosphorus input for pervious developed lands (1.3 lbs P/acre/year) was appropriate to represent the aggregate fertilization rates in the CBW. The panel also found that the response to the change in phosphorus inputs applied to pervious land was consistent with the limited empirical research available.

From Section 5 of Aveni et al. (2013), “The [Phase 5.3.2] model scenario reflected a 100 percent reduction in the phosphorus fertilizer applied to pervious land, and the results are shown in [Table 4-7]. The change in the urban load ranged between 6 and 17 percent, depending on the state, which appears to be consistent with the limited empirical research in the upper Midwest watersheds where fertilizer P restrictions have been enacted”.

Table 4-7: Change from a 100 percent reduction in pervious developed fertilizer



Bay State	TP Reduction (million pounds)	% Change in Pervious Load	% Change in Urban Load
DE	0.003	- 31.7	-13.0
DC	0.001	- 35.3	-6.0
MD	0.085	- 35.9	-12.3
NY	0.017	-37.8	-16.5
PA	0.076	- 33.3	-14.9
VA	0.178	-38.1	-14.6
WV	0.008	-35.1	- 7.3
TOTAL	0.367	-36.4	-13.8

[1] 2010 Delivered Loads
Source: Gary Shenk, CBPO, April 10, 2012 spreadsheet of CBWM 5.3.2. model runs assuming 0% P application rates

The Phase 5.3.2 PQUAL module response to the change in phosphorus inputs applied to pervious development land use was tested. Using the 1997 No Action scenario as a base scenario, a total of 4 scenarios were run where phosphate inputs were increased and decreased (-60 percent, -30 percent, +30 percent, and +60 percent). A strong linear relationship was found in the Chesapeake Bay Watershed between total phosphate output and total fertilizer input. The sensitivity slope for phosphate (PO_4) is 0.1917 and the linear regression yielded an R^2 of 0.8978. Sensitivities to sediment and stormflow also were found using this method. These sensitivities were applied to all developed land uses.

4.5 Transference of Sensitivities to Phase 6 Land Uses

Phase 6 and Phase 5.3.2 Model land uses are similar but not entirely equivalent. Therefore, sensitivities determined from Phase 5.3.2 required translation. This was accomplished by adjusting the sensitivity for each Phase 5.3.2 land use by the ratio of the average load, calculated in Section 2, for the Phase 6 land use to the Phase 5.3.2 land use and input type on which the sensitivity originally was developed. The adjustment accounts for the greater retention capacity of lower-loading land uses and guards against the calculation of negative loading rates in low-loading land uses.

Some Phase 5.3.2 land uses do not have the same inputs as the translated Phase 6 load source. In these cases, a different Phase 5.3.2 land use was mapped to the Phase 6 load source for that input. As such, the translation of Phase 5.3.2 land use to Phase 6 load source is specific to each input. In most cases, the Phase 5.3.2 land use could be directly related to a Phase 6 load source for all inputs.

Table 4-8: Load source multiplier for Nitrogen. Ratio of Phase 5.3.2 to Phase 6 average land use load for each input.

Land Class	Phase 5.3.2 Land Use	Phase 6 Load Source	Input	Load Ratio Multiplier
Cropland	hightill with manure	Double Cropped Land	AtmDep	0.535

	hightill with manure	Double Cropped Land	CropCov	0.535
	hightill with manure	Double Cropped Land	Fert	0.535
	hightill with manure	Double Cropped Land	Legume	0.535
	hightill with manure	Double Cropped Land	Manure	0.535
	hightill with manure	Double Cropped Land	Uptake	0.535
	hightill with manure	Full Season Soybeans	AtmDep	0.481
	hightill with manure	Full Season Soybeans	CropCov	0.481
	hightill with manure	Full Season Soybeans	Fert	0.481
	hightill with manure	Full Season Soybeans	Legume	0.481
	hightill with manure	Full Season Soybeans	Manure	0.481
	hightill with manure	Full Season Soybeans	Uptake	0.481
	hightill with manure	Grain with Manure	AtmDep	0.949
	hightill with manure	Grain with Manure	CropCov	0.949
	hightill with manure	Grain with Manure	Fert	0.949
	hightill with manure	Grain with Manure	Manure	0.949
	hightill with manure	Grain with Manure	Uptake	0.949
	hightill without manure	Grain without Manure	AtmDep	0.575
	hightill without manure	Grain without Manure	CropCov	0.575
	hightill without manure	Grain without Manure	Fert	0.575
	hightill without manure	Grain without Manure	Uptake	0.575
	hightill with manure	Other Agronomic Crops	AtmDep	0.305
	hightill with manure	Other Agronomic Crops	CropCov	0.305
	hightill with manure	Other Agronomic Crops	Fert	0.305
	hightill with manure	Other Agronomic Crops	Legume	0.305
	hightill with manure	Other Agronomic Crops	Manure	0.305
	hightill with manure	Other Agronomic Crops	Uptake	0.305
	hightill with manure	Silage with Manure	AtmDep	1.098
	hightill with manure	Silage with Manure	CropCov	1.098
	hightill with manure	Silage with Manure	Fert	1.098
	hightill with manure	Silage with Manure	Manure	1.098
	hightill with manure	Silage with Manure	Uptake	1.098
	hightill without manure	Silage without Manure	AtmDep	0.667
	hightill without manure	Silage without Manure	CropCov	0.667
	hightill without manure	Silage without Manure	Fert	0.667
	hightill without manure	Silage without Manure	Uptake	0.667
	hightill with manure	Small Grains and Grains	AtmDep	0.569
	hightill with manure	Small Grains and Grains	CropCov	0.569
	hightill with manure	Small Grains and Grains	Fert	0.569
	hightill with manure	Small Grains and Grains	Manure	0.569
	hightill with manure	Small Grains and Grains	Uptake	0.569
	hightill with manure	Specialty Crop High	AtmDep	0.908

	hightill with manure	Specialty Crop High	CropCov	0.908
	hightill with manure	Specialty Crop High	Fert	0.908
	hightill with manure	Specialty Crop High	Manure	0.908
	hightill with manure	Specialty Crop High	Uptake	0.908
	hightill with manure	Specialty Crop Low	AtmDep	0.21
	hightill with manure	Specialty Crop Low	CropCov	0.21
	hightill with manure	Specialty Crop Low	Fert	0.21
	hightill with manure	Specialty Crop Low	Legume	0.21
	hightill with manure	Specialty Crop Low	Manure	0.21
	hightill with manure	Specialty Crop Low	Uptake	0.21
developed	regulated impervious developed	MS4 & CSS Buildings and Other	AtmDep	0.598
	regulated impervious developed	MS4 & CSS Roads	AtmDep	0.757
	regulated impervious developed	MS4 & CSS Tree Canopy over Impervious	AtmDep	0.678
	regulated pervious developed	MS4 & CSS Tree Canopy over Turfgrass	AtmDep	0.472
	regulated pervious developed	MS4 & CSS Tree Canopy over Turfgrass	CropCov	0.472
	regulated pervious developed	MS4 & CSS Tree Canopy over Turfgrass	Fert	0.472
	hay without nutrients	MS4 & CSS Tree Canopy over Turfgrass	Uptake	1.382
	regulated pervious developed	MS4 & CSS Turf Grass	AtmDep	0.62
	regulated pervious developed	MS4 & CSS Turf Grass	CropCov	0.62
	regulated pervious developed	MS4 & CSS Turf Grass	Fert	0.62
	hay without nutrients	MS4 & CSS Turf Grass	Uptake	1.814
	nonregulated impervious developed	Non-Regulated Buildings and Other	AtmDep	0.794
	nonregulated impervious developed	Non-Regulated Roads	AtmDep	0.985
	nonregulated impervious developed	Non-Regulated Tree Canopy over Impervious	AtmDep	0.9
	nonregulated pervious developed	Non-Regulated Tree Canopy over Turfgrass	AtmDep	0.514
	nonregulated pervious developed	Non-Regulated Tree Canopy over Turfgrass	CropCov	0.514
	nonregulated pervious developed	Non-Regulated Tree Canopy over Turfgrass	Fert	0.514
	hay without nutrients	Non-Regulated Tree Canopy over Turfgrass	Uptake	1.382

	nonregulated pervious developed	Non-Regulated Turf Grass	AtmDep	0.674
	nonregulated pervious developed	Non-Regulated Turf Grass	CropCov	0.674
	nonregulated pervious developed	Non-Regulated Turf Grass	Fert	0.674
	hay without nutrients	Non-Regulated Turf Grass	Uptake	1.814
	regulated pervious developed	Regulated Construction	AtmDep	1.484
Natural	forest	CSS Forest	AtmDep	0.413
	forest	CSS Mixed Open	AtmDep	0.603
	forest	Harvested Forest	AtmDep	2.922
	forest	Headwater or Isolated Wetland	AtmDep	0.413
	forest	Mixed Open	AtmDep	0.603
	forest	Non-tidal Floodplain Wetland	AtmDep	0.413
	forest	True Forest	AtmDep	0.413
Pasture	hay without nutrients	Ag Open Space	AtmDep	0.804
	hay without nutrients	Ag Open Space	CropCov	0.804
	hay without nutrients	Ag Open Space	Uptake	0.804
	alfalfa	Legume Hay	AtmDep	0.664
	alfalfa	Legume Hay	CropCov	0.664
	pasture	Legume Hay	Fert	0.703
	alfalfa	Legume Hay	Legume	0.664
	pasture	Legume Hay	Legume	0.703
	alfalfa	Legume Hay	Manure	0.664
	alfalfa	Legume Hay	Uptake	0.664
	hightill with manure	Other Hay	AtmDep	0.212
	hightill with manure	Other Hay	CropCov	0.212
	pasture	Other Hay	CropCov	0.989
	hightill with manure	Other Hay	Fert	0.212
	hightill with manure	Other Hay	Legume	0.212
	hightill with manure	Other Hay	Manure	0.212
	hightill with manure	Other Hay	Uptake	0.212
	pasture	Pasture	AtmDep	0.95
	pasture	Pasture	CropCov	0.95
	pasture	Pasture	Fert	0.95
	pasture	Pasture	Legume	0.95
	pasture	Pasture	Manure	0.95
	pasture	Pasture	Uptake	0.95

Table 4-9: Load source multiplier for phosphorus. Ratio of Phase 5.3.2 to Phase 6 average land use load for each input.

Land Class	Phase 5.3.2 Land Use	Phase 6 Load Source	Input	Load Ratio Multiplier
Cropland	hightill with manure	Double Cropped Land	Stormflow	0.72
	hightill with manure	Double Cropped Land	Sediment	0.72
	hightill with manure	Double Cropped Land	Soil P	0.72
	hightill with manure	Double Cropped Land	WEP	0.72
	hightill with manure	Full Season Soybeans	Stormflow	0.72
	hightill with manure	Full Season Soybeans	Sediment	0.72
	hightill with manure	Full Season Soybeans	Soil P	0.72
	hightill with manure	Full Season Soybeans	WEP	0.72
	hightill with manure	Grain with Manure	Stormflow	0.72
	hightill with manure	Grain with Manure	Sediment	0.72
	hightill with manure	Grain with Manure	Soil P	0.72
	hightill with manure	Grain with Manure	WEP	0.72
	hightill with manure	Grain without Manure	Stormflow	0.72
	hightill with manure	Grain without Manure	Sediment	0.72
	hightill with manure	Grain without Manure	Soil P	0.72
	hightill with manure	Grain without Manure	WEP	0.72
	hightill with manure	Other Agronomic Crops	Stormflow	0.72
	hightill with manure	Other Agronomic Crops	Sediment	0.72
	hightill with manure	Other Agronomic Crops	Soil P	0.72
	hightill with manure	Other Agronomic Crops	WEP	0.72
	hightill with manure	Silage with Manure	Stormflow	0.72
	hightill with manure	Silage with Manure	Sediment	0.72
	hightill with manure	Silage with Manure	Soil P	0.72
	hightill with manure	Silage with Manure	WEP	0.72
	hightill with manure	Silage without Manure	Stormflow	0.72
	hightill with manure	Silage without Manure	Sediment	0.72
	hightill with manure	Silage without Manure	Soil P	0.72
	hightill with manure	Silage without Manure	WEP	0.72
	hightill with manure	Small Grains and Grains	Stormflow	0.72
	hightill with manure	Small Grains and Grains	Sediment	0.72
	hightill with manure	Small Grains and Grains	Soil P	0.72
	hightill with manure	Small Grains and Grains	WEP	0.72
	hightill with manure	Specialty Crop High	Stormflow	0.72
	hightill with manure	Specialty Crop High	Sediment	0.72
	hightill with manure	Specialty Crop High	Soil P	0.72
	hightill with manure	Specialty Crop High	WEP	0.72
	hightill with manure	Specialty Crop Low	Stormflow	0.72
	hightill with manure	Specialty Crop Low	Sediment	0.72

	hightill with manure	Specialty Crop Low	Soil P	0.72
	hightill with manure	Specialty Crop Low	WEP	0.72
developed	nonregulated pervious developed	MS4 & CSS Tree Canopy over Turfgrass	Fert	0.833
	nonregulated pervious developed	MS4 & CSS Turf Grass	Fert	1.093
	nonregulated pervious developed	Non-Regulated Tree Canopy over Turfgrass	Fert	0.833
	nonregulated pervious developed	Non-Regulated Turf Grass	Fert	1.093
Natural	pasture	Harvested Forest	Stormflow	0.19
	pasture	Harvested Forest	Sediment	0.19
	pasture	Headwater or Isolated Wetland	Stormflow	0.061
	pasture	Headwater or Isolated Wetland	Sediment	0.061
	pasture	Mixed Open	Stormflow	0.347
	pasture	Mixed Open	Sediment	0.347
	pasture	Non-tidal Floodplain Wetland	Stormflow	0.061
	pasture	Non-tidal Floodplain Wetland	Sediment	0.061
	pasture	True Forest	Stormflow	0.061
	pasture	True Forest	Sediment	0.061
Pasture	pasture	Ag Open Space	Stormflow	0.657
	pasture	Ag Open Space	Sediment	0.657
	pasture	Legume Hay	Stormflow	0.657
	pasture	Legume Hay	Sediment	0.657
	pasture	Legume Hay	Soil P	0.657
	pasture	Legume Hay	WEP	0.657
	pasture	Other Hay	Stormflow	0.657
	pasture	Other Hay	Sediment	0.657
	pasture	Other Hay	Soil P	0.657
	pasture	Other Hay	WEP	0.657
	pasture	Pasture	Stormflow	0.657
	pasture	Pasture	Sediment	0.657
	pasture	Pasture	Soil P	0.657
	pasture	Pasture	WEP	0.657

The final sensitivities for all land uses is available as appendix 4B: Sensitivities.csv.

4.6 Sensitivity of Atmospheric Emissions

The Phase 6 Model takes atmospheric deposition of nitrogen as one of the major inputs as discussed in Section 3.11. Most land use-based load sources have a sensitivity to nitrogen deposition. Deposition is driven by emissions of NOx and ammonia to the atmosphere, but the overall mass-balance accounting of loads to and from the atmosphere is outside the scope of the Phase 6 Watershed Model

In some cases, BMPs or other effects may change the emissions to the atmosphere, and it is necessary to estimate the effect that this change in emissions has on loads to the Bay. As of this writing, manure treatment technologies are the only BMPs that restrict ammonia emissions. However, the CBP Modeling Workgroup determined on September 22, 2016 that the following analysis applies to all tracked actions that change nitrogen emissions (Modeling Workgroup Minutes September 22, 2016).

Changes in atmospheric emissions from a single point result, in theory, in a change in deposition to the entire watershed and even beyond the Chesapeake Bay watershed boundaries. This theoretical change in deposition would alter the delivered load from each land source in each land-river segment by an infinitesimal amount with the sum of delivered load change being some fraction of the emission change. If credit for emission reductions were to accrue to individual land uses, a typical acre would get about a millionth of a pound reduction for a typical manure treatment BMP reducing ammonia emissions. There would also be a change in deposition to the surface of the tidal waters. On August 9, 2016 the CBP Modeling Workgroup (Modeling Workgroup Minutes August 9, 2016) recommended that the credit for nitrogen load reduction for both tidal deposition and watershed deposition, with subsequent delivery to tidal waters, be attributed directly to the implemented BMP. Credit for nitrogen loads to the Bay from emission reduction BMPs are expected to be low in terms of absolute pounds reduced, both because of the low numbers of BMPs that create emission reductions and the low ratio of emitted loads to loads that reach the Bay. The Modeling Workgroup did not request a full series of atmospheric model runs because of resource limitations, and so in the sections to follow, approximate methods based on the available data are used to develop tidal Bay nitrogen load reductions related to air source reductions at a point.

4.6.1 Oxidized nitrogen ratio of emission to deposition

The CMAQ Model has long been used to estimate atmospheric deposition of nitrogen in the Chesapeake Bay watershed and the conterminous United States. Section 3.11 of the Phase 6 documentation goes into details of the simulation and results of CMAQ. Responding to a CBP request, Robin Dennis made a presentation of CMAQ results to the Modeling Workgroup on January 8, 2013 (Modeling Workgroup Minutes January 8, 2013) giving relationships between oxidized nitrogen emissions by state and nitrogen deposition to each watershed state. Table 4-10 gives values for the kilograms of nitrogen deposited within the Chesapeake Bay watershed area of each state per ton of oxidized nitrogen (as N) emitted in each state. Oxidized nitrogen in CMAQ corresponds to nitrate or NO_3 in the Phase 6 Model. These values are converted to percent in Table 4-11. Note that states near the center of the watershed have a return rate to the watershed of between 10 percent and 20 percent of what it emitted. States on the extremes of the watershed have between 5 percent and 10 percent return to the watershed.

Table 4-10: State transfer coefficients for oxidized nitrogen to state watershed area (kg N deposited per ton N emitted)

	Emitter					
Receptor	DE	MD	NY	PA	VA	WV
DE	5.4	2.31	0.44	0.87	1.1	0.44
MD	19.46	57.16	5.3	14.33	20.95	10.6
NY	5.31	7.25	11.5	10.47	4.76	4.73
PA	23.86	49.09	16.37	62.28	24.79	28.11
VA	19.55	43.34	7.84	20.59	85.05	27.7

WV	1.88	6.04	1.03	3.73	5.5	9.88
Total	75.46	165.19	42.48	112.27	142.15	81.46

Table 4-11: State transfer coefficients for oxidized nitrogen to state watershed area (percent)

	Emitter					
Receptor	DE	MD	NY	PA	VA	WV
DE	0.60%	0.25%	0.05%	0.10%	0.12%	0.05%
MD	2.15%	6.30%	0.58%	1.58%	2.31%	1.17%
NY	0.59%	0.80%	1.27%	1.15%	0.52%	0.52%
PA	2.63%	5.41%	1.80%	6.87%	2.73%	3.10%
VA	2.16%	4.78%	0.86%	2.27%	9.38%	3.05%
WV	0.21%	0.67%	0.11%	0.41%	0.61%	1.09%
total	8.32%	18.21%	4.68%	12.38%	15.67%	8.98%

4.6.2 Reduced Nitrogen Ratio of Emission to Deposition

Table 4-10 was provided for oxidized nitrogen but not reduced nitrogen. Reduced nitrogen corresponds to ammonia or NH_3 in the Phase 6 Model. To translate Table 4-10 to reduced nitrogen, more information on the transport of atmospheric nitrogen is needed. Dennis (1997) introduced the calculation of an airshed and made calculations of the percent of deposition that originated from emissions within the watershed. Paerl et al. (2002) extended the analysis to oxidized and reduced nitrogen. The values were updated in Dennis et al. (2010) and again in an analysis transmitted to the Chesapeake Bay Program on April 3, 2011. The 2011 analysis found that 50 percent of the oxidized nitrogen deposited in the Chesapeake Bay watershed and 75 percent of the reduced nitrogen deposited in the Chesapeake Bay watershed originated within the Chesapeake Bay watershed. These values can be used to translate the values in Table 4-11 to reduced nitrogen.

Define the following variables:
E_{NO} = Chesapeake Bay watershed emissions of *oxidized* nitrogen.
E_{NH} = Chesapeake Bay watershed emissions of *reduced* nitrogen.
F_{NO} = Fraction of *oxidized* nitrogen emitted in the watershed that returns to the watershed. These are estimated values presented in Table 4-11.
F_{NH} = Fraction of *reduced* nitrogen emitted in the watershed that returns to the watershed. These are the unknown values that must be estimated to credit practices much as manure treatment technologies.
R = ratio of nitrogen leaving watershed to nitrogen entering watershed. Assumed constant for oxidized and reduced nitrogen.

The relationship of these variables to each other is represented in Figure 4-10. The amount of oxidized nitrogen emitted in the watershed that is deposited in the watershed is equal to $E_{NO}F_{NO}$. If 50 percent of the oxidized nitrogen that is deposited in the watershed is from outside the watershed, then the amount of deposited oxidized nitrogen that arrives from outside the watershed must also be equal to $E_{NO}F_{NO}$. The amount of oxidized nitrogen emitted in the watershed that leaves the watershed is $E_{NO}(1-F_{NO})$.

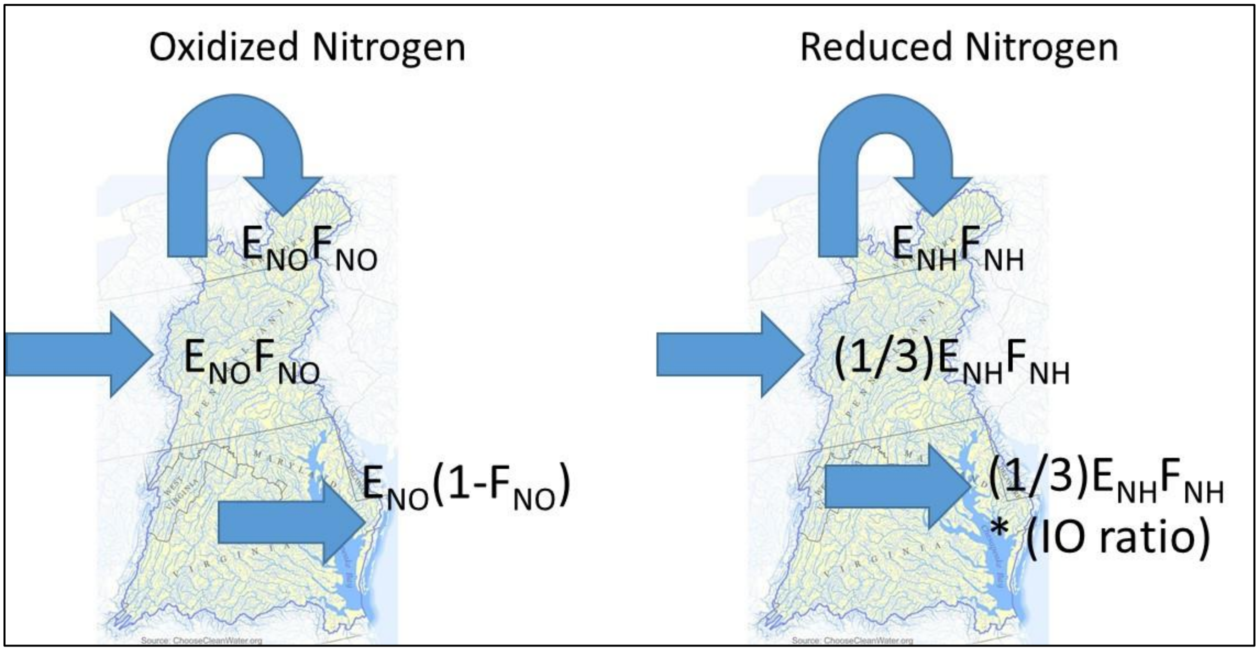


Figure 4-10: Definition of atmospheric deposition variables

For reduced nitrogen, 75 percent of deposited nitrogen originates within the watershed, so if the amount of reduced nitrogen that is both emitted and deposited in the watershed is $E_{NH}F_{NH}$ then the amount that originates outside of the watershed is $(1/3)E_{NH}F_{NH}$. There is an assumed constant ratio of nitrogen leaving the watershed to nitrogen entering the watershed so the amount of reduced nitrogen leaving the watershed is $(1/3)E_{NH}F_{NH}R$. R for oxidized nitrogen is equal to $E_{NO}(1-F_{NO})/E_{NO}F_{NO}$.

The fraction of emitted reduced nitrogen that is deposited in the watershed can now be expressed as a function of F_{NH} which is available in Table 4-11.

Equation 4-2: Fraction of emitted reduced nitrogen that is returned to the watershed

$$F_{NH} = E_{NH}F_{NH} / (E_{NH}F_{NH} + (1/3)E_{NH}F_{NH} * (E_{NO}(1-F_{NO})/E_{NO}F_{NO})$$

Equation 4-2 can be simplified to

Equation 4-3: Simplified version of reduced nitrogen fraction

$$F_{NH} = 3 / (2 + 1/F_{NO})$$

Applying Equation 4-3 to Table 4-11 results in the values in Table 4-12.

Table 4-12: State transfer coefficients for reduced nitrogen to state watershed area (percent)

	Emitter					
Receptor	DE	MD	NY	PA	VA	WV
DE	1.76%	0.76%	0.15%	0.29%	0.36%	0.15%
MD	6.17%	16.79%	1.73%	4.59%	6.62%	3.43%
NY	1.74%	2.36%	3.71%	3.38%	1.56%	1.55%
PA	7.50%	14.65%	5.22%	18.11%	7.77%	8.75%

VA	6.20%	13.08%	2.55%	6.51%	23.68%	8.63%
WV	0.62%	1.97%	0.34%	1.22%	1.80%	3.20%
Total	23.98%	49.61%	13.70%	34.11%	41.80%	25.70%

4.6.3 Total delivered to tidal waters

To arrive at the total reduction in delivered load, the direct deposition to the tidal Chesapeake must be added to the watershed load and the deposition to the watershed must be attenuated to account for terrestrial and non-tidal aquatic processing.

The area of the tidal Chesapeake is 4,470 square miles. The area of the surrounding states of Maryland, Delaware, and Virginia within the Chesapeake Watershed is 31,362 square miles. The area of the Bay is 14.3 percent of the surrounding watershed area and so it is estimated to receive 14.3 percent of the combined deposition of those three states from each emitter state.

The Beta 3 Draft Phase 6 CAST Watershed Model was run to estimate the percent of deposited nitrogen that reaches the Bay. The WIP scenario was run with the TMDL allocation atmospheric deposition and also with the current atmospheric deposition. The change in load was recorded in Table 4-13 as a percentage relative to the change in input.

Table 4-13: Percent of deposited atmospheric nitrogen that reaches tidal water

Receptor	Delivered
DE	11.84%
MD	15.48%
NY	8.06%
PA	19.28%
VA	7.33%
WV	6.91%
Bay	100.00%

Multiplying the delivery values in Table 4-13 by the fraction deposited in Table 4-11 and Table 4-12 gives the results in Table 4-14 and Table 4-15, which are summarized in Table 4-16.

Table 4-14: Percentage of emitted oxidized nitrogen that reaches tidal waters

	Emitter					
Receptor	DE	MD	NY	PA	VA	WV
DE	0.07%	0.03%	0.01%	0.01%	0.01%	0.01%
MD	0.33%	0.98%	0.09%	0.24%	0.36%	0.18%
NY	0.05%	0.06%	0.10%	0.09%	0.04%	0.04%
PA	0.51%	1.04%	0.35%	1.32%	0.53%	0.60%
VA	0.16%	0.35%	0.06%	0.17%	0.69%	0.22%
WV	0.01%	0.05%	0.01%	0.03%	0.04%	0.08%
Bay	0.70%	1.62%	0.21%	0.56%	1.69%	0.61%
Total	1.83%	4.13%	0.83%	2.43%	3.36%	1.74%

Table 4-15: Percentage of reduced nitrogen that reaches tidal waters

	Emitter					
Receptor	DE	MD	NY	PA	VA	WV
DE	0.21%	0.09%	0.02%	0.03%	0.04%	0.02%
MD	0.96%	2.60%	0.27%	0.71%	1.03%	0.53%
NY	0.14%	0.19%	0.30%	0.27%	0.13%	0.12%
PA	1.45%	2.82%	1.01%	3.49%	1.50%	1.69%
VA	0.45%	0.96%	0.19%	0.48%	1.74%	0.63%
WV	0.04%	0.14%	0.02%	0.08%	0.12%	0.22%
Bay	2.02%	4.37%	0.63%	1.63%	4.38%	1.74%
Total	5.27%	11.17%	2.43%	6.70%	8.93%	4.96%

Table 4-16: Percentage of emitted oxidized and reduced nitrogen that reaches the tidal waters

	Emitter					
	DE	MD	NY	PA	VA	WV
Reduced	5.27%	11.17%	2.43%	6.70%	8.93%	4.96%
Oxidized	1.83%	4.13%	0.83%	2.43%	3.36%	1.74%