Delmarva Coastal Bays NLM (Nitrogen Loading Model)

User's Guide and Documentation

Mark J. Brush[1], Lora A. Harris[2], Juliette C.P. Giordano[1], and Joanna K. York[3]

[1] Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, VA
Phone: 804-684-7402 (Brush); Email: brush@vims.edu

[2] University of Maryland Center for Environmental Science, Chesapeake Biological Laboratory, Solomons, MD
Phone: 410-326-7391; Email: harris@umces.edu

[3] College of Earth, Ocean, and Environment, University of Delaware, Newark, DE
Phone: 302-831-7040; Email: jyork@udel.edu

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INTRODUCTION

This document provides user instructions and background information for the Delmarva Coastal Bays Nitrogen Loading Model (NLM), a spreadsheet model for estimating annual average loads of total nitrogen (TN) delivered through groundwater from coastal watersheds to receiving waterbodies (Fig. 1). The NLM also includes inputs through point source discharges and direct atmospheric deposition onto the coastal bays. The NLM was originally developed by Valiela et al. (1997) on Cape Cod, MA, and subsequently adapted to Chincoteague Bay by Cole (2005) and to Gargathy and Burton's Bays in Virginia by Giordano et al. (2011). We subsequently tested the NLM in 22 sub-watersheds across the Delmarva and expanded the model across the seaside of the Delmarva Peninsula, covering the watersheds of each coastal bay, with support from two regional VA-MD-DE Sea Grant awards (NA074170047; NA10OAR4170085), using the version developed by Giordano et al. (2011) as a starting point. The accompanying Microsoft Excel workbook contains blank versions of the NLM in which the user may enter their own input values for any watershed of interest in metric or English units. The file also contains multiple worksheets with versions of the NLM parameterized as described below for each coastal bay watershed along the Delmarva Peninsula. The final page of the workbook summarizes predicted loads for each Delmarva coastal bay watershed.

Rates of atmospheric deposition and fertilization, crop yields and nitrogen contents, attenuation factors, and general parameterization of the NLM for the Delmarva Coastal Bays that we outline below were drawn in some cases from the original model (Valiela et al. 1997) and in many cases were adapted to local conditions when possible; rationale is provided for these selections below. However, end users of the Delmarva Coastal Bays NLM should consider this description as supporting information, keeping in mind that the assumptions and parameterization of the model are easily edited in the spreadsheet we have provided. In many cases, we suspect that managers and planners working at a smaller watershed scale may have better data to improve parameterization. For example, plat level data at the municipal or county level in a GIS system may be used to better estimate the population on septic or characterize lawn coverage. We invite users of this model to amend parameters and inputs as suited to their application.

We begin by providing an overview of the spreadsheet layout and instructions for users to enter or modify data and parameters. This is followed by a description of default model parameters and input data, updated from Giordano et al. (2011).

For additional information please contact the authors; contact information is provided on the cover page.

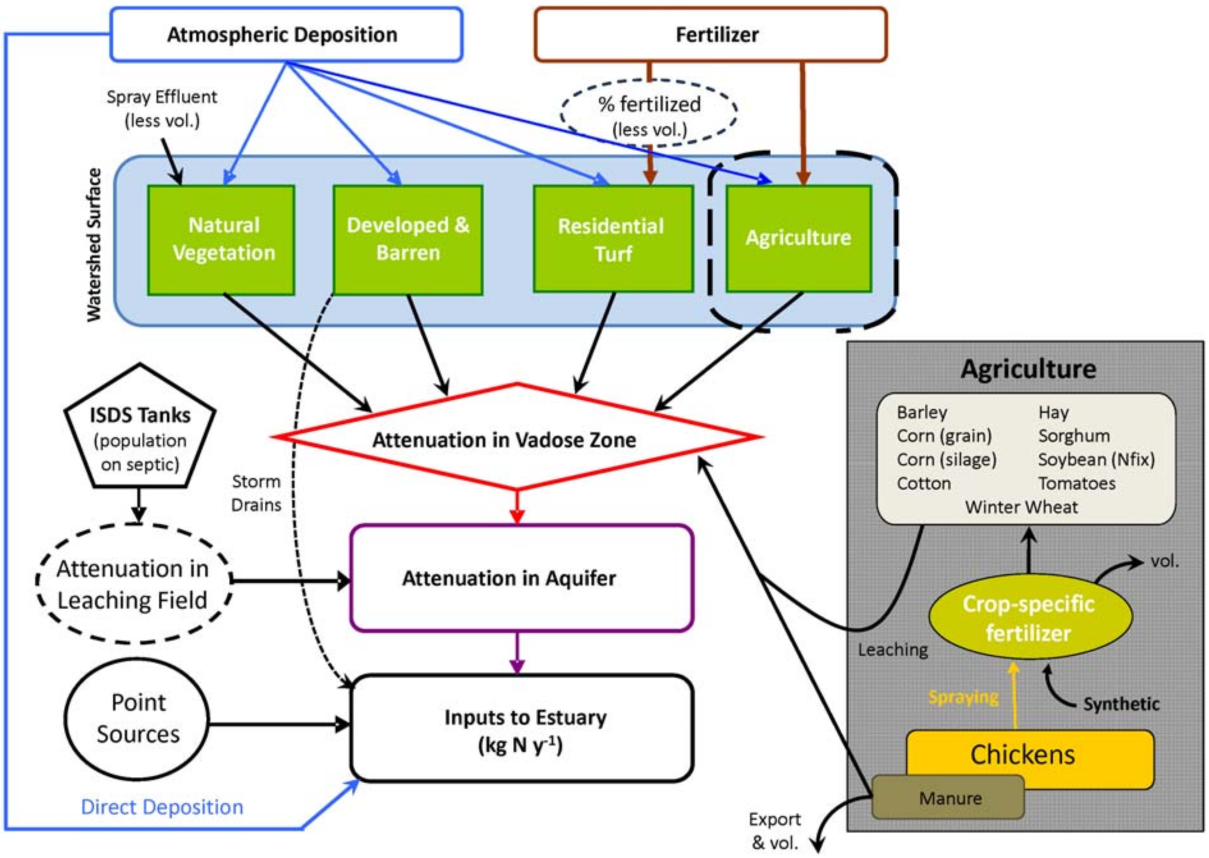

Fig. 1. Schematic of the NLM. Adapted from Giordano (2009). See text for details. "vol." = volatilization.

USER INSTRUCTIONS

Overview: The first page of the associated NLM workbook contains background and citation information for the model. The second and third worksheets provide blank versions of the NLM where users can enter their own input values for a watershed of interest in metric or English units, respectively. Following these pages, the workbook contains a worksheet for each coastal bay watershed along the Delmarva Peninsula, starting with Rehoboth Bay in Delaware and ending with Magothy Bay in Virginia (Fig. 2). These sheets have already been parameterized with our best estimates of input values as described in the Methods section below; however the user is free to change these values as they deem appropriate. The final page of the workbook synthesizes predicted loads for all coastal bay watersheds in various units.

Overview and operation of the NLM spreadsheet model: The following overview applies to any page in the associated NLM workbook; we suggest the reader refer to either the "BLANK NLM – Metric" worksheet or the "BLANK NLM – English" worksheet as these contain all the features we refer to below. The NLM spreadsheet consists of four sections oriented vertically across the page. These are described in detail below.

Input Data: The leftmost section consists of user-defined inputs needed to run the model. The first box asks for miscellaneous information on atmospheric deposition, point sources, population on septic systems, number of chickens (termed poultry in the model), surface area of the adjacent coastal bay (optional input), and spray effluent deposition rate and application area. The remaining boxes ask for land use distributions, first for non-agricultural and then for agricultural lands, fertilization rates for turf (i.e., lawns) and crops, and agricultural (i.e., crop) yields. The final two entries in this section allow the user to specify if excess poultry waste is exported from the watershed, and the fraction of impervious surfaces that drain directly to tidal waters through storm drains (as opposed to entering the groundwater). Note that these two options along with spray effluent are only available in the blank versions of the NLM and not on the versions already parameterized for specific coastal bay watersheds.

Required units are listed after each parameter or at the top of each section. Inputs need to be entered in metric units in the "BLANK NLM – Metric" worksheet, and in English units in the "BLANK NLM – English" worksheet; the latter spreadsheet converts user inputs into metric units for use in the rest of the model. Comments within each cell provide a description of each term (BLANK NLM spreadsheets only).

Parameters: The next section of the NLM spreadsheet contains parameters for the various calculations within the model. Some of these are from the original Valiela et al. (1997) version of the model and others are specific to the Delmarva as described in the Methods section below. Parameters include terms for attenuation of atmospheric deposition through various land uses, terms for human waste, turf fertilization, and agriculture, and attenuation in groundwater. Unless the user has specific information on these parameters for their watershed, these values should not be changed.

N Input to Groundwater and *Crop Lookup Tables:* The next section of the NLM spreadsheet contains model calculations for the various inputs of nitrogen to the land surface and groundwater due to atmospheric deposition, fertilizer application, poultry operations, spray effluent, plant uptake, and crop harvest. These calculations should not be changed by the user.

Results: The final section to the far right of the NLM spreadsheet displays model output for predicted annual TN load leaving the watershed after attenuation through the vadose zone and aquifer. These calculations should not be changed by the user. Loads are computed separately from the groundwater (from all sources except wastewater), wastewater sources (septic tanks plus spray effluent), point sources (if any exist), and direct atmospheric deposition onto the coastal bay. If no area of the coastal bay is entered, the latter term will be zero. The cell highlighted in yellow sums all these inputs and represents total predicted TN load (kg N y^{-1}) from all sources. For the blank NLM spreadsheets, this represents the TN load exiting the watershed of interest. For the spreadsheets parameterized for specific coastal bays, this also represents the load assumed to enter into the receiving bay, including direct atmospheric deposition onto the bay surface. The table below this cell computes the percent of the total load originating from each source.

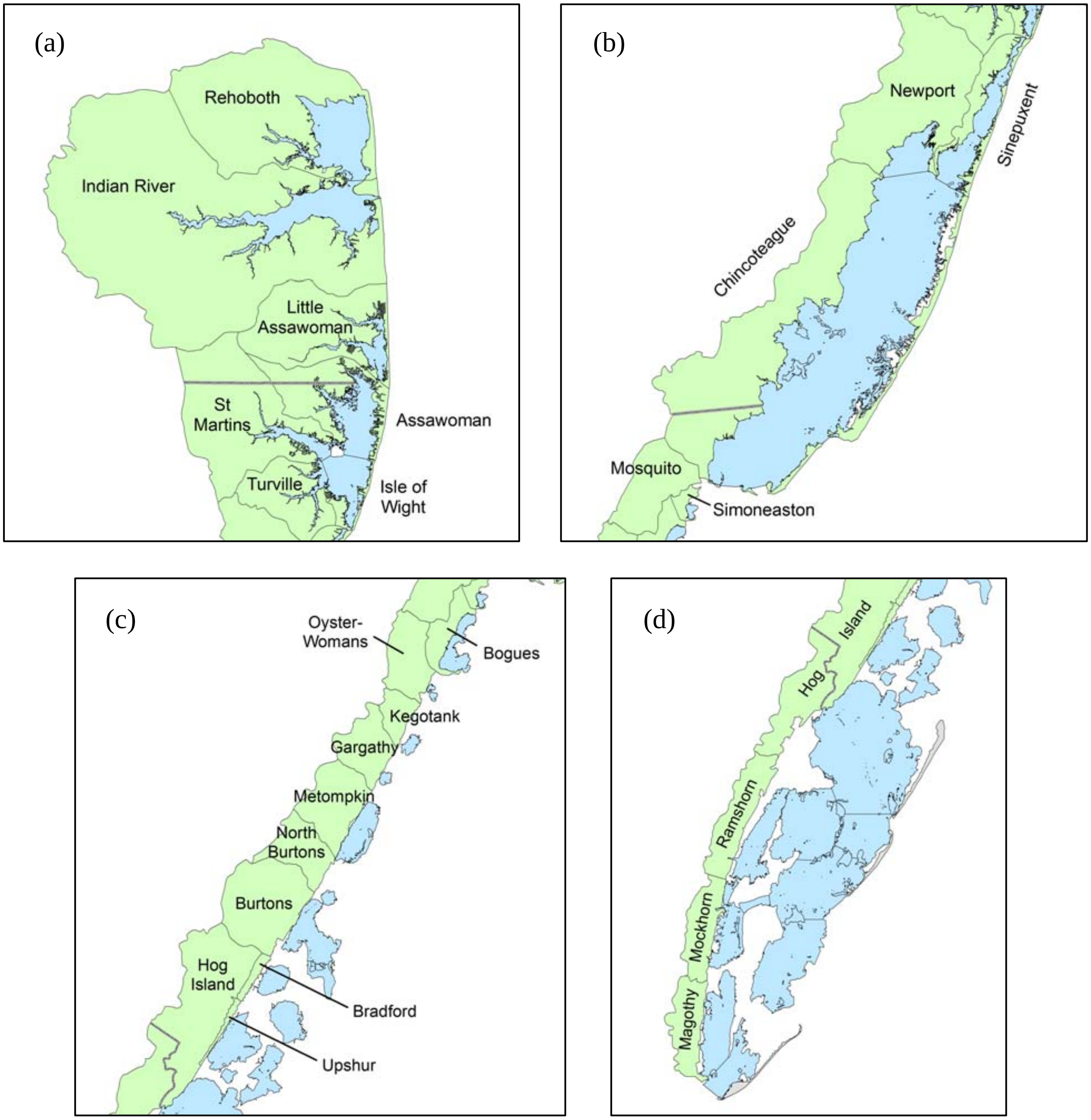

Fig. 2. Delmarva coastal bay watersheds parameterized in the NLM. (a) Delaware and northern Maryland bays, (b) southern Maryland and northernmost Virginia Bays, (c) mid Virginia bays, (d) southern Virginia bays. Thick grey lines delineate state and county boundaries.

DATA SOURCES AND MODEL CALCULATIONS

The NLM was initially applied to 22 sub-watersheds across the Delmarva Peninsula with measured loads, including 14 in Virginia, 7 in Maryland, and 1 in Delaware. Once calibrated to loads from these sub-watersheds, the NLM was used to estimate annual TN loads from all coastal bay watersheds along the Delmarva Peninsula. Most of the measured loads used in calibration were obtained in the early 2000s, so data used to parameterize the model were primarily obtained from this time period.

Watershed delineation: Sub-watershed boundaries in Virginia were previously delineated by Stanhope et al. (2009). Sub-watershed boundaries in Maryland and Delaware were delineated in ArcMap 9.3 (ESRI ArcGIS 9) using the Hydrology Toolbox and a 10-meter surface digital elevation model (DEM) raster dataset (USGS National Elevation Dataset). The fill sink function was first used to fill natural and artificial depressions in the DEM to avoid complications in the subsequent calculation of groundwater flow direction in each cell using the flow direction tool. The non-weighted cell flow accumulation function was then used to compute the cumulative number of upstream cells flowing into each downstream cell, followed by creation of pour points using the coordinates for the gauging stations, and finally by automated delineation of the surrounding watersheds based on the flow accumulation map. Snap distances for the pour points were determined iteratively through visual comparison of resulting watershed delineations and the DEM as well as flowlines from the high resolution USGS National Hydrography Dataset (NHD).

For delineation of the full coastal bay watersheds in Delaware, we used the DEM data and approach outlined above. In Maryland and Virginia, previously delineated coastal bay watersheds by the Maryland Department of Natural Resources and Virginia Coast Reserve Long-Term Ecological Research Program were updated and refined using the 10-meter DEM data and high resolution NHD flowlines.

Land use / land cover: Land use / land cover data were obtained from the University of Maryland Regional Earth Science Application Center (RESAC 2000). This dataset classifies land use as developed (low, medium, and high intensity, transportation, and extractive), cropland, hay/pasture, barren, forest (deciduous, evergreen, and mixed), grasslands, urban/residential (trees and recreational grass), and wetlands (deciduous wooded, evergreen wooded, emergent, and mixed) with 30 x 30 m resolution. Land use in the NLM is aggregated into four major categories: natural vegetation, developed (essentially impervious surfaces), turf (i.e., lawns), and agriculture (Fig. 1). Given the presence of barren and extractive areas in the RESAC dataset, these were aggregated into a fifth category termed ‘barren’.

Natural vegetation was taken as the sum of forest, natural grass, and upland wetlands from the RESAC dataset. Fringing salt marshes were excluded from the watershed delineations and not included in model calculations since deposition to the marsh surface is likely sequestered within the marshes. We acknowledge that denitrification is an important process in tidal wetlands, and this process may be included in future versions of the NLM. However, given the anticipated use of the NLM for the purpose of planning in support of watershed implementation plans, keeping loads to non-tidal portions of the watershed is in line with current management practices.

Developed area was taken as the sum of low, medium, and high intensity development plus transportation areas in the RESAC dataset. Residential areas in the RESAC dataset were classified as turf for the NLM. Agricultural area was taken as the sum of croplands and pasture/hay from the RESAC dataset. Barren area was taken as the sum of barren and extractive areas in the RESAC dataset.

Atmospheric deposition and transmission: Each land use category is subjected to an annual rate of atmospheric nitrogen deposition of 7.1 kg N ha^{-1} y^{-1} and 6.2 kg N ha^{-1} y^{-1} in DE/MD and VA, respectively. Deposition was calculated based on annual rates of both wet (National Atmospheric Deposition Program – NADP) and dry (EPA Clean Air Status and Trends Network – CASTNet) deposition measured at monitoring stations closest to the watersheds in each state for the period 2004-08. NADP stations included Trap Pond State Park (DE99), Wye (MD13), and Assateague Island National Seashore – Woodcock (MD18) for watersheds in Delaware and Maryland, and Harcum (VA98) and Smith Island (MD15) for watersheds in Virginia. Measured rates of wet deposition were increased to account for the typical 10-20% underestimation of deposition due to losses of organic nitrogen and ammonium from precipitation samples (Keene et al. 2002). Dry deposition for all watersheds used rates measured at the CASTNet station at the Blackwater National Wildlife Refuge (BWR139), the only station in the region.

We note that these rates of deposition are lower than the values of 11.6 and 12.9 kg N ha^{-1} y^{-1} reported for the DE/MD coastal bay and Chesapeake Bay watersheds, respectively, by Meyers et al. (2001). We have chosen to parameterize the NLM with the more recent rates computed directly at local monitoring stations, but the user may wish to use Meyers et al.'s (2001) higher value. These authors also reported lower rates of direct deposition onto the coastal bays themselves at 7.87 kg N ha^{-1} y^{-1}, and 9.35 kg N ha^{-1} y^{-1} onto Chesapeake Bay; the former value is close to our estimated value for Delaware and Maryland. Based on these results, it may be desirable to use different rates of deposition onto the watersheds and coastal bays themselves, but we have decided to use a constant rate in this version of the model.

Deposition is subjected to three attenuation stages in the model which represent the combined biogeochemical processing, immobilization, and removal due to plant uptake (35-38% transmitted), losses in the vadose zone (39% transmitted), and losses in the aquifer (65%

transmitted). Deposition onto developed areas directly enters the vadose zone without plant uptake, unless routed directly to tidal waters by the user on the BLANK NLM spreadsheets. The latter is accomplished by entering the fraction of impervious surfaces draining directly to tidal waters in cell C60; a value of 0 directs all deposition onto developed surfaces into the vadose zone while a value of 1 directs 100% of this deposition directly to tidal waters.

Residential nitrogen inputs: Residential inputs of nitrogen enter the model through fertilization of lawns (turf), septic field leaching, and spray effluent (the latter on the BLANK NLM spreadsheets only). We assumed that only 34% of lawn area is fertilized, at a rate of 105 kg N ha^{-1} y^{-1} with 39% volatilization loss at the watershed surface (Valiela et al. 1997). This value is close to the average fertilizer application rate of 106.9 kg N ha^{-1} y^{-1} reported by Law et al. (2004) for suburban communities in Baltimore, MD. Turf fertilization is subject to attenuation in the vadose zone and aquifer as for atmospheric deposition.

To compute the septic load, population estimates were obtained from US Census Bureau GIS shapefiles by census block (TIGER database; 2000 census). Population in each census block was normalized to block area and the resulting densities were merged with the watershed shapefile in GIS (union command). Computed population densities were then used to back calculate total population sizes in each NLM watershed. The resulting population estimates were used to calculate septic wastewater inputs assuming a contribution of 4.8 kg N $person^{-1}$ y^{-1} with a 60% transmission of nitrogen from septic tanks and leach fields and 66% transmission through septic plumes before entering the aquifer where they are subject to the same attenuation as for atmospheric deposition (Valiela et al. 1997).

These estimates of septic nitrogen loading are reduced to account for the presence of public sewer systems, as these either remove a portion of the septic input or concentrate it as a point source elsewhere. There are currently only two public sewer systems in the Virginia portion of the Eastern Shore, both almost completely contained within the Chesapeake Bay watershed and therefore outside our study system. However, a series of public systems exist in Maryland and Delaware which must be accounted for to avoid overestimation of the septic load. GIS coverages of sewered areas were obtained from Worcester County, MD and Sussex County, DE, together with information on the number of residents serviced by the Towns of Selbyville, Millsboro, and Georgetown, DE from each town's most recent comprehensive plan. Two private sewer companies also service some communities within the Delaware coastal bay watersheds; however, it is not currently possible to account for this portion of the population. The areas serviced by sewer systems were combined with the TIGER data to estimate the total population served by public sewers, and these numbers were removed from our calculations of the septic nitrogen input. We also note that population estimates used in the NLM reflect the permanent, year-round population and do not include seasonal residents and visitors; however, most of the seasonal population is assumed to be serviced by public sewer systems and therefore does not contribute to the septic load.

Some of the effluent from treatment plants that collect waste from these public sewer systems enters the lagoons as a point source which is accounted for separately (see below). However, many of the plants in Maryland and Delaware spray their effluent onto the land surface. Some fraction of the effluent is sprayed onto agricultural fields, and this input is already accounted for as a portion of crop fertilizer requirements (see below). In order to not double count this portion of the sprayed effluent, we have decided not to pursue accounting for the portion sprayed onto non-agricultural land at this time. However, we have included optional inputs for spray effluent in the BLANK NLM spreadsheets that may be used if watershed specific information is available. Necessary input includes effluent application rate and area of fields receiving spray effluent. We have included a default volatilization value of 40% and route all spray effluent onto natural vegetation using the associated transmission rates for that land use category.

Crop agriculture: Agricultural land area was broken into the main crops found on the Eastern Shore: barley, corn grown for grain, corn grown for silage, cotton, hay, sorghum, soybeans, tomato plasticulture (Virginia only), and wheat. Individual tomato fields were digitized from the 2007 Virginia Base Mapping Project (VBMP) digital orthophotographs. Total tomato area was subtracted from the total agricultural area in watersheds where it occurred. The remaining agricultural area was divided among the other crops based on the area of each crop harvested within each county as reported by the USDA National Agricultural Statistics Service (NASS) for the time period 2000 to 2009 (quickstats.nass.usda.gov).

Recommended fertilization rates were compiled from state cooperative extension publications for each state (Table 1). For the state of DE, we used values from MD given the similarity between areas and crops grown and the lack of DE extension publications directly addressing general crop fertilization. Mean crop nitrogen contents were obtained from Crop Nutrient Tool in the USDA national PLANTS database (plants.usda.gov) (Table 1). Crop yields in the model represent averages as calculated from the NASS data from 2000 to 2009 with the exception of yield for tomatoes which was obtained from Giordano et al. (2011) (Table 2). For all three states, we used a soybean nitrogen fixation rate of 200 kg N ha^{-1} y^{-1}, which represents an intermediate value (Unkovich and Pate 2000; Schipanski et al. 2010).

Nitrogen lost to groundwater from crops is computed as the difference between fertilizer application (computed from application rate and crop area) or soybean nitrogen fixation and nitrogen removal through harvest (computed from yield, nitrogen content, and crop area). Fertilizer requirements in the model are first met with poultry waste which is a common practice on the Eastern Shore unless the waste is exported from the watershed (see below), with any remaining requirements met by synthetic fertilizers. The original Valiela et al. (1997) NLM assumed that 39% of synthetic fertilizers were lost due to volatilization; while this term appears on the NLM spreadsheet it is not used in calculations as it causes most crop nutrient losses to be negative (i.e., net uptake rather than loss). Crop nutrient losses are subject to attenuation in the vadose zone and aquifer as for atmospheric deposition.

Poultry operations: The NLM also computes nitrogen production by high intensity poultry (i.e., chicken) operations on the Eastern Shore. Poultry houses were identified using the VBMP imagery in Virginia and orthophotographs from the USDA National Agriculture Imagery Program (NAIP) in Maryland and Delaware. The annual number of chickens in each watershed was calculated based on the number of poultry houses, a value of 25,000 chickens per standard house size using the National Chicken Council's estimate of 0.8 ft^2 per bird, and assuming a rotation of 5.5 flocks per year (Rhodes et al. 2009; Giordano et al. 2011). Annual production of TN by poultry was computed from the annual number of chickens using a nitrogen production rate of 0.054 kg N $bird^{-1}$ y^{-1} and assuming 50% volatilization (Cole 2005).

The default version of the model applies poultry waste to crops to meet fertilizer requirements as described above; waste in excess of fertilizer needs when it occurs is assumed to enter the groundwater and is subject to attenuation in the vadose zone and aquifer as for atmospheric deposition. Another common practice on the Eastern Shore is to transport excess poultry waste out of the watershed. We have added this option in cell C58 on the BLANK NLM spreadsheets; entering "yes" removes poultry waste from the watershed while entering "no" retains it in the watershed.

Point sources: Point source inputs were identified using the EPA Water Discharge Permits website (www.epa.gov/enviro/html/pcs/pcs_query.html). This website provides data on measured monthly discharge and nutrient concentrations for computation of loads. These loads are assumed to enter directly into tidal waters without attenuation.

Direct atmospheric deposition: Open water surface areas of each coastal bay were computed in ArcGIS 9 using the high resolution NHD dataset for the Delmarva Peninsula. Computed rates of atmospheric deposition described above were combined with the open water area of the receiving coastal bay to estimate direct deposition of TN to the water surface.

Table 1. Crop fertilization rates and nitrogen contents used in the NLM. Crop N contents were computed using the default % moisture settings in the USDA Crop Nutrient Tool.

Crop	**DE/MD Fertilization Rate**[1] kg N ha^{-1} y^{-1}	**VA Fertilization Rate**[2] kg N ha^{-1} y^{-1}	**Crop N Content** kg N kg^{-1} harvest
Barley	94	110	0.0194
Corn (grain)	154	152	0.0142
Corn (silage)	132	152	0.0039
Cotton	70	121	0.0018
Hay[3]	129	102	0.0191
Sorghum	83	83	0.0166
Soybeans	0	0	0.0590
Tomatoes[4]	202	202	0.0015
Winter Wheat	94	99	0.0188

[1] Primary: Coale (2002, 2010); Secondary: Basden et al. (2006)

[2] Primary: Brann et al. (2009), Reiter et al. (2015); Secondary: VDCR (2005), Basden et al. (2006)

[3] Represents the average fertilization rate for several hay varieties.

[4] DE/MD fertilization rate uses the value from Virginia.

Table 2. Crop yields used in the NLM, derived from the National Agricultural Statistics Service (NASS); tomato yields are from Giordano et al. (2011). See text for details. A dash indicates that a particular crop is not grown in the corresponding region. Units are kg crop ha^{-1} y^{-1} and reflect standard % moisture contents at harvest.

Crop	**DE**[1]	**MD**[2]	**VA – Accomack**[3]	**VA – Northampton**[4]
Barley	4,089	4,673	4,501	4,526
Corn (grain)	8,471	8,210	8,059	8,808
Corn (silage)	37,462	46,740	-	-
Cotton	-	-	564	824
Hay	-	5,061	5,508	-
Sorghum	4,645	-	-	-
Soybeans	2,198	2,466	2,297	2,246
Tomatoes	-	-	44,832	44,832
Winter Wheat	4,157	3,974	4,109	4,227

[1,2] Watersheds entirely in DE and MD (see Fig. 2a-b). Yields from MD were used for Chincoteague since most of the watershed lies in MD. Assawoman and St. Martins watersheds lie in both DE and MD so average values were computed for these watersheds.

[3,4] Watersheds entirely in Accomack and Northampton Counties, VA (see Fig. 2c-d). Hog Island watershed lies in both counties so average values were computed for this watershed.

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