Digital Data Used to Relate Nutrient Inputs to Water Quality in the Chesapeake Bay Watershed, Version 3.0

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U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

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By John W. Brakebill and Stephen D. Preston

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ABSTRACT

Chesapeake Bay restoration efforts are focused on improving water quality, living resources, and ecological habitats by 2010. One aspect of the water-quality restoration is the refinement of strategies designed to implement nutrient-reduction practices within the Bay watershed. These strategies are being refined and implemented by resource managers of the Chesapeake Bay Program (CBP), a partnership comprised of various Federal, State, and local agencies that includes jurisdictions within Delaware, Maryland, New York, Pennsylvania, Virginia, West Virginia, and the District of Columbia. The U.S. Geological Survey (USGS), an active member of the CBP, provides necessary water-quality information for these Chesapeake Bay nutrient-reduction strategy revisions and evaluations.

The formulation and revision of effective nutrient-reduction strategies requires detailed scientific information and an analytical understanding of the sources, transport, and delivery of nutrients to the Chesapeake Bay. The USGS is supporting these strategies by providing scientific information to resource managers that can help them evaluate and understand these processes. One statistical model available to resource managers is a collection of SPAtially Referenced Regressions On Watershed (SPARROW) attributes, which uses a nonlinear regression approach to spatially relate nutrient sources and watershed characteristics to nutrient loads of streams throughout the Chesapeake Bay watershed. Developed by the USGS, information generated by SPARROW can help resource managers determine the geographical distribution and relative contribution of nutrient sources and the factors that affect their transport to the Bay.

Nutrient source information representing the late 1990s time period was obtained from several agencies and used to create and compile digital spatial datasets of total nitrogen and total phosphorus contributions that served as input sources to the SPARROW models. These data represent atmospheric deposition, point-source locations, land-use, land-cover, and agricultural sources such as commercial fertilizer and manure applications.

Watershed-characteristics datasets representing factors that affect the transport of nutrients also were compiled from previous applications of the SPARROW models in the Chesapeake Bay watershed. Datasets include average-annual precipitation and temperature, slope, soil permeability, and hydrogeomorphic regions.

Nutrient-input and watershed-characteristics datasets representing conditions during the late 1990s were merged with a connected network of stream reaches and watersheds

to provide the spatial detail required by SPARROW. Stream-nutrient load estimates for 125 sampling sites (87 for total nitrogen and 103 for total phosphorus) served as the dependent variables for the regressions, and were used to calibrate models of total nitrogen and total phosphorus depicting late 1990s conditions in the Chesapeake Bay watershed.

Spatial data generated for the models can be used to identify the location of nutrient sources, while the models' nutrient estimates can be used to evaluate stream-nutrient load contributed locally by each source evaluated, the amount of local load generated that is transported to the Bay, and the factors that affect the nutrient transport. Applying the SPARROW methodology to late 1990s information completes three time periods (late 1980s, early 1990s, and late 1990s) of viable data that resource managers can use to evaluate the water-quality conditions within the Bay watershed in order to refine restoration goals and nutrient-reduction strategies.

INTRODUCTION

Nutrient enrichment is a serious problem contributing to the degradation of water quality in the Chesapeake Bay, the Nation's largest estuary, draining a 64,000-square-mile watershed that includes parts of Delaware, Maryland, New York, Pennsylvania, Virginia, West Virginia, and the District of Columbia (fig 1). The Bay is listed as an "impaired water body" under the Clean Water Act, and is required to have improved water-quality conditions by the year 2010 (U.S. Environmental Protection Agency, 2000). Reducing the amounts of nutrients, sediment, and toxic substances entering the Bay will improve water quality. The Chesapeake Bay Program (CBP), a Federal-State partnership charged with coordinating efforts to restore water quality to the Chesapeake Bay, has formulated management strategies designed to reduce nutrients entering the Chesapeake Bay from its tributaries.

A tool developed by the USGS that can be helpful to the Bay restoration efforts is a set of spatially referenced regression models that relate nutrient sources to stream loads. SPAtially Referenced Regressions On Watershed attributes (SPARROW) is the method used to build the regression models that retain and utilize detailed spatial information to statistically relate water-quality measurements to nutrient sources and the watershed characteristics that affect the transport of nutrients throughout the watershed (Smith and others, 1997; Preston and others, 1998). By retaining spatial referencing, the geographic distribution and relative contribution of nutrient sources and the factors that affect nutrient transport can be examined by resource managers at various scales, such as stream-nutrient load estimates and source percentages contributed locally to each stream, as well as percentages of the load that reach Chesapeake Bay.

Models of total nitrogen and total phosphorus using the SPARROW methodology were successfully developed in the Chesapeake Bay watershed representing the late 1980s and early 1990s (Version 1.0 and 2.0) (Preston and Brakebill, 1999; Brakebill and Preston, 1999; Brakebill and others, 2001). Completing Version 3.0 provides resource managers three separate time periods to potentially evaluate the water-quality conditions in the Bay watershed, investigate nutrient sources and relative contributions, and revise nutrient-reduction strategies.

Purpose and Scope

The USGS is investigating processes related to nutrient sources and transport through multiple studies designed to provide scientific information to resource managers responsible for the restoration and protection of the Chesapeake Bay and its watershed. Two main goals of USGS Chesapeake Bay studies related to this report include: (1) enhancing the prediction and monitoring of nutrient delivery to the Bay; and (2) disseminating information and enhancing decision-support tools.

This report describes the processes used to create, compile, and obtain the necessary digital spatial datasets generated with a geographic information system (GIS) for the purpose of applying the SPARROW methodology to develop total nitrogen and total phosphorus models in the Chesapeake Bay watershed representing the late 1990s (Version 3.0). Also presented in this report are the spatial datasets representing estimates of nutrient yields produced by the SPARROW models. The nutrient datasets represent atmospheric deposition, point sources, land-use and land-cover, and manure and commercial fertilizer applications. Potential delivery factors discussed in this report include precipitation, temperature, slope, soil permeability, and hydrogeomorphic regions. Datasets representing nutrient load estimates (displayed as yield) include stream-nutrient loads generated locally, the amount of local generation that is transported to the Bay independent of upstream load, and the total load that is transported to the Bay. These estimates--incremental, delivered, and total--are presented as all nutrient sources combined, and each nutrient source individually as evaluated by the models.

This report also serves as a mechanism to distribute digital spatial data generated for and by the Version 3.0 SPARROW modeling applications. Metadata for digital datasets related to Version 3.0 of SPARROW can be found in the appendix of this report. The metadata describes in detail the data sources, applications, methods, attributes, and procedures used to create the spatial datasets, as well as providing information on how to obtain the data.

Acknowledgments

The authors thank Robert Kellogg, U.S. Department of Agriculture, Michael Langland, U.S. Geological Survey, and the U.S. Environmental Protection Agency's Chesapeake Bay Program Office for providing datasets necessary for the application of SPARROW in the Chesapeake Bay watershed. The authors also thank Richard Smith, Gregory Schwarz, and Richard Alexander of the U.S. Geological Survey, developers of the SPARROW approach, for providing technical assistance.

DATASETS

Numerous digital datasets were created within the Chesapeake Bay watershed and surrounding area from various sources using Environmental Systems Research Institute's (ESRI) Arc/Info GIS software. These datasets include a segmented-watershed network, water-quality data, nutrient-input sources, and watershed characteristics representing the late 1990s. The segmented-watershed network, merged with nutrient input-source and land-characteristic data, provides input values for each stream reach to the models. The water-quality data provide an independent variable necessary for calibration of the models.

All spatial datasets reside in the Albers Equal-Area Conic projection with a central meridian of 96 degrees in the North American Datum (NAD) of 1983 (Snyder, 1987). Datasets described in this report are distributed for general use by the USGS, except where noted.

Water-Quality Data

A log-linear regression model known as ESTIMATOR (Cohn and others, 1989) was used to estimate annual stream-nutrient loadings derived from water-quality and stream-discharge data collected by numerous State and Federal agencies (Langland and others, 1995) using the methods described in Preston and Brakebill (1999). Load-estimate regressions were calibrated based on actual stream-discharge and concentration data. Loads based on long-term average-daily discharge were estimated using the calibrated regressions, specifying the year 1997 for the trend component, and an average time series (average daily flow values for the period 1950 - 2000) for the flow terms. By use of this method, stream loads were estimated for 125 streamflow data-collection sites (87 for total nitrogen and 103 for total phosphorus) within the Chesapeake Bay watershed, and were used as the dependent variables in the calibration of SPARROW (fig. 2).

Prior to the load calculations, latitude and longitude coordinates and station identification numbers of the data-collection sites (water quality and streamflow) were obtained from the State and Federal data bases of the various collection agencies and used to generate point-location datasets. A GIS was used to associate each water-quality sampling site with an appropriate streamflow data-collection site and stream reach. Attributes for the generated streamflow dataset consist of a station identification number for the water-quality and flow-collection sites, and 1997 loading estimates for total nitrogen (87 sites) and total phosphorus (103 sites).

Segmented-Watershed Network

The segmented-watershed network (fig. 3) serves two functions. It provides the framework to spatially reference nutrient-source and land-characteristic data for input to the models, and is also used to illustrate the spatial distribution of predicted stream-nutrient loads and their potential for delivery to the Chesapeake Bay. The two major components of a segmented-watershed network are the stream reaches and their associated watershed boundaries. The connected stream reaches, represented by a single line that defines surface-water pathways, are identified in the dataset by a unique identification number (E3RF1) and contain various stream characteristics used in model calibration and prediction. The associated watersheds, linked by E3RF1, are also used to spatially reference nutrient sources, watershed characteristics, and nutrient predictions (Brakebill and Preston, 2003; Brakebill and others, 2001).

Version 3.0 of SPARROW for the Chesapeake Bay watershed was based on the stream-reach network used in Version 2.0, with minor modifications, such as the inclusion of reservoir locations. These locations were obtained from a digital dataset representing dams of major reservoirs (Ruddy and Hitt, 1990), and USGS 1:100,000-scale Digital Raster Graphics (DRG) (U.S. Geological Survey, 1999a). Sixty-eight reservoirs were located on the stream reach network using Arc/Info GIS by placing a node on the reach at the location of the reservoir dam and at the surface-water edge upstream of the dam that was viewed from the DRG. Nodes are endpoints of lines that maintain the identity, direction, and location of intersected linear features. This topological information is used to define reach-to-reach connectivity and allows for the identification of each reach upstream or downstream of any location along the stream network (Environmental Systems Research Institute, 1992b). Placing nodes at the beginning and end of a reservoir location created “reservoir reaches” which were used in the identification and attribution of E3RF1 and other appropriate reservoir characteristics.

To ensure that load estimates used for model calibration were consistently referenced to the downstream end of a reach, a node was also placed at each streamflow sampling location and assigned the appropriate USGS station identification number (STAID). Placing nodes at reservoir and streamflow sampling locations also ensured that a watershed would be generated at each calibration site and dam location on its associated reach.

Cell-based Digital Elevation Models (DEMs) are a raster representation of a continuous surface commonly used to characterize the Earth’s surface. The distance between sampling points used to generate the DEM help determine the resolution, accuracy, and cell size of the data. Knowing the direction of surface-water flow from each elevation cell within a DEM is critical for constructing water pathways and watershed boundaries, since it represents the steepest downslope direction that water on a surface will flow. Once this direction is known, the identification of cells flowing into any given cell can be identified, accumulated, and used to create water pathways, and with further analysis, watershed boundaries (Environmental Systems Research Institute, 1992a). The Version 2.0 stream-reach network utilized seamless 30-meter cell DEMs from the National Elevation Data Base (U.S. Geological Survey, 1999b) to calculate the flow direction used to generate the water pathways that would make up the stream-reach network (Brakebill and Preston, 2003; Brakebill and others, 2001). The same 30-meter flow-direction grid and the reach network for Version 3.0 were used together to generate a 30-meter grid of watershed drainage areas for each stream reach. This process began by converting the reach network back into a 30-meter grid using the unique reach identifier (E3RF1) as a value item. Watershed areas for each reach (all cells with the same E3RF1 value) were generated using all reach cells that represent the stream channel, or the lowest points within the watershed (Environmental Systems Research Institute, 1992a). By use of this method, all cells that represent a single reach are used as pour points, rather than only a single cell representing the absolute lowest point on the downstream end of a reach. This improves the chance of a more accurate definition of the watershed area. This method also maintains the E3RF1 value from the associated reach network in the watershed dataset, and serves as an identification tool as well as a common field to related datasets.

Nutrient-Input Sources

Digital datasets of atmospheric deposition, septic systems, point-source locations of nutrient discharges, land-use, land-cover, and agricultural fertilizer (commercial) and manure, were created and compiled from numerous sources. They represent potential nutrient-input contributions to the Chesapeake Bay watershed and were considered for the nitrogen and phosphorus models. This section describes the nutrient-input datasets and the processes used to create and compile them.

Atmospheric Deposition

Linear spatial interpolation of National Atmospheric Deposition Program (NADP) data for 191 point measurements within the continental United States provided 1997 mean wet-deposition atmospheric estimates for nitrate (Alexander and others, 2001; National Atmospheric Deposition Program, 1994). The latitude and longitude coordinates of the atmospheric monitoring stations were used to create a spatial dataset of the sampling sites attributed with the 1997 mean deposition value. A Triangulated Irregular Network (TIN) (Environmental Systems Research Institute, 1992c) was calculated by interpolating data values between the sampling locations. The area within the Chesapeake Bay region was extracted and converted into a 1,000-meter grid (fig. 4). This cell size was selected because it was well suited to the spatial distribution of the atmospheric monitoring stations. Smaller cell sizes did not significantly improve the quality of the interpolated information to warrant such a large dataset. The atmospheric-deposition grid was then used with the segmented-watershed network to calculate a mean-wet deposition value for each watershed segment.

Point Sources

Locations of point-source discharges (fig. 5) and average-annual loads of total nitrogen and total phosphorus for facilities within the Chesapeake Bay watershed were obtained from the CBP office for the years 1995 through 1997 (Wiedeman and Cosgrove, 1998). The data are based on information from the U.S. Environmental Protection Agency’s (USEPA) Permit Compliance System (PCS) National Pollutant Discharge Elimination System (NPDES) discharge monitoring reports, with modifications from individual State agencies responsible for monitoring point-source discharges. The original point-source data compiled by the CBP resides as monthly-discharge data, by facility, in lb/yr (pounds per year). Details on the calculation of annual loads using concentration and flow data by discharging facility can be found in Wiedeman and Cosgrove (1998).

Latitude and longitude coordinates of point-source discharging facilities were used to generate a point dataset populated with other supporting information from the CBP point-source data base, such as facility name, facility type, NPDES number, receiving water, and water pathway to Chesapeake Bay. Point-source locations were verified using a GIS by comparing the receiving water and pathway information from the CBP data base with USGS DRGs (U.S. Geological Survey, 1999a) and the SPARROW reach network.

Average-annual loads for total nitrogen and total phosphorus by facility for 1995, 1996, and 1997 were averaged over the number of years the facility had data during the three-year time period, and converted to kg/yr (kilograms per year). SPARROW watershed segment numbers (E3RF1) were assigned to the locations of each point source by merging the polygon dataset representing SPARROW watershed segments with the point-source location dataset. Average loads of nitrogen and phosphorus for each watershed were then summed for each nutrient within each watershed segment.

Land-Use and Land-Cover

Land-use and land-cover data are used in various ways with SPARROW. Spatially, locations of potential nutrient sources such as agricultural lands are not only identified, but also provide the basis for distributing county census data of commercial fertilizer and manure applications within the agricultural area of a watershed segment. This serves as a means to further distribute county census data of a particular nutrient source to a smaller area. Areas of potential sources and land characteristics of non-agricultural lands within each watershed segment, such as urban, forest, and wetlands, also are identified and used as nutrient inputs and delivery characteristics in the models.

Version 2.0 of the SPARROW models relied on a modified version of the multi-resolution landscape characterization (MRLC) land-cover data representing the 1992 time period (Loveland and Shaw, 1996). These data are a classified mosaic of 30-meter resolution Landsat 5 Thematic Mapper (TM) data compiled from source imagery ranging from March 1988 through April 1992, and are now part of the National Land-Cover Dataset (NLCD) (U.S. Geological Survey, 2000a).

A new land-cover dataset comparable to the 1992 National Land-Cover Dataset (NLCD) was developed in order to support Version 3.0 of the SPARROW models in the Chesapeake Bay watershed representing the 1997 time period. The new land-use and land-cover data were created using an experimental change detection process that identifies areas of spectral change between individual Landsat images collected in 1992 and 1997. The areas depicting change were then processed using methods similar to those used in the NLCD land-cover mapping. Classification schemes for the 1992 and updated 1997 30-meter resolution Chesapeake Bay land-cover dataset also needed to be compatible, so the NLCD classification scheme was adopted. Fifteen land-cover classifications were aggregated to seven classifications, which include open water, urban, hay/pasture/grass, row crops, forest, wetlands, and barren land. The hay/pasture/grass and row crop categories were combined to create an agriculture class (fig. 6). The time period of the source TM imagery for the 1997 land-cover data ranged from May 1996 through May 1998 (U.S. Geological Survey, 2000b). The extent of the 1997 land-use and land-cover data went slightly beyond the Chesapeake Bay watershed boundary and did not include entire county jurisdictions that may have been partially inside the watershed. The 1992 NLCD data outside the watershed boundary were used in these cases, so a total county land-use and land-cover area could be calculated.

Acres of each land-use and land-cover within a SPARROW watershed segment were calculated and used as potential nutrient sources and watershed characteristics for the models. Combined acres of row crop and hay/pasture/grass classifications within each watershed segment also were used to further distribute county manure generation and commercial fertilizer application statistics to calculate loading estimates of nitrogen generated from agricultural sources.

Additional estimates of land-use and land-cover were supplied by the CBP in the form of 1997 acres of conventional-till, conservation-till, hay, and pasture lands within the Chesapeake Bay watershed for each county and CBP watershed model segment (CBPWS) (Donigian and others, 1994) using Crop Tillage and county Agricultural Census data bases (Gutierrez-Magness and others, 1997). To spatially distribute the acres of CBP land-use within each SPARROW watershed segment, it was assumed that conventional-till, conservation-till, hay, and pasture land-uses were distributed equally throughout the row crop and hay/pasture/grass (agricultural) classifications of the 1997 land-cover dataset. Acres of land-use provided by the CBP were used with application rates of agricultural nutrient sources to estimate the mass of nutrient per watershed segment. The processes used to distribute the county-based statistics of agricultural nutrient sources to the appropriate land-use are described in the Agricultural Sources section of this report.

Agricultural Sources

Several datasets representing annual estimates of nutrients from agricultural sources were evaluated using SPARROW. Animal manure data compiled by the Natural Resources Conservation Service (NRCS) were evaluated and included county estimates of annual nutrients from manure excreted, and annual nutrients recoverable from manure generated by livestock held in confinement (Kellogg and others, 2000; Lander and others, 1998). Annual county application rates of manure spread on various land-uses compiled by the CBP (Palace and others, 1998) were also evaluated. Commercial fertilizer data evaluated include county estimates of annual nutrients based on fertilizer sales from the Bureau of Census compiled by the National Water Quality Assessment (NAWQA) program (D. Lorenz, U.S. Geological Survey, written commun., 2002) and county fertilizer application rates on various land-uses compiled by the CBP (Palace and others, 1998).

Using SPARROW version 3.0, the total nitrogen model showed the best statistical fit using county-based NRCS nutrient estimates of recoverable manure generated by livestock held in confinement, and county-based fertilizer estimates compiled by the NAWQA program. The total phosphorus model showed the best statistical fit using both manure and fertilizer application estimates generated by the CBP (figs 7 and 8).

NRCS nutrient estimates from livestock manure are based on animal population numbers by county, derived from the 1997 Agricultural Census (U.S. Bureau of the Census, 2000). The basic building block of the estimation process is an animal unit, which represents 1,000 pounds of animal weight, including all beef, dairy, swine, and poultry animals.

In order to distribute county-based nutrient estimates from agricultural sources, it was assumed that manure and commercial fertilizer would be applied to areas classified as both row-crop and pasture lands (agricultural land) combined. The modified 1997 30-meter land-cover data were used to calculate the total number of 30-meter agricultural cells within each county. County-based estimates of nutrient load for each source were divided by the number of agricultural cells within each county. This produced a nutrient-load estimate for each agricultural cell. Load estimates for each 30-meter cell then were summed by SPARROW watershed segment to obtain nutrient-load estimates from commercial fertilizer and recoverable manure generated by confined livestock for each SPARROW watershed segment. This process distributed the county load estimates throughout the agricultural land within a SPARROW watershed segment.

Spatially distributed load estimates using the CBP agricultural data were calculated slightly differently because of the geographical units the source information resided in. Acres of conventional-till, conservation-till, hay, and pasture representing agricultural lands were provided by county and CBPWS (COSEG), while application rates (weight per area) of manure and commercial fertilizer from the CBP were estimated by State and CBPWS (STSEG) for each agricultural land-use (Palace and others, 1998). A single application rate by COSEG for each agricultural source and land-use was determined and multiplied by the acres of specific land-use that corresponded to the application rate within each COSEG. This produced a load for each land-use within a COSEG. Loads for each land-use were then summed to calculate a total load for each COSEG. The total load for each COSEG was then divided by the number of 30-meter agricultural cells within each COSEG to produce a load value for each 30-meter agricultural cell. Load estimates for each 30-meter cell then were summed by SPARROW watershed segment to obtain nutrient-load estimates from commercial fertilizer and manure for each SPARROW watershed segment.

Watershed Characteristics

Watershed characteristics represent potential factors that can affect the transport of nutrients and are used in SPARROW model calibration. The sources and processes used to create and compile datasets of average-annual precipitation and temperature, slope, soil permeability, and hydrogeomorphic regions (HGMRs) are described in this section. With the exception of HGMR and slope, the sources for land-characteristic data used for Version 3.0 of the SPARROW models are identical to the sources of land-characteristic data used in version 2.0 (Brakebill and others, 2001) and Version 1.0 (Brakebill and Preston, 1999).

Precipitation

Total monthly precipitation data and point locations for 1,695 sites within the Chesapeake Bay region were obtained from the U.S. Historical Climatology Network (USHCN) for 1950 - 1994 (Karl and others, 1990). Average precipitation was calculated for each site and a point dataset was created from the latitude and longitude coordinates provided. A TIN was calculated by interpolating data values between the sampling locations within the Chesapeake Bay region (Environmental Systems Research Institute, 1992c). The TIN was then converted to a 1-kilometer grid (fig. 9) and used with the watershed grid to calculate an average precipitation value for each SPARROW watershed segment.

Temperature

Monthly temperature data and point locations for 149 sites were obtained from the U.S. Historical Climatology Network (USHCN) for 1950 - 1994 (Karl and others, 1990). Average-annual temperature was calculated for each site and a point dataset was created from the latitude and longitude coordinates provided. A TIN was calculated by interpolating data values between the sampling locations within the Chesapeake Bay region (Environmental Systems Research Institute, 1992c). The TIN was converted to a 1-kilometer grid (fig. 10) and used with the watershed grid to calculate an average temperature value for each SPARROW watershed segment.

Slope

Slope for the Chesapeake Bay area was calculated from a 30-meter DEM (U.S. Geological Survey, 1999a). The area containing the Chesapeake Bay watershed was extracted, and the slope function in Arc/Info’s GRID module (Environmental Systems Research Institute, 1992a) was used to create a 30-meter GRID with percent slope values for each cell ranging from 0 to 125 percent (fig. 11). An average percent slope for each SPARROW watershed segment then was calculated.

Soil Permeability

Soil data originating from the State Soil Geographic Data Base (STATSGO) (Schwarz and Alexander, 1995) was converted into a 30-meter grid format using Arc/Info's GRID module. The grid was attributed with a numeric value in in/hr (inches per hour) representing the permeability of the soil. The value was calculated as a layer-thickness weighted average across soil layers of a simple average of high and low measurements of the soil layer contained in the original STATSGO dataset (U.S. Soil Conservation Service, 1994). The Chesapeake Bay watershed area was extracted (fig. 12), and an average soil permeability was calculated for each SPARROW watershed segment.

Hydrogeomorphic Regions

HGMRs for the Chesapeake Bay watershed (fig. 13) were generated based on physiographic and lithologic settings (Brakebill and Kelley, 2000). Each polygon was attributed with a single HGMR code representing that region. The polygons were converted to a 30-meter grid format using Arc/Info's GRID module, and merged with the segmented watershed grid. The area of each HGMR within each SPARROW watershed segment was calculated and used as input to the models.

Nutrient Yield Estimates

Three types of nutrient estimates--incremental, delivered, and total--predicted by SPARROW for total nitrogen and total phosphorus representing the late 1990s are presented by segmented watershed as yields in kg/ha (kilograms per hectare). These estimates represent stream-nutrient loads from all nutrient sources evaluated by the models. Nutrient sources include atmospheric deposition, point sources, land-use and land-cover, and commercial fertilizer and manure application. Nutrient estimates are presented as contributions from all sources combined and from each source individually.

Incremental yield (load per area), which represents the local generation of nutrients, is the amount of nutrient that is generated locally (independent of upstream load) and contributed to the downstream end of each stream reach. Each stream reach and associated watershed is treated as an independent unit, quantifying the amount of nutrient generated (figs. 14 -20). Delivered yield (load per area) is the amount of nutrient that is generated locally for each stream reach and weighted by the amount of in-stream loss that would occur with transport from the reach to Chesapeake Bay. The cumulative loss of nutrients from generation to delivery to the Bay is dependent on the traveltime and in-stream loss rate of each individual reach (figs. 21-27). Total yield (load per area) is the amount of nutrient including upstream load contributed to each stream reach (figs. 28-34). These estimates are calculated by stream reach (E3RF1), and account for all potential sources cumulatively and individually (Preston and Brakebill, 1999). These data, in conjunction with the segmented-watershed network, provide a useful tool for determining the spatial distribution of nutrient sources and the potential for nutrient delivery into the Chesapeake Bay.

SUMMARY

The SPAtially Referenced Regressions On Watershed attributes (SPARROW) approach uses a nonlinear statistical method to define relations among upstream nutrient sources, downstream nutrient loads, and the watershed characteristics that potentially affect nutrient delivery to streams. The SPARROW methodology provides a statistical basis for estimating stream-nutrient loads (predictions) and additional spatial detail on environmental factors and transport processes included in the regression models. To date, three time periods have been modeled using the SPARROW methodology in the Chesapeake Bay watershed. Information generated for and by the models provides resource managers with the potential to evaluate water-quality conditions and spatial similarities and changes in nutrient sources and their relative contributions over time.

Supporting SPARROW is a digitally based network of stream reaches and watersheds. This network provides the primary foundation for detailed spatial referencing of nutrient sources, watershed characteristics, and nutrient predictions within a Geographic Information System. Spatial referencing provides resource managers with an enhanced tool that can be used at various scales to evaluate the geographic distribution and relative contribution of nutrient sources and the factors that affect nutrient transport.

Nutrient-source and watershed-characteristics datasets representing 1997 conditions compiled from various sources were merged with the segmented-watershed network to provide input information for the models. Nutrient-source datasets include atmospheric deposition, point-source locations, land-use, land-cover, and agricultural sources such as commercial fertilizer and manure. Watershed characteristics include land-use, land-cover, average-annual precipitation and temperature, slope, hydrogeomorphic regions, and soil permeability. Nutrient-yield estimates for each segmented watershed based on model predictions representing conditions of the late 1990s also are presented in this report, and are being distributed by the U.S. Geological Survey for general use. These estimates are presented as contributions from all sources combined and from each source individually.

REFERENCES CITED

Alexander, R.B., Smith, R.A., Schwarz, G.E., Preston, S.D., Brakebill, J.W., Srinivasan, R., and Pacheco, P.A., 2001, *Atmospheric nitrogen flux from the watersheds of major estuaries of the United States: An application of the SPARROW watershed model,in: Nitrogen loading in coastal water bodies: An atmospheric perspective*, American Geophysical Union Monograph 57, Valigura, R., Alexander, R., Castro, M., Meyers, T., Paerl, H., Stacey, P., and Turner, R. E. (eds.) pp. 119-170, accessed November 22, 2004, at http://water.usgs.gov/nawqa/sparrow/coast/agu_sparrow.html

Brakebill J.W., and Kelley, S.K., 2000, Hydrogeomorphic regions of the Chesapeake Bay watershed: U.S. Geological Survey Open-File Report 00-424, accessed October 10, 2000, at http://water.usgs.gov/lookup/getspatial?hgmr

Brakebill, J.W., and Preston, S.D., 1999, Digital data used to relate nutrient inputs to water quality in the Chesapeake Bay watershed, Version 1.0: U.S. Geological Survey Open-File Report 99-60, accessed May 10 2000, at http://md.usgs.gov/publications/ofr-99-60/report.html

Brakebill, J.W., and Preston, S.D., 2003, A digital hydrologic network supporting spatially referenced regression modeling in the Chesapeake Bay watershed, In: proceedings of EPA's EMAP Symposium 2001: Coastal Monitoring Through Partnerships, Environmental Monitoring and Assessment Jan-Feb [81:1-3] 73-84 403 p.

Brakebill, J.W., Preston, S.D., and Martucci, S.K., 2001, Digital data used to relate nutrient inputs to water quality in the Chesapeake Bay watershed, Version 2.0: U.S. Geological Survey Open-File Report 01-251, accessed May 2002, at http://md.water.usgs.gov/publications/ofr-01-251/

Cohn, T.A., Delong, L.L., Gilroy, E.J., Hirsch, R.M., and Wells, D.K., 1989, Estimating constituent loads: Water Resources Research, v. 25, n. 05, p. 937-942

Donigian, A.S., Bicknell, B.R., Patwardhan, A.S., Linker, L.C., and Chang, C., 1994, Chesapeake Bay Program watershed model application to calculate Bay nutrient loadings—Final facts and recommendations: Annapolis, Maryland, U.S. Environmental Protection Agency Chesapeake Bay Program Office, Report # EPA 903-R-94-042, 283 p.

Environmental Systems Research Institute, Inc., 1992a, Arc/Info Users Guide, Cell-based modeling with GRID, 2nd ed: Redlands, California, 267 p.

____1992b, Arc/Info Users Guide, Network analysis, 2nd ed: Redlands, California, 192 p.

____1992c, Arc/Info Users Guide, Surface modeling with TIN, 2nd Edition: Redlands, California, 192 p.

Gutierrez-Magness, A.L., Hannawald, J.E., Linker, L.L., and Hopkins, K.J., 1997, Chesapeake Bay watershed model application and calculation of nutrient and sediment loadings, appendix E: Phase IV Watershed land-use and model linkages to the airshed and estuarine models: Annapolis, Maryland, U.S. Environmental Protection Agency Chesapeake Bay Program Office, Report # EPA 903-R-97-019, 142 p.

Karl, T.R., C.N. Williams, Jr., F.T. Quinlan, and T.A. Boden, 1990: United States Historical Climatology Network (HCN) Serial Temperature and Precipitation Data, Environmental Science Division, Publication No. 3404, Carbon Dioxide Information and Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN, 389 pp. Data accessed January 12, 1998, at http://www.ncdc.noaa.gov/oa/climate/research/ushcn/ushcn.html

Kellogg, R.L., Lander, C.H., Moffitt, D., and Gollehon, N., 2000, Manure nutrients relative to the capacity of cropland and pastureland to assimilate nutrients: Spatial and temporal trends for the U.S: Washington, D.C., Natural Resource Conservation Service, Publication No. nps00-0579, 93 p.

Lander, C.H., Moffitt, D., and Alt, K., 1998, Nutrients available from livestock manure relative to crop growth requirements: Resource Assessment and Strategic Planning Working Paper 98-1, 6 p.

Langland, M.J., Lietman, P.L., and Hoffman, S.A., 1995, Synthesis of nutrient and sediment data for watersheds within the Chesapeake Bay drainage basin: U.S. Geological Survey Water-Resources Investigations Report 95-4233, 121 p.

Loveland, T. R., and Shaw, D. M., 1996, Multi-resolution land characterization: Building collaborative partnerships, GAP analysis: A landscape approach to biodiversity planning, *in*: Scott, J.M., Tear, T., and Davis, F., eds., Proceedings of the ASPRS/GAP Symposium, Charlotte, North Carolina, National Biological Service, Moscow, Idaho, p. 83-89.

National Atmospheric Deposition Program/National Trends Network, 1994, NADP/NTN Annual data summary: Precipitation chemistry in the United States 1993: National Resource Ecology Laboratory, Colorado State University, Fort Collins, Colorado, 465 p. Data accessed October 10, 2000, at http://ceos.neonet.nl/metadata/dif/NADP_NTN.xml

Palace, M.W., Hannawald, J.E., Linker, L.C., Shenk, G.W., Storrick, J.M., and Clipper, M.L., 1998, Chesapeake Bay watershed model application and calculation of nutrient and sediment loadings, appendix H: Annapolis, Maryland, U.S. Environmental Protection Agency Chesapeake Bay Program Office, , 91p. Accessed November 22, 2004, at http://www.chesapeakebay.net/pubs/777.pdf

Preston, S.D. and Brakebill, J.W., 1999, Applications of spatially referenced regression modeling for the evaluation of total nitrogen loading in the Chesapeake Bay watershed: U.S. Geological Survey Water-Resources Investigations Report 99-4054, 12 p. Accessed November 22, 2004, at http://md.usgs.gov/publications/wrir-99-4054

Preston, S.D., Smith, R.A., Schwarz, G.E., Alexander, R.B., and Brakebill, J.W., 1998, Spatially referenced regression modeling of nutrient loading in the Chesapeake Bay *in* Proceedings of the First Federal Interagency Hydrologic Conference: Las Vegas, Nevada, April 19-23, 1998, 8 p.

Ruddy, B.C., and Hitt, K.J., 1990, Summary of selected characteristics of large reservoirs, 1st ed.: U.S. Geological Survey Open-File Report OFR-90-163 accessed November 22, 2004, at http://water.usgs.gov/lookup/getspatial?reservoir

Schwarz, G.E., and Alexander, R.B., 1995, State Soil Geographic (STATSGO) data base for the conterminous United States Version 1.1: U.S. Geological Survey Open-File Report 95-449 (scale 1:250,000), accessed February 10, 1998, at URL http://water.usgs.gov/lookup/getspatial?ussoils

Smith, R.A., Schwarz, G.E., and Alexander, R.B., 1997, Regional interpretation of water-quality monitoring data: Water Resources Research, 33 (12) 2781 – 2798, accessed November 22, 2004, at http://water.usgs.gov/nawqa/sparrow/wrr97/results.html

Snyder, J. P., 1987, Map Projections—A working manual: U.S. Geological Survey Professional Paper 1395, 383 p.

U.S. Bureau of the Census, 2000, 1997 Census of Agriculture: The Bureau, Washington D.C. (machine readable data files).

U.S. Environmental Protection Agency, 2000, Chesapeake 2000: Annapolis, Maryland, Chesapeake Bay Program Office, accessed November 22, 2004, at http://www.chesapeakebay.net/agreement.htm

U.S. Geological Survey, 1999a, USGS Digital Raster Graphics accessed November 23, 2004, at http://topomaps.usgs.gov/drg/

____ 1999b, USGS National Elevation Data Base (NED): U.S. Geological Survey, accessed May 10 2000, at http://ned.usgs.gov/

____ 2000a, National Land-cover Data Base (NLCD), accessed October 2000, at http://edcwww.cr.usgs.gov/programs/lccp/mrlcreg.html.

____2000b, Chesapeake Bay 1997 Land-cover Dataset: U.S. Geological Survey EROS Data Center Report, 32 p.

U.S. Soil Conservation Service, 1994, State Soil Geographic (STATSGO) database: Washington, D.C., National Soil Survey Center, Publication number 1492, 88 p.

Wiedeman, A., and Cosgrove, A., 1998, Chesapeake Bay watershed model application and calculation of nutrient and sediment loadings, appendix F: Annapolis, Maryland, U.S. Environmental Protection Agency Chesapeake Bay Program Office, Report # EPA 903, 50 p.

APPENDIX

Metadata for Digital Datasets