

# Assessment of Eutrophication in Estuaries: Pressure-State-Response and Source Apportionment

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**Abstract**—The National Estuarine Eutrophication Assessment (NEEA) Update Program is a management oriented program designed to improve monitoring and assessment efforts through the development of type specific classification of estuaries that will allow improved assessment methods and development of analytical and research models and tools for managers which will help guide and improve management success for estuaries and coastal resources. The assessment methodology, a Pressure-State-Response (PSR) approach, uses a simple model for determination of Pressure and statistical criteria for indicator variables (where possible) to determine State. The Response determination is mostly heuristic although research models are being developed to improve this component. The three components are determined individually and then combined into a single rating.

In addition to the PSR approach, it is also valuable to identify and quantify the anthropogenic nutrient input sources to estuaries so that management measures can be targeted for maximum effect. Since nitrogen is often the limiting nutrient in estuarine systems, the sources of nitrogen have been determined for eleven coastal watersheds on the U.S. east coast using the WATERSN model. In general, estuaries in the Northeastern U.S. receive most of their nitrogen from human sewage, followed by atmospheric deposition. This is in contrast to some watersheds in the Mid-Atlantic (Chesapeake Bay) and South Atlantic (Pamlico Sound) which receive most of their nitrogen from agricultural runoff.

## Introduction

Nutrient pollution has recently been identified as the greatest threat to U.S. coastal water quality (Boesch and others 2001, CSO 1999, NRC 2000). Sources of nutrients include atmospheric deposition, groundwater, and point and non-point sources. Potential consequences of nutrient enrichment range from ecological changes to socio-economic impairments (for example, fisheries) to serious human health threats (fig. 1).

Symptoms of eutrophication include low dissolved oxygen, nuisance and toxic algal blooms, shifts in algal community composition, and losses of submerged aquatic plants that serve as habitat for fish species important to coastal fisheries. These impacts cause economic losses to tourism, and to commercial and recreational fisheries (Lipton 2003, Lipton and Hicks 1999, 2003). Additionally, weakening or destroying native flora and fauna provides the opportunity for colonization by invasive species.

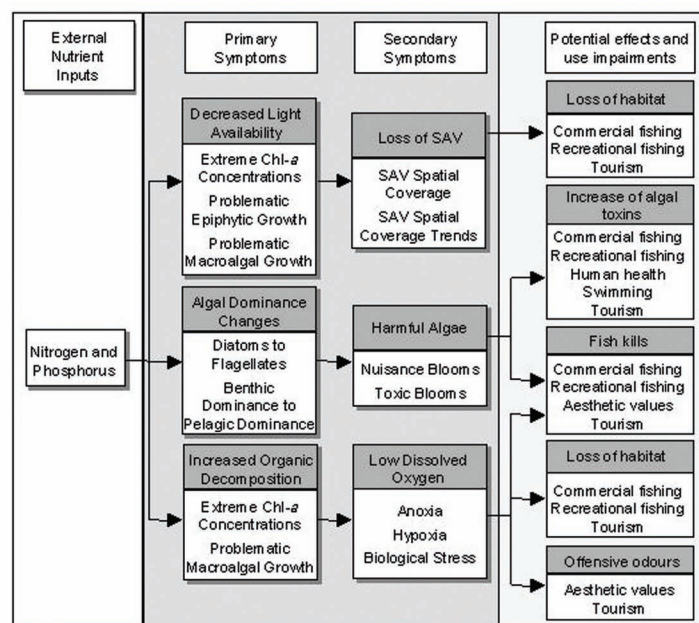


Figure 1. Conceptual model of eutrophication.

The National Estuarine Eutrophication Assessment (NEEA) Update Program is a management oriented program designed to improve monitoring and assessment efforts through the development of type specific classification of estuaries that will allow improved assessment methods, development of analytical and research models and tools for managers which will help guide and improve management success for estuaries and coastal resources.

The objectives of this paper are to describe the NEEA methodology and the program plan for update of the assessment that was recommended at the National Estuarine Eutrophication Assessment Update Workshop in September, 2002 (Bricker and others 2004) and to link nitrogen (N) source apportionment modeling to this assessment work.

## NOAA's Estuarine Eutrophication Assessment

The intent of the NEEA update is to develop a monitoring and assessment program for periodic assessment updates that will inform managers, researchers, and politicians about the success of legislation and management measures designed to address eutrophication issues. This program is meant to be a companion program to the National Research Program for Nutrient Pollution in Coastal Waters (Howarth and others 2003) and interactive with European Commission efforts such as the Water Framework Directive 2000/60/EC (WFD, for example; Coast 2003) and OSPAR (2002).

In the early 1990s in response to the knowledge that some estuaries were showing signs of nutrient related degradation as evidenced by hypoxia in Long Island Sound, Chesapeake Bay and Mobile Bay (Welsh 1991) and the concern that this might be a wide spread problem, NOAA conducted a nationwide assessment to discern the magnitude, severity and location of eutrophic conditions. The intent was to learn whether these problems were local, regional or national in scale, to determine probable causes, and to provide this information to managers such that observed problems could be addressed at the appropriate level (national, state or local legislation). The National Estuarine Eutrophication Assessment (NEEA) involved about four hundred participants from academia, state, federal and local agencies who provided information and data for one hundred thirty eight U.S. estuaries and coastal waters (NOAA 1996, 1997a, b, a, 1998). Assessment results show that nutrient related water

quality problems occur on a national basis (Bricker and others 1999, fig. 2).

Since the release of the NEEA there has been interest in an update of the assessment given the expected increase in problems in the future as coastal populations, use of fertilizers and fossil fuels continue to increase (Bricker and others 1999, NRC 2000). There is interest in improvement of the accuracy and applicability of the methodology including:

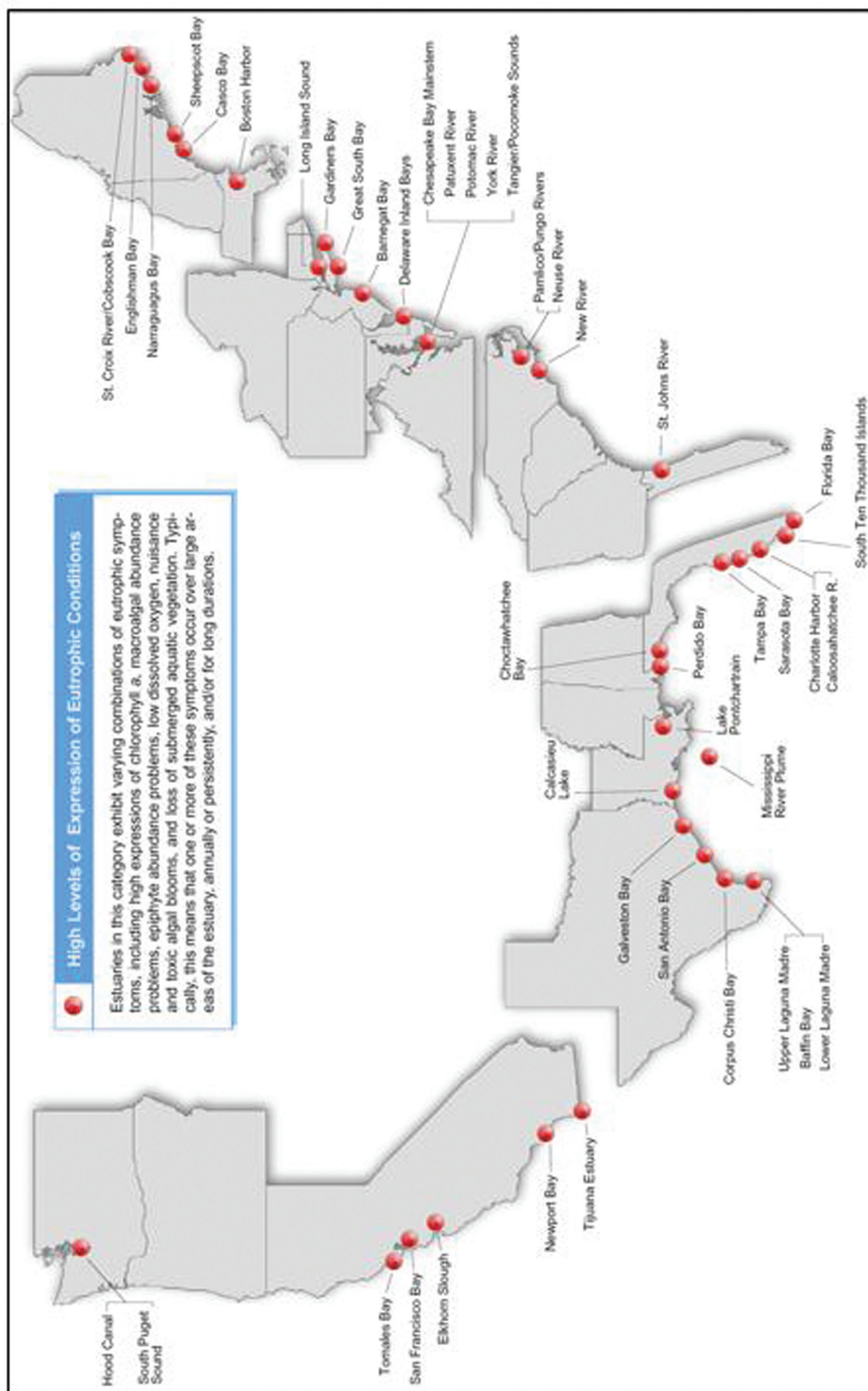
- update of the assessment to learn whether the systems that were expected to become worse have done so,
- the use of data to complement and inform “expert knowledge,”
- development of a type classification to improve the accuracy of the assessment methods,
- improvement of assessment methods to include, for example, type specific selection of indicator variables and variable thresholds,
- development of a socioeconomic indicator to complement the existing indices and to establish a meaningful framework for assessing impairments to human uses and specifying appropriate responses,
- development of tools and predictive models that are useful to resource managers and can help them to make informed decisions and to assess alternative management strategies,
- apportionment of nutrient sources to support implementation of appropriate management measures.

### *The NEEA/ASSETS Assessment Methodology*

The NEEA model (Bricker and others 1999), and recent modifications described in the Assessment of Estuarine Trophic Status (ASSETS; Bricker and others 2003), uses a Pressure-State-Response framework to assess eutrophication in three component parts:

- Overall human influence (OHI) on development of conditions (Pressure),
- Overall eutrophic conditions (OEC) within a water body (State), and
- Determination of future outlook (DFO) for conditions within the system (Response)

The original method is described here in brief, as are recent improvements and modifications made by ASSETS (Bricker and others 2003). A full description of the original method can be found in Bricker and others (1999) and details for modifications can be found in Bricker and others (2003) and Ferreira and others (submitted).



**Figure 2.** Map showing U.S. estuaries with “High” levels of eutrophic expression (from Bricker and others 1999).



## **Determination of pressure—Overall Human Influence (OHI)**

Pressure is determined by combining in a matrix an estimation of susceptibility of a system which is based on the ability of a system to dilute and flush nutrients from the system and the level of nutrient inputs from the watershed. Participants in the NEEA used watershed nutrient model estimates (SPARROW; Smith and others 1997), watershed population density and other demographic data in the Coastal Assessment and Data Synthesis (CADS 1999) to estimate inputs, and hydrologic and physical data from CADS (1999) to determine susceptibility.

In ASSETS, improvements were made to the original methodology by applying a simple model to compare anthropogenic nutrient loading and natural background concentrations. The model also factors in potential nutrient inputs from oceanic sources thus addressing the question of whether management measures would be successful. For a full description of model development see Bricker and others (2003) and Ferreira and others (submitted).

## **Determination of state—Overall Eutrophic Condition (OEC)**

Six variables were selected from the original 16 used in the NEEA (Bricker and others 1999) for determination of OEC. These were divided into two groups, primary or early stage symptoms (chlorophyll a, epiphytes, macroalgae) and secondary (dissolved oxygen, SAV loss, harmful algal bloom occurrence) or well developed eutrophication symptoms. Statistical criteria are used for quantifying chlorophyll a and dissolved oxygen (90th percentile for chlorophyll and 10th percentile for dissolved oxygen; Bricker and others 2003). Additional improvements to the original “expert knowledge” methodology have been proposed for macroalgae, epiphytes and submerged aquatic vegetation based on comparison of potential area of colonization and effective colonized area. Presently these are still determined heuristically.

An area weighted estuary wide value for each variable is determined based on concentration, spatial coverage, and frequency of extreme occurrences. The primary symptom expression level is determined by averaging the three estuary level of expression values, while the highest of the three secondary symptoms is selected. These values are combined in a matrix to determine an overall ranking of eutrophic conditions for the estuary.

## **Determination of response—Determination of Future Outlook (DFO)**

Response is determined by a matrix that combines susceptibility of the system with expected future changes in nutrient loads. Predictions of nutrient loading (increase, decrease, unchanged) are based on predicted population increase, planned management actions and expected changes in watershed uses.

## **Synthesis—grouping of pressure, state and response indicators**

An additional modification to the original methodology (ASSETS; Bricker and others 2003) combines the OEC, OHI, and DFO into a single overall score falling into one of five categories: high, good, moderate, poor or bad. These categories are color-coded following the convention of the EU Water Framework Directive (2000/60/EC), and provide a scale for setting eutrophication related reference conditions for different types of systems.

## **Additional modifications: NEEA update program**

Further modifications that are presently being pursued in the NEEA update program include: the development of a type classification based on physical and hydrologic characteristics using the Deluxe Integrated System for Clustering Operations (DISCO) tool (Smith and Maxwell 2002). Preliminary results are promising (Smith and others 2004) and will be used to determine type specific reference conditions and thresholds for desirable/undesirable conditions for indicator variables. Additionally, indicator variables are being evaluated by type to ensure that all types of estuaries are assessed with indicators that are relevant. For instance, in types where there is no SAV under natural conditions, an alternative indicator will be used.

A socio-economic/human use indicator is being developed where changes in fish catch rate are related to changes in water quality in the manner of Lipton and Hicks (1999, 2003) and Mistiaen and others (2003). Preliminary analysis of Long Island Sound data shows that as nitrogen inputs decrease, dissolved oxygen and recreational catch of striped bass increase. The increase in catch is shown to be related to changes in oxygen when other influences (for example, fishermen avidity and experience, temperature, changes in fish stock) are accounted for (Mason and others 2004).

In addition to the assessment and typology activities of the NEEA, the quantification of the relative importance of

various sources of nutrient pollution to estuaries is considered to be a critical step for coastal management.

## Source Apportionment

Primary productivity in aquatic ecosystems is most often limited by either nitrogen or phosphorus. In most estuarine systems, nitrogen is the limiting nutrient, in contrast to freshwater systems where phosphorus limits production. This study focuses on identifying the sources of nitrogen pollution to eleven watersheds on the U.S. east coast.

Nitrogen inputs to coastal systems originates from both point and non-point sources. Point sources include: wastewater treatment plants (WWTP) and industrial discharges. Non-point sources include: agricultural runoff, septic systems, and urban and suburban runoff. Atmospheric deposition of N (AD-N) has also been identified as a potentially important source of N for many coastal ecosystems (Nixon 1995, Paerl and others 2002, Valiela and others 1992, Whitall and others 2003).

Quantitatively describing the sources of nitrogen pollution to an estuary is necessary for the implementation of appropriate and effective management strategies for reducing nitrogen loading, and ultimately, the effects of eutrophication.

## WATERS N Model Description

A useful approach for quantifying the relative importance of each source of nitrogen to coastal receiving waters

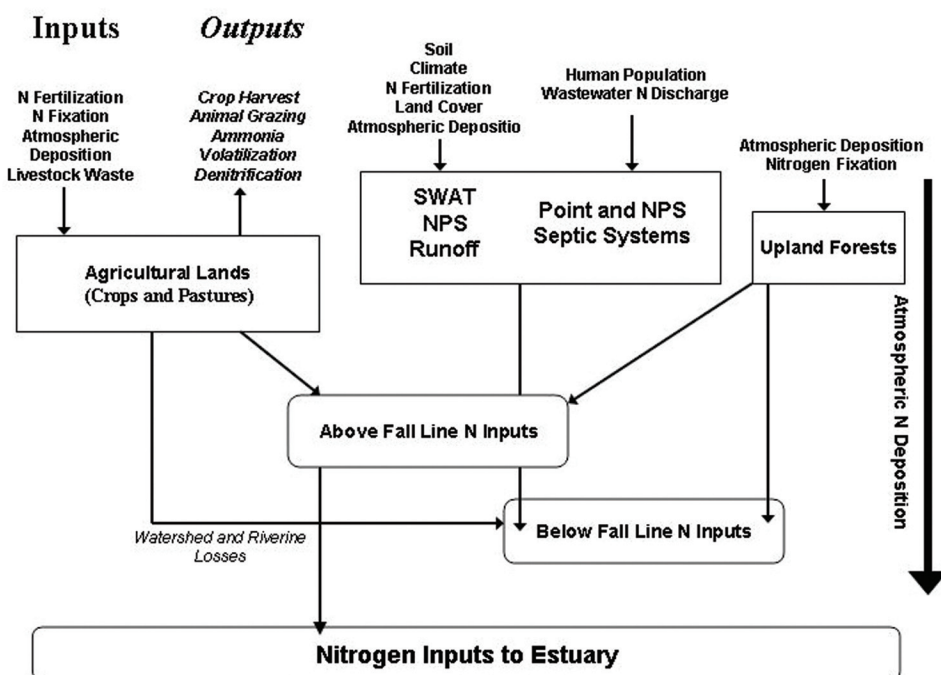
is a numerical watershed model. The model used in this study was the Watershed Assessment Tool for Evaluating Reduction Strategies for Nitrogen (WATERSN, fig. 3). The mass balance approach of this model has been presented previously (Castro and others 2000, Castro and Driscoll 2002, Castro and others 2003, Whitall and others in prep) but is described briefly here.

This model estimates the amount of N available for transport to estuaries from lands in agricultural production (crops, orchards, and pastures), urban areas, and forests. The quantity of N exported from agricultural lands to the surface waters of the watershed is estimated as the difference between N inputs and N outputs. Nitrogen inputs for the agricultural budgets include:

- N fertilization (fertilizer sales data by county),
- N fixation (unique values by crop; Castro and others 2000),
- livestock waste (the difference between feed imports and production of meat, milk, and eggs), and
- atmospheric deposition of  $\text{NH}_4^+$  and  $\text{NO}_3^-$  (from National Atmospheric Deposition Program/National Trends Network data).

Outputs from agricultural lands include:

- crop harvest (agricultural census data),
- pasture grazing (agricultural census data),
- volatilization of  $\text{NH}_3$  (10% of fertilizer and atmospheric deposition, 15% of animal waste; Schlesinger and Hartley 1992) and
- denitrification (10% of inputs; Meisinger and Randall 1991).



**Figure 3.** Conceptual diagram of Watershed Assessment Tool for Evaluating Reduction Strategies for Nitrogen (WATERSN) model.

Nitrogen export from urban areas includes:

- wastewater treatment plant effluent (point sources),
- leachate from septic systems and
- non-point source runoff (from SWAT model predictions; Neitsch and others 2001) from pervious and impervious surfaces in urban areas.

Atmospheric deposition of inorganic N and non-symbiotic N fixation were assumed to be the only N inputs to forests. The contribution made by AD-N to the total N runoff from upland forests was assumed to be the same proportion that AD-N made to the total N inputs. N export from upland forests is estimated using a non-linear regression relationship between wet deposition of  $\text{NH}_4^+$  and  $\text{NO}_3^-$  and stream water N export of dissolved inorganic N ( $\text{NH}_4^+$  and  $\text{NO}_3^-$ ) using results of numerous forest watershed studies in the U.S. (Driscoll unpublished data, Neitsch and others 2001). Dissolved organic N contribution to the total N loads is assumed to be equal to 50% of the inorganic N load exported from forests (Castro and Driscoll 2002). Rates of in-stream N loss were based on literature values and calibrated by comparing predicted and measured riverine fluxes. Castro and others (2003) calibrated the model against U.S. Geological Survey (USGS) National Stream Quality Accounting Network (NASQAN) for 18 watersheds in the eastern U.S. by adjusting the watershed and riverine N sinks. The calibrated model loadings agreed well (slope=0.995,  $r^2=0.9997$ ) with USGS loading values.

It is important to note that all biogeochemical models, no matter how complex, are simplifications of the natural world and are therefore limited in their predictive capacities. With an understanding of the imperfections of any given model, it can be used as a tool to address questions of interest to environmental managers.

## ***WATERSN Results—Northeastern and Middle Atlantic United States***

The WATERSN model was used to determine the sources of nitrogen for Casco Bay, Great Bay, Merrimack River, Buzzards Bay, Massachusetts Bay, Narragansett Bay, Long Island Sound, Raritan Bay, Delaware Bay, Chesapeake Bay, and Pamlico Sound (fig. 4). The results presented here compare well with independently published SPARROW model results (Smith and others 1997).

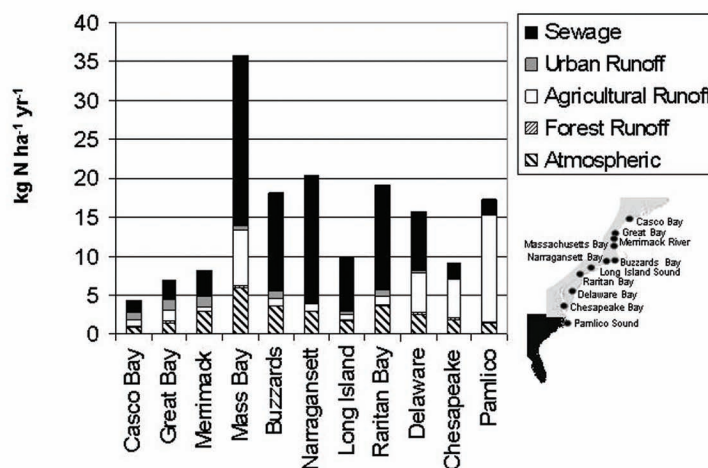
For the purposes of this study, the Northeast has been operationally defined as Delaware Bay and north. Chesapeake Bay and Pamlico Sound are defined as Mid-Atlantic estuaries. Patterns in sources of nitrogen to east coast estuaries vary by region with striking differences between the Northeast and the Mid-Atlantic.

In the Northeast, human sewage is the major source of N loading for all estuaries (36-81%). In addition, runoff from atmospheric deposition (14-35%), urban areas (<1-20%), agricultural systems (4-20%) and forest lands (<1-5%) contributes N to these coastal ecosystems. Atmospheric N deposition, either through direct deposition to the estuary surface or through watershed runoff of atmospheric deposition, was generally the second highest source of N. A notable exception to this pattern is Delaware Bay, where the second highest source of N was agricultural runoff.

In the Chesapeake Bay and Pamlico Sound, agricultural runoff dominates the N loading (55% and 79%, respectively) with wastewater effluent (21% and 12%) and atmospheric deposition also contributing significant loads (22% and 8%, respectively). Loadings from urban (2% and <1%) and forest runoff (1% and <1%) made up smaller portions of the total N load to these systems. This difference in patterns between regions reflects both the differences in watershed populations, which drives the sewage flux, and differences in land use (agricultural vs. non-agricultural).

It is also important to note that the nitrogen pollution that contributes to the atmospheric depositional flux originates from a variety of sources. It is difficult to determine exactly what portion of the deposited nitrogen originates from each source, but the relative sources of atmospheric emissions can be quantified. The airsheds, or atmospheric pollutant source areas, for estuaries on the eastern U.S. seaboard have been delineated previously (Paerl and others 2002). The sources of nitrogen oxide ( $\text{NO}_x$ ) emissions for the airsheds of the eleven study estuaries vary by airshed and include:

- on-road mobile sources (31-38%),
- non-road mobile sources (12-21%),



**Figure 4.** Nitrogen source apportionment for 11 U.S. east coast estuaries. Location of estuaries (inset).

**Table 1.** Watershed and Estuary characteristics.

| System            | Watershed Area <sup>1</sup> (km <sup>2</sup> ) | Estuarine Area <sup>2</sup> (km <sup>2</sup> ) | Total N load to estuary <sup>1</sup> (kg N ha <sup>-1</sup> yr <sup>-1</sup> ) | % Ag <sup>1</sup> | % Sewage <sup>1</sup> | % AD-N <sup>1</sup> | OEC <sup>3</sup> |
|-------------------|------------------------------------------------|------------------------------------------------|--------------------------------------------------------------------------------|-------------------|-----------------------|---------------------|------------------|
| AD-N <sup>1</sup> | OEC <sup>3</sup>                               |                                                |                                                                                |                   |                       |                     |                  |
| Casco Bay         | 2188                                           | 427                                            | 4.2                                                                            | 5                 | 41                    | 35                  | MH               |
| Great Bay         | 2491                                           | 47                                             | 6.9                                                                            | 19                | 36                    | 20                  | MH               |
| Merrimack River   | 12458                                          | 16                                             | 8.2                                                                            | 5                 | 70                    | 19                  | U                |
| Massachusetts Bay | 2089                                           | 768                                            | 35.8                                                                           | 5                 | 81                    | 14                  | M                |
| Buzzards Bay      | 1021                                           | 639                                            | 18.1                                                                           | 20                | 62                    | 17                  | ML               |
| Narragansett Bay  | 4018                                           | 416                                            | 20.3                                                                           | 8                 | 70                    | 18                  | ML               |
| Long Island Sound | 40774                                          | 3259                                           | 9.8                                                                            | 6                 | 70                    | 19                  | MH               |
| Raritan Bay       | 36114                                          | 799                                            | 19.1                                                                           | 4                 | 75                    | 16                  | M                |
| Delaware Bay      | 30792                                          | 2070                                           | 15.7                                                                           | 34                | 47                    | 17                  | ML               |
| Chesapeake Bay    | 160765                                         | 5470                                           | 9.0                                                                            | 55                | 21                    | 22                  | H                |
| Pamlico Sound     | 25090                                          | 452                                            | 17.3                                                                           | 79                | 12                    | 8                   | U                |

The sum of percentages equals less than 100% because forest runoff and urban runoff make up minor parts of the nitrogen budget for each of these systems. Please see figure 3 for their contributions.

<sup>1</sup> From Whitall and others (in prep). "Ag" is agricultural runoff; "AD-N" is atmospheric nitrogen deposition.

<sup>2</sup> From S. Smith 2004. Preliminary NOAA estuarine typology database, August 2003.

<sup>3</sup> From Bricker and others 1999. "OEC" is overall eutrophic condition. ML = moderate low; M = moderate; MH = moderate high; H = high; U = unknown.

- area sources (9-28%),
- fossil fuel combustion from electric utilities (19-23%) and
- industrial sources (9-12%) (USEPA 1998).

Anthropogenic emissions of ammonia (NH<sub>3</sub>) also vary between airsheds and include:

- agricultural animal waste (60-73%),
- chemical fertilizers (13-16%),
- domestic animals (4-7%),
- human breath and perspiration (3-7%),
- sewage treatment plants and septic systems (3-6%),
- industrial point sources (2%) and
- mobile sources (1-2%) (Strader and others 2001).

## Conclusions

In summary, the intent of the National Estuarine Eutrophication Assessment Update Program is to improve monitoring and assessment efforts through the development of type specific classification of estuaries. This will allow for the improvement of assessment methods and the development of analytical and research models and tools for managers which will help guide and improve management success for estuaries and coastal resources.

An important component of the NEEA Update Program is identification and quantification of nutrient sources to estuaries that are sensitive to eutrophication. Here, nitrogen sources to eleven east coast estuaries have been reported. There are stark regional differences

between watersheds in the Northeast (dominated by human sewage followed by atmospheric deposition/agriculture) and the Mid-Atlantic (dominated by agricultural runoff followed by atmospheric deposition/human sewage). These regional differences highlight the need for the sort of typology work (DISCO cluster analysis) that is being conducted as part of the NEEA Update Program. These differences will dictate the appropriate management strategies that will be most successful in protecting and remediating waterbodies that are sensitive to and degraded by nutrient inputs. Generally, these results suggest that sewage related nutrients should be further reduced in the Northeast region while reductions in agriculturally related nutrients should be the focus of management efforts in the Mid Atlantic region. Both regions would also benefit from efforts to reduce/limit atmospheric nutrient sources.

These results show that the WATERSN model can be applied to most estuaries and is a useful tool for resource managers. A similar modeling approach could be used to quantify the phosphorus loading to P sensitive estuaries to provide the basis for development of a comprehensive nutrient management plan that includes both P and N.

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