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ENVIRONMENTAL ASSESSMENT

Assessment of Eutrophication in Estuaries: Pressure–State–Response and Nitrogen Source Apportionment

David Whitall · Suzanne Bricker · Joao Ferreira · Ana M. Nobre · Teresa Simas · Margarida Silva

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Abstract A eutrophication assessment method was developed as part of the National Estuarine Eutrophication Assessment (NEEA) Program. The program is designed to improve monitoring and assessment of eutrophication in the estuaries and coastal bays of the United States with the intent to guide management plans and develop analytical and research models and tools for managers. These tools will help guide and improve management success for estuaries and coastal resources. The assessment method, a Pressure-State-Response approach, uses a simple model to determine Pressure and statistical criteria for indicator variables (where applicable) to determine State. The Response determination is mostly heuristic, although research models are being developed to improve that component. The three components are determined individually and then combined into a single rating. Application to several systems in the European Union (E.U.), specifically in Portugal, shows that the method is transferable, and thus is useful for development of management measures in both the Unites States and E.U. This approach identifies and quantifies the key anthropogenic nutrient input sources to estuaries so that management measures can target inputs for maximum effect. Because nitrogen is often the limiting nutrient in estuarine systems, examples of source identification and quantification for nitrogen have been developed for 11 coastal watersheds on the U.S. east coast using the WATERSN model. In general, estuaries in the Northeastern United States 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. Source identification is important for implementing effective management measures that should be monitored for success using assessment methods, as described herein. For instance, these results suggest that Northeastern estuaries would likely benefit most from improved sewage treatment, where as the Mid and South Atlantic systems would benefit most from agricultural runoff reductions.

Keywords Eutrophication · Estuaries · Nitrogen · Modeling · United States · European Union · Assessment

D. Whitall (✉) · S. Bricker
NOAA, National Ocean Service, National Centers for Coastal Ocean Science, 1305 East West Highway, Silver Spring, MD 20910, USA
e-mail: dave.whitall@noaa.gor

J. Ferreira · A. M. Nobre · T. Simas
IMAR—Institute of Marine Research, Centre for Ecological Modelling, DCEA-FCT, Qta. Torre, 2829–516 Monte de Caparica, Portugal

M. Silva
Instituto do Ambiente, Rua da Murgueira, 9–Zambujal, Apartado 7587 Alfragide, 2720 Amadora, Portugal

Introduction and Background

Nutrient pollution has recently been identified as the greatest threat to U.S. coastal water qulity (Boesch and others 2001, NRC 2000, CSO 1999). Sources of nutrients include atmospheric deposition, groundwater, surface waters, and land-based point and nonpoint sources. Additionally, oceanic sources may be relevant for some systems. Potential consequences of nutrient enrichment range from ecological changes to socio-economic impairments (for example, fisheries, aquaculture), 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 constitute a habitat for species important to coastal fisheries. These impacts cause economic losses to tourism, and to commercial and recreational fisheries (Lipton and Hicks 1999, 2003). Additionally, weakening or destroying native flora and fauna provides the opportunity for colonization by invasive species.

The National Estuarine Eutrophication Assessment (NEEA) Program is a management-oriented program designed to improve monitoring and assessment efforts to evaluate and provide the basis for successful management. Program components focus on the development of type-specific classification of estuaries, improved assessment criteria, and on the use of assessment results to guide development of analytical and research models and tools for managers. The intent is to make these tools accessible to help improve management success for estuaries and coastal resources. This paper describes results of the application of the Assessment of Estuarine Trophic Status (ASSETS) eutrophication method, developed as part of the NEEA Program, from the original study of 138 U.S. coastal waterbodies and a more recent application to several E.U. systems, illustrating the transferability of the method. Furthermore, the paper shows ongoing and needed method improvements, in particular the value and need for more detailed characterization of nutrient inputs. Models are used here to apportion nitrogen sourees in case studies using a subset of the 138 U.S. systems for which required data were available.

Methods

Eutrophication Assessment

In the early 1990s, signs of nutrient-related degradation in estuaries, as evidenced by hypoxia in Long Island Sound, Chesapeake Bay, and Mobile Bay (Welsh 1991), and the concern that this might be a widespread problem, led NOAA to conduct a nationwide assessment of the magnitude, severity, and location of eutrophic conditions. The intent was to learn whether these problems were national, regional, or local in scale, to determine probable causes, and to provide information to managers on observed problems that could be addressed at the appropriate level (national, state, or local). The National Estuarine Eutrophication Assessment (NEEA) involved about four hundred participants from academia, state, federal and local agencies, who provided information and data for 138 U.S. estuaries and coastal water bodies (NOAA 1996, 1997a, 1997b, 1997c,

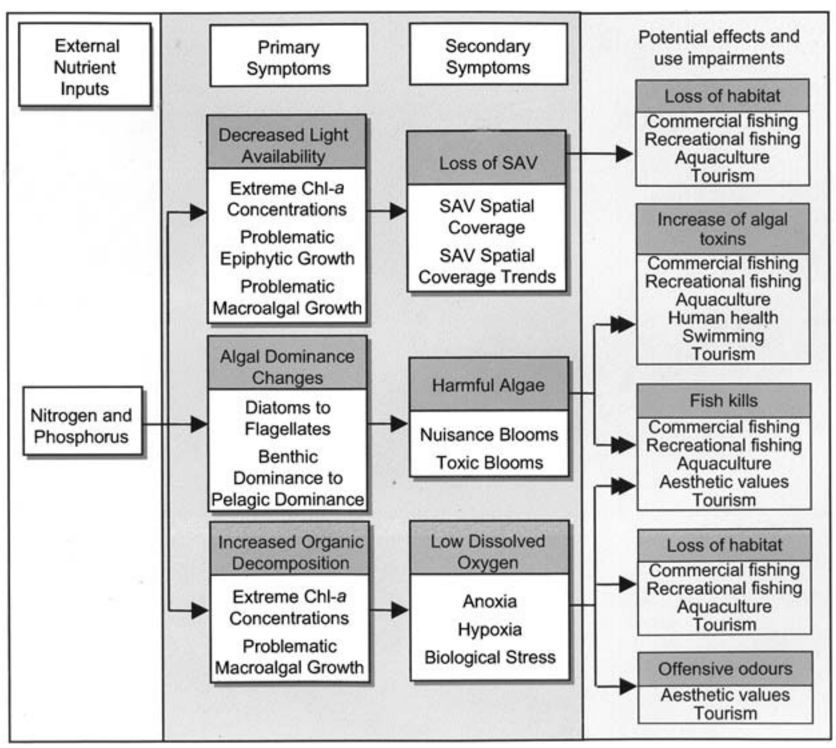

Fig. 1 Conceptual model of eutrophication, (Note that epiphytes are no longer used because of inadequate data availabilily)

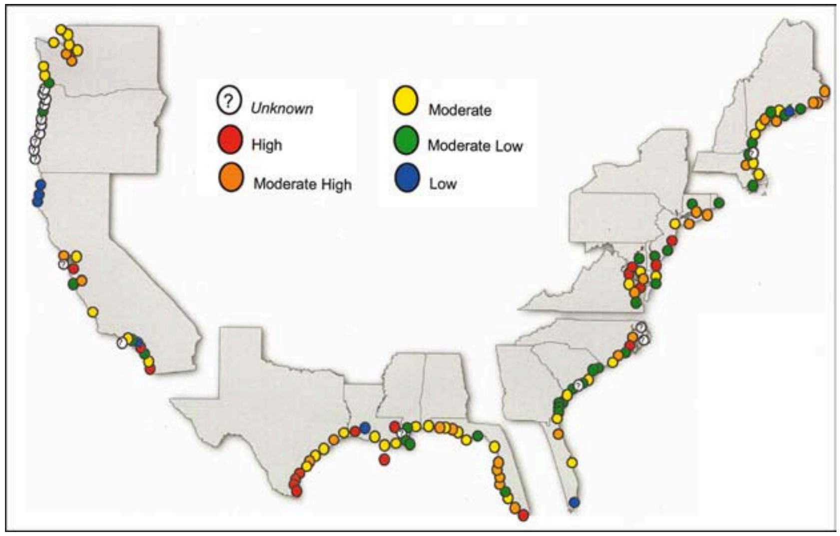

Fig. 2 Results of the National Estuarine Eutrophication Assessment for Overall Eutrophic Conditions. Results are a combination of six indicators: Chl a, macroalgae, epiphytes,, dissolved oxygen, loss of submerged aquatic vegetation, and occurrence of nuisance and toxic algal blooms (from Bricker and others 1999)

1998). Assessment results show that nutrient-related water quality problems were occurring on a national basis (Bricker and others 1999; Fig. 2).

Since the release of the NEEA in 1999, there has been interest in updating the assessment given the expected increase in problems in the future as coastal populations, fertilizer use, and fossil fuel consumption grew (Bricker and others 1999, NRC 2000). There is also interest in improving the accuracy and applicability of the methodology including:

1. the use of data to complement and inform ''expert knowledge'';
2. development of a type classification to improve accuracy;
3. improvement of assessment methods to include, for example, type-specific selection of indicator variables and variable thresholds;
4. development of a socioeconomic indicator for assessing impairments to human uses and specifying appropriate responses;
5. development of tools and predictive models useful to resource managers for making informed decisions and assessing alternative management strategies; and
6. apportionment of nutrient sources to support selection and implementation of appropriate management measures, i.e., the incorporation of driving forces into the assessment method (Bricker and others 2004).

Furthermore, an update of the assessment will validate the previous findings, to learn whether the systems that were expected to become worse have done so.

Presently, the U.S. NEEMA results are being updated via an online data collection survey and a national review workshop. The results, representing decadal changes in nutrient-related water quality in U.S. systems from the early 1990s to the early 2000s, are expected for release in early 2007 (http://www.eutro.us). Additionally, other program components such as the type classification and development of a socioeconomic indicator (Bricker and others 2006) are under way.

The ASSETS Assessment Methodology

The NEEA model (Bricker and others 1999) was developed into a Pressures–State–Response framework, termed Assessment of Estuarine Trophic Status (ASSETS; Bricker and others 2003), which assesses eutrophication in three components:

1. Influencing Factors on development of conditions (Pressure);
2. Overall Eutrophic Condition within a water body (State) and;
3. Future Outlook for conditions within the system (Response).

The method is described here in brief, although 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), Nobre and others (2005), and Ferreira and others (2007).

Determination of Pressure—Influencing Factors

A matrix is used to determine Pressure, an estimate of system susceptibility based on its ability to dilute and flush nutrients and the level of nutrient input from the watershed. In the original study, 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) were used to estimate inputs, and CADS hydrologic and physical data to determine susceptibility, Model estimates can still be used as estimators of input; however, the ASSETS method uses a simple model that compares anthropogenic nutrient loading with natural background concentrations. This is an improvement to the model-generated estimates because water quality data are from the system and the timeframes are consistent with data used for the condition assessment.

Watershed models most often use a ''base year'' that may not be consistent with the timeframe of the assessment data, Additionally, because the ASSETS model factors in potential nutrient inputs from oceanic sources, it determines the potential success of management measures. For a full description of model development, see Bricker and others (2003) and Ferreira and others (2007).

Determination of State—Overall Eutrophic Condition

Five variables from an original list of 16 (Bricker and others 1999) are used to determine overall eutrophic condition. These were divided into two groups:

I. primary or early-stage symptoms

1. chlorophyll *a*; and
2. macroalgae; note that although epiphytes were used in the original study, there were inadequate data on a national basis to support the use of this indicator in further assessments (Bricker and others 2006); and

II. secondary or well-developed eutrophication symptoms

1. dissolved oxygen;
2. submerged aquatic vegetation (SAV) loss; and
3. harmful algal bloom occurrence.

Statistical criteria are used to quantify chlorophyll *a* and dissolved oxygen (90th percentile for chlorophyll and 10th percentile for dissolved oxygen Bricker and others 2003), Additional improvements to the method for macroalgae and submerged aquatic vegetation have been proposed based on a comparison of potential area of colonization and effective colonized area. Presently, macroalgae are determined heuristically (i.e., expert identification of problems based on detrimental impacts of algal biomass on a biological resource) and SAV is determined by observed changes in spatial coverage irrespective of potential for colonization.

The eutrophic rating is expressed as an estuary-wide value, using area-weighting for each of the five variables (e.g., dissolved oxygen), based on concentration, spatial coverage, and frequency of extreme occurrences. The primary symptom expression level is an average of the level of expression values for the two primary symptoms, and the worst of the three secondary symptoms (selected for precautionary reasons) represents the secondary symptom expression level. These values are combined in a matrix to determine the overall eutrophic ranking for each estuary.

Determination of Response—Future Outlook

Response is determined using a matrix that combines susceptibility of the system with expected 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. The intent of the Response component, the least robust of the three, is to highlight systems where presently there is no significant impact but where increased pressure is expected as the watershed is developed. This component should serve to provide an early warning for systems that are at risk from future watershed development in watersheds that might still be protected from future degradation.

Synthesis—Grouping of Pressure, State, and Response Indicators

In an additional modification to the original methodology (ASSETS; Bricker and others 2003), the Influencing Factors, Overall Eutrophic Condition, and Future Outlook are combined into a single overall score falling into one of five categories: high, good, moderate, poet, or bad. These categories match the convention of the E.U. Water Framework Directive (2000/60/EC) and are color coded .providing a simple scale for setting reference conditions useful for different types of systems.

Additional Modifications: NEEA Update Program

Further modifications are being pursued in the NEEA Program, including the development of a type classification based on physical and hydrologic characteristics that influence the expression of nutrient-related impacts, such as phytoplankton blooms and low dissolved oxygen, using a clustering approach (DISCO clustering tool; Smith and Maxwell 2002). The intent is to classify U.S. waterbodies according to potential response to nutrient inputs to facilitate assessment, monitoring, and thus management of nutrient-related water quality problems. Classification is being used in the United States (to address Clean Water Act regulatory requirements (e.g., Environmental Protection Agency (EAP) sponsored Nutrient Criteria Development project) and in the European Union (to address Water Framework Directive requirements, e.g., Bettencourt and others 2004) as a tool to help identify reference conditions and impairments as well as to determine the causes of impairment and appropriate management response. The assumption is that waterbodies within the same group (type) will respond similarly to a particular stressor and likely also to management measures. The approach to this type classification is to identify physical and hydrologic characteristics that will determine the level of response (e.g., growth of algae) of a system, rather than developing groupings (types) based on the response (e.g., algal biomass). This approach considers the potential response within each type of system (see Kurtz and others 2006 for additional classification approaches). The results will be used to reevaluate type-specific reference conditions and thresholds for desirable/undesirable response for indicator variables such as chlorophyll *a* to improve eutrophic status assessment accuracy. For example, the current ''low impact'' range in the ASSETS method of chlorophyll *a* is 0 – 5 μg/L. However, in sensitive systems such as Florida Bay, a concentration of 5 μg/L is indicative of major nutrient-related impacts. Type classification will allow indicator thresholds and ranges to be modified to scales appropriate and relevant to each type of system. For example, in types without SAV under natural conditions, an alternative indicator will be used and other indicator thresholds will be appropriate to the system type, making the assessment more accurate and useful for determining of impairment and possible management remedies.

Preliminary type classification results using the DISCO (Deluxe Integrated System for Clustering Operations) clustering approach are promising (Smith and others 2004) and are presently being tested for load–response relationships using the SPARROW nitrogen load estimates and SeaWiFS 1-km scale color converted to chlorophyll *a* concentrations, This work is being conducted in conjunction with EPA Nutrient Criteria Development and includes participation from EPA, U.S. Geological Survey (USGS), and NOAA in collaboration with additional agencies and universities.

A socioeconomic/human use indicator is being developed to complement the water quality assessment. One promising approach links changes in fish catch rate to changes in water quality (Lipton and Hicks 1999, 2003, 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 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). Additionally, a regional analysis of the Gulf of Maine and Mid-Atlantic systems has been promising and, with further research regarding species appropriate to other regions, could be developed into a nationally applicable assessment tool (Bricker and others 2006).

In addition to the assessment and typology activities of the NEEA Update, the relative importance of various nutrient pollution sources to estuaries is a critical step for improving the method and utilized for evaluating the results and guiding successful coastal management.

Linking Pressure to State and Response: How Can These Results Be Used?

The ASSETS assessment method should be applied on a periodic basis to track trends in nutrient-related water quality over time in order to test management-related hypotheses and provide a basis for more successful management. The null hypothesis being tested in this approach is: The change in anthropogenic pressure as a result of management response does not result in a change of state. The hypothesis is tested, e.g., to verify whether decreased pressure improves State, or whether increased pressure deteriorates State. In many cases, a reduction in pressure will result in an improvement of State, but in some cases, such as naturally occurring harmful algal bloom (HAB) advected from offshore, it will not.

There are several ways to test this hypothesis: (a) Through the use of historical data for the system in question; (b) By comparison to a reference system of a similar type in better/worse State; (c) By enacting changes in nutrient loading through legislation and/or voluntary agreement by discharges and monitoring potential changes in State over time; and (d) Through the use of ecosystem models describing the State by means of indicators such as chlorophyll *a* or dissolved oxygen as a function of nutrient loads and other relevant variables (i.e., ASSETS method). The latter appears to provide the most comprehensive method for determining the changes in a system and reasons for changes from which appropriate management measures can be developed, while minimizing the social costs of scenario analysis.

If the null hypothesis is false, it is then required to evaluate the changes in socioeconomic drivers leading to the required changes in pressure. After these management measures are taken, two subsequent monitoring steps are required: (a) The verification of the effectiveness of the measures as regards changes in pressure via monitoring and periodic assessment of conditions; and (b) The verification that the changes in pressure are producing the desired/predicted changes in state. The costs of implementation of the measures taken (i.e., the changes in Drivers) must be evaluated in the light of the expected gains in total economic value linked to the changes in state. The objective function is the highest net value (total economic value minus costs of implementation) achievable given a limited budget for modification.

Source Apportionment

Primary productivity in aquatic ecosystems is most often related to nitrogen or phosphorus limitations. Nitrogen is most often the limiting factor in estuaries, in contrast to freshwater systems where phosphorus often limits production. Some estuaries do exhibit co-limitation by nitrogen or phosphorus or limitation that varies spatially and by season. The analysis of driving forces and their coupling to the ASSETS framework focuses on nitrogen sources identification for 11 watersheds on the U.S. East Coast. Nitrogen inputs originate from both point and nonpoint sources. Point sources include the following: wastewater treatment plants (WWTP) and industrial discharges. Non-point sources includes the following: agricultural runoff, septic systems, and urban and suburban runoff. Atmospheric deposition of N (AD-N) is also a potentially important source of N for many coastal ecosystems (Valiela and others 1992, Nixon and others 1996, Paerl and others 2002, Whitall and others 2003).

Quantifying the sources of nitrogen pollution to an estuary is necessary for appropriate and effective management strategies to reduce nitrogen loading, and ultimately, the effects of eutrophication.

WATERS N Model Description

Numerical watershed models can provide useful approach for quantifying the relative importance of nitrogen sources to coastal receiving waters. 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 is described briefly here; a full description can be found in Castro and others (2000), Castro and Driscoll (2002), Castro and others (2003), and Whitall and others (2004). Individual model components are described in Table 1.

Atmospheric deposition of inorganic N (AD-N) and nonsymbiotic 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 proportional to AD-N in total N inputs. N export from upland forests is estimated using a nonlinear regression relationship between wet deposition of NH_4^+ and NO_3^- and stream water N export of dissolved inorganic N export of dissolved inorganic N (NH_4^+ and NO_3^-) using results of numerous forest watershed studies in the United States (Neitsch and others 2001, Driscoll unpublished data). The dissolved organic N contribution to the total N load is assumed

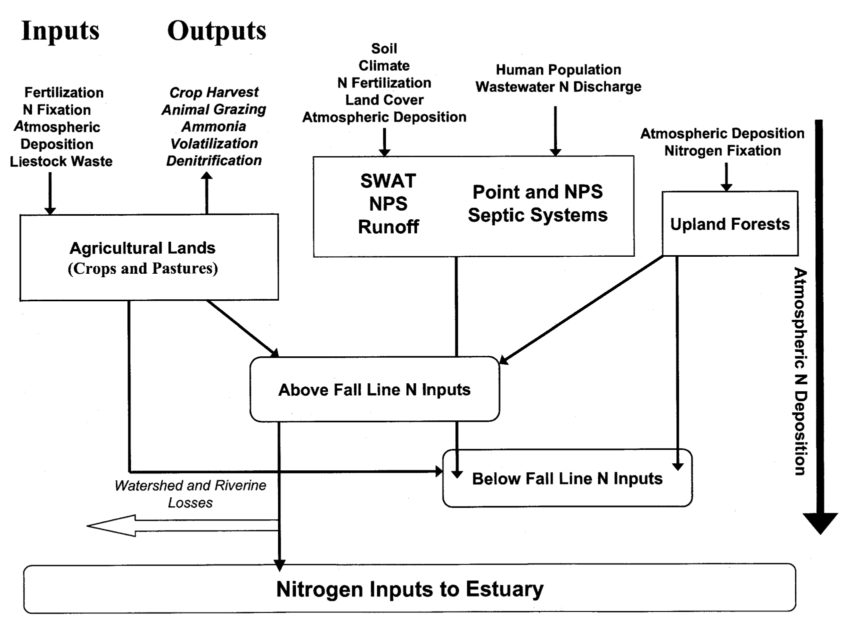

Fig. 3 Conceptual diagram of Watershed Assessment Tool for Evaluating Reduction Strategies for Nitrogen (WATERSN) model

Table 1 Components of WATERSN model

Term	Flux Type	Notes	Reference
N fertilization	Agricultural input	Fertilizer sales data by county	NOAA-SPO 2005[a]
N fixation	Agricultural input	Unique values by crop	Castro and others 2000
Livestock waste	Agricultural input	Difference between feed imports and the production of meat/milk/eggs	Internal model calculation
Atmospheric deposition	Agricultural input	Annual N deposition values from National Atmospheric Deposition Program	National Atmospheric Deposition Program/ National Trends Network 2005[b]
Crop harvest	Agricultural output	Agricultural Census data	NASS 2005[c]
Pasture grazing	Agricultural Joutput	Agricultural Census data	NASS 2005[c]
Volatilization of NH_3	Agricultural output	10% of fertilizer and atmospheric deposition; 15% of animal waste	Schlesinger and Hartley 1992
Denitrification	Agricultural output	10% of inputs	Meisinger and Randall 1991
Wastewater Treatment Plant effluent	Urban export	Based on populatipn on sewer systems	Internal model calculation
Leachate from septic systems	Urban export	Based on population not on sewer systems	Internal model calculation
Nonpoint source runoff	Urban export	From SWAT model[d]	Neitsch and others 2001

[a] National Oceanic and Atmospheric Administration (NOAA) Special Projects Office (SPO) (2005) http://www.spo.nos.noaa.gov/projects/cads.data_references/fertilizers/fertilizer_doc.pdf

[b] http://www.nadp.sws.uiuc./edu/

[c] National Agricultural Statistics Services (NASS) (2005) http://www.nass.usda.gov/QuickStats/

[d] Soil and Water Assessment Tool (SWAT)

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 USGS National Stream Quality Accounting Network for 18 watersheds in the eastern United States 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 from monitoring at gauging stations.

With an understanding of the imperfections of any given model, they can be used to address questions of interest to environmental managers, The WATERSN model was used to estimate 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 as examples of the usefulness of this approach (Fig. 4, Table 2). This model could be applied to the Portuguese systems. Unfortunately, funding and personnel constraints make that application beyond the scope of the current project.

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 of nitrogen sources to east coast estuaries vary by region with striking differences between the Northeast and the Mid-Atlantic.

Results and Discussion

ASSETS Results for Portuguese Systems

Since the original ASSETS evaluation of U.S. estuaries (Fig. 2), the methodology has also been applied to Portuguese systems (Ferreira and others 2003) to test applicability to systems outside the United States. The same criteria and methods were applied to the Portuguese systems as were applied to the U.S. systems, so the results are directly comparable. Table 3a lists physical and demographic characteristics of the 10 systems that have been evaluated, and Table 3b summarizes statistics for the Portuguese and U.S. systems. The Portuguese systems' physical and demographic characteristics fall within the range of the 138 U.S. systems, although the U.S. systems have a much wider range of values and the U.S. systems have a much larger median catchment, estuary area, and estuary volume.

Fig. 4 Nitrogen source apportionment for 11 U.S. East Goast estuaries presented as kg of nitrogen per hectare of watershed area. Location of estuaries (inset)

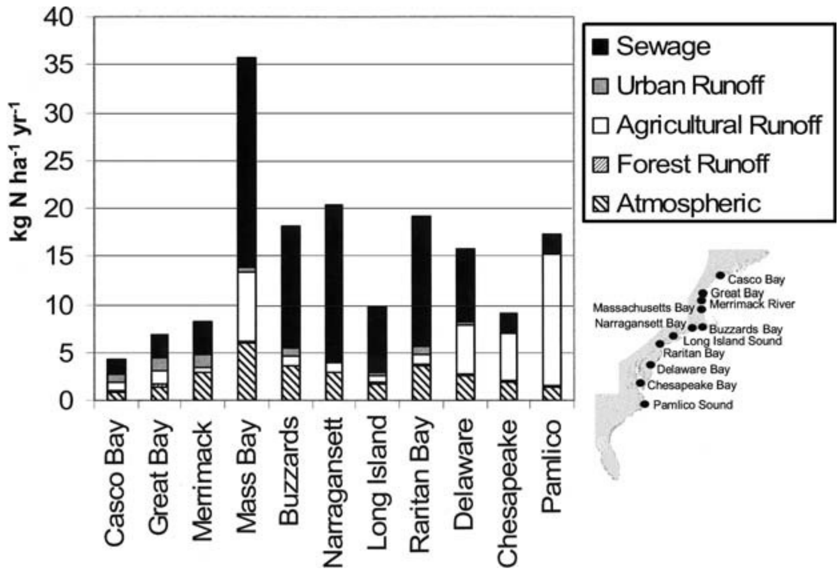

Table 2 Watershed and estuary characteristics for WATERSN model application

System	Watershed area[a] (km^2)	Estuarine area[b] (km^2)	N load per unit watershed arear[a] (kg N $km^{-2}yr^{-1}$)	N load per unit estuary area (tons N km^{-2} yr^{-1})	OEC[c]
Casco Bay	2188	427	449.5	2.3	MH
Great Bay	2491	47	667.8	36.3	MH
Merrimack River	12,458	16	825.1	642.4	U
Massachusetts Bay	2089	768	7408.6	7.9	M
Buzzards Bay	1021	639	1045.0	3.4	ML
Narragansett Bay	4018	416	2101.7	20.3	ML
Long Island Sound	40,774	3259	977.5	12.2	MH
RaritanBay	36,114	799	2110.6	95.4	M
Delaware Bay	30,792	2070	1669.1	25.8	ML
Chesapeake Bay	160,765	5470	919.6	13.1	H
Pamlico Sound	25,090	452	1808.4	8.1	U

[a] From Driscoll and others (2003)

[b] From S. Smith (2003)

[c] From Bricker and others (1999)

OEC Overall Eutrophic Condition, ML moderately low, M moderate, MH moderately high, H high, U unknown

Determination of Pressure—Influencing Factors

Table 4 shows the susceptibility results and the relative input from point and non point sources of nutrients for U.S. and Portuguese systems (see Table 3 for total nitrogen loads). Note that the Portuguese systems are all of moderate or low susceptibility, whereas the U.S. systems are mostly moderate to high. This is due to the larger tidal range in the Portuguese systems and smaller relative depth, suggesting that as a rule there is greater exchange of water relative to total volume in the Portuguese systems than in U.S. systems. Although there are some regional differences with the United States, on a national level nitrogen sources are similar between the two countries, with the dominant source being nonpoint and the majority of nonpoint source-related nutrients coming from agriculture, though the Portuguese systems are slightly more agriculturally dominated than the U.S. systems. Influencing Factor (a combination of nutrient load and susceptibility) is low to moderately high for the Portuguese systems and mostly moderate and moderately high for U.S. systems (Table 5). This difference is caused by the higher susceptibility of the U.S. systems.

Table 3 Characteristics of 10 Portuguese systems (a) and summary characteristics for 10 Portuguese (Ferreira and others 2005) and 139 United States estuaries and coastal waterbodies (b, from Smith 2003)

a. Systems	Catchment area (km^2)	Estuary area[2] (km^2)	Estuary volume[2] (10^6 m^3)	Mean depth (m)	Tidal range (m)	Residence time (days)	Watershed population ($\times 10^3$)	N load/ estuary surface area (10^3 tons km^2 yr^{-1})
Minho estuary	17.1	23	67	4	2	1.5	1,000	0.47
Lima estuary	2.5	5	19	2	2	1	80	0.22
Douro estuary	97.6	6	65	8	2	<2	4123	6.67
Ria de Aveiro	3.4	60	84	1	2	4	700	0.02
Mondego estuary	6.7	9	21	2	3	2	66	0.02
Tagus estuary	80	330	2200	11	2.6	19	9030	0.09
Sado estuary	7.7	170	770	10	2.7	21	270	0.01
Mira estuary	1.6	3	17	6	2.4	—	26	0.05
Ria Formosa	0.8	49	92	2	2	0.3	168	0.02
Gudiana estuary	66.8	18	96	7	2	12	1900	0.56

b.	Catchment area (km^2)	Estuary area (km^2)	Estuary volume (10^6 m^3)	Average depth (m)	Tide height (m)	Tidal FW flushing (days)	Watershed population (10^3)	N Load/ estuary surface area (10^3 tons km^2 yr^{-1})
PT systems						Res time[a]		
Min	0.8	3	17	1	2	0.3	26	0.01
Max	97.6	330	2200	11	3	21	9030	6.67
Median	7.2	20.5	75.5	5	2	3	485	0.07
US systems								
Min	22	1	0.2	0.05	0.03	0	0.196	7.3×10^{-5}
Max	2.9×10^6	6974	99,000	96	5.6	3841	73,009	2.28
Median	3975	237	665	2.84	1.03	4	216	0.01

[a] Note that the available data related to residence time for U.S. systems are tidal freshwater flushing. This will be similar to residence time for systems which are not dominated by riverine flows. Caution should be used when comparing PT with U.S. systems for this variable

Determination of State—Overall Eutrophic Condition

The overall eutrophic conditions in the U.S. systems are moderately low to high, whereas the conditions assessed in Portuguese systems are all low to moderate (Table 5, Fig. 2 and 5). The reason that the Portuguese systems are not as impacted as the U.S. is likely because of the higher tidal range that contributes to shorter residence times.

Determination of Response—Future Outlook

For most U.S. systems, conditions are expected to worsen with only eight systems expected to improve (Table 5). By contrast, half of the tested Portuguese systems were expected to improve, with conditions in the remaining systems expected to remain unchanged (Table 5). This is likely related to investments in WWTP in Portugal over the past two decades, financed by the E.U. Cohesion Fund (European Commission, 2006) since Portugal joined the European Union. Wastewater treatment improvements have occurred in the United States since the 1970s, yielding some point source nutrient reductions. However, additional treatment required to remove nitrogen did not become prominent until the late 1990s. Some of these efforts have resulted in noted improvements (e.g., dissolved oxygen in Long Island Sound), although in some systems these improvements are now being counter balanced by the increased populations in coastal watersheds. In the same manner, it is expected that nutrient inputs to the Portuguese systems will decrease from these improvements, whereas in the United States the nonpoint sources have remained a focus of management efforts.

Synthesis—Grouping of Pressure, State, and Response Indicators

The combination of the three indicators into the single ASSETS score shows that the Portuguese systems all have Moderate to High scores, with lower relative impacts and future conditions expected to remain the same or improve. This contrasts with more than half of the U.S. systems that are rated as Poor or Bad quality because of the higher levels of impact and the expec-

Table 4 Results of susceptibility and analysis of importance of non-point source nutrient loads for U.S. and Portuguese systems (from Bricker and others 1999, Ferreira and others 2003, SPARROW results modified by CADS 1999)

Region	Susceptibility (as number of systems)			Nutrient inputs[a] (as % of systems)	
	High	Moderate	Low	>50% of total input as NPS	Ag as >30% NPS
No.Atlantic	0	6	12	78	0
Mid-Atlantic	15	7	0	91	60
So. Atlantic	8	9	4	100	81
Gulf of Mexico	12	23	2	100	85
Pacific Coast	14	18	7	89	50
U.S. total	49	63	25	92	50
Portugal	0	5	5	89	67

[a] As percent of 130 U.S. systems for which there were Spatially referenced regressions on watershed attributes (SPARROW) estimates and percent of 10 Portuguese systems for which nutrient sources were available

Sparrow; Non-point source (NPS)

Table 5 Results for U.S. and Portugal (PT) for influencing factors, overall eutrophic condition and Determination of Future Outlook

Scale	Influencing factors		Overall eutrophic condition		Determination of future outlook			ASSETS		
	U.S.	PT	U.S.	PT	Scale	U.S.	JPT	Scale	U.S.	PT
High	14	0	16	0	Worsen High	27	0	Bad	18	0
Medium high	43	4	28	0	Worsen Low	59	0	Poor	53	0
Medium	38	1	40	1	No Change	44	5	Moderate	28	3
Medium low	25	2	31	4	Improve Low	8	3	Good	19	2
Low	17	3	7	2	Improve High	0	1	High	2	2
Unknown	2	0	17	3	Unknown	1	1	Unknown	21	3

tation that conditions will become worse (Table 5). These results, however, show the transferability of this methodology and its application to a wide variety of waterbodies, not just U.S. systems, and that results can be compared internationally. A primary strength of this finding is the use of these results to determine appropriate management measures on a broad scale. Of critical importance for management application is the determination of the sources of nutrient input. Although it was not possible to include model analyses for the Portuguese systems at this time, we highlight the use of models for this use in several of the U.S. system, with the understanding that this modeling approach can be applied to Portuguese and other systems, provided the necessary data are available.

WATERSN Results—Northeastern and Middle Atlantic United States

In the Northeast, human sewage is the major source of N loading for all nine estuaries evaluated (36–81%, Figure 4), In addition, runoff from atmospheric deposition (14–35%), urban areas (<1–20%), agricultural systems (4–20%), and forested land (<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. An exception to this pattern is noted for Delaware Bay, where the second highest source of N was agricultural runoff as watershed transition towards more agricultural land use in the Mid-Atlantic region.

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. nonagricultural).

It is important that the atmospheric depositional flux originates from a variety of sources. Because of a lack of comprehensive source-receptor models, it is difficult to determine exactly what portion of the deposited nitrogen originates from each source, but the relative contribution of sources can be quantified from emissions inventories. The airsheds, or atmospheric pollutant source areas, for estuaries on the eastern U.S. seaboard have been delineated previously (Paerl and

Fig. 5 Results of application of NEEA/ASSETS eutrophication assessment method to Portuguese systems for Overall Eutrophic Condition (from Ferreira and others 2003)

others 2002). The sources of nitrogen oxide (NO_x) emissions for the airsheds of the 11 study estuaries vary by airshed and include on-road mobile sources (31–38%), nonroad mobile sources (12–21%), area sources (9–28%), fossil fuel combustion from electric utilities (19–23%), and industrial sources (9–12%) (U.S. EPA 1998). Anthropogenic emissions of ammonia (NH_3) 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 (l–2%) (Strader and others 2001).

The modeled WATERSN loading results presented here compare well with independently published SPARROW model results (Smith and others 1997). The quantification nutrient loading drivers plays a key role in integrating social sciences and natural sciences to provide sustainable ecosystem management. ASSETS provides the core approach for ecosystem assessment, but it is important to note that there are some problems that cannot be improved through management (e.g., some kinds of toxic blooms). For problems that will potentially respond to management measures, once identification of management targets is made and measures implemented, it is important to continue monitoring to evaluate the success of such measures. Most importantly, periodic assessments allow for the adaptation of management measures that are not working and provide a basis for success.

Conclusions

In summary, the NEEA Program provides a strong basis for nutrient-related water quality management through application of the ASSETS assessment method; however, improvements are needed. Presently, steps are being taken to improve the method through development of type-specific criteria to better reflect conditions; a human use/socioeconomic indicator to complement the water quality indicator and put eutrophication-related losses in perspective; and development of tools for managers to evaluate their systems such as the present U.S. online survey to update U.S. results from the 1999 study that automatically calculates the Pressure, State, Response, and ASSETS scores upon entry of specifically requested data (http://www.eutro.us). These concurrent activities will lead to the improvement of the assessment method and the development of analytical and research models and tools for managers to help guide and improve management success for estuaries and coastal resources. The method has proven applicable in systems in the United States, the European Union (e.g., Portugal as shown in this study, Ireland, and China; http://www.eutro.org/syslist.aspx), and thus can be expected to be useful for management of coastal water bodies worldwide.

An important component of the NEEA Program is identification and quantification of nutrient sources to estuaries that are sensitive to eutrophication, allowing an appropriate and successful management response focused on the key driving forces. Here, nitrogen sources to 11 U.S. East Coast estuaries have been reported. There are clear 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 differences highlight the need for type classifications that NEEA Program can provide. These system differences often dictate the management strategies that will be most successful in protecting and remediating specific 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 whereas 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 a variety of 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. Future work will apply these source apportionment models to Portuguese systems.

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