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An integrated methodology for assessment of estuarine trophic status

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Abstract

This paper describes an integrated methodology for the Assessment of Estuarine Trophic Status (ASSETS), which may be applied comparatively to rank the eutrophication status of estuaries and coastal areas, and to address management options. It includes quantitative and semi-quantitative components, and uses field data, models and expert knowledge to provide Pressure-State-Response (PSR) indicators.

A substantial part of the concepts underlying the approach were developed as the United States National Estuarine Eutrophication Assessment (NEEA), which was applied to 138 estuaries in the continental United States. The core methodology relies on three diagnostic tools: a heuristic index of pressure (*Overall Human Influence*), a symptoms-based evaluation of state (*Overall Eutrophic Conditions*), and an indicator of management response (*Definition of Future Outlook*).

Recently, the methodology has been extended and refined in its application to European estuaries, and a more quantitative approach to some of the metrics has been implemented. In particular, the assessment of pressure is carried out by means of simple modeling techniques, comparing anthropogenic nutrient loading with natural background concentrations, and the quantitative criteria for classification of system state based on different symptoms have been refined to improve comparability.

The present approach has been intercalibrated with the original NEEA work, for five widely different U.S. estuaries (Long Island Sound, Neuse River, Savannah River, Florida Bay and West Mississippi Sound) with good results. ASSETS additionally aims to contribute to the EU Water Framework Directive classification system, as regards a subset of water quality and ecological parameters in transitional and coastal waters.

Keywords: Eutrophication; Estuary; Index; NEEA; EU water framework directive; Model

1. Introduction

During the past four decades it has become clear that eutrophication is a significant problem in many estuaries and coastal zones. Symptoms such as high levels of chlorophyll *a* (Boynton et al., 1982; Nixon and Pilson, 1983), excessive seaweed and epiphyte blooms, occurrence of anoxia and hypoxia (Whitledge, 1985; Gerlach, 1990; CENR, 2000), and harmful and toxic algal blooms (ORCA, 1992; Rabalais et al., 1996) have occurred in many areas, including some U.S estuaries, (e.g. toxic blooms in the Pamlico and Nuese River Estuaries, Burkholder et al., 1992a, 1995, 1999; harmful blooms in Lower Laguna Madre, Whitledge and Pulich, 1991) the southern North

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Sea (Gillbricht, 1988), Baltic Sea (Bonsdorff et al., 1997), Mediterranean Sea (e.g. Lac de Tunis: Kelly and Naguib, 1984), Northern Adriatic (Chiaudani et al., 1980), Australia (Hodgkin and Birch, 1982; Hodgkin and Hamilton, 1993) and Japan (Okaichi, 1989; Okaichi, 1997).

Nutrient enrichment of coastal areas may have far-reaching consequences, such as fish-kills (Glasgow and Burkholder, 2000), interdiction of shellfish aquaculture (Joint et al., 1997), loss or degradation of sea grass beds (McGlathery, 2001; Twilley et al., 1985; Burkholder et al., 1992a) and smothering of bivalves and other benthic organisms (Rabalais and Harper, 1992). These modifications have significant economic and social costs (Turner et al., 1998), some of which may be readily identified (e.g. direct costs such as productivity losses), whilst others (e.g. indirect and non-use values) are more difficult to determine and tend to be ignored (Turner et al., 1999).

Eutrophication in estuaries has historically been quantified using the classical freshwater approach (e.g. Carlson, 1977), i.e. through the measurement of variables such as transparency, nutrients and chlorophyll *a* (chl *a*) and the establishment of nutrient-based classification systems, following what Cloern (2001) terms a "Phase I" approach. However, in the last decades it has been recognized that estuarine and coastal eutrophication is potentially a far more subtle problem, which may manifest itself, e.g. through the appearance of nuisance and harmful algae, or through changes in the composition of intertidal and sub-tidal benthic communities. Furthermore, it has become apparent that nutrient concentrations may not be a robust diagnostic variable: high concentrations are not an obligatory indicator of eutrophication, and low concentrations do not necessarily indicate absence of eutrophication (Cloern, 2001; Dettmann, 2001). Nutrients are the primary cause, but there are many other factors that determine the ultimate level and type of expression of eutrophic symptoms within an estuary including tidal exchange, freshwater inflow, etc (Cloern, 1999; NRC, 2000; Boesch, 2002).

Over the last few decades, the increase in research effort and discussion on coastal eutrophication processes has advanced of our understanding of the problems, and produced recommendations for remediation and proposed research (e.g. NAS, 1969; Neilson and Cronin, 1981; Hinga et al., 1991; USEPA, 1994; Bricker and Stevenson, 1996; NRC, 2000). "Threshold risk levels" have been tentatively defined for specific compartments such as submerged aquatic vegetation (SAV) (Stevenson et al., 1993; Burkholder et al., 1992b; Boynton et al., 1996; Dunton, 1996), and increasingly effective models have been developed to explore cause/effect relationships (NOAA and EPA, 1988; Madden and Kemp, 1996; Lowery, 1996; Weisberg et al., 1993; Dettmann, 2001).

Furthermore, the need for evaluating the eutrophication status of estuarine and coastal systems, in order to support policy definition, has led to the development of different methods which use symptoms-based multiparameter assessment. Well-known examples are the United States National Estuarine Eutrophication Assessment (NEEA) (Bricker et al., 1999) and the OSPAR Comprehensive procedure (OSPAR, 2001).

The NEEA approach uses a combination of primary and secondary symptoms to derive an Overall Eutrophic Condition (OEC) index, which is then associated with a measure of Overall Human Influence (OHI) and the Definition of Future Outlook (DFO). This approach contains the essential components of a Pressure (OHI)-State (OEC)-Response (DFO) model, although the OHI also reflects aspects of the state of the system, since it includes a susceptibility metric (Fig. 1).

In this paper we outline the NEEA methodology developed by Bricker et al. (1999), and extend it to:

(i) apply a modeling approach based on the relative contribution anthropogenic of natural nutrient loading to improve the estimation of pressure (OHI);
(ii) combine relational databases, Geographical Information Systems (GIS) and statistical criteria in a more quantitative procedure for the determination of parameter values for evaluation of state (OEC).

Some key results of the application of NEEA are given for a range of estuarine systems, covering widely different conditions (tidal amplitude, nutrient loading, discharge regime). The application of the ASSETS methodology is shown for two European and five U.S. estuaries, and an intercalibration of results with the original NEEA approach is illustrated for 82 U.S. estuaries.

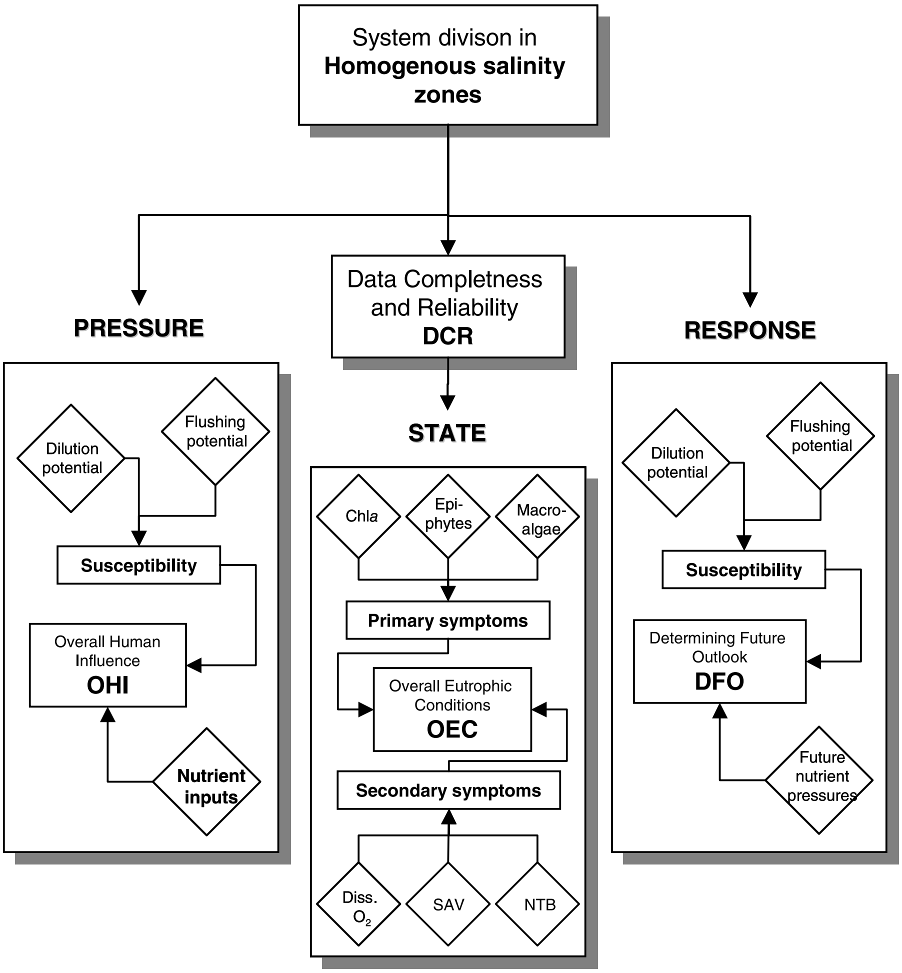

Fig. 1. Flow chart of the ASSETS methodology.

2. Methodology

2.1. Indicator selection and characterization

The NEEA methodology has been described in detail by Bricker et al. (1999). Sixteen nutrient related water quality parameters were considered (Table 1). These eutrophication indicators were selected in order to:

- Ensure that accurate characterization of eutrophic conditions could be accomplished and compared among highly varied systems;
- Allow a clear separation of estuaries, bearing in mind that eutrophication is a process rather than a state.

Although not all parameters exist or were measured for all systems, the suite used is broad enough to assess all estuarine types, with emphasis on the magnitude, timing, and predictability of extreme conditions of various indicators observed during the annual cycle.

The response ranges (Table 2) were selected to be simple to use and to separate estuaries on a gradient whenever possible. The value ranges were developed from data for the whole U.S. and from discussions

Table 1
List of nutrient related water quality parameters considered in the overall U.S. NEI survey

Parameters	Existing conditions	Trends
Chlorophyll *a*	Surface concentrations Hypereutrophic (>60 ug l^{-1}) High (>20, $\leq$60 ug l^{-1}) Medium (>5, $\leq$20 ug l^{-1}) Low (>0 and $\leq$5 ug l^{-1}) Limiting factors to algal biomass (N, P, Si, light, other) Spatial coverage[d], months of occurrence, frequency of occurrence[e]	Concentrations[a,b] Limiting factors Contributing factors[c]
Turbidity	Secchi disk depths High (<1 m) Medium ($\geq$1, $\leq$3 m) Low (>3 m) Blackwater area Spatial coverage[d], months of occurrence, frequency of occurrence[e]	Concentrations[a,b] Contributing factors[c]
Suspended solids	Concentrations Problem (significant impact upon biological resources) No problem (no significant impact) Months of occurrence, frequency of occurrence[b]	(No trends information collected)
Nuisance algae Toxic algae	Occurrence Problem (significant impact upon biological resources) No problem (no significant impact) Dominant species Event duration (hours, days, weeks, seasonal, other) Months of occurrence, frequency of occurrence[b]	Event duration[a,b] Frequency of occurrence[a,b] Contributing factors[c]
Macroalgae	Abundance	Abundance[a,b]
Epiphytes	Problem (significant impact upon biological resources) No problem (no significant impact) Months of occurrence, frequency of occurrence[e]	Contributing factors[c]
Nitrogen	Maximum dissolved surface concentration High ($\geq$1 mg l^{-1}) Medium ($\geq$0.1, <1 mg l^{-1}) Low ($\geq$0 and <0.1 mg l^{-1}) Spatial coverage[d], months of occurrence	Concentrations[a,b] Contributing factors[c]
Phosphorus	Maximum dissolved surface concentration High ($\geq$0.1 mg l^{-1}) Medium ($\geq$0.01, <0.1 mg l^{-1}) Low ($\geq$0 and <0.01 mg l^{-1}) Spatial coverage[d], months of occurrence	Concentrations[a,b] Contributing factors[c]
-Anoxia (0 mg l^{-1}) -Hypoxia (>0, $\leq$2 mg l^{-1}) -Biol. Stress (>2, $\leq$5 mg l^{-1})	Dissolved oxygen concentration Observed No observed Stratification (degree of influence) High Medium Low	Min. avg. monthly bottom dissolved oxygen conc.[a,b] Frequency of occurrence[a,b] Event duration[a,b] Spatial coverage[a,b] Contributing factors[c]

Table 1 (*Continued*)

Parameters	Existing conditions	Trends
	Not a factor	
	Water column depth	
	Surface	
	Bottom	
	Throughout the water column	
	Spatial coverage[d], months of occurrence, frequency of occurrence	
Primary productivity	Dominant primary producer: pelagic, benthic, other	Temporal shift
Planktonic community	Dominant taxonomic group (number of cells): diatoms, flagellates, blue-green algae, diverse mixture, other	Contributing factors
		Temporal shift
		Contributing factors[b]
Benthic community	Dominant taxonomic group (number of organisms): Crustaceans, Molluscs, Annelids, Diverse mixture, other	Temporal shift
		Contributing factors[c]
Submerged aquatic vegetation (SAV)	Spatial coverage[a]	Spatial coverage[a,b]
Intertidal wetlands		Contributing factors[c]

[a] Direction of change: increase, decrease, no trend.
[b] Magnitude of change: high (>50, ≤100%), medium (>25, ≤50%), low (>0, ≤25%).
[c] Point source(s), nonpoint source(s), other.
[d] Spatial coverage (% of salinity zone): high (>50, ≤100%), medium (>25, ≤50%), low (>10, ≤25%), very low (>0, ≤10%), no SAV/Wetlands in system.
[e] Frequency of occurrence: episodic (conditions occur randomly), periodic (conditions occur annually or predictably), persistent (conditions occur continually throughout the year).

with regional experts, and the criteria used to classify responses were designed to distinguish the magnitude of eutrophic symptoms among estuaries. Since estuaries within a region may respond similarly and/or be subject to similar input sources, these criteria may not distinguish among estuaries within a region, however, they do distinguish among estuaries on a wider geographic basis.

2.2. Data acquisition

The data used for determination of OEC were collected in a series of surveys carried out by NOAA on eutrophic conditions and trends in 138 U.S. estuaries and the Mississippi/Atchafalaya River Plume (NOAA, 1996, 1997, 1997a,b, 1998, 1999). The estuaries included in the assessment are those characterized in the National Estuarine Inventory (NEI; NOAA, 1985) and are representative of the U.S. estuarine resources with regard to size, salinity distribution and other physical and hydrological characteristics. Together, they represent >90% of the U.S. estuarine surface area and >90% of the freshwater inflow to the coastal region. The NEI salinity characterization provides a consistent spatial framework for information collection. Each parameter was originally characterized for three salinity zones defined in the NEI: Tidal freshwater (<0.5 psu), Mixing (0.5–25 psu) and Seawater (>25 psu), although not all salinity zones are present in all estuaries. This model provides a consistent basis for comparisons among these highly variable systems.

Data acquisition was implemented by questionnaire on existing conditions (i.e. observations during a typical flow year) and for available trends from 1970 to present (Hinga et al., 1991); the responses were subsequently complemented by site visits and discussion with regional experts. Ancillary information on the timing of events was also requested, including time-

Table 2
Indicator parameters and rationale, thresholds and justification for primary and secondary symptoms of estuarine eutrophication

Indicator and rationale	Thresholds and ranges	Threshold justification
Algal blooms: Chl *a* is used as an indicator of phytoplankton primary productivity. Highest concentrations in an estuary during the annual bloom period were recorded. High levels cause dieoff of SAV and low bottom water dissolved oxygen.	Hypereutrophic: >60 μg Chl *a* l^{-1} High: >20 but ≤60 μg Chl *a* l^{-1} Medium: >5 but ≤20 μg Chl *a* l^{-1} Low: >0 but ≤5 μg Chl *a* l^{-1}	• Estuaries with highest annual Chl *a* less than 5 μg l^{-1} appear unimpacted (Nixon and Pilson, 1983), however, this level is detrimental to survival of corals (Lapointe and Matzie, 1996). • At 20 μg l^{-1} SAV shows declines (Stevenson et al., 1993) and community shifts from diverse mixture to monoculture (Twilley et al., 1985). • At 60 μg l^{-1} high turbidity and low bottom water dissolved oxygen are observed (Jaworski, 1981).
Macroalgae and epiphytes: excessive macroalgal and epiphyte growth is known to suffocate bivalves and cause dieoff of SAV.	Problem: detrimental impact to biological resources (e.g. dieoff of SAV) No problem: no apparent impacts on biological resources	There is no standard measure or threshold above which macroalgae and/or epiphytes are considered to be a problem to the biological resources, and it is rare to find quantitative information. However some studies show that: • Macroalgae (*Ulva* or *Enteromorpha*) above 100 g dry wt m^{-2} causes SAV dieoff (Dennison et al., 1992). • Epiphyte colonizing SAV at a dry weight equal to the dry wt cm^{-2} of the host plant will cause dieoff of the host plant (Dennison et al., 1992). • In the absence of a standard concentration determinations were heuristic.
Nuisance and toxic blooms: problem conditions for toxic blooms result from the production of toxin by the organism. For nuisance blooms, excessive abundance of small organisms that clog siphons of filter feeders.	Problem: detrimental impact to biological resources (e.g. dieoff of filter feeding bivalves and fish, respiratory irritation) No problem: no apparent impacts on biological resources	Nutrient input increases cause changes in nutrient ratios that promote growth of nuisance and toxic algae (Rabalais et al., 1996). • Threshold determination is difficult because toxicity of chemicals produced by the different species vary, e.g. some dinoflagellates become toxic at cell counts in excess of 10^6 cells l^{-1}, others are a problem at 10^5 cells l^{-1}; *Pfiesteria piscicida* is toxic at levels below 10^2 cells l^{-1} (Burkholder et al., 1992a,b). • In the absence of a standard concentration determinations were heuristic.
Dissolved oxygen concentrations: bottom water dissolved oxygen concentration has become a standard measurement to assess the general condition of a water body due to its importance to the survival of benthic organisms.	Anoxia: 0 mg l^{-1} Hypoxia: >0 but ≤2 mg l^{-1} Biologically stressful: >2 but ≤5 mg l^{-1}	• Bottom water concentrations of 2 mg l^{-1} or less, have significantly reduced benthic macroinfauna and epifauna, and success of trawling for demersal species (Rabalais and Harper, 1992). The range of 2–5 mg l^{-1} is included in this survey since field and laboratory observations have also shown oxygen stress responses in invertebrate and fish fauna at these concentrations (Rabalais and Harper, 1992).
Submerged aquatic vegetation (SAV): the measure of SAV is spatial coverage since this is the most common data available, though diversity and density of plants is available for some estuaries.	High: ≥50 and ≤100% estuarine surface water area Medium: ≥25% but <50% of estuarine surface water area Low: ≥1% but <25% estuarine surface water area Very low: ≥0 but <10%	Submerged vascular plants, such as *Zostera marina* and *Potamogeton perfoliatus*, are though to play a vital role in the ecology of nearshore environments to depths of 1–2 m. These plants attenuate variable inputs of nutrients and sediment, and are thought to be invaluable nursery areas. In relatively pristine waterbodies, SAV thrive while die-off and absence of SAV is generally believed to be an indication of an eutrophic condition, associated with high turbidity caused by increased nutrient and Chl *a* concentrations (Orth and Moore, 1984; Stevenson et al., 1993; Boynton et al., 1996). Additionally, high nutrient concentrations may cause an imbalance in nutrient supply ratios leading to dieoff of SAV (Burkholder et al., 1992a,b).

frame of extreme conditions, whether events are periodic or episodic and typical event duration (e.g. days, weeks, seasonal). The trends information collected by the survey is the most variable, with some systems having no trends data and others (e.g. Narragansett Bay) having information from as far back as the beginning of the 20th century.

A reliability assessment of each status and trend response was requested to provide a basis for comparing information from the same estuary and between estuaries. The reliability assessment evaluation provides a method of describing how accurately the information collected represents the conditions within an estuary. Since this information varies from statistically tested scientific data to general observations, the reliability assessment varies from "highly confident" to "speculative".

2.3. Index development

2.3.1. Pressure—overall human influence

In the original NEEA application, a workshop-based approach was used to assess pressure factors: Participants used eutrophic condition assessment results in combination with other U.S. databases including SPARROW estimates of N input (Smith et al., 1997), watershed population density (US Bureau of Census, undated), and susceptibility (NOAA and EPA, 1988). The ASSETS methodology has applied a simple model to combine human pressure and system susceptibility, which is described below.

2.3.1.1. Equations for the determination of OHI. If only conservative (i.e. mixing) processes are considered, an equation for OHI may be derived based on a simple "Vollenweider" mass balance model, modified to include the dispersive exchange between an estuarine black box and the ocean (Ferreira, 2000). Only dissolved inorganic nitrogen (DIN) is considered, and non-conservative terms are neglected since only the *relative proportions* of DIN derived from anthropogenic and ocean sources are of interest in the evaluation of pressure. Although nitrogen sources and sinks, e.g. due to benthic fluxes and primary production, clearly affect the final DIN concentration, these will be evaluated as metrics of system state, in the second stage of the methodology. Even if some of these processes were considered as secondary internal nitrogen sources, they would affect only the magnitude of the nitrogen load, not the relative importance of anthopogenic and natural sources.

$$\frac{\mathrm{d}M_\mathrm{w}}{\mathrm{d}t} = M_\mathrm{in} - M_\mathrm{out} \qquad (1)$$

where M_w is the mass of nitrogen in the estuary (kg); t is the time (s); M_in is nitrogen loading to the estuary ($\mathrm{kg\,s^{-1}}$); M_out is nitrogen discharge from the estuary ($\mathrm{kg\,s^{-1}}$).

M_out is composed of an advective outflow term and a dispersive exchange term (Eq. (2)).

$$M_\mathrm{out} = m_\mathrm{out} v_\mathrm{out} + k_\mathrm{e,s}\,(m_\mathrm{w} - m_\mathrm{sea}) \qquad (2)$$

where m_w is nitrogen concentration in the estuary ($\mathrm{kg\,m^{-3}}$); m_out is nitrogen concentration in the outflow ($=m_\mathrm{w}$ for a one box model) ($\mathrm{kg\,m^{-3}}$); v_out is advective outflow (=river inflow) ($\mathrm{m^3\,s^{-1}}$); m_sea is nitrogen concentration in the ocean ($\mathrm{kg\,m^{-3}}$); $k_\mathrm{e,s}$ is bulk dispersion coefficient between the estuary and ocean ($\mathrm{m^3\,s^{-1}}$).

Which allows Eq. (1) to be rewritten as:

$$\frac{\mathrm{d}M_\mathrm{w}}{\mathrm{d}t} = M_\mathrm{in} - m_\mathrm{out} v_\mathrm{out} - k_\mathrm{e,s}\,(m_\mathrm{w} - m_\mathrm{sea}) \qquad (3)$$

For the hypothetical case where there is no nitrogen in seawater (i.e. $m_\mathrm{sea} = 0$), and considering $M_\mathrm{in} = Qm_\mathrm{in}$, and $v_\mathrm{out} = Q$, where Q is the river flow ($\mathrm{m^3\,s^{-1}}$) and m_in the nitrogen concentration in the inflow, Eq. (3) may be expressed as:

$$\frac{\mathrm{d}M_\mathrm{h}}{\mathrm{d}t} = Qm_\mathrm{in} - Qm_\mathrm{out} - k_\mathrm{e,s}\, m_\mathrm{h} \qquad (4)$$

where M_w becomes M_h, the human-derived mass, and m_w becomes m_h, the human-derived concentration. If we consider a steady state for salinity:

$$k_\mathrm{e,s} = \frac{Qs_\mathrm{e}}{\Delta s} \qquad (5)$$

where s_e is mean estuarine salinity (no units); t is time (s); Δs is difference between offshore salinity s_o and mean estuary salinity (no units) it follows that, if the system is well mixed (i.e. $m_\mathrm{out} = m_\mathrm{h}$):

$$\frac{\mathrm{d}M_\mathrm{h}}{\mathrm{d}t} = Qm_\mathrm{in} - Qm_\mathrm{h} - \frac{Qs_\mathrm{e}}{\Delta s} m_\mathrm{h} \qquad (6)$$

Considering that for a sufficiently large integration period (e.g. over a year) $\mathrm{d}M_\mathrm{h}/\mathrm{d}t = 0$, i.e. the system is in steady state:

$$\frac{m_h s_e}{\Delta s} = m_{in} - m_h \quad (7)$$

Which allows m_h, the nitrogen concentration in the estuary to be expressed simply as:

$$m_h = \frac{m_{in}}{1 + s_e/\Delta s} \quad (8)$$

Which rearranged becomes:

$$m_h = \frac{m_{in}(s_o - s_e)}{s_o} \quad (9)$$

Eq. (9) gives the nitrogen concentration in the estuary due solely to basin loading, but accounts for the dilution effect of tidal exchange, which is reflected in the salinity terms. Conversely, if only nutrient input from offshore seawater is considered, Eq. (1) may be rearranged by neglecting M_{in}, since human-derived land input is zero:

$$\frac{dM_b}{dt} = -m_{out} v_{out} - k_{e,s}(m_w - m_{sea}) \quad (10)$$

where M_w becomes M_b, the background mass, and m_w becomes m_b, the background concentration. Considering $v_{out} = Q$ and $m_{out} = m_b$ (see above) and Eq. (5), Eq. (10) may be rewritten as:

$$\frac{dM_b}{dt} = -Qm_b - \frac{Qs_e m_b}{\Delta s} + \frac{Qs_e m_{sea}}{\Delta s} \quad (11)$$

Considering, as before that the system is in steady-state, and canceling Q:

$$\frac{s_e m_{sea}}{\Delta s} = m_b \left(1 + \frac{s_e}{\Delta s}\right) \quad (12)$$

which may be rearranged to yield:

$$m_b = \frac{m_{sea} s_e}{s_o} \quad (13)$$

From Eqs. (9) and (13) m_c, the expected total concentration of DIN, considering only conservative processes may be obtained as:

$$m_c = m_h + m_b \quad (14)$$

and the overall human influence is defined as m_h/m_c expressed as a percentage, which is classified into one of five grades (Table 3). This approach considers that the background nutrient loads from the watershed are negligible compared to human pressure.

There are several aspects regarding the use of the above equations which need careful consideration:

Table 3
Thresholds and categories used to classify overall human influence

Class	Thresholds	Score
Low	0 to <0.2	5
Moderate low	>0.2 to 0.4	4
Moderate	>0.4 to 0.6	3
Moderate high	>0.6 to 0.8	2
High	>0.8	1

(i) Apart from the natural difficulty in establishing the mean salinity of an estuarine system, the concept of mean salinity only makes sense in systems where there is some regularity in the river discharge. In torrential estuaries, such as those of the southern and western U.S. and southern Europe, where rainfall is concentrated in a short period of the year and peak discharges may be two orders of magnitude above the modal flow, it is more appropriate to use the median salinity for calculating dilution;
(ii) In cases where there is pronounced vertical stratification, both the dilution volume and the estuarine salinity should be that of the upper layer, i.e. surface layer s_e should be used. Possible improvements to the model in these cases include the addition of a vertical dispersion coefficient and the inclusion of a different nutrient concentration for each layer;
(iii) Most estuarine systems are subject to human-derived nutrient inputs both from upstream watershed sources and from direct discharges of effluents into the estuary itself. The loading from the estuarine perimeter may easily be combined with the river-borne loading as a summation term in cases where both are important;
(iv) In coastal lagoons, where river inputs are not important, the nutrient loading may be essentially due to urban effluents and diffuse discharges. For such cases, the present approach will not work, since it considers freshwater discharge as the main nutrient vector to an estuary.

2.3.2. State—overall eutrophic condition

A subset of six parameters from the set of 16 given in Table 1 was selected to provide an index of state, expressed as overall eutrophic condition. These are divided into two groups, indicative of primary (early)

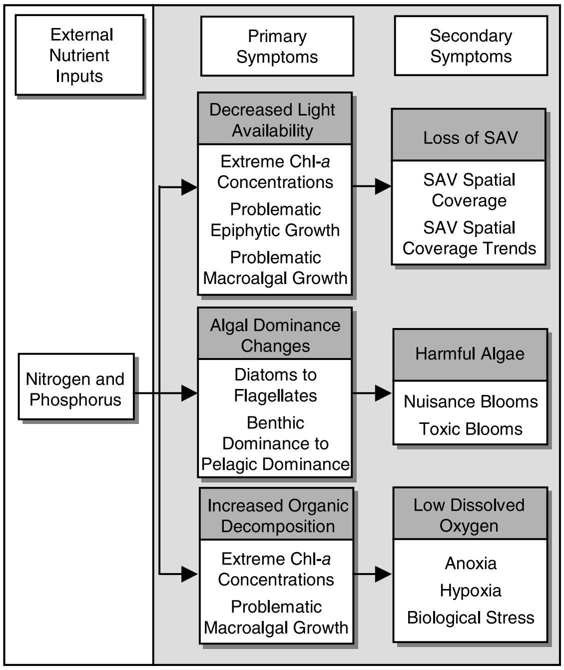

Fig. 2. Conceptual model of primary and secondary symptoms of eutrophication.

and secondary (advanced) symptoms of eutrophication. Chlorophyll *a*, macroalgae and epiphytes are considered to be primary symptoms—excessive concentration or abundance are considered to diagnose early stages of an eutrophication problem. Low dissolved oxygen (DO), losses of SAV, and occurrence of nuisance and/or toxic algal blooms are considered to be secondary symptoms, i.e. indicators of well developed eutrophic conditions (Fig. 2).

In NEEA, a method was developed to combine results for this subset of symptoms (parameters) into an indicator of overall eutrophic condition based on the concentration, spatial coverage, and frequency of occurrence of extreme or problem occurrences. No formulation was developed, but rather a logic stepwise decision method was used (Table 4):

1. For each primary symptom an area weighted expression value for each zone was determined, and the symptom level of expression S_l was then obtained by summation (Eq. (15)).

$$S_l = \sum_{1}^{n} \left(\frac{A_z}{A_e} E_l \right) \qquad (15)$$

where A_z is the surface area of each zone; A_e is the total estuarine surface area; E_l is the expression value at each zone; n is the number of estuarine zones.

2. The level of expression of the primary symptoms for the estuary P_l is determined by calculating the average of the three estuary level of expression values (Eq. (16)) and the estuary is then assigned a category for primary symptoms according to Table 5.

$$P_l = \frac{1}{p} \sum_{1}^{p} \left[\sum_{1}^{n} \left(\frac{A_z}{A_e} E_l \right) \right] \qquad (16)$$

where p is number of primary symptoms.

3. For each secondary symptom (dissolved oxygen, submerged aquatic vegetation loss and nuisance and toxic blooms), an area weighted expression value for each zone is determined as described in (1) above. The level of expression of secondary symptoms for the estuary is determined by choosing the highest of the three estuary level symptom expression values. Secondary symptoms are considered to be a clear indicator of problems, and the application of the precautionary principle means that the highest (worst-case) value dictates the classification. The estuary is then assigned a category for secondary symptoms according to Table 5.
4. Finally, the primary and secondary symptoms are compared in a matrix to determine an overall ranking of eutrophic conditions for the estuary (Fig. 3).

In the U.S. NEEA study, the assessments for each of the estuaries studied were reviewed and interpreted at a National Assessment Workshop by experts familiar with local conditions.

ASSETS develops the concepts in several ways, mainly by providing a more robust framework for evaluating the OEC index. The key improvements, which were applied to four North-East Atlantic estuaries in the European Union, are described below.

2.3.2.1. Data assimilation. A relational database has been used to store the raw data required for calculation of OEC, and combined with a geographical information system (GIS) to improve zone definition and to calculate weighted values for each parameter. A GIS system based on the bathymetry grid was implemented, and salinity zones were determined, using median values extracted from the database—the

Table 4
Logical decision process for determination of overall eutrophic condition

PRIMARY SYMPTOMS

Chlorophyll a

IF	*AND*	*AND*	*THEN*	
Concentration	Spatial coverage	Frequency	Expression	Value
Hypertrophic or High	High	Periodic	High	1
	Moderate	Periodic	High	1
	Low	Periodic	Moderate	0.5
	Very low	Periodic	Moderate	0.5
	High	Episodic	High	1
	Moderate	Episodic	Moderate	0.5
	Low / Very Low	Episodic	Low	0.25
	Any Spatial Coverage	Unknown	Flag A	0.5
	Unknown	Any frequency	Flag A	0.5
Medium	High	Periodic	High	1
	Moderate	Periodic	Moderate	0.5
	Low / Very low	Periodic	Low	0.25
	High	Episodic	Moderate	0.5
	Moderate / Low / Very Low	Episodic	Low	0.25
	Any Spatial coverage	Unknown	Flag A	0.5
	Unknown	Any frequency	Flag A	0.5
Low	Any spatial coverage	Any frequency	Low	0.25
Unknown	Unknown	Unknown	Not included in calculation at zone level	

Epiphytes

IF	*AND*	*THEN*	
Problems	Frequency	Expression	Value
Observed	Periodic	High	1
	Episodic	Moderate	0.5
	Unknown	Flag B	0.5
Unkonwn	Unknown	Not included in calculation at zone level	

Macroalgae

IF	*AND*	*THEN*	
Problems	Frequency	Expression	Value
Observed	Periodic	High	1
	Episodic	Moderate	0.5
	Unkonwn	Flag C	0.5
Unknown	Unknown	Not included in calculation at zone level	

SECONDARY SYMPTOMS

Dissolved Oxygen

IF	*AND*	*AND*	*THEN*	
Observed	Spatial coverage	Frequency	Expression	Value
Anoxia	High	Periodic	High	1
	Moderate	Periodic	High	1
	Low	Periodic	Moderate	0.5
	Very Low	Periodic	Low	0.25
	High	Episodic	Moderate	0.5
	Moderate / Low / Very Low	Episodic	Low	0.25
	Unknown	Any frequency	Flag A	0.25
Hypoxia	High	Periodic	High	1
	Moderate	Periodic	Moderate	0.5
	Low / Very Low	Periodic	Low	0.25
	High	Episodic	Moderate	0.5
	Moderate / Low / Very Low	Episodic	Low	0.25
	Unknown	Any frequency	Flag B	0.25
Biological stress	High	Periodic	Moderate	0.5
	Moderate / Low / Very Low	Periodic	Low	0.25
	Any spatial coverage	Episodic	Low	0.25
	Unknown	Any frequency	Flag C	0.25

SAV Loss

IF	*AND*	THEN	
Problems	Magnitude of Loss	Expression	Value
Observed	High	High	1
	Moderate	Moderate	0.5
	Low	Low	0.25
	Unknown	Flag D	0.25

Nuisance and Toxic Blooms

IF	*AND*	*AND*	*THEN*	
Problems	Duration	Frequency	Expression	Value
Observed Nuisance Blooms	M, WM, WS, S, PR	Periodic	High	1
	DW, W, V	Periodic	Moderate	0.5
	D	Periodic	Low	0.25
	M, WM, WS, S, PR	Episodic	Moderate	0.5
	DW, V, W	Episodic	Low	0.25
	D	Episodic	Low	0.25
	Unknown	Any frequency	Flag E	0.25
Observed Toxic Blooms	M, WM, WS, S, PR	Periodic	High	1
	DW, W, V	Periodic	Moderate	0.5
	D	Periodic	Low	0.25
	M, WM, WS, S, PR	Episodic	Moderate	0.5
	DW, W, V	Episodic	Low	0.25
	D	Episodic	Low	0.25
	Unknown	Any frequency	Flag F	0.25

Table 5
Categories for primary and secondary symptoms

Estuary expression value	Level of expression category
≥0 to ≤0.3	Low
>0.3 to ≤0.6	Moderate
>0.6 to ≤1	High

median avoids excessive weighting of low or high outliers in the data distribution. An application of the method is illustrated in Fig. 4. The spatial weight of each sampling station, calculated through GIS and the Thiessen polygon method, was also used to analyze the spatial coverage and the frequency of a given parameter within the salinity zone, in the calculation of data completeness and reliability.

2.3.2.2. Calculation of symptom values. Some primary symptoms (e.g. epiphytes) and secondary symptoms (e.g. toxic blooms) may only be assessed heuristically. Others, however, such as chlorophyll *a* (primary) and dissolved oxygen (secondary) are evaluated on the basis of quantitative values. In order to improve comparability between systems, ASSETS extends the original NEEA approach by setting statistical criteria which are used to obtain overall values for each salinity zone from the dataset. It is recognized that the calculation of chlorophyll *a* concentrations must be based on commonly observed peaks, rather than a single exceptional one, and must reflect a significant event in space and/or time. Similarly, low values of dissolved oxygen should be representative of system conditions, and not a single minimum value. This follows the philosophy applied by the NEEA study, and has been defined in the present work using a percentile system. The criteria used have been the percentile 90 value for chlorophyll *a*, and the percentile 10 value for dissolved oxygen. The stations for each salinity zone are grouped as metadata (Fig. 5) and the data extracted are processed in a spreadsheet to determine the input values for the symptom expression calculations.

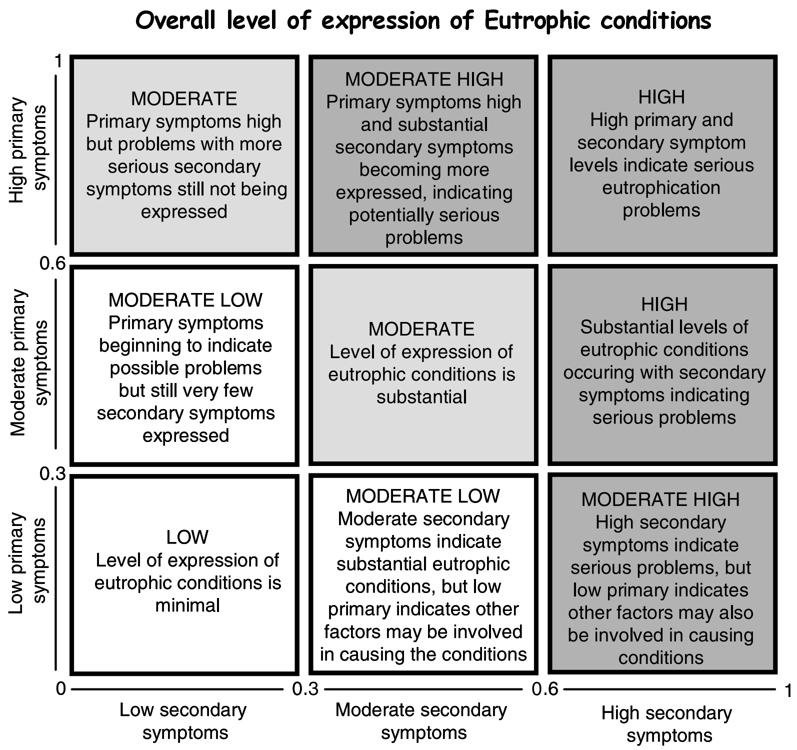

Fig. 3. Determination of overall eutrophic condition based on primary and secondary symptoms.

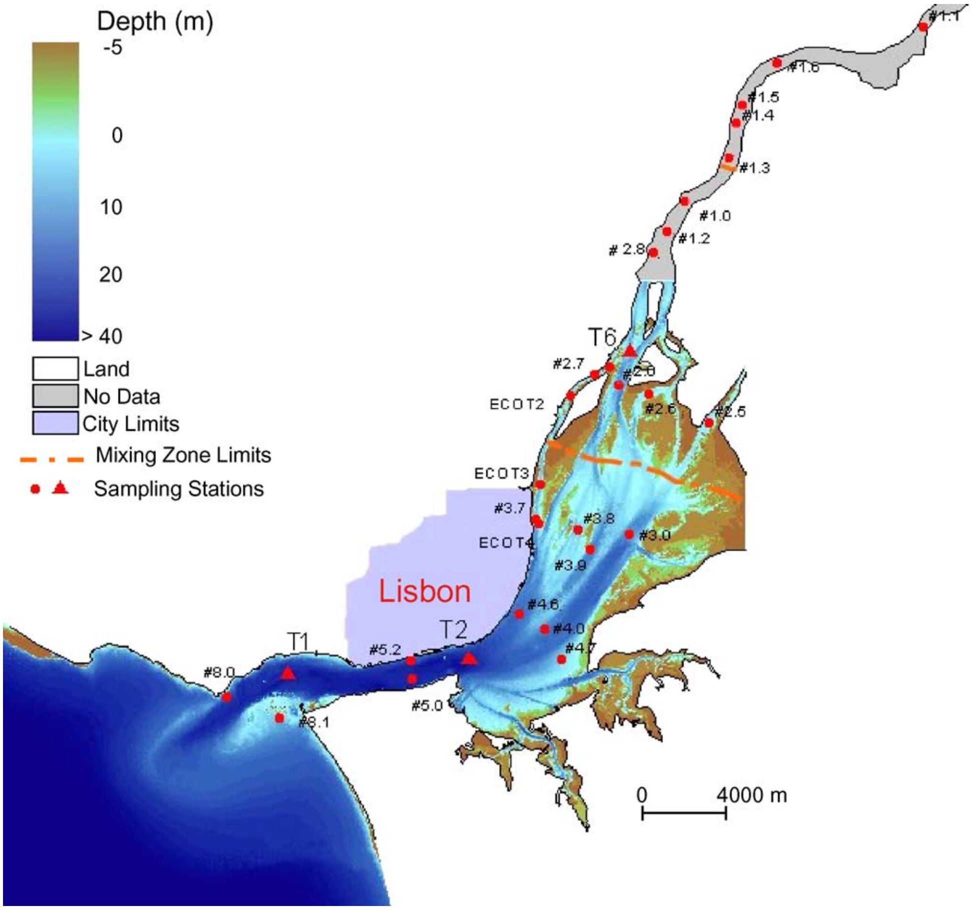

Fig. 4. Zonation of an estuary (Tagus, Portugal) for salinity, using a relational database and GIS.

2.3.3. Response—determination of future outlook

The response is based on an assessment of the susceptibility of the system and its foreseeable evolution. The susceptibility component of the approach evaluates the capacity of a system to dilute and/or flush nutrients (Fig. 6) and is combined with a projection of future outlook. In NEEA this was initially based on demographic projections, which were complemented by expert knowledge to grade a system into one of three categories:

1. Future nutrient pressures decrease;
2. Future nutrient pressures are unchanged;
3. Future nutrient pressures increase.

The decision chart for definition of future outlook, based on susceptibility and future nutrient pressures, is shown in Fig. 7. This is an area where development is clearly needed, in order to provide a more robust framework for including response into the ASSETS methodology. Assessment of nutrient pressures must be carried out based on a combination of drivers, which include demographic trends, treatment and remediation plans, and changes in watershed uses, particularly in agricultural practices (see, e.g. Boesch et al., in prep). Since these drivers will affect pressures, but the state of an estuary will be related not only to the pressures but also to physical factors such as susceptibility, there is a clear need for screening models (e.g. Tett et al., in press) which will include elements from both natural and social sciences in order to explore future management scenarios.

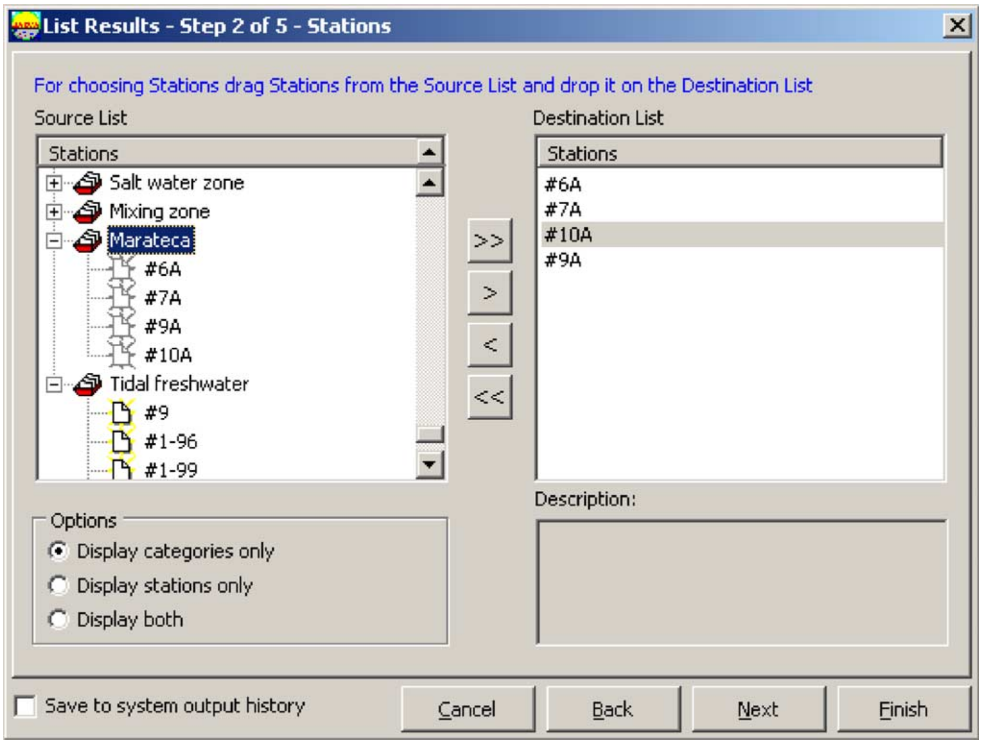

Fig. 5. Metadata for sampling stations, grouped by salinity zone, used for determining OEC symptoms.

2.4. Synthesis—grouping of pressure, state and response indicators

The representation of the ASSETS indices, which are a combination of the three components, is carried out by combining the various scores to provide an overall grade. The individual classifications for pressure, state and response shown in Table 6 are combined to provide a grade which may fall into one of five categories: High, good, moderate, poor or bad. These categories are colour-coded following the convention of the EU Water Framework Directive (2000/60/EC), and provide a scale for setting reference conditions for different types of transitional waters, with regard to eutrophication. There are five possible grades for each component, which theoretically allows 5^3 possibilities, but 31 combinations were excluded as being highly improbable or impossible. Table 6 includes 94 different combinations, which were distributed heuristically.

The *High* grade will not be assigned if the expected response will worsen system conditions, but a system may be rated as *Good* based on high or good conditions of pressure and state, even if the expectation is that it will worsen in the future. A grade of *Moderate* allows the greatest combination of pressure and response, as long as the state generally scores in the *Moderate low* or *Moderate* OEC classes. Poor and Bad grades reflect a range of undesirable pressure and state conditions, even if there are management plans for recovery. Since the response metric also includes susceptibility (Fig. 7), if high pressures lead to an undesirable state, it is unlikely that a system will be highly responsive to remediation in the short-term, because it will most likely be moderately or highly susceptible.

3. Results and discussion

The focus of this paper is on the ASSETS methodology, which means that only a relatively short set of results is presented, covering the following two points:

- Illustration of the range of systems studied in NEEA, with examples of how the developments in

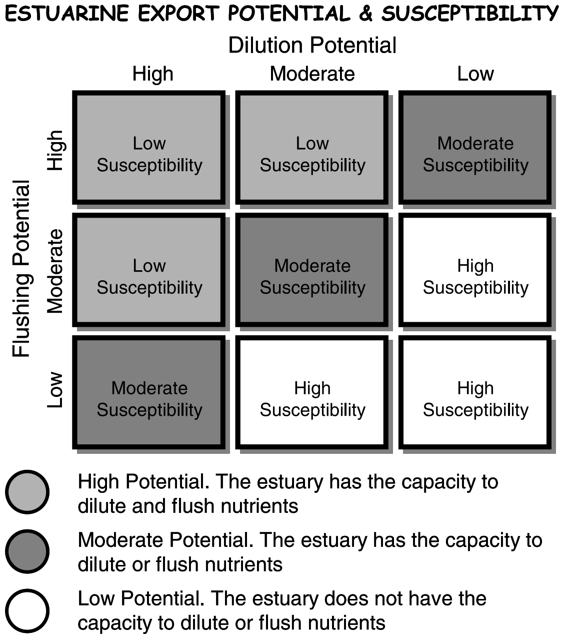

Fig. 6. Susceptibility classes based on dilution and flushing potential.

OHI and OEC have been incorporated and validated against the original work;

- Review of estuary classifications combining pressure, state and response.

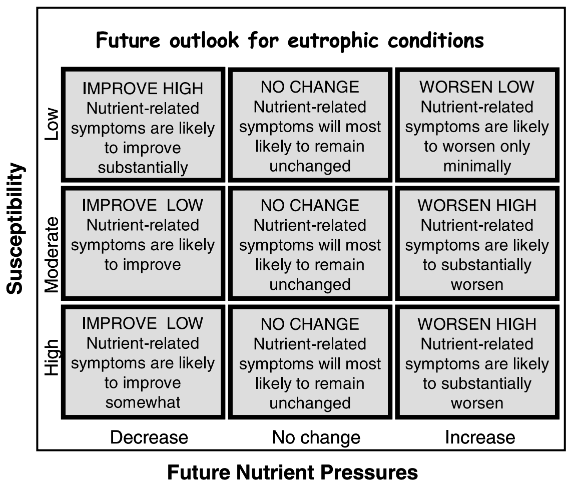

Fig. 7. Definition of future outlook based on susceptibility and future nutrient pressures.

3.1. NEEA systems and extension of OHI and OEC

A significant part of the U.S. systems evaluated in NEEA is presented in Fig. 8. Eighty-two systems on the U.S. Atlantic seaboard and Gulf of Mexico are shown, of which 27% have moderately low OEC symptoms, 31% are graded moderate, 22% are moderately high and 18% have high OEC. An analysis by region shows that the Gulf region has a majority of systems with moderate OEC, whereas the areas further north have a higher percentage of systems in the moderate low category. There are a number of reasons for this including long growing season and warm waters due to the subtropical climate, low freshwater inflow, shallow depth and low tidal energy which all contribute to making these systems more highly susceptible than estuaries in other regions. The low tidal flushing, in addition to the other factors, increases the coupling between pressure and state, and the use of dissolved oxygen (rather than percentage O_2 saturation) as an OEC secondary symptom probably also plays a role. Whilst it is unquestionable that absolute levels of dissolved oxygen are a key factor for ecosystem health, it must also be recognized that estuaries with higher salinity and temperature are far more fragile in terms of oxygen storage capacity, and pressure should be interpreted accordingly.

The application of the percentile-based approach to provide a more robust analysis for OEC is illustrated for chlorophyll *a* (Fig. 9a) and dissolved oxygen (Fig. 9b) with data from the Tagus estuary. Exceptionally high (chl *a*) and low (D.O.) values which may occur very occasionally are not considered using this approach, which means that there is less risk of a system being wrongly classified due to outliers. It is important to validate this conclusion against a more extensive set of data from the NEEA survey.

The application of the ASSETS approach for determination of OHI was carried out in Chesapeake Bay mainstem, Potomac, Patuxent and James River estuaries, Charleston Harbour and Tomales bay in the U.S. and the Sado, Tagus and Elbe in the E.U. (Table 7). The results shown for the U.S. estuaries generally appear to match the categories assigned in NEEA, but further tests are needed so as to include a wider range of estuary types and regions. The estuaries in the Chesapeake area are all highly affected by human activity, both in terms of pressure and of the state modifica-

Table 6
Aggregation of pressure (OHI), state (OEC) and response (DFO) components to provide an overall classification grade[a]—percentage of total valid combinations shown in brackets

Grade	5	4	3	2	1
Pressure (OHI)	Low	Moderate low	Moderate	Moderate high	High
State (OEC)	Low	Moderate low	Moderate	Moderate high	High
Response (DFO)	Improve high	Improve low	No change	Worsen low	Worsen high

Metric	Combination matrix	Class
P	5 5 5 4 4 4	High (5%)
S	5 5 5 5 5 5	
R	5 4 3 5 4 3	
P	5 5 5 5 5 5 5 4 4 4 4 4 3 3 3 3 3 3	Good (19%)
S	5 5 4 4 4 4 4 5 5 4 4 4 5 5 5 4 4 4	
R	2 1 5 4 3 2 1 2 1 5 4 3 5 4 3 5 4 3	
P	5 5 5 5 5 4 4 4 4 4 4 4 3 3 3 3 3 3 3 2 2 2 2 2 2 2 2 2 1 1	Moderate (32%)
S	3 3 3 3 3 4 4 3 3 3 3 3 5 5 4 4 3 3 3 4 4 4 4 4 3 3 3 2 3 3	
R	2 1 5 4 3 2 1 5 4 3 2 1 2 1 2 1 5 4 3 5 4 3 2 1 5 4 3 5 5 4	
P	4 4 4 4 4 3 3 3 3 3 3 3 2 2 2 2 2 2 1 1 1 1 1	Poor (24%)
S	2 2 2 2 2 3 3 2 2 2 2 2 3 3 2 2 2 2 3 3 3 2 2	
R	5 4 3 2 1 2 1 5 4 3 2 1 2 1 4 3 2 1 3 2 1 5 4	
P	3 3 3 3 3 2 2 2 2 2 1 1 1 1 1 1 1 1	Bad (19%)
S	1 1 1 1 1 1 1 1 1 1 2 2 2 1 1 1 1 1	
R	5 4 3 2 1 5 4 3 2 1 3 2 1 5 4 3 2 1	

[a] Note that the NEEA classification has been changed in ASSETS so that the high score now corresponds to high status, rather than a high level of a problem symptom.

tions induced by it, which is reflected in the grading for state and in the overall ASSETS grades for the systems, which do not surpass moderate. Charleston Harbour is classed as moderate in the NEEA OHI and has an equivalent grade (0.498) in ASSETS. For Tomales Bay, the calculated OHI of 0.090 of reflects a lower level of human influence, associated with reduced human pressure (the watershed contains only 11,000 inhabitants) and a lesser influence of freshwater on the system. This is despite the fact that the OEC score is a precautionary moderate high in NEEA (two or poor in ASSETS) because of the occurrence of nuisance and toxic algal blooms. These are often documented as starting offshore and moving into the bay, which has an interesting parallel with many western Iberian estuaries and rias, where toxic blooms generally start in frontal systems offshore and are advected into the estuaries. In both areas, it is still unclear whether prevailing conditions within the estuaries assist in maintaining bloom conditions, for instance through factors

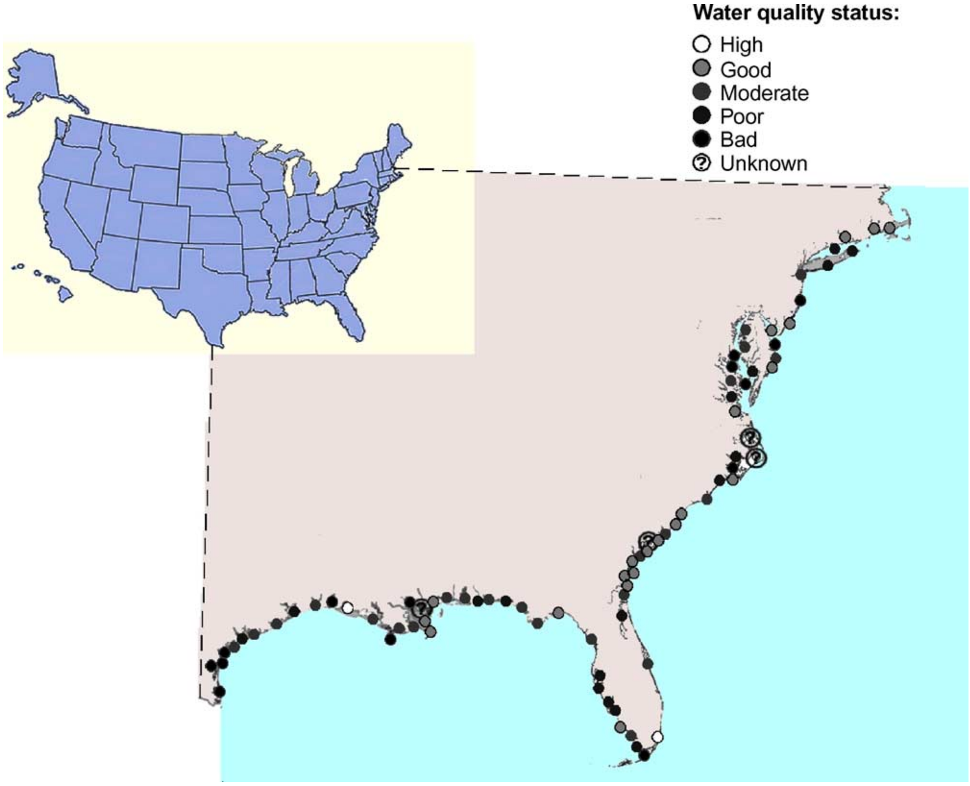

Fig. 8. OEC grading for estuaries on the U.S. eastern seaboard and Gulf of Mexico (converted to ASSETS categories)—adapted from Bricker et al. (1999).

such as cultivation of bivalve filter-feeders (see e.g. Nunes et al., 2003).

The Sado and Tagus are examples of mesotidal estuaries where tidal exchange and turbidity preclude manifestations of OEC secondary symptoms such as hypoxia, as is also the case for S. Francisco Bay (Cloern, 2001), although, e.g. the annual nitrogen input to the Tagus is about 14,000 t per year.

Table 7
Overall human influence calculated with the ASSETS approach and compared to the NEEA score

System	ASSETS OHI score	ASSETS OHI class	NEEA OHI classification
Chesapeake Bay mainstem[a]	0.977	Bad	1
Potomac estuary[a]	0.969	Bad	2
Patuxent estuary[a]	0.933	Bad	2
James River[a]	0.921	Bad	2
Charleston Harbour[b]	0.498	Moderate	3
Tomales Bay	0.090	High	–
Sado estuary	0.299	Good	–
Tagus estuary	0.599	Moderate	–
Elbe estuary	0.998	Bad	–

[a] Data for OHI calculation provided by the Maryland Department of Natural Resources, 2003 and the US Environmental Protection Agency Chesapeake Bay Program Office.

[b] Offshore salinity unavailable from sampling data, 35 was used. Data for OHI calculation derived from South Carolina Department of Health and Environmental Control (1999, 2003).

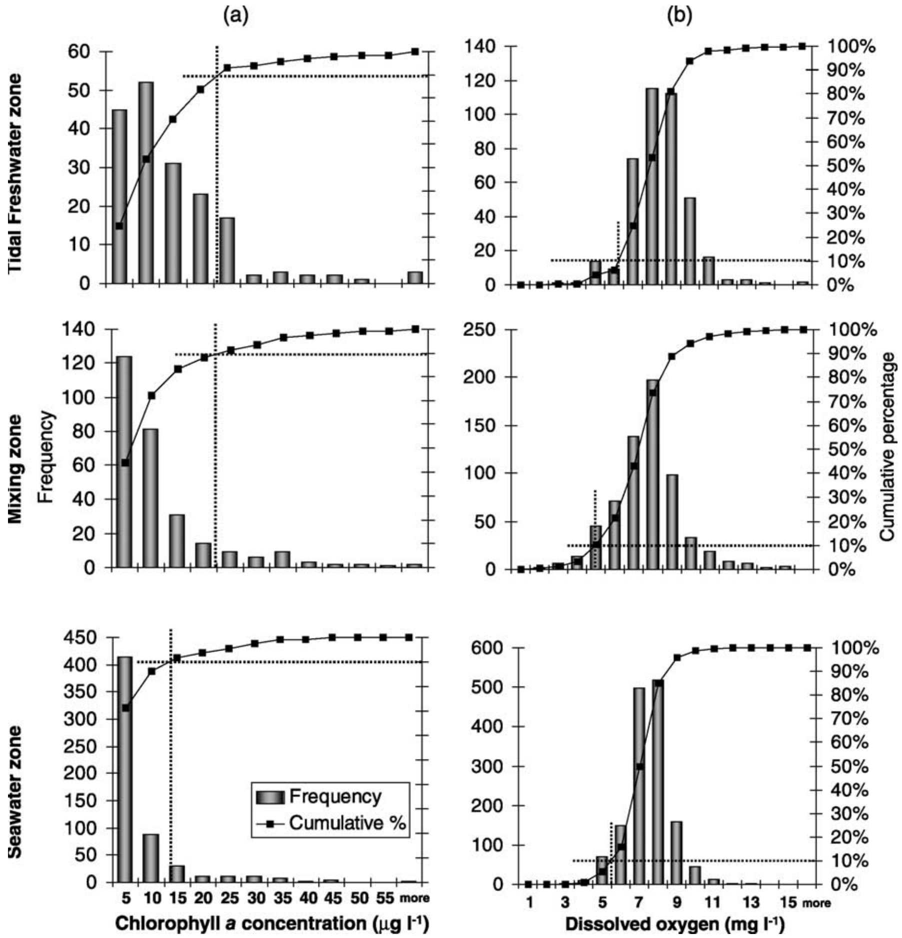

Fig. 9. (a) Percentile 90 for chlorophyll *a* values and (b) percentile 10 for the dissolved oxygen values, in the three salinity zones of the Tagus estuary.

For estuaries with a highly irregular freshwater discharge regime such as these, the difference between the mean and median estuarine salinity is significant (e.g. for the Sado the mean is 30.3 and the median is 33.4) and affects the OHI results in terms of susceptibility. The Elbe estuary in Germany is, in sharp contrast, a heavily impacted system where human influence accounts for virtually 100% of OHI.

3.2. Synthesis of PSR results

The OHI, OEC and DFO results for the 77 systems shown in Fig. 8 (five had insufficient data) have been combined using the matrix in Table 6, in order to provide an overall score for each system. The overall ASSETS scores are shown in Fig. 10. Although the NEEA approach did not explicitly combine the three index components, the overall knowledge about these systems which was developed based on regional expertise was used to make a comparison with the ASSETS index, both to test for accuracy and for the capacity to distinguish the magnitude of eutrophic symptoms among estuaries.

Additionally, results are presented for two estuaries in the E.U., which are shown as an example of the application of this approach to Northeast Atlantic systems. The comparison made between ASSETS and the three NEEA components was essentially based on

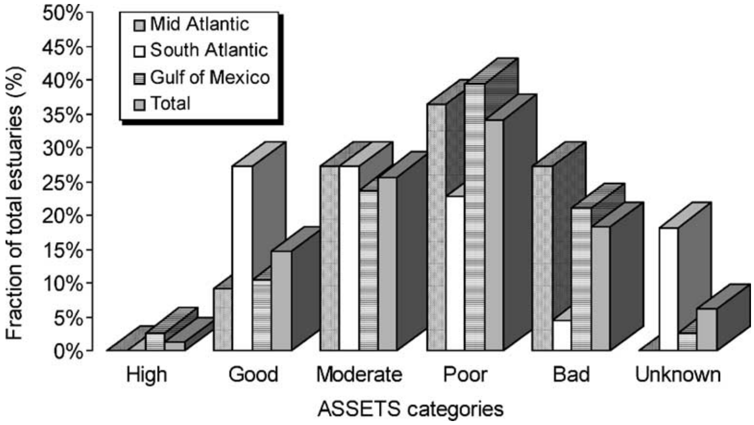

Fig. 10. Distribution of OEC grades for estuaries on the U.S. eastern seaboard and Gulf of Mexico.

(a) the results of five widely different systems (Long Island Sound, Neuse River, Savannah River, Florida Bay and West Mississippi Sound—Table 8); and (b) the relative proportion of each class given by ASSETS, and the comparison of this distribution with NEEA rankings (Fig. 10).

The five U.S. systems shown in Table 8 have ASSETS scores ranging from bad to good, and the individual classifications for OHI, OEC and DFO would indicate that the index is a good synthesis of the three different NEEA components.

The percentage distribution shown in Fig. 10 is as expected according to the NEEA study, and places the majority of systems in the good, moderate and poor categories. More good and moderate systems are located in the South Atlantic zone (54% of the total) whereas estuaries in the other regions appear to be more degraded.

For both (a) and (b), there is a good match between the two classification systems, so the ASSETS matrix (Table 6) is considered to be an adequate first approach for synthesis of pressure, state and response descriptors. It must be considered that this classification system is based on expert knowledge, and is subject to refinements. Some adjustments for PSR combinations were made based on NEEA results for the Eastern U.S. and Gulf of Mexico, and validation of the present scale may be carried out on other estuarine datasets, in particular on U.S. west coast estuaries, where NEEA has been applied. There are a number of estuaries and coastal areas in the E.U. where this approach can be tested, e.g. parts of the Baltic Sea and major estuaries such as the Scheldt and the Po.

Many eutrophication models are reported in the literature, ranging from simple statistical approaches (e.g. Vollenweider, 1975) to complex 2D and 3D dynamic simulations (e.g. Radach and Moll, 1989; Baretta et al., 1995). These models tend to relate nutrient concentrations to phytoplankton blooms, and in some cases link phytoplankton and detrital dynamics

Table 8
Overall score tables, with E.U. Water Framework Directive colours for seven estuaries in the U.S. and E.U.

System	Pressure (OHI)	State (OEC)	Response (DFO)	ASSETS grade
Long Island Sound	Moderate high—2	Moderate high—2	No change—3	(yellow)
Neuse River	High—1	High—1	No change—3	(red)
Savannah River	Low—5	Moderate—3	Worsen low—2	(orange)
Florida Bay	Moderate high—2	High—1	Improve low—4	(red)
West Mississippi Sound	Moderate—3	Moderate low—4	No change—3	(green)
Tagus	Low—5	Moderate low—4	Improve low—4	(green)
Sado	Low—5	Low—5	Improve high—5	(blue)

to dissolved oxygen. Such models have been successful in freshwater systems such as lakes and reservoirs (e.g. Jørgensen, 1976) and in the last decades have been applied with relative success to coastal ecosystems (e.g. Lancelot et al., 1997; Le Gall et al., 2000).

In estuaries and coastal lagoons, a general eutrophication model may have to account for factors such as tidal range effects, toxic algal species, benthic symptoms of eutrophication, or top-down control of phytoplankton by filter-feeders. A number of dynamic models have successfully focussed on specific aspects of eutrophication, such as the growth of opportunistic seaweeds (e.g. Alvera-Azcárate et al., 2003; Ménesguen and Salomon, 1988), but the relationship between nutrient pressure and estuarine changes of state is simultaneously so complex and so variable that a general dynamic model is still an ambitious goal.

The approach described in this work may be classified as a screening model (for other examples, see CSTT, 1997; Stigebrandt, 2001), where a more simplified approach based on a combination of data, dynamic simulations, statistical modelling and other techniques such as GIS may profitably be combined into a management tool.

ASSETS is intended as a model for broad assessment of organic enrichment, both within and between systems, and it contains some of the elements of state and biological structure identified by Boesch and Paul (2001) as potential indicators of ecosystem health. These indicators contribute to the practical implementation of frameworks such as the Vigor-Organization-Resilience model (Costanza and Mageau, 2001), but as pointed out by Boesch and Paul (2001), substantial advances are required to the state-of-the-art before robust application is possible by decision-makers of the concept of ecosystem health.

4. Conclusions

The methodology presented in this paper strives to build on the work of the U.S. NEEA, by providing a more consistent analysis based on a Pressure-State-Response framework. OHI is quantified by means of a more formal approach, and the application of GIS and statistical thresholds to OEC determination is aimed at improving comparability. As stated previously, nutrient concentrations are not necessarily a robust descriptor of eutrophication in estuarine systems (see, e.g. Cloern, 2001; Boesch, 2002), in contrast to techniques developed historically for freshwater. This is an important point to bear in mind, considering the limited cost-benefit of the sampling effort necessary to compensate for the natural variability of dissolved substances in estuaries. Likewise, turbidity is of only relative interest since, in many mesotidal or macrotidal systems, suspended matter in the water column is dictated more by the difference in current velocity and bed shear stress over the fortnightly Spring–Neap cycle than by phytoplankton blooms.

DFO is an area where more effort is clearly needed, in order to provide a robust assessment of potential management response. The involvement of social scientists and economists is essential for developing interdisciplinary metrics flexible enough to accommodate different watershed development components such as agricultural change, effluent treatment and demographic changes, and also estuarine uses such as aquaculture. These metrics must incorporate cost functions, in order to provide decision-makers with the tools necessary for valued judgement regarding ecosystem conservation and rehabilitation.

ASSETS combines the three different NEEA components to provide a single grade for classifying estuarine systems into one of five categories. Since OEC was the most developed component of the NEEA approach, quantitative comparisons between systems tended to be based on state. Whilst this is appropriate, it seems nevertheless desirable to attempt to develop the U.S. classification into a more unified system, where the relationship between pressure, state and response may be clear to management, and therefore encourage more proactive approaches to maintenance of estuarine health. ASSETS additionally aims to contribute to the classification systems which are a requirement for the E.U. Water Framework Directive, as regards some quality elements for transitional waters.

Both the U.S. and the E.U. share many common features in their estuarine systems and coastal zone: diverse tidal range and anthropogenic inputs, a wide range of uses and conflicts, and intense demographic pressure on the coastal zone. There are also obvious differences: Enclosed "estuarine" seas such as the Baltic, and subtropical areas such as the Gulf of Mexico. It is apparent that there is much to gain in trying to simultaneously leverage commonality and differences into a unified system or systems which may accommodate the great diversity of pressure, state and responses. ASSETS aims to be one more stepping stone in that direction.

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