Comparison of five methods for assessing impacts of nutrient enrichment using estuarine case studies

Michelle Devlin · Suzanne Bricker · Suzanne Painting

Abstract There are several approaches for assessing nutrient enrichment impacts in marine waters including the OSPAR* Comprehensive Procedure, the TRIX* ranking process, the WFD, ASSETS* and EPA NCA*. They differ in definitions and application, but all use key indicators for evaluating eutrophication status. Data from two estuaries in the United Kingdom (UK) were used to test the hypothesis that these five methods would result in the same outcome. The intent is to provide managers with information for selecting an appropriate method, insight about how each method works, how results from different methods compare and a basis for improvement of methods. Results from all approaches indicate that both estuaries required management intervention, but detailed results differed. Methods using more than one biological indicator show that secondary biological impacts were minimal, with the exception of moderate macroalgal problems in the Medway. Comparison of final results was difficult due to differences in: timeframes of data analysis (seasonal versus annual), characteristics included in indicator metrics (concentration, spatial coverage, frequency of occurrence), and methods for combining indicators to determine eutrophication status. This comparison suggests that use of annual data, inclusion frequency of occurrence, spatial coverage and, secondary biological indicators in the index, and a multi-category rating scale results in a more representative assessment.

Keywords Eutrophication · Assessment · WFD · OSPAR · ASSETS · TRIX · EPA NCA

Abbreviations

OSPAR	Oslo Paris Convention for the Protection of the Northeast Atlantic
TRIX	Trophic Index
ASSETS	Assessment of Estuarine Trophic Status
EPA NCA	Environmental Protection Agency National Coastal Assessment
WFA	Water Framework Directive

M. Devlin (✉)
Catchment to Reef Research Group, ACTFR, James Cook University, Townsville, QLD, Australia
e-mail: michelle.devlin@jcu.edu.au

S. Bricker
National Oceanic and Atmospheric Administration, Center for Coastal Monitoring and Assessment, 1305 East West Highway, Silver Spring, MD, USA

S. Painting
Centre for Environment, Fisheries and Aquaculture Science, Pakefield Rd., Lowestoft, Suffolk, UK
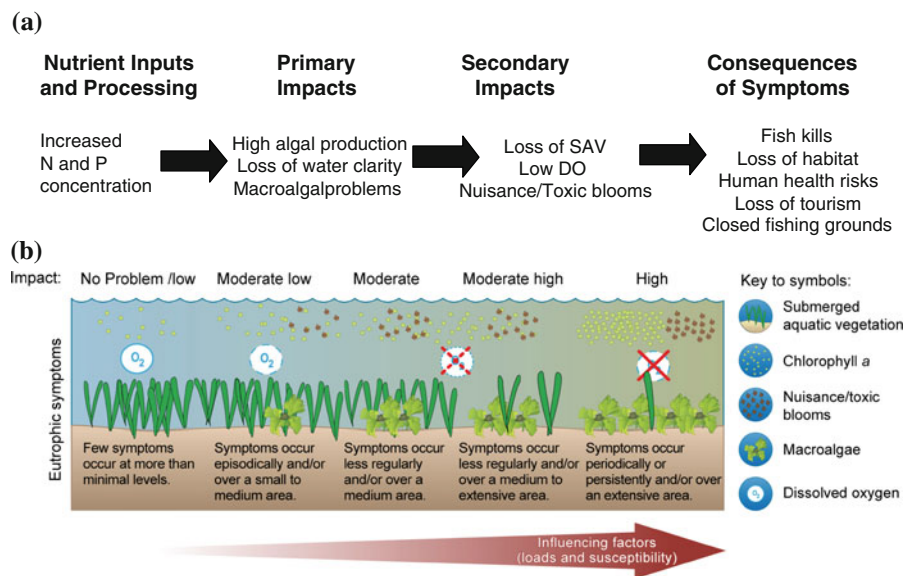
Introduction

The detection and assessment of nutrient enrichment is an important environmental and socio-economic issue in the management and conservation of coastal and marine waters. The primary biological response to nutrient enrichment in aquatic environments, given

Fig. 1 Potential impacts of anthropogenic nutrient enrichment in coastal and marine waters. **a** Summary of primary and secondary impacts, and consequences of symptoms. Secondary impacts indicate undesirable disturbance to the system. **b** Gradient of secondary impacts, ranging from no problem/low (best) to high (worst) in response to influencing factors. *N* nitrogen, *P* phosphorus, *SAV* submerged aquatic vegetation, *DO* dissolved oxygen (from Bricker et al. 2007, 2008)

suitable environmental conditions (such as light availability and water temperatures), is the growth of phytoplankton and higher plants (Fig. 1). Known consequences of nutrient enrichment include increased primary production, increased biomass of primary producers such as phytoplankton (indicated by concentrations of chlorophyll-*a* [hereafter Chl-*a*]), and depletion of dissolved oxygen (hereafter DO) due to decomposition of accumulated biomass, resulting in local hypoxic or anoxic conditions. Other consequences can include shifts in species composition, blooms of nuisance and toxic algae and macroalgae, increased growth of epiphytic algae, red tides, water discolouration and foaming, loss of submerged vegetation (hereafter SAV) due to shading, and changes in benthic community structure due to oxygen deficiency or the presence of toxic phytoplankton species (Tett 1987; Gillbricht 1988; Lancelot et al. 1987; Boynton et al. 1996; Bricker et al. 1999, 2003, 2007; Smayda and Reynolds 2001). The range of impacts from nutrient enrichment can span from single cell production to major trophic shifts. It is not possible, nor feasible, to monitor or assess all parts of a marine system to identify all impacts, so a selection of indicators is required that will adequately describe the eutrophic status of the environment.

The development of classification systems and ecological assessment tools is an important and technically challenging aspect of assessing the consequences of nutrient enrichment. Assessments typically combine a selection of key indicators that enable reasonable evaluation of the overall status of eutrophication in coastal and marine waters, which enables managers and policy makers to make decisions about the mediation of problems linked to nutrient enrichment. In recent years, a number of assessment methods have been developed and used to assess the eutrophication status of coastal and marine waters for management purposes. Historically, in both the United States (US) and European Union (EU) the management and protection of coastal and marine environments from impacts of nutrient enrichment has been the responsibility of local and national agencies.

In the EU, water-related directives have set objectives for the protection and maintenance of EU coastal and marine water quality. Various EU directives (such as the Urban Waste Water Directive [UWWTD, CEC 1991a], the Nitrates Directive [ND, CEC 1991b], the Habitats Directive [HD, CEC 1992], the Water Framework Directive [WFD, CEC 2000] and the Marine Strategy Framework Directive [MSFD, CEC 2008]), the Oslo Paris Convention (OSPAR 2003a, b), the Helsinki Commission (HELCOM, Andersen and Laamanen 2009) and TRIX (Vollenweider et al. 1998) all consider the assessment of eutrophication through measurement of key indicators such as concentrations of nutrients, Chl-*a* and DO (Table 1). Some of the more recent directives (WFD, MSFD) and OSPAR include the additional identification of secondary impacts and

Table 1 Key indicators used by the different approaches for assessing eutrophic conditions

	UK WFD	OSPAR COMPP	TRIX	ASSETS	EPA NCA
Nutrient loads		X		X	
Nutrient concentrations	X	X	X		X
Water clarity		X			X
DO	X	X	X	X	X
Chl-*a*	X	X	X	X	X
Phytoplankton abundance/indicator species	X	X			
HABs or algal toxins	X	X		X	
Macroalgal abundance	X	X		X	
SAV	X	X		X	
Organic carbon/organic matter		X			
Zoobenthos kills or fish kills	X	X			

Chl-a chlorophyll-*a*, *SAV* submerged aquatic vegetation, *DO* dissolved oxygen, *HABs* harmful algal blooms

undesirable disturbance to the ecosystem (e.g. low DO events, toxic algal blooms).

In the US, the Environmental Protection Agency (EPA) generally delegates responsibility to state water management bodies to implement standards and criteria to assess compliance with the Clean Water Act of 1972. This Act is the primary federal water protection law in the US with goals of eliminating discharge of contaminants to surface waters and ensuring that they meet standards necessary for human sports and recreation. The EPA and the National Oceanic and Atmospheric Administration (NOAA) support regulatory decisions by providing research and assessment results (Borja et al. 2008). The data and information required by the US Clean Water Act, Coastal Zone Management Act, Harmful Algae and Hypoxia Research and Control Act and Oceans Act are the basis for the development and application of the ASSETS (Bricker et al. 1999, 2003, 2007; Xiao et al. 2007; Ferreira et al. 2007) and EPA NCA (USEPA 2001a, 2005, 2008) assessment methods. They compare measurements of key indicators to reference conditions to provide information on pollutants of concern.

The overall aim of this study was to apply these approaches to two estuarine systems in the United Kingdom (UK) and to test the hypothesis that they would all result in the same final assessment of eutrophication status when applied to the same data. The intent was to make a side-by-side comparison of these methods to provide managers with information they could use to select one or more of the methods

for use, or to improve methods already in use. The Thames and Medway estuaries, located on the east coast of England (Fig. 2), were selected as test areas to apply and compare results of the five eutrophication assessment methods. Both are large, sheltered, macro-tidal, well-mixed estuaries (Rogers et al. 2003; Table 2). Data were obtained from national programmes that monitor water quality, including measurements of phytoplankton community structure, Chl-*a*, DO, harmful algal blooms (HABs), macroalgae and SAV.

Methods

General description of study areas

The Thames estuary (248 km^2) is one of the largest of 170 inlets on the coast of Great Britain and includes the area in which the River Thames meets the North Sea. This estuary has one of the largest watersheds in the UK (12,935 km^2) and constitutes a major shipping route. The estuary supports regions of mudflats, open beaches, salt marshes and over 900 km of chalk stream systems. The Thames river basin district also contains 40 special areas of conservation and nearly 500 Sites of Special Scientific Interest, which identify the very best wildlife and geological sites in the UK, with a high level of protection and management (www.sssi.naturalengland.org.uk/). However, much of the watershed is dominated by urban areas including parts of London, which has a population of
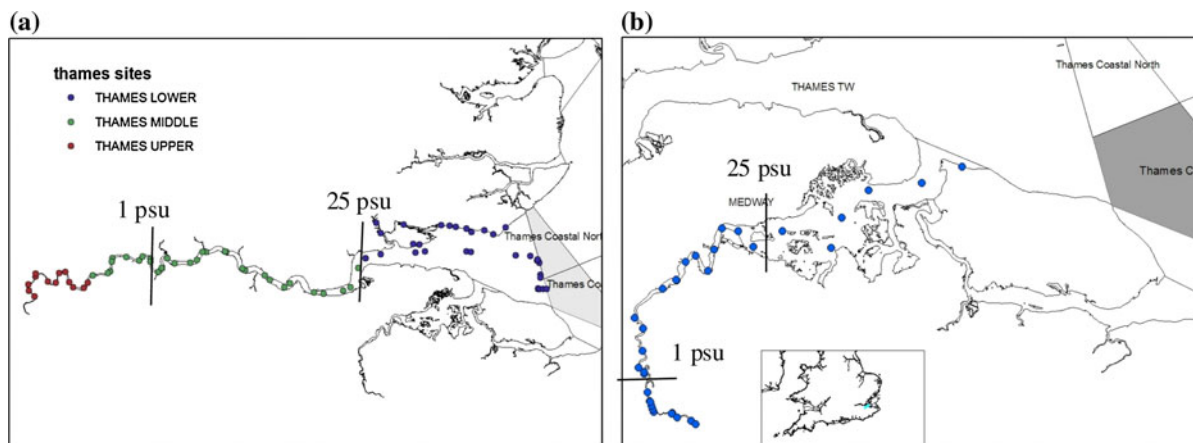
Fig. 2 The study areas, where *dots* denote sites monitored under a long-term national program. **a** Thames estuary—indicating divisions into *lower*, *middle* and *upper regions* under the WFD (see scale). Data from the *lower* and *middle regions* were combined for application of the WFD, OSPAR COMPP,

TRIX and EPA NCA assessments. For ASSETS, 2 salinity zones (1–25 psu and >25 psu) were evaluated separately and then combined for an estuary-wide area weighted final score. **b** Medway estuary, located at the lower end of the Thames. Data were combined as for the Thames

over 13 million people (Table 2). The Thames estuary is impacted by pollution as a result of the high population density. In addition, there are five main sewage treatment works and over 40 combined sewer overflows entering the Thames estuary. To the west, the watershed is dominated by agriculture and experiences a large volume of land run-off.

The Medway estuary is smaller than the Thames (57 km^2) with a much smaller human population (Table 2), and consequently is subject to lower urban and agricultural pressures than the Thames. The shoreline is deeply indented with many islands, salt marshes, and large areas of brackish marshes. Like the Thames, the Medway serves as a shipping route.

Data description

To apply the five assessments to the study estuaries we used water quality data from the UK Environment Agency database containing long-term records of nutrients, Chl-*a* and DO. Consistent national standards for marine environmental quality were developed for UK waters and regular sampling at a network of estuarine, coastal and offshore monitoring stations (the National Marine Monitoring Programme, NMMP) was implemented in 1987. Sixty-eight sampling sites are located along the estuarine gradient in the Thames Estuary and twenty are located in the Medway Estuary (Fig. 2). Nutrients,

Chl-*a*, phytoplankton counts and DO data obtained at least monthly between 2000 and 2007 were used in this study. Although the frequency of sampling was variable among these sites, there were >2500 Chl-*a* and >1600 DO data points for the Medway Estuary, and >1800 Chl-*a* and >2800 DO data points for the Thames Estuary (Table 2; Fig. 3). Data from sites where salinity was <1 psu were not included to avoid potential bias from freshwater species and sampling and analytical inconsistencies. Data required by the EPA NCA method were subsampled from the database during the index period to reproduce the sampling requirements of one sample per year.

Data on macroalgae and SAV were obtained from the Environment Agency and historical monitoring sources (Butcher 1941; Hughes and Paramor 2004; www.uktag.co.uk). Data on HABs were obtained directly from the Environment Agency and from other monitoring programmes (e.g. the shellfish monitoring programme of the UK Food Standards Agency, FSA) via the Centre for Environment, Fisheries and Aquaculture Science (CEFAS).

Overview of assessments

Five methods were used to evaluate the eutrophication status of the Thames and Medway estuaries in the UK; the WFD as used in the UK (UK WFD), the OSPAR Comprehensive Procedure (OSPAR COMPP), the

Table 2 Characteristics of the two study sites, Medway and Thames estuaries, and summary of main data used in this study

	Medway estuary	Thames estuary
Estuarine area (km^2)	56.57	247.73
Mixing zone area (km^2)	5.09	46.69
Seawater zone area (km^2)	51.48	201.04
Location	East Coast UK	East Coast UK
Total load (10^3 kg N year^{-1})	17.6	37147
Discharge (m^3 s^{-1})	38.2	65.8 (at London)
Average depth (m)	6.2	6.9
Tidal height (m)	7.0	7.2
Length (km)	113	370
Catchment area (10^3 km^2)	2.41	12.9
Typology	Sheltered, macrotidal, well mixed estuarine area	Sheltered, macrotidal, well mixed estuarine area
Pressures	Urban	Urban
	Agricultural	Agricultural
	Flood barriers	Flood barriers
Catchment population (10^6 people)	1.65	13.0
Population density (people km^{-2})	411	4,761 (London area)
Data availability	Monthly	Weekly–Monthly
	2000–2007	2000–2007
Mean annual SPM (mg l^{-1})	47.6	34.2
Mean annual DIN (μM)	172	133
Mean winter DIN (μM)	192.0	76.2
Mean summer DIN (μM)	156.8	46.2
Mean annual Chl-*a* (μg l^{-1})	6.2	19.1
Mean summer Chl-*a* (μg l^{-1})	15.1	28.2
Mean growing season Chl-*a*	7.1	19.9
Phytoplankton abundance: % total taxa counts $>10^6$	7.4	15.5
Phytoplankton abundance: % single species counts >500,000 cells l^{-1}	7.3	24.1
Mean annual DO (mg l^{-1})	8.51	7.1
Mean summer[a] DO (mg l^{-1})	6.8	5.0
Annual DO (mg l^{-1})—10th percentile	5.5	3.4
Annual DO (mg l^{-1})—5th percentile	5.03	2.9
Summer[a] DO (mg l^{-1})—5th percentile	4.8	2.4
SAV areal coverage, shoot density, diversity	N/A	N/A

N/A not applicable, *SPM* suspended particulate matter, *DIN* dissolved inorganic nitrogen, *Chl-a* chlorophyll-*a*, *SAV* submerged aquatic vegetation, *DO* dissolved oxygen

[a] Summer = June 1–September 30

Trophic Index (TRIX), the EPA National Coastal Assessment (EPA NCA), and the Assessment of Estuarine Trophic Status (ASSETS). These methods are described briefly below, and in greater detail in Tables 3, 4 and 5. The application of these methods to the Medway estuary using data from 2000 to 2007 is demonstrated in Tables 6, 7, 8, 9 and 10 (see "Results and discussion").

WFD (UK)

The overall aim of the WFD is to achieve good ecological status in all EU member state waterbodies by 2015, where good status represents a slight (no more than 50%) deviation from reference conditions. Assessments are carried out at a waterbody level where waterbodies are differentiated by typology. Specific

Fig. 3 Data (2000–2007) for concentrations of dissolved inorganic nitrogen (*DIN*), chlorophyll (*Chl-a*) and dissolved oxygen (*DO*) in the Thames (T1–T6) and Medway (M1–M6) estuaries. Data shown per year (T1, T3, T5 and M1, M3, M5) include all data from all stations sampled (Fig. 2), at salinities >1 psu. Data are also shown by month (T2, T4, T6 and M2, M4, M6) where Jan–Dec = 1–12. Note that data points may represent many superimposed samples. Very high values for DIN and Chl-*a* typically represent the low salinity end of each estuary, where nutrients enter the systems and freshwater phytoplankton dominate
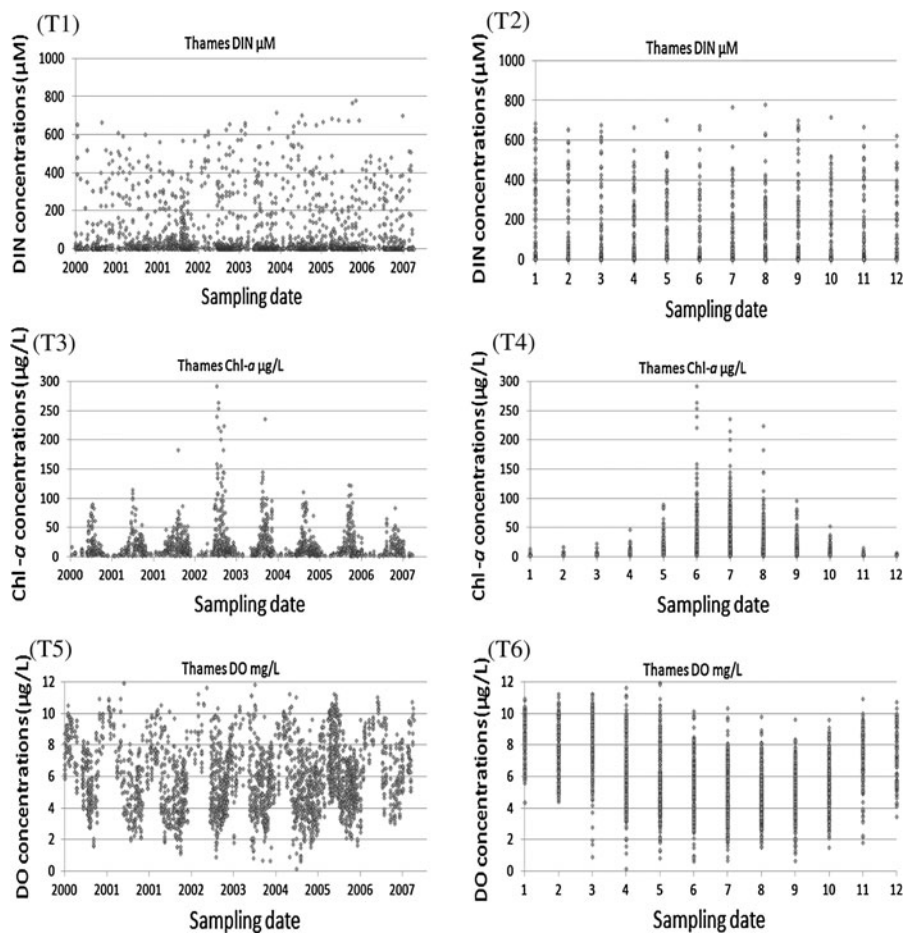
reference conditions have been developed for each type of system where waterbody type is defined by characteristics including tidal range, mixing, exposure and salinity (Tables 3, 4 and 5). Each EU member state is required to adopt the WFD assessment process, though the selection of waterbody types, reference conditions, specific indicator variables and assessment methods can differ among member states (Vincent et al. 2002; Anon 2009). Each state must report the ecological status of each biological quality element (BQE) (including marine plants, benthic invertebrates and transitional fish). The WFD assessment process as used in the UK for eutrophication assessment and presented here for the marine plants component, focuses primarily on nutrient concentrations and marine primary producers, including phytoplankton (biomass, abundance and composition), macroalgae (biomass and areal extent) and angiosperms (biomass and areal extent) (Devlin et al. 2007a, b; Painting et al. 2007; Best et al. 2007). This approach is a shift from

targets based only on water chemistry to targets based on the ecological structure of natural systems (Pollard and Huxham 1998).

The WFD requires the classification of all surface waterbodies into one of five ecological status classes: High, Good, Moderate, Poor or Bad. The ecological status of each waterbody is assessed using three BQEs, each of which yield an Environmental Quality Ratio (EQR) between zero (Bad status) and one (High status). The BQEs related to eutrophication assessment, applied after an initial assessment of risk of eutrophication that is based on nutrient load, turbidity, flushing time and tidal range include phytoplankton, macroalgae and angiosperms. The final assessment also includes a measure of Physicochemical status, focusing on dissolved inorganic nitrogen (DIN) and DO measurements. The final score for each BQE within a waterbody is accompanied by a data quality measurement and a confidence of class (CofC). The CofC calculates the uncertainty

Fig. 3 continued
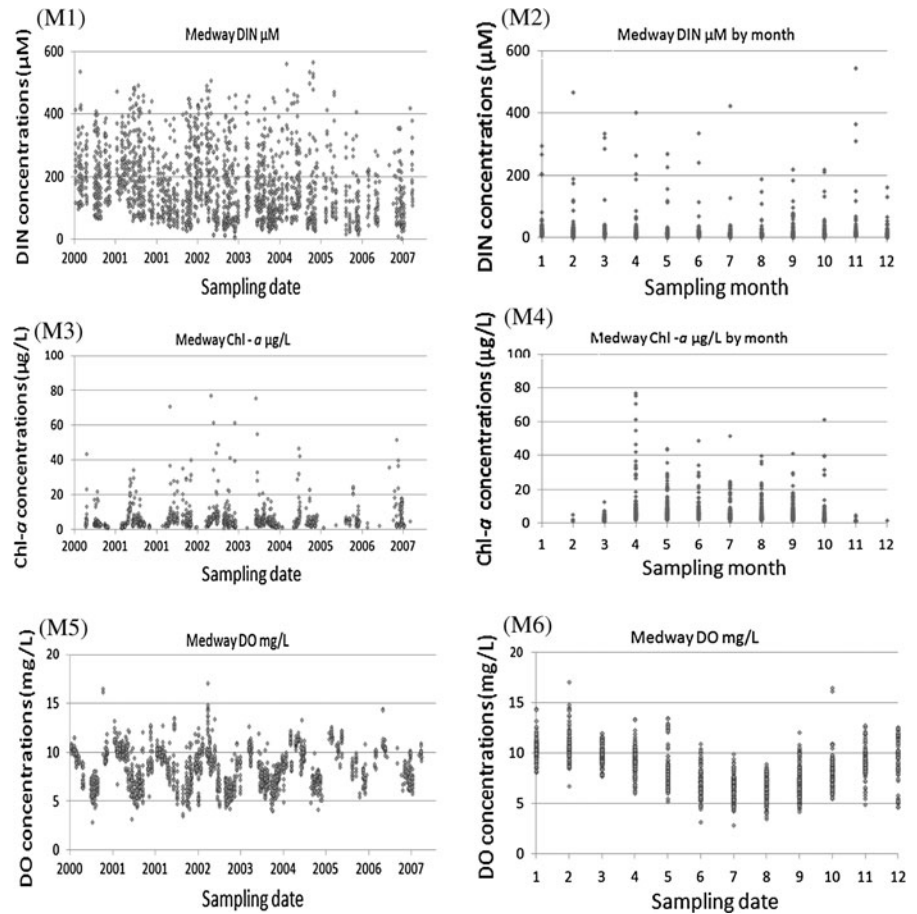
in the estimate of each EQR to determine the most probable class (the one with the highest probability of occurring) and state the level of confidence that status is good or better, or moderate or worse.

Each BQE consists of one or more indicators that measure different aspects of the biological community. For example, in the UK WFD method for estuarine waters, the phytoplankton element consists of two different indicators, Chl-*a* concentration and phytoplankton cell abundance (Devlin et al. 2007a, b). For each indicator, final measurements are converted into a normalised ecological quality ratio (EQR) via a two-step process. The first step converts the data to a numerical scale between zero and one, where the status class boundaries are not equidistant. The second step transforms these values into an equal-width class scale between zero and one. The final score for the phytoplankton BQE is calculated as the average of the two normalised scores from each indicator, and related to one of the five assessment classes (Table 5). This process is repeated for the indicators that make up the macroalgae and angiosperm BQEs. Overlaying this is the integration of the physico-chemical assessment (nutrient and other chemical conditions) with the final BQE assessments (Table 4). Classification of final status is determined for each waterbody using a one-out-all-out approach; if results for one BQE or the physico-chemical element are less than good (i.e. Moderate to Bad), the waterbody is assigned the worst among the ratings (Anon 2007). For example, a waterbody with a High (best) status for phytoplankton but with a Moderate status for macroalgae will be assigned a Moderate classification for eutrophication status.

The UK WFD method is a multi-dimensional ecological assessment (i.e. not specifically for eutrophication) that also analyses fish, benthic invertebrates and pollutants. However, for the purposes of this paper, only the nutrients and marine plants associated with eutrophic pressures will be discussed.

Table 3 Details of approaches used for assessment of eutrophication status, including indicator variables, terminology for grouping of variables (e.g. Primary Symptoms are equivalent to Direct Effects), time and space scales for data analysis, and combination methods

		UK WFD[1]	OSPAR[2]	TRIX[3]	ASSETS[4]	EPA NCA[5]
Grouping of Variables	Influencing or Causative Factors (OSPAR Category I)	Nutrient load	DIN and DIP concentration, Nutrient ratios, Nutrient load	DIN and TP concentration	DIN and DIP loads	
	Primary Symptom, Direct Effects (OSPAR Category II)	Chl-*a*, PP indicator species, seasonal changes in cell abundance of diatom, dinoflagellates, Macroalgae, SAV	Chl-*a*, PP indicator species, Macroalgae, Microphytobenthos, SAV	Chl-*a*	Chl-*a* Macroalgae	
	Secondary Symptoms, Indirect Effects (OSPAR Category III)	DO	DO, Zoobenthos kills and/or fish kills, Organic carbon, Organic matter	DO	Nuisance/toxic blooms, SAV, DO	
	Other Possible Effects (OSPAR Category IV) or No Grouping (EPA NCA)		Algal toxins			DIN and DIP concentration, Water Clarity, Chl-*a*, DO
Temporal Sampling Framework		Annual Chl-*a* and DO, Winter DIN, monthly PP groups	Growing season Chl-*a* (March – September), Winter DIN, Summer DO	Annual	Annual	One sample per year (per station) within summer index period (June 1 - September 30)
Spatial sampling framework		Sampling in estuaries and coastal waterbodies defined by salinity. Results are reported by waterbody	Sampling in estuarine, coastal or offshore waterbody types defined by salinity	Sampling mostly in larger offshore systems. Results are reported by region	Sampling in salinity zones is synthesized to waterbody, then to regional and then to national level. Results reported for all levels	Sampling is regional. Data are synthesized to national level. Results reported for regional and national levels
Assessment of indicators		Deviation from reference conditions	Deviation from reference conditions	Placement on scale from 1 - 10 TRIX units	Deviation from reference conditions	Deviation from reference conditions
Determination of thresholds (see Table 5)		Type-specific thresholds (e.g. estuarine vs coastal types) determined from previous studies and long-term reference data sets. Validated within European intercalibration process	Regional, type and salinity specific thresholds determined by previous studies. Agreed upon by OSPAR member countries	Scaling coefficients are used to fix upper and lower limits so that index values fall between 0 and 10	Thresholds determined from national data and studies	Thresholds determined from national data and studies

Table 3 continued

	UK WFD[1]	OSPAR[2]	TRIX[3]	ASSETS[4]	EPA NCA[5]
Combination Method (see Table 3)	Indicator scores (normalised to 0 – 1 scale) are averaged within each BQE (i.e. PP, Macroalgae and SAV). Final score (0 – 1) related to classification status. Worst BQE score determines final classification for waterbody	One-out-all-out procedure used for both individual Categories and for Overall Classification: if one component of a Category is a Problem then the whole Category is considered a Problem. If one Category fails then the final status is considered a Problem Area	Linear combination of logarithms of variables modified by a scaling coefficient	Scores of average primary and worst secondary indicators are combined in matrix. Secondary impacts have higher weight	Indicators are individually assessed and classified as Good, Fair or Poor/No Data. Water Quality Index is based on percent of samples that are Good, Fair, Poor/No Data per site or region. Variables are not weighted

Only ASSETS includes Future Outlook

DIN dissolved inorganic nitrogen, *DIP* dissolved inorganic phosphorus, *TP* total phosphorus, *Chl-a* chlorophyll-*a*, *DO* dissolved oxygen, *SPM* suspended particulate matter, *SAV* submerged aquatic vegetation, *spp.* species, *PP* phytoplankton, *BQE* biological quality element

[a] CEC (1991a, b)

[b] OSPAR (2002, 2005, 2008)

[c] Vollenweider et al. (1998)

[d] Bricker et al. (1999, 2003, 2007), Ferreira et al. (2007), www.eutro.org and www.eutro.org/register

[e] USEPA (2001a, b, 2005, 2008)

Table 4 Summary of procedures used for evaluating the eutrophic status of estuarine and coastal waters and categories used for final classification

Method	Summary of assessment procedure	Categories for final classification of status, and colour coding (Fig. 4)
WFD[a] used in the UK	Considers physico-chemical and biological QEs. For each element, one or more indicators are used. EQRs are calculated for each indicator using the ratio between measurements and reference condition. An EQR is calculated for each quality element by averaging the indicator scores for all components within each QE. The final BQE score, a number between 0 (worst) and 1 (best) relates to the five equidistant boundary classes. The worst classification status for the BQE's and the physico-chemical status are taken as the overall water body status. In this one-out-all-out approach, if any element has a state less than or equal to Moderate, then the water body is considered to be impacted	Classification status is calculated from the worst BQE BQE's are integrated by normalising outputs to 0–1 score (EQR score): High (best, blue) Good (green) Moderate (yellow) Poor (orange) Bad (worst, red)
OSPAR COMPP[b]	Thresholds are set for each indicator for estuarine, coastal and offshore waters. The full OSPAR COMPP procedure is applied only to areas indicated as Potential Problem Area or Problem Area by the screening procedure. Indicators are used in Categories I to IV to determine levels of nutrient enrichment and impacts, and combined within each category in a one-out-all-out process. A final assessment as Problem Area (+), Potential Problem Area or Non Problem Area (−) is made after evaluating scores for Categories I–IV with the one-out-all-out approach	Problem area (+) Potential problem area Non problem area (−)
TRIX[c]	The annual average of all parameters are combined without assigning individual parameter ratings, to give a ranking between 0 and 10, where: $$TRIX = [\log10(Chl\ a) + \log10(aD\%O) + \log10(DIN) + \log10(TP) - k]/m$$ The coefficients $k = -1.5$ and $m = 1.2$ are fixed to establish the lower and upper limits of the index	Index is scaled from 0 to 10, ranging from oligotrophy (scarcely productive—open sea) to eutrophy (highly productive)
ASSETS[d]	Three components are included: Influencing Factors (IF), Eutrophic condition (EC) and Future Outlook (FO) and the three components are combined into one ASSETS rating. Only the EC component is included in this study. Five indicators are evaluated: primary symptoms (Chl-a, macroalgae) and secondary symptoms (DO, SAV, nuisance/toxic blooms). Area-weighted values are calculated from salinity zone assessments and area-weighted system wide ratings are made for each variable. Primary (average) and secondary (worst) symptom scores are combined in a matrix to determine an overall score or rating for eutrophic condition of the waterbody	The final scores for eutrophication status are: High (worst, red) Moderate high (orange) Moderate (yellow) Moderate low (green) Low (best, blue) Colour codes are consistent with WFD scales

Table 4 continued

Method	Summary of assessment procedure	Categories for final classification of status, and colour coding (Fig. 4)
EPA NCA[e]	The Water Quality Index (WQI) uses a combination of DIN, DIP, DO, Chl-*a* and Water Clarity for assessment. Indicator scores are determined using the percentage of samples that are Good, Fair or Poor/No Data, e.g. DIN:	A final WQI assessment is determined by site and then by region and nation: Good (green) Fair (yellow) Poor (red)
	Good: <10% of samples are Poor and >50% are Good	
	Fair: 10–25% of samples are Poor and/or >50% are Poor or Fair	
	Poor: >25% of samples are Poor	
	All indicators are combined in a similar fashion to determine the rating for a site:	
	Good = A maximum of one indicator is Fair and no indicators are Poor	
	Fair = One of the indicators is rated Poor or two or more indicators are Fair	
	Poor = Two or more of the five indicators are rated Poor	
	To determine the WQI by region and nation, results from each area are used to determine a final assessment score where:	
	Good: <10% of areas are in Poor condition and >50% are Poor or Fair	
	Fair: 10–20% of areas are in Poor condition or >50% are Fair or Poor	
	Poor: >20% of areas are in Poor condition	

Pressures (nutrient loading) and Future Outlook are not included here, as they are not used by all approaches

EQR ecological quality ratio, *DIN* dissolved inorganic nitrogen, *DIP* dissolved inorganic phosphorus, *TP* total phosphorus, *Chl-a* chlorophyll *a*, *DO* dissolved oxygen, *SAV* submerged aquatic vegetation, *spp.* species, *BQE* biological quality element, *PP* phytoplankton, *QE* quality element

[a] CEC (1991a, b)

[b] OSPAR (2002, 2005, 2008)

[c] Vollenweider et al. (1998)

[d] Bricker et al. (1999, 2003, 2007), Ferreira et al. (2007), www.eutro.org and www.eutro.org/register

[e] USEPA (2001a, b, 2005, 2008)

Table 5 Thresholds for concentrations of chlorophyll-*a* (Chl-*a*), dissolved oxygen (DO) and dissolved inorganic nitrogen (DIN) for the four assessments

Method	Chl-*a* reference thresholds ($\mu g\ l^{-1}$)	DO reference thresholds ($mg\ l^{-1}$)	DIN reference thresholds	Source and criteria
UK WFD	BIOMASS INDICATOR: In the UK, five statistical measures of Chl-*a* biomass are made over two salinity bands using combined data for a six year reporting cycle. Compliance with the threshold is given a score of 1 for each statistical measurement, with an optimum score of 10. The final score (a value between 0 [bad] to 10 [best]) is normalized to an equidistant EQR score (0 – 1). SALINITY RANGE – LOW (0 – 25ppt) **No Chl-*a* measurement Threshold** 1: Average Chl-*a* conc, $\leq$15$\mu g\ l^{-1}$ 2: Median Chl-*a* conc, $\leq$12$\mu g\ l^{-1}$ 3: % Chl-*a* less than 10 $\mu g\ l^{-1}$ >70% 4: % Chl-*a* less than 20 $\mu g\ l^{-1}$ >80% 5: % Chl-*a* greater than 50 $\mu g\ l^{-1}$ <5% SALINITY RANGE – HIGH (>25 ppt) **No Chl-*a* measurement Threshold** 6: Average chl-*a* conc, $\leq$10$\mu g\ l^{-1}$ 7: Median chl-*a* conc, $\leq$8$\mu g\ l^{-1}$ 8: % Chl-*a* less than 10 $\mu g\ l^{-1}$ >75% 9: % Chl-*a* less than 20 $\mu g\ l^{-1}$ >85% 10: % Chl-*a* greater than 50 $\mu g\ l^{-1}$ <5% TOTAL SCORE EQR STATUS CLASS 0 - 2 0.000 - 0.133 Bad 3 - 4 0.200 - 0.300 Poor 5 - 6 0.400 - 0.500 Moderate 7 - 8 0.600 - 0.700 Good 9 - 10 0.800 - 1.000 High TAXA ABUNDANCE INDICATOR: Cell counts for each sampling period are used to calculate the number of times the threshold is exceeded (as %) when: 1.Any Single taxon (species) >500,000 cell l^{-1} 2.Total Abundance > 10^6 cells l^{-1} Normalised score calculated by reference condition (5%) divided by value. Final EQR normalised to equidistant boundaries (0 to 1)	*Annual 5th percentiles*: >5.7 mg l^{-1} = High 4.0 <5.7 mg l^{-1} = Good 2.4<4.0 mg l^{-1} = Mod 1.6 <2.4 mg l^{-1} = Poor <1.6 mg l^{-1} = Bad EQR High: 0.8 – 1.0 Good: 0.6 – 0.8 Mod: 0.4 – 0.6 Poor: 0.2 – 0.4 Bad: 0.0 – 0.2 For DO, 5th percentile of all data (collected monthly). Reporting period is typically over 6 years.	Winter DIN thresholds for UK estuaries: (clear estuaries) as μM: as mg l^{-1}: <20 = High <0.28 = High <30 = Good <0.42 = Good <45 = Mod <0.63 = Mod <67 = Poor <0.94 = Poor >67 = Bad >0.94 = Bad These thresholds are for clear waters only, defined by mean annual SPM (SPM < 10 mg l^{-1}) In turbid waters (>10 mg l^{-1} SPM), a secondary threshold (70 μM, 0.98 mg l^{-1}) may be applied, where <70 μM (0.98 mg l^{-1}) = Good >70 μM (0.98 mg l^{-1}) = Moderate If the secondary threshold is applied, then 99th percentiles are calculated from the data and compared to the threshold.	**Chl-*a*** Devlin et al., 2007a, 2007b, www.ukwfd.org **DO** Best et al., 2007 **DIN** Devlin et al., 2007a www.ukwfd.org.au

Table within Taxa Abundance Indicator:

% exceedances	Normalised score (= ref/value)	Final EQR
0-10	1.0--0.5	0.8 - 1.0
10--20	0.5--0.25	0.6 - 0.8
20--40	0.25--0.13	0.4 - 0.6
40--60	0.13--0.08	0.2-0.4
60--100	0.08--0.0	0 - 0.2

OSPAR Comprehensive Procedure

The OSPAR Common Procedure (OSPAR CP) is designed to fulfil requirements of the OSPAR Commission that seeks to reduce nutrient inputs by 50% of 1985 levels in areas where nutrient inputs are likely to cause nutrient pollution (OSPAR 2008; Claussen et al. 2009; Topcu et al. 2009). This procedure uses a two step process: a screening procedure and a full assessment. Only areas designated as Potential Problem Area or Problem Area in the screening procedure require the second step, the application of the full OSPAR Comprehensive Procedure (COMPP, Fig. 4; Table 4). Problem Areas are defined as areas for which there is evidence of anthropogenically induced eutrophication (OSPAR 2003a). The OSPAR COMPP is applied to areas defined by salinity based typology as estuarine (0–20 psu), coastal (30–34.5 psu) or offshore (>34.5 psu).

Table 5 continued

Method	Chl-*a* reference thresholds (µg l^{-1})	DO reference thresholds (mg l^{-1})	DIN reference thresholds	Source and criteria
ASSETS	*Annual 90th percentile*: 0-5 µg l^{-1} = Low 5-20 µg l^{-1} = Moderate >20 µg l^{-1} = High >60 µg l^{-1} = Hypereutrophic *Spatial coverage of worst case conditions*: 0-10% = Very Low 10 – 25% = Low 25% - 50% = Moderate >50% = High *Frequency of occurrence of worst case conditions*: Persistent Periodic Episodic	*Annual 10th percentile*: 0 mg l^{-1} = Anoxia 0-2 mg l^{-1} = Hypoxia 2-5 mg l^{-1} = Biologically Stressful *Spatial coverage of worst case conditions*: 0-10% = Very Low 10 – 25% = Low 25% - 50% = Moderate >50% = High *Frequency of occurrence of worst case conditions*: Persistent Periodic Episodic	ASSETS does not use nutrient concentrations in the assessment formulation, only nutrient loads	Bricker et al. 1999, 2003, 2007 **Chl-*a*** 90th percentile of annual data is used. These thresholds are used for all systems except Florida Bay for which thresholds are lower (i.e. High [worst] for Florida waters = 2 – 5 µg l^{-1}) **DO** 10th percentile of annual data is used
EPA NCA	*Summer value*: 0-5 µg l^{-1} = Good 5-20 µg l^{-1} = Fair >20 µg l^{-1} = Poor	*Summer value*: >5 mg l^{-1} = Good 2-5 mg l^{-1} = Fair <2 mg l^{-1} = Poor	*Summer value*: as µM: as mg l^{-1}: <7 = Good <0.1 = Good 7-36 = Fair 0.1-0.5 = Fair >36 = Poor >0.5 = Poor	EPA 2001, 2005, 2008 Data from the summer index period are used for determination of Chl-*a* and DIN condition at individual sites of US East, Gulf and West coast systems. Reference conditions are different for sensitive waterbodies
OSPAR COMPP	*Growing season 90th percentile*: Threshold = 15 µg l^{-1} >15 µg l^{-1} = threshold exceeded indicating a Problem Area Maximum and mean concentrations may also be compared to this threshold.	*5th percentile of growing season data:* Threshold = 4 mg l^{-1} <4 mg l^{-1} = threshold exceeded indicating a Problem Area	*Winter DIN for UK estuaries*: Threshold = 30 µM (0.42 mg l^{-1}) >30 µM = threshold exceeded indicating a Problem Area N:P Ratio Threshold: 24:1 where >24:1 is indicative of a Problem Area	OSPAR 2005, 2008 A one-out-all-out procedure is used to determine the classification of each of the four Categories and for the Overall Assessment

Thresholds are not used in the TRIX approach. For DIN, the WFD (as applied within the UK) and OSPAR use µM units, while EPA NCA uses mg l^{-1}. Thresholds are given here in both units to enable comparisons among methods

Mod moderate, *SPM* suspended particulate matter

The method includes four components: I—Causative Factors, II—Direct Effects, III—Indirect Effects, and IV—Other Possible Effects of nutrient enrichment. Nutrients are used to determine Causative Factors; Chl-*a*, phytoplankton, SAV, macroalgae and microphytobenthos are used to evaluate Direct Effects; DO, changes in species composition or kills of zoobenthos and/or fish are used to determine Indirect Effects; and Other Possible Effects include presence of algal toxins (OSPAR 2002; Claussen et al. 2009). Salinity related and/or region-specific threshold values are used (except for fish kills) to determine scores (+ or −), where (+) indicates a Problem Area where the indicator exceeds the threshold for acceptable water quality (i.e. reference value +50%, Table 3; Foden et al. 2009, this volume). Classification of status is determined for each category using a one-out-all-out approach where if one indicator within the component indicates a Problem Area then the whole category receives a Problem Area rating. The final classification of eutrophication status is determined from the four category ratings, also using a one-out-all-out approach (Table 4).

TRIX

The trophic index (TRIX) is defined by a linear combination of the logarithms of four state variables: Chl-*a*, DO as the absolute percent deviation from saturation (aD%O), DIN and total phosphorus (TP; Tables 3, 4). These indicators are expressions of productivity (Chl-*a*, DO) and nutritional factors (DIN, TP). Scaling coefficients are introduced to fix

Table 6 Results for the Medway estuary from application of the ASSETS method to annual data, 2000–2007

Zone area km²	Zone	Primary Symptoms					Secondary Symptoms					Zone Score
		Chl-a 90th percentile µg l⁻¹	Chl-a spatial coverage	Chl-a Frequency of occurrence	Macroalgae abundance	Macroalgae Frequency of occurrence	DO 10th percentile mg l⁻¹	DO* Spatial coverage	DO Frequency of occurrence	Nuisance/Toxic Algae	SAV	
5	Mixing	13.5	High (>50%)	Periodic	Problem	Episodic	5.5	N/A	N/A	No Problem	N/A	Moderate
56	Seawater	7.14	High (>50%)	Periodic	Problem	Episodic	7.0	N/A	N/A	No Problem	N/A	Moderate
Indicator ratings		High (Area weighted 90th percentile concentration = 7.7 µg l⁻¹)			Moderate		No Problem (Area weighted 10th percentile concentration = 6.9 mg l⁻¹)			No Problem	N/A	
Final ASSETS rating							**Moderate**					

Results are shown per salinity zone and per indicator (*Chl-a* chlorophyll *a*, *DO* dissolved oxygen, *SAV* submerged aquatic vegetation), and for the whole estuary, using area weightings (*N/A* means not applicable). The average impact of primary symptoms = high (see Tables 3, 4). The score for secondary symptoms = low/no problem. The overall rating for eutrophic condition from ASSETS is moderate. High indicates the worst, and low the best rating possible

[a] Since DO is above the threshold indicating no problem, the spatial area is marked as N/A because it is automatically considered to be high spatial coverage

the lower and upper limit values of the index to provide scores (Fig. 4) in the range of zero (scarcely productive-open sea) to ten (highly productive) TRIX units (Giovanardi and Vollenweider 2004). There is no weighting of indicators. TRIX has typically been applied for comparison of eutrophication impacts at the regional level, and has been used to compare waterbodies that varied in condition from oligotrophic to eutrophic, such as the Black, Aegean, Adriatic, Tyrrhenian and Baltic Seas (Giovanardi and Vollenweider 2004; Vascetta et al. 2004).

EPA NCA

The US EPA's National Coastal Assessment (NCA) is implemented through a federal—state partnership, and is designed to answer questions on environmental conditions in coastal waterbodies. The results supplement the US Clean Water Act (CWA) where waterbodies identified as not meeting state water quality criteria for designated uses require actions to correct pollution caused impairments (USEPA 2001a, 2003, 2005, 2008). Of the five EPA NCA indices of condition in coastal waterbodies, the Water Quality Index (WQI) is the indicator describing nutrient related conditions and will be the only one discussed here.

This method uses five indicators: DIN, dissolved inorganic phosphorus (DIP), Chl-*a*, water clarity (by Secchi depth and by comparison of light reaching the water surface and at 1 m depth) and DO (Table 3). The WQI uses the EPA Environmental Monitoring and Assessment Program's (EMAP) probabilistic randomly selected sampling framework where samples are taken once per year by region during a summer index period (June through September; USEPA 2001a). An evaluation is made for each of the five indicators at each site by comparison with regionally defined reference conditions determined from national studies (Table 3). A combined water quality index rating is calculated for each site (Tables 3, 4), then for the region and the nation based on the ratio of individual indicators that are rated as Good, Fair or Poor (e.g. condition is Good if none are rated Poor and only one is rated Fair).

ASSETS

The US National Estuarine Eutrophication Assessment method and modifications, called Assessment of

Table 7 Results for the Medway estuary from application of the EPA NCA method and data from the summer index period, 2000–2007

Indicator	EPA NCA ratings (by number of stations[a])			Scores	Final indicator rating	Final EPA NCA rating
	Poor	Fair	Good			
DIN	16	0	0	80% poor	Poor	**Poor**
DIP	17	0	0	85% poor	Poor	
Chl-*a*	0	4	12	20% fair, 60% good	Good	
DO	0	1	15	5% fair, 75% good	Good	
Water clarity[b]	1	1	0	Insufficient data	Poor	

The maximum number of stations sampled = 20*. Scores were calculated from the percent of stations in good, fair or poor condition (Tables 3, 4). The overall rating for eutrophic condition based on the EPA NCA is poor

DIN dissolved inorganic nitrogen, *DIP* dissolved inorganic phosphorus, *Chl-a* chlorophyll *a*, *DO* dissolved oxygen

[a] Some stations were missing data for some variables

[b] Very limited data

Estuarine Trophic Status (ASSETS) is designed to address requirements of the US Clean Water Act and the Harmful Algal Bloom and Hypoxia Research and Control Act (Bricker et al. 1999, 2003, 2006, 2007, 2008, 2009; Ferreira et al. 2007; Xiao et al. 2007; Scavia and Bricker 2006; http://www.eutro.org/register). ASSETS has been applied to 141 US waterbodies, several waterbodies under EU WFD requirements (e.g. Ferreira et al. 2003; Nobre et al. 2005; Bricker et al. 2007), and to systems in China and Australia (Xiao et al. 2007; Bricker et al. 2006, 2007; http://www.eutro.org/syslist.aspx). The ASSETS assessment includes examination of influencing factors (nutrient inputs as they are modified by natural hydrology of the system), eutrophic condition (nutrient related water quality conditions), and future outlook (forecast of future conditions based on predicted changes in nutrient loads). The assessment then combines results of the three components into a single overall rating (Tables 3, 4). The eutrophic condition component is the only one that will be discussed here.

ASSETS assigns an eutrophic condition rating based on five indicators, or symptoms, that are assessed by salinity zone (tidal 0–0.5 psu, mixing 0.5–25 psu, seawater >25 psu). An area-weighted system score is determined from the salinity zone results. Ratings for Chl-*a* and macroalgae, considered primary symptoms, are averaged while the worst of three secondary symptom ratings (DO, changes in areal coverage of SAV, nuisance and toxic bloom occurrence) is selected in a precautionary approach.

This approach is used given that the secondary symptoms are indicative of well developed eutrophication impacts and an average might under-represent eutrophication status. Instead, the worst case of the three ratings is used as a precaution against neglecting to apply management measures or more intense study in cases where it is needed. Symptom scores are determined by combining the occurrence, spatial coverage and frequency of occurrence of concentrations that are considered a problem and comparing to reference conditions and thresholds determined from national studies. Confidence in the assessment is determined as the Data Confidence and Reliability (DCR) that is based on sampling frequency and spatial distribution of available data (Bricker et al. 1999, 2003). Primary and secondary results are combined by matrix into a single system score. The ASSETS assessment results in an eutrophic condition rating that falls into one of five grades: High (worst), Moderate High, Moderate, Moderate Low, Low (Best). (The ASSETS desktop program is available at http://www.eutro.org/register.)

Methodological differences and their potential impacts on assessment results

Spatial considerations

The assessments presented here are normally applied over different spatial scales to provide waterbody or region-specific assessments of nutrient impacts

Table 8 Results for the Medway estuary from application of the UK WFD approach to annual and seasonal data, 2000–2007

		Summary of assessment procedure	UK WFD calculation	EQR and assessment of status per element
Transitional waters – physico-chemical and biological quality elements.	Nutrient concentration	Mean winter concentration was normalised to 25 psu and compared to nutrient thresholds (Table 5). The threshold for Moderate (30μM) was exceeded. SPM data indicates turbid waters, and the 90th percentile measurement of DIN was tested against a second threshold (70 μM). The 90th percentile exceeded the higher threshold and the waterbody was assessed as Moderate.	Mean Winter DIN : 165μM (11.7 mg l^{-1}) Annual SPM = 47.6 mg l^{-1} i.e. "intermediate" turbidity status. The 90th percentile Winter DIN was measured as 303μM (22 mg l^{-1}), exceeding the secondary threshold (70 μM, 0.98 mg l^{-1})	EQR for nutrient element = 0.23 Status = Moderate
	Phyto-plankton abundance/ indicator species	Cell counts for each sampling period were used to calculate the number of times (as a percentage) when: 1. Any Single taxon (species) >500,000 cell l^{-1} 2. Total Abundance > 10^6 cells l^{-1} Normalised score calculated by reference condition (5%) divided by value. Final EQR normalised to equidistant boundaries (0 to1).	The threshold was exceeded for a single taxon (24.1 %), and for total abundances (15.8%). Average exceedance of count thresholds is 19.8%. Normalised score = 0.26 Final EQR = 0.61	Average EQR for PP element = 0.61 (PP)+ 1.0 (Chl-a)=1.61/2 FINAL EQR for the BQE = 0.8 STATUS = High
	Chlorophyll	A set of statistical measures of spring/summer Chl-a (mean, median, percent exceedances) is used to assess data. Five measures are used per waterbody. Here, two salinity zones were assessed, giving a possible maximum of 10 results. Zone A (1-25 ppt/psu): Zone B (>25-35 ppt/psu): 1. Mean <15 μg l^{-1} 6. Mean <10 μg l^{-1} 2. Median <12 μg l^{-1} 7. Median <8 μg l^{-1} 3. >70% samples <10 μg l^{-1} 8. >75% samples <10 μg l^{-1} 4. >80% samples <20 μg l^{-1} 9. >85% samples <20 μg l^{-1} 5. <5% samples <50μg l^{-1} 10. <5% samples >50μg l^{-1} Note: under the WFD, salinity of 5-25 ppt/psu = estuaries or TW*, and >25-35 ppt/psu = coastal waterbodies	Data were separated into high and low salinity zones. Zone A Zone B Mean Chl-a = 7.9 and 4.0 Median Chl-a = 4.2 and 2.9 % <10 μg l^{-1} = 83% and 95% %<20 μg l^{-1} = 91% and 99% %>50 μg l^{-1} = 2% and 0.2% All statistical measures (n = 10) in both salinity zones were less than the thresholds TOTAL Score = 10 Final EQR = 1.0	

Inset table within Phyto-plankton row:

% exceedances	Normalised score (= ref/value)	Final EQR
0–10	1.0–0.5	0.8–1.0
10–20	0.5–0.25	0.6–0.8
20–40	0.25–0.13	0.4–0.6
40–60	0.13–0.08	0.2–0.4
60–100	0.08–0.0	0–0.2

(Fig. 5). We have ignored these delineations and applied all five assessments to the entire area of each estuary (salinity 1–34.5 psu). The OSPAR COMPP, for example, is applied to estuarine, coastal and offshore waters, some of which are outside the boundary of areas typically evaluated by the WFD. The TRIX and EPA NCA methods use a regional spatial basis for assessment. The ASSETS assessment is normally applied to estuarine salinity zones that are then area-weighted to provide a system wide result and thus management can be targeted to the most impacted zone. Here, all methods were applied to the same area and existing data (2000–2007) were used to represent the spatial and temporal variability within the system. The change in waterbody area

should not impact the assessment results since the reference conditions and thresholds of each method include waters of this type and salinity.

Sampling timeframe and frequency

The five assessment methods use data that span different timeframes, which can potentially influence results. ASSETS and TRIX use data over an annual cycle for all indicators. The OSPAR COMPP is based on spring and summer data for Chl-a, summertime data for DO and mean winter concentrations of nutrients (Table 3). The UK WFD assessment is based on annual data for Chl-a and DO, and winter data for nutrients. The EPA NCA uses seasonal data

Table 8 continued

	Summary of assessment procedure	UK WFD calculation	EQR and assessment of status per element
Macroalgal Abundance	Five indicators are used to calculate the Macroalgae BQE • the average % cover of algae in the available intertidal habitat (AIH) • the total area (in ha) • the average biomass (g/m^2) per m^2 of the AIH, • the average biomass of algae per meter squared over the affected area only • the presence of entra ined algae (the % of quadrats where algae is seen to be growing deeper than 3cm into the underlying sediment indicating the likelihood of regeneration),	• % cover of algae (ha) = >15% • Total area (in ha) > 500ha • % biomass (AIH) >500g.m^{-2} • % biomass (affected area only) >500g.m^{-2} • % of entrained algae = 0 Scores from each indicator combined to an EQR for the overall BQE	EQR for Macroalgal element = 0.58 Status = Moderate
SAV	Based on shoot loss (if any), number of species present and the loss of the spatial extent (if any) of the SAV beds.	Lack of measurements for SAV communities in Medway.	N/A
DO	**WFD Status** **Marine 5th percentile** High 5.7 mg l^{-1} Good 4.0 <5.7 mg l^{-1} Moderate 2.4 <4.0 mg l^{-1} Poor 1.6 <2.4 mg l^{-1} Bad <1.6 mg l^{-1} Final classification based on the calculation of the 5%ile DO	5th percent (whole year) = 5.04	Status = Good
Final UK WFD Rating		**Moderate**	

The final classification for ecological status is Moderate

High indicates the best, and low the worst rating possible

EQR ecological quality ratio, *DIN* dissolved inorganic nitrogen, *DIP* dissolved inorganic phosphorus, *TP* total phosphorus, *Chl-a* chlorophyll a, *DO* dissolved oxygen, *SAV* submerged aquatic vegetation, *spp.* species, *BQE* biological quality element, *PP* phytoplankton, *QE* quality element, *AIH* available intertidal habitat, *ha* hectares

* TW = transitional waterbody type which determines the reference values used for WFD assessment method

** No evidence was found of any other indirect impacts, e.g. zoobenthos/fish kills and harmful algal blooms. *Note*: Some EU member states use DO as an indicator under the physico-chemical element, but we have used DO as an indicator of indirect impacts of nutrient enrichment, consistent with the OSPAR method

for all indicators with a once-per-year sample taken within an index period (i.e. June–September). This may underestimate nutrient conditions since nutrient concentrations will be low given the uptake by phytoplankton and other marine plants during summertime. Use of limited seasonal data can bias results due to the variability in peak bloom (as measured Chl-*a*) timing as shown in Narragansett Bay where the timing of the traditional winter-spring bloom has been delayed or eliminated during the past several decades (Nixon 2009). In particular, Nixon (2009) shows that from 1958 to 1977, maximum blooms occurred in the first four months of the year 95% of the time, while in years since 1977 maximum blooms occurred in the first four months of the year only 43% of the time. This means that more than half the time,

seasonal Chl-*a* data may underestimate the worst case conditions they are attempting to capture. This has important implications for the final results of the eutrophication assessment and thus also to the required management response.

Reference conditions and thresholds

There is some confusion and considerable debate around the terminology for and use of reference conditions, background conditions and threshold values. For applications of the OSPAR COMPP, participating EU countries were required to determine reference conditions representing near pristine water quality, and to calculate acceptable thresholds allowing no more than 50% deviation from

Table 9 Results for the Medway from application of the OSPAR COMPP method to annual and seasonal data 2000–2007

Category	Indicator	Statistical results	Threshold value	Indicator rating
I	DIN	Mean winter DIN value (25 ppt) = 165 μM (2.31 mg l^{-1})	20 μM	+
I	DIP	Mean DIP value (25 ppt) = 8.2 μM (0.115 mg l^{-1})	0.68 μM	+
I	Nutrient ratios	Mean DIN:DIP = 20:1	24:1	−
II	Chl-a	90th percentile summer Chl-a concentration = 35.6 μg l^{-1}	15 μg l^{-1}	+
		Mean summer Chl-a = 15.1 μg l^{-1}		
II	Phytoplankton abundance/ indicator spp.	Combined % of exceedances for the two phytoplankton groups = 19.8%	25%	−
II	Macroalgae abundance	% Affected area <15%	500 g over 15% AIH (Table 8)	+
		% Biomass of affected area >500 g m^{-2} <10%		
II	SAV	No grasses historically or at present	N/A	N/A
III	DO	5th percentile summertime DO concentration = 4.5 mg l^{-1}	4 mg l^{-1}	−
III	Zoobenthos kills or fish kills	No fish kills reported over sampling period	N/A	−
IV	HABs/algal toxins	None reported	N/A	−
Final OSPAR assessment rating		**Problem area**		

Out of ten indicators, six showed no increased trends or elevated levels when compared to thresholds. Indicators in Categories I and II exceeded thresholds (from Table 5 and Foden et al. 2009, this volume). However there was no evidence of secondary or other impacts in Categories III and IV. The Final Classification from this approach is Problem Area

DIN dissolved inorganic nitrogen, *DIP* dissolved inorganic phosphorus, *Chl-a* chlorophyll a, *DO* dissolved oxygen, *SAV* submerged aquatic vegetation, *N/A* not applicable, *AIH* available intertidal habitat

+, increased trends, elevated levels (compared to threshold values), shifts or changes in the respective assessment parameters/ indicators

−, neither increased trends nor elevated levels nor shifts nor changes in the respective assessment parameters

Table 10 Results of application of the trophic index (TRIX) to data for the Medway estuary, 2000–2007

	Total DIN (μg l^{-1})	Total DIP (μg l^{-1})	Chl-a (μg l^{-1})	DO (%)	aD%O	TRIX	Final TRIX rating
Medway	2439	340	7.1	84.7	15.3	7.9	Highly productive

Annual averages were calculated for use in the TRIX algorithm (Table 3; Vollenweider et al. 1998)

DIN dissolved inorganic nitrogen, *DIP* dissolved inorganic phosphorus, *DO* dissolved oxygen

reference conditions. Threshold values applied in the UK application of the OSPAR COMPP and the reference conditions from which they were derived are summarised by Foden et al. (2009, this volume). Other EU countries (e.g. Germany, see Topcu et al. 2009) have determined reference conditions relevant to their waterbodies, which can therefore differ from those determined for UK waters. The UK WFD determines type specific thresholds that are intercalibrated with other EU countries. The ASSETS and EPA NCA methods use thresholds that are determined from national studies. The TRIX method does not use thresholds for individual indicators.

Fig. 4 Comparison of classification categories used by the different approaches, shown relative to WFD categories. Terminologies are different but the scaling is similar, e.g. high condition status in ASSETS is equivalent to bad condition status in the WFD. The OSPAR COMPP and TRIX methods do not use *colour coding* (adapted from Claussen et al. 2009). * For OSPAR COMPP, potential problem area is not represented since it is more a reflection of 'unknown' than of conditions between problem area and non problem area

There is similarity and general consistency among the methods for three key indicators (Chl-*a*, DO and DIN), for example DO values less than 4 mg l^{-1} and Chl-*a* values greater than 10 μg l^{-1} are taken as indicators of nutrient enrichment for all methods. This reflects the effectiveness of these key indicators in identifying stages of eutrophication (Table 5; see also Borja et al. 2009). In an effort to maximize the assessments' accuracy, in some methods the thresholds for some indicators are modified. For example, thresholds are lowered for systems that are sensitive to nutrients and thus show impacts at lower levels of nutrient input (e.g. Chl-*a* thresholds are lower in Florida Bay—ASSETS, EPA NCA; Bricker et al. 2007; EPA 2005) while thresholds are elevated for systems that are less sensitive and less susceptible to impacts of nutrient enrichment (e.g. DIN thresholds are higher in turbid east coast UK estuaries, UK WFD, Devlin et al. 2008, 2009; Table 5). While regional modification of thresholds is recommended where specific conditions (i.e. turbidity) are regionally uniform, it may inadvertently bias results if used without proper consideration. TRIX uses a fixed scale for assigning status based on the trophic index score rather than threshold values (Table 5).

Water column indicators: nutrients, chlorophyll, DO

The TRIX method uses a combination of N, P, Chl-*a*, and DO saturation (Tables 1, 3 and 4), which may produce biased results because it assumes that eutrophication processes are mainly reflected as changes in phytoplankton biomass. This does not hold true in estuaries and shallow systems where other primary producers (e.g. macroalgae [e.g. Nobre et al. 2005], seagrasses, etc.) may contribute a significant amount to total production. The EPA NCA method uses the same assumption as the TRIX method and may therefore introduce the same bias in the results.

While all methods except ASSETS include indicators based on water column nutrients (Tables 1, 5), concentrations may not necessarily correlate with a biological impact (Cloern 2001) and thus, results may not accurately represent eutrophic conditions. For example, a severely degraded system may exhibit low concentrations due to uptake by phytoplankton and macroalgae, particularly during the growing season. Conversely a relatively healthy system may have high concentrations due to high turbidity, low algal uptake, strong filter feeder populations, or may flush nutrients so quickly that primary producers do not have the opportunity to bloom extensively (Cloern 1999, 2001; Ferreira et al. 2005).

The OSPAR COMPP method uses 90th percentile and mean values, and sometimes the maximum of Chl-*a* in the growing season (OSPAR 2005), with concentrations >50% above a reference condition indicative of a Problem Area or (+) rating. The 5th percentile of DO concentrations is used by the OSPAR COMPP, with a value of >50% below a reference condition indicative of a Problem Area or (+) rating. The ASSETS method uses the 90th percentile of Chl-*a* and the 10th percentile for DO compared to reference concentrations. For both of these indicators, ASSETS combines the concentrations with the spatial extent of concentrations that are considered a problem, determined as the ratio of the
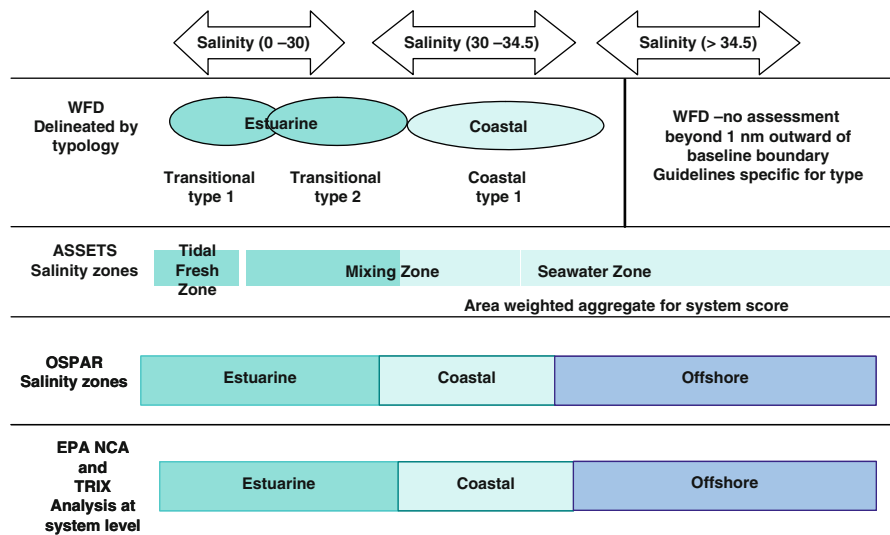
Fig. 5 A comparison of spatial scales used by the different assessment approaches. OSPAR COMPP regions for assessment are typically offshore of the WFD waterbodies, but like ASSETS and EPA NCA, the approach may be applied to any waterbody

number of stations above (for Chl-*a*) or below (for DO) the thresholds to the total number of stations (GIS determined spatial areas can also be used). The frequency of occurrence of concentrations that are considered a problem (as periodic, episodic or persistent) is included in the metric to determine the final indicator rating (Bricker et al. 1999, 2003, 2007; Table 5). The inclusion of the spatial distribution and frequency of occurrence is important for accurately evaluating the true scale and magnitude of nutrient impact on an estuary (Bricker et al. 1999, 2003).

The WFD is applied slightly differently across EU member states. In the UK, a number of tools have been developed to assess impacts of nutrient enrichment on the phytoplankton community, which include a Chl-*a* measurement, an index for phytoplankton community composition, and (more recently) an index for seasonal succession (Devlin et al. 2007a, b). In estuarine waters, the Chl-*a* indicator includes five statistical measures applied to two salinity bands (total = 10 measures): mean, median, % of samples <10 μg Chl-*a* l^{-1}, % of samples <20 μg Chl-*a* l^{-1}, % of samples >50 μg Chl-*a* l^{-1} (Tables 1, 4 and 5). The index for community composition uses two separate measures of abundance in estuaries, viz. the total cell count and single species count (see Results and discussion section). The 5th percentile of annual DO concentrations and mean winter nutrient concentrations are applied in the physico-chemical element.

Other biological indicators: macroalgae, HABs, seagrasses

The measurement of secondary biological impacts that are indicative of nutrient enrichment is a key difference among the assessments. Inclusion of these indicators provides a more robust picture of the scope of nutrient related impairments including evidence of disturbance (e.g. low DO events, toxic algal blooms).

As previously discussed, TRIX and EPA NCA do not use additional biological indicators which may lead to a result different than results of the other three methods. The UK WFD, ASSETS and OSPAR COMPP methods all include additional biological measurements (Tables 1, 6, 7, 8, 9 and 10), although the way in which they are included varies among assessment methods.

The ASSETS method includes indicators for macroalgal abundance and nuisance and toxic bloom occurrences. While there are standards indicating the concentration of cells that result in nuisance (e.g. *Aureococcus anophagefferens*, Gastrich and Wazniak 2002) and toxic (e.g. *Karenia brevis*, USFDA 2007) blooms, there is no standard number of cells that indicates unacceptable or dangerous concentrations for mixed phytoplankton communities. Likewise there is no standard measure for the level at which macroalgae biomass becomes a problem in US waters. Thus, for both macroalgae and nuisance and

toxic bloom occurrences an heuristic method is used for determination of status, where they are considered a problem if there is a negative impact on any biological resource and/or human activity (e.g. causes low DO, fish kills, illness in humans, smothers benthic organisms, etc.). This manner of determination allows for all observations to be used despite the lack of a standard measure or metric. Both indicators include the frequency of occurrence of problems and the nuisance and toxic bloom indicator also includes the duration of blooms to try to reflect the magnitude of bloom problems in a comprehensive way. The ASSETS method also uses observed changes in the areal distribution of SAV, including the magnitude of observed areal losses, where losses are considered a problem.

The OSPAR COMPP and UK WFD methods both use quantitative measurements of secondary biological impacts with a macroalgae indicator based on levels of biomass and area covered. Larger marine plants such as SAV (i.e. angiosperms by WFD terminology) are based on number of species present and areal loss or gain. HABs are not specifically measured under WFD or OSPAR COMPP guidelines, though nuisance algae such as *Phaeocystis* sp. are measured as part of the indicator for phytoplankton abundances and indicator species. Algal toxins are included in the OSPAR COMPP Category IV: Other Possible Effects.

Combining indicator metrics into an overall rating

The calculations for combining the individual indicators into a final assessment of eutrophication status vary among methods (Table 4). The WFD as applied in the UK uses a combination of biological and physico-chemical outcomes where the worst case assessment outcome is used to classify the waterbody as one of five categories: High, Good, Moderate, Fair or Poor.

The OSPAR COMPP method evaluates the components of Category I to determine whether there is evidence of anthropogenic nutrient enrichment. Evaluations of Category II indicators are used to determine evidence of accelerated growth of primary producers (i.e. phytoplankton, SAV, macroalgae, microphytobenthos). DO is used as an indicator of Indirect Effects that are caused by, for example,

excessive phytoplankton or macroalgal biomass, and algal toxins are used as an indicator of Other Possible Effects. A one-out-all-out approach is used to determine the rating (+ or −) of each category. The final classification as Problem Area, Non Problem Area or Potential Problem Area is determined from the four Category scores, also using a one-out-all-out approach.

The ASSETS assessment, in a precautionary approach, combines the average of the primary and worst of the secondary symptom ratings by a matrix, thus giving higher weighting to the symptoms that indicate a greater level of disturbance. Here, if one indicator changes it is possible it will be reflected in the overall rating. The ASSETS assessment results in a rating based on a five grade scale: High (worst), Moderate High, Moderate, Moderate Low, Low (best).

The EPA NCA method uses the proportion of Poor versus Good/Fair scores for individual indicators to determine the final rating (Good, Fair or Poor) with no weighting of indicators. TRIX does not have a scoring component for individual indicators but calculates a final score from the combination of the four components into a linear model with a scaling factor so that the resulting score is between zero (oligotrophic) and ten (trophic) TRIX units, with grades of Productive, Moderately Productive and Scarcely Productive. The TRIX and EPA NCA methods give equal weight to all indicators but the lack of inclusion of additional biological indicators means that the eutrophic rating can indicate worst case conditions without evidence of secondary biological disturbances.

Results and discussion

Despite differences, the five approaches compared here all identify a common action threshold where management intervention is recommended or required (Fig. 4). For the WFD, this is the boundary between Good and Moderate status, which is comparable with boundaries between Moderate Low and Moderate impact (ASSETS), Good and Fair (EPA NCA), Non Problem Area and Problem Area (OSPAR) and Scarcely Productive and Moderately Productive (TRIX). The differences in the number of final

assessment categories (two for OSPAR COMPP, three for EPA NCA and TRIX, and five for the UK WFD, ASSETS) make it difficult to compare results directly. For example, it is not possible to know whether the OSPAR COMPP Problem Area rating is closer to the worst rating in the five grade scales, or is closer to a Moderate rating. Since these assessments are designed to evaluate conditions in order to guide development of management measures, the methods that give a more representative indication of conditions may be more useful for this task. While it may be easier to score a system on a scale that is either acceptable or unacceptable such as the OSPAR COMPP, it may be more difficult to identify small changes in eutrophic

condition, as a result of management or of further degradation, than it is with methods that have a three or five grade scale.

Detailed results from the application of the five methods (ASSETS, EPA NCA, TRIX, OSPAR COMPP and UK WFD) are shown for the Medway estuary only (Tables 6, 7, 8, 9 and 10) to illustrate the calculations behind the assessment outputs. The same calculations were applied to the Thames, and the final results are presented. Ten indicators are used among the five assessments, with final outcomes indicating that both the Medway (Table 11) and the Thames (Table 12) have Moderate to High level impacts associated with nutrient enrichment.

Table 11 Final outcomes for the Medway estuary from application of five eutrophication assessment methods to data from 2000 to 2007

Medway

Element	Indicators	UK WFD	ASSETS	EPA NCA	OSPAR COMPP[a]	TRIX
Physico-chemical	DIN	Moderate		Poor	+	*
	DIP			Poor	+	*
	Water Clarity			Fair/Poor		
Phytoplankton	Chlorophyll-*a*	Good	High (worst)	Good	+	*
	HABS/Algal toxins		Low (best)		−	
	Phytoplankton Indicator species.	High (best)			−	
	Overall BQE for phytoplankton (WFD only)	High (best)				
Macro-algae	Macroalgae abundance	Moderate	Moderate		+	
SAV	Submerged Aquatic Vegetation	N/A	N/A		N/A	
Other	Zoobenthos kills/Fish kills				−	
	Dissolved Oxygen	Good	Low (best)	Good	−	*
Trophic Index						7.9
Final assessment of Eutrophication Condition		Moderate	Moderate	Poor	Problem Area	Highly Productive

Outcomes are shown as text and as colour coding where appropriate (from Fig. 4). The outcomes for the UK WFD BQEs are based on the average EQR for the element (from Table 8). Plus (+) scores from the OSPAR COMPP indicate that the indicator values exceed the threshold value. For TRIX, * indicates variables used in the assessment (see Tables 1, 3). Cells were left blank if the indicator was not used as part of the assessment

DIN dissolved inorganic nitrogen, *DIP* issolved inorganic phosphorus, *HABs* harmful algal blooms, *BQE* biological quality element, *EQR* ecological quality element, *N/A* = Not applicable

[a] For OSPAR COMPP

+, increased trends, elevated levels, shifts or changes in the respective assessment parameters

−, neither increased trends nor elevated levels nor shifts nor changes in the respective assessment parameters

Table 12 Final outcomes for the Thames estuary from application of five eutrophication assessment methods to data from 2000 to 2007

Element	Indicators	UK WFD	ASSETS	EPA NCA	OSPAR COMPP[a]	TRIX
Physico-chemical	DIN	Moderate		Poor	+	*
	DIP			Poor	+	*
	Water Clarity			Poor		
Phytoplankton	Chlorophyll-*a*	Moderate	High (worst)	Poor	+	*
	HABS/Algal toxins		Low (best)		−	
	PP Indicator sp.	High (best)			−	
	Overall BQE for phytoplankton assessment (WFD only)	Good				
Macro-algae	Macroalgae abundance	High (best)	Low (best)		+	
SAV	Submerged Aquatic Vegetation	N/A	N/A		N/A	
Other	Zoobenthos/fish kills				−	
	Dissolved Oxygen	Moderate	Low (best)	Fair	−	*
Trophic Index						8.5
Final assessment of Eutrophication Condition		Moderate	Moderate	Poor	Problem Area	Highly Productive

Outcomes are shown as text and as colour coding where appropriate (from Fig. 4). The outcomes for the UK WFD BQEs are based on the average EQR for the element (from Table 8). Plus (+) scores from the OSPAR COMPP indicate that the indicator values exceed the threshold value. For TRIX, * indicates variables used in the assessment (see Tables 1, 3). Cells were left blank if the indicator was not used as part of the assessment

DIN dissolved inorganic nitrogen, *DIP* issolved inorganic phosphorus, *HABs* harmful algal blooms, *BQE* biological quality element, *EQR* ecological quality element, *N/A* = Not applicable

[a] For OSPAR COMPP

+, increased trends, elevated levels, shifts or changes in the respective assessment parameters

−, neither increased trends nor elevated levels nor shifts nor changes in the respective assessment parameters

Medway assessment outcomes

Results for the overall eutrophic condition based on application of the UK WFD and ASSETS approaches (Table 11) give an overall status of Moderate. The OSPAR COMPP classifies the Medway as a Problem Area. Outcomes from the EPA NCA and TRIX classify the status of the Medway as Poor and Highly Productive, respectively, which is a worse rating than results of the other methods. The reason for the worse rating is that the ASSETS and UK WFD use secondary biological indicators that show only Moderate (i.e. for macroalgae) problems, which mediate the worse scores of the nutrient and high biomass outcomes. However, all of the assessment scores indicate that the waterbody is below the threshold indicating acceptable water quality and thus would necessitate management intervention to reduce and manage nutrient loads.

The nutrient indicator assessment results are Moderate for UK WFD, (+) or Problem Area for OSPAR COMPP and Poor for EPA NCA (Table 11, see also Tables 7, 8 and 9). The EPA NCA shows a more severe rating than the UK WFD, despite the concentrations of the EPA NCA samples having a much lower summer mean (1.94 mg l^{-1}) than mean winter concentrations of the UK WFD (11.7 mg l^{-1}). The UK WFD assessment result of Moderate reflects the use of turbidity as a mitigating factor in the UK WFD process whereby a higher threshold is used for

DIN (>0.98 mg l^{-1} = Moderate) in turbid systems than in clear systems (>0.42 mg l^{-1} = Moderate). Once a waterbody is designated as turbid (i.e. > 10 mg l^{-1} SPM) then assessment ratings for nutrient status cannot fall below Moderate (i.e. to Poor or Bad) due to low light conditions (Anon 2008). The EPA NCA results show a more severe rating than the UK WFD because the thresholds are not modified to accommodate the high turbidity. The accommodation for high turbidity conditions makes a difference since if the rating for the EPA DIN indicator, and by extension the DIP indicator, was Moderate then the rating for the waterbody would be Moderate. Likewise, the UK WFD rating for the Medway would be Poor if the threshold was not elevated (Tables 5, 7).

The scores for Chl-a a are Good based on the UK WFD and EPA NCA methods, but are rated a Problem by the OSPAR COMPP method and High (worst) for ASSETS (Table 11). The differences are explained by the use of spatial and frequency components in the ASSETS method, the once per year sampling of the EPA NCA method, the use of only growing season data by OSPAR, and the use of annual Chl-a data in multiple statistical measurements used by the UK WFD. The ASSETS method calculated the 90th percentile of annual Chl-a data as 13.5 and 7.1 μg l^{-1} for the mixing (5 km^2) and seawater (51 km^2) zones respectively, both of which fall into the Moderate category (Table 5). When combined with high spatial coverage of the Moderate Chl-a values and periodic frequency of occurrence within both zones (see Fig. 3b), the end result is a High (worst) rating for Chl-a. The 90th percentile of the growing season (spring–summer) data for the OSPAR COMPP is 35.6 μg l^{-1}, resulting in a rating of Problem area or (+) when compared to the OSPAR Chl-a threshold (>15 μg l^{-1}). The Good rating based on application of the EPA NCA method may be biased by the sampling timeframe since highest values of Chl-a typically occur in the months of April and June (Fig. 3b), and the sample index period is June–September. The once per index period samples may have missed the time of maximum bloom concentrations. In fact, for 2 years (2001 and 2003) samples used in the assessment were from July sampling dates while in all other years the samples used were from August to September.

Results for the UK WFD Chl-a indicator are rated as High (best) because 10 (out of a maximum of 10) statistical measurements did not exceed the threshold value (N = 10, EQR = 1.0; Table 5). Results from the phytoplankton indicators (single species and total taxa counts) are classified as Good (% exceedances = 19.8%, EQR = 0.61; Table 5). The two EQR scores are combined for a final classification of High (best; average EQR = 0.8) for the phytoplankton BQE (Table 8).

The results for DO are consistent among all methods (Table 11) despite the use of different timeframes (i.e. annual or seasonal) for data analysis (Table 5). Results from all methods indicate no significant problems with DO in the Medway estuary which rarely falls below 4 mg l^{-1} (Fig. 3c).

Macroalgal surveys carried out on the Medway have shown the affected area to be greater than 15% and the mean biomass (over affected areas) to be greater than 500 g m^{-2} resulting in a status of Moderate based on the UK WFD method and Problem area or (+) based on the OSPAR COMPP method. The ASSETS method results show a Moderate level of macroalgal abundance due to observed problems on a periodic basis (Fig. 6a; Table 11). It should be noted that the heuristic method used by the ASSETS method and data from measured surveys give the same result. However, there are no problems indicated by any method for HABs, phytoplankton indicator species, or kills of zoobenthos or fish. Due to the high turbidity of estuarine waters, seagrasses are insignificant and thus are noted as Not Applicable. Seagrasses are not included in the UK WFD, OSPAR COMPP and ASSETS assessment calculations.

In summary, the combination of high nutrients, high periodic Chl-a biomass and the presence of macroalgal blooms indicates that this is a Problem Area requiring some form of management intervention.

Thames assessment outcomes

The results of the application of the WFD and ASSETS methods classify the Thames as Moderate in status (Table 12). Results of the EPA NCA and TRIX, classify the Thames as Poor and Highly Productive respectively, signifying worse conditions than the results of the UK WFD and ASSETS. The

OSPAR COMPP results show the Thames to be a Problem Area which is consistent with both the Moderate and Poor results. As with the Medway, despite the differences in assessments, they all identify the Thames estuary as impacted by nutrients and requiring management intervention.

All approaches indicated anthropogenic nutrient enrichment of the Thames. There are, however, differences among ratings which are due to the differences in the application of each indicator assessment. For the UK WFD, the high turbidity conditions found in the Thames estuary (Devlin et al. 2009) mediates the nutrient assessment rating by applying a higher nutrient threshold (see Table 5; Devlin et al. 2008) resulting in a Moderate rating. The EPA NCA method rates nutrient concentrations as Poor for both DIN and DIP and the OSPAR COMPP method results in a rating of Problem levels or (+).

All approaches show evidence of accelerated growth of phytoplankton, measured as Chl-*a*, as a response to nutrient enriched conditions. Scores for Chl-*a* are Moderate for UK WFD, Problem levels or (+) for OSPAR COMPP, Poor for EPA NCA and High (worst) for ASSETS. The 90th percentile for the ASSETS analysis gives a result of 50 and 11.6 μg l^{-1} in the mixing and seawater zones, respectively. The combination of these higher concentrations with high spatial coverage (over >50% of the waterbody) and the periodic or annual occurrence of such high concentrations, leads to the most severe rating of High (worst). The EPA NCA assessment method results in a Chl-*a* rating of Poor since concentrations were above 5 μg l^{-1} at >93% of all stations and above 20 μg l^{-1} at more than 25% during the summertime sampling period (i.e. June–September; Fig. 3 T3 and T4). Results from the OSPAR COMPP show that the 90th percentile of summertime Chl-*a* values (68 μg l^{-1}) are greater than the threshold of 15 μg l^{-1} resulting in a rating of Problem Area or (+). Results for the UK WFD Chl-*a* indicator are classified as Moderate (0.40) because 5 out of a maximum of 10 statistical measurements exceeded a reference value (N = 5, EQR = 0.4, Table 5). Results from the UK WFD phytoplankton indicators (single species and total taxa counts) are classified as High (best; % exceedances = 7.4%, EQR = 0.85, Table 5). The two EQR scores are combined for a final classification of Good (average EQR = 0.63) for the phytoplankton BQE.

The results for the assessment of DO vary among methods with ASSETS results giving a rating of Low or best condition, compared to results of other methods of Good (UK WFD), Fair, (EPA NCA) and Non Problem Area or (−) for OSPAR COMPP. The seasonal versus annual timeframes of data seem to account for these differences as the use of annual data results in a higher concentration (better condition) of DO than growing season or summertime data only. For ASSETS, 10th percentile DO concentrations were calculated to be 3.2 and 6.7 mg l^{-1} in the mixing (47 km^2) and seawater zones (201 km^2) respectively whereas for the OSPAR COMPP and UK WFD, DO was calculated to be 2.4 mg l^{-1} (Table 4) over the whole system (Fig. 3c). Additionally, once the spatial coverage (low in both zones) and frequency of occurrence (periodic) are considered, the ASSETS rating remains low or best condition. The difference in sampling timeframes (annual data for ASSETS and UK WFD, summertime for OSPAR COMPP) and statistical criteria (fifth percentile for UK WFD, 10th percentile for ASSETS) as well as the consideration of spatial distribution of observed concentrations that are considered a problem, results in ASSETS giving a less severe score compared to the others, though showing that there are sometimes low DO values within the mixing zone.

The indicators of ecosystem function are fairly consistent among the three methods that include such measures, showing no significant problems with HABs, phytoplankton indicator species or macroalgal abundance, and no recorded zoobenthos or fish kills. It should be noted that in this system, as for the Medway, high turbidity limits seagrass growth. This indicator is considered Not Applicable and is not used in the assessment calculations.

In contrast to the Medway, where there was evidence of secondary biological impacts in the detection of macroalgal blooms, the Thames has no measured biological disturbance, however, the final assessment for all approaches was below the acceptable management guidelines suggesting that management is recommended or required.

Conclusion

The application of the five different eutrophication assessment methods to two estuarine systems in the

UK in this study resulted in similar final assessment results when applied to the same data (2000–2007). All approaches indicated that both waterbodies required management intervention to reduce the impacts of nutrient enrichment. However, detailed results among the methods differed; those that use more than one biological indicator indicated (except for Moderate macroalgal problems in the Medway) that secondary biological impacts of nutrient enrichment were minimal. There are differences in timeframes for analysis of data (seasonal versus annual), characteristics used in the indicator metrics (concentration, spatial coverage, frequency of occurrence) and the way that indicators are combined to determine the final eutrophication status. These differences resulted in variable results for some indicators, such as nutrients (e.g. Moderate for UK WFD and Poor for EPA NCA) and Chl-a (e.g. ASSETS was High [worst] and UK WFD and EPA NCA were both Good for Medway). However, all methods show that management actions are recommended or required for both estuaries.

Comparison of the application of and results from the five approaches highlighted differences and complexities of application among the methods. Since eutrophication assessment is required by many countries and, along with targeted research, contributes to the development of management measures it is important that scientists, resource managers and legislators understand how well conditions are represented by the methods they use. Results from this study illustrate that there is a common understanding of the progression of eutrophication and the changes in key parameters that indicate eutrophication status. While not promoting the use of any single method, there are characteristics of specific methods that appear to make them more accurate with respect to evaluation of conditions than some other methods. Those characteristics recommended for inclusion in assessment methods to assure that results are useful for management include:

- The selection of thresholds should accommodate the relative sensitivity (e.g. adjusted DIN threshold on account of high turbidity) of the system to nutrient related degradation so that conditions are not mis-represented;
- Use of annual data and sampling through the year will increase the likelihood that eutrophic conditions will be observed and accurately evaluated;

- The use of spatial coverage, frequency of occurrence, and duration (for HABs) in an indicator metric provides a way to capture more comprehensively, the magnitude of the problem;
- Inclusion of secondary biological indicators (e.g. macroalgal abundance, nuisance and toxic blooms) provides a fuller picture of the scope of nutrient related problems;
- The combination of indicators into an overall condition rating should use a method that is able to detect changes due to successful management measures or pollutant related degradation. For example, the use of a multi-grade scale for indicators and for overall eutrophic condition provides greater sensitivity to detect changes in condition with successive assessments than a two-grade scale;
- Nutrient loads should be linked to impairments within the assessment process so that results will be relevant and useful for the development of targeted and successful management measures.

While these recommendations should not be considered inclusive, we hope that these observations will be helpful to resource managers for selecting an appropriate eutrophication assessment method, and to improve methods that are already being used.

References

Andersen JH, Laamanen M (eds) (2009) HELCOM. Eutrophication in the Baltic Sea: an integrated thematic assessment of the effects of nutrient enrichment and eutrophication in the Baltic Sea region. Baltic Sea Environmental Proceedings No. 115B

Anon (2007) Recommendations on surface water classification schemes for the purposes of the Water Framework Directive. UK Technical Advisory Group on the Water Framework Directive. http://www.wfduk.org/

Anon (2008) United Kingdom Environmental Standards and Conditions (Phase 2). A report for the UK Technical

Advisory Group on the Water Framework Directive. http://www.wfduk.org/

Anon (2009) River Basin Characterisation report for the Water Framework Directive. A report to the Environment Agency United Kingdom. http://www.defra.gov.uk/environment/water/wfd/article5/index.htm

Best M, Wither A, Coates S (2007) Dissolved oxygen as a physicochemical supporting element in the Water Framework Directive. Mar Pollut Bull 55(1–6):91–103

Borja A, Bricker SB, Dauer DM, Demetriades NT, Ferreira JG, Forbes AT, Hutchings P et al (2008) Overview of integrative tools and methods in assessing ecological integrity in estuarine and coastal systems worldwide. Mar Pollut Bull 56:1519–1537

Borja A, Basset A, Bricker S, Dauvin JC, Elliott M, Harrison T, Marques JC, Weisberg S, West R (2009) Classifying ecological quality and integrity of estuaries. In: Wolanski E, McLusky D (eds) Treatise on estuarine and coastal science. Elsevier, Amsterdam

Boynton WR, Hagy JD, Murray L, Stokes C, Kemp WM (1996) A comparative analysis of eutrophication patterns in a temperate coastal lagoon. Estuaries 19:408–421

Bricker SB, Clement CG, Pirhalla DE, Orlando SP, Farrow DRG (1999) National Estuarine Eutrophication Assessment: effects of nutrient enrichment in the nation's estuaries. NOAA National Ocean Service Special Projects Office and National Centers for Coastal Ocean Science, Silver Spring. http://coastalscience.noaa.gov/publications/eutro_report.pdf

Bricker SB, Ferreira JG, Simas T (2003) An integrated methodology for Assessment of Estuarine Trophic Status. Ecol Model 169:39–60

Bricker SB, Lipton D, Mason A, Dionne D, Keeley D, Krahforst C, Latimer J, Pennock K (2006) Improving methods and indicators for evaluating coastal water eutrophication: a pilot study in the Gulf of Maine. NOAA Technical Report 20. http://ccma.nos.noaa.gov/news/feature/GulfofMaine.html

Bricker SB, Longstaff B, Dennison WC, Jones A, Boicourt K, Wicks C, Woerner J (2007) Effects of nutrient enrichment in the nation's estuaries: a decade of change National Estuarine Eutrophication Assessment update. NOAA Coastal Ocean Program Decision Analysis Series No. 26. National Centers for Coastal Ocean Science, Silver Spring, MD. http://ccma.nos.noaa.gov/news/feature/Eutroupdate.html

Bricker SB, Longstaff B, Dennison WC, Jones A, Boicourt K, Wicks C, Woerner J (2008) Effects of nutrient enrichment in the nation's estuaries: a decade of change. Harmful Algae 8:21–32

Bricker SB, Dennison WC, Dunton KH, Ferreira JG, Hall MR, Herrera-Silveira JA, Longstaff BJ, Morales-Ojeda S, Onuf CP, Pastres R, Thomas JE, Wazniak CE (2009) The coastal bays in context. In: Dennison WE, Thomas JE, Cain CJ, Cain TJB (eds) Shifting sands, environmental and cultural change in Maryland's coastal bays. IAN Press, Cambridge

Butcher RW (1941) Zostera: report on the present conditions of eelgrass on the coasts of England based on a survey during August to October 1933. Int Wildfowl Inq 1:49–65

Claussen U, Zevenboom W, Brockmann U, Topcu D, Bot P (2009) Assessment of the eutrophication status of transitional, coastal and marine waters within OSPAR. Hydrobiologia 629(1):49–58. doi:10.1007/s10750-009-9763-3

Cloern JE (1999) The relative importance of light and nutrient limitation of phytoplankton growth: a simple index of coastal ecosystem sensitivity to nutrient enrichment. Aquat Ecol 33:3–16

Cloern JE (2001) Our evolving conceptual model of the coastal eutrophication problem. Mar Ecol Prog Ser 210:223–253

Council of European Communities (CEC) (1991a) Council Directive of 21 May 1991 concerning urban waste water treatment (91/271/EEC). Off J Eur Commun L135:40–52 (30.5.91)

Council of European Communities (CEC) (1991b) Council Directive of 31 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources (91/676/EEC). Off J Eur Commun L375:1–8

Council of European Communities (CEC) (1992) Habitats Directive

Council of European Communities (CEC) (2000) Council Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for community action in the field of water policy. Off J Eur Commun L327:1–73

Council of European Communities (CEC) (2008) Council Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive)

Devlin MJ, Best M, Coates D et al (2007a) Establishing boundary classes for the classification of UK marine waters using phytoplankton communities. Mar Pollut Bull 55:91–103

Devlin MJ, Painting S, Best M (2007b) Setting nutrient thresholds to support an ecological assessment based on nutrient enrichment potential primary production and undesirable disturbance. Mar Pollut Bull 55:65–73

Devlin MJ, Barry J, Mills DK, Gowen RJ, Foden J, Tett P (2008) Relationships between suspended particulate material light attenuation and secchi depth in UK marine waters. Estuar Coast Shelf Sci 79:429–443

Devlin MJ, Barry J, Mills DK, Gowen RJ, Foden J, Greenwood N, Pearce D, Tett P (2009) Estimating the diffuse attenuation coefficient from optically active constituents in UK marine waters. Estuar Coast Shelf Sci 82:73–83

Ferreira JG, Simas T, Nobre A, Silva MC, Schifferegger K, Lencart-Silva J (2003) Identification of sensitive areas and vulnerable zones in transitional and coastal Portuguese systems. Application of the United States National Estuarine Eutrophication Assessment to the Minho Lima Douro Ria de Aveiro Mondego Tagus Sado Mira Ria Formosa and Guadiana systems. INAG/IMAR 2003

Ferreira JG, Wolff WJ, Simas TC, Bricker SB (2005) Does biodiversity of estuarine phytoplankton depend on hydrology? Ecol Model 187:513–523

Ferreira JG, Bricker SB, Simas TC (2007) Application and sensitivity testing of an eutrophication assessment method on coastal systems in the United States and European Union. J Environ Manag 82(4):433–445

Foden J, Devlin M, Mills DK, Malcolm SJ (2009) Searching for undesirable disturbance: the OSPAR eutrophication

assessment method applied to marine waters of England and Wales. Biogeochemistry (this volume)

Gastrich MD, Wazniak C (2002) A brown tide bloom index based on the potential harmful effects of the brown tide alga, *Aureococcus anophagefferens*. Aquat Ecosyst Health Manag 33:175–190

Gillbricht M (1988) Phytoplankton and nutrients in the Helgoland region. Helgolander Meeresuntersuchungen 42:435–467

Giovanardi F, Vollenweider RA (2004) Trophic conditions of marine coastal waters: experience in applying the Trophic Index TRIX to two areas of the Adriatic and Tyrrhenian seas. J Limnol 63(2):199–218

Hughes R, Paramor O (2004) On the loss of saltmarshes in south-east England and methods for their restoration. J Appl Ecol 41:440–448

Lancelot C, Billen G, Sournia A, Weisse T, Colijn F, Veldhuis MJ, Davies W, Wassman A (1987) Phaeocystis blooms and nutrient enrichment in the continental coastal zones of the North Sea. Ambio 16:38–46

Nixon SW (2009) Eutrophication and the macroscope. Hydrobiologia 629:5–19

Nobre AM, Ferreira JG, Newton A, Simas T, Icely JD, Neves R (2005) Managing eutrophication: integration of field data ecosystem-scale simulations and screening models. J Mar Syst 56(3/4):375–390

Oslo Paris Convention for the Protection of the North Sea (OSPAR) (2002) Common assessment criteria their assessment levels and area classification within the Comprehensive Procedure of the Common Procedure. OSPAR Commission for the Protection of the Marine Environment of the North-East Atlantic. http://www.ospar.org

Oslo Paris Convention for the Protection of the North Sea (OSPAR) (2008) Annex 4. Second OSPAR Integrated Report on the Eutrophication Status of the OSPAR Maritime Area OSPAR Commission, 2008 Publication 372/2008, 106 pp

OSPAR Commission (2003a) The OSPAR Integrated Report 2003 on the Eutrophication Status of the OSPAR Maritime Area based upon the first application of the comprehensive procedure. OSPAR Publication 2003, ISBN:1-904426-25-5

OSPAR Commission (2003b) Strategies of the OSPAR Commission for the protection of the marine environment of the north-east Atlantic (Reference number: 2003-21). EUC 03/17/1-E Annex 31, p 22

OSPAR Commission (2005) Common procedure for the identification of the Eutrophication Status of the OSPAR Maritime Area reference number: 2005-3: supersedes agreements 1997-11 and 2002-20. Source: EUC 2005 Summary Record—EUC 05/13/1 Annex 5 as amended and endorsed by OSPAR 2005 Summary Record—OSPAR 05/21/1 §§ 6.2-6.5 and Annex 6

Painting SJ, Devlin MJ, Malcolm SJ, Mills C, Mills DK, Parker ER, Tett P, Wither A, Burt J, Jones R, Winpenny K (2007) Assessing the impact of nutrient enrichment in estuaries: susceptibility to eutrophication. Mar Pollut Bull 55:74–90

Pollard P, Huxham M (1998) The European Water Framework Directive: a new era in the management of aquatic ecosystem health? Aquat Conserv Mar Freshw Ecosyst 8:773–792

Rogers SJ, Allen P, Balson R et al (2003) Typology for the transitional and coastal waters for UK and Ireland (Contractors: Aqua-fact International Services Ltd BGS CEFAS IECS JNCC). Funded by Scotland and Northern Ireland Forum for Environmental Research Edinburgh and Environment Agency of England and Wales. SNIFFER Contract Ref: WFD07 (230/8030)), 94 pp

Scavia D, Bricker SB (2006) Coastal eutrophication assessment in the United States. Biogeochemistry 79:187–208

Smayda TJ, Reynolds CS (2001) Community assembly in marine phytoplankton: application of recent models to harmful dinoflagellate blooms. J Plankton Res 23:447–461

Tett P (1987) Plankton. In: Baker JM, Wolff JW (eds) Biological surveys of estuaries and coasts. Cambridge University Press, Cambridge, pp 280–341

Topcu D, Brockmann U, Ulrich C (2009) Relationship between eutrophication reference conditions and boundary settings considering OSPAR recommendations and the Water Framework Directive—examples from the German Bight. Hydrobiologia 629:91–106

United States Environmental Protection Agency (USEPA) (2001a) National Coastal Condition Report I. United States Environmental Protection Agency, Office of Research and Development, Office of Water, Washington, DC. EPA-620/R-01/005. http://www.epa.gov/nccr

United States Environmental Protection Agency (USEPA) (2001b) Environmental Monitoring and Assessment Program (EMAP): National Coastal Assessment Quality Assurance Project Plan 2001–2004. United States Environmental Protection Agency, Office of Research and Development, National Health and Environmental Effects Research Laboratory, Gulf Ecology Division, Gulf Breeze, FL. EPA/620/R-01/002. http://www.epa.gov/emap/nca/html/docs/c2k_qapp.pdf

United States Environmental Protection Agency (USEPA) (2003) Guidance for 2004 Assessment, Listing and Reporting Requirements Pursuant to Sections 303(d) and 305(b) of the Clean Water Act. United States Environmental Protection Agency, Office of Water, Office of Wetlands, Oceans, and Watersheds

United States Environmental Protection Agency (USEPA) (2005) National Coastal Condition Report II. United States Environmental Protection Agency, Office of Research and Development, Office of Water, Washington, DC. EPA-620/R-03/002. http://www.epa.gov/nccr

United States Environmental Protection Agency (USEPA) (2008) National Coastal Conditions Report III. United States Environmental Protection Agency, Office of Research and Development/Office of Water, Washington, DC, 20460. EPA/842-R-08-002. http://www.epa.gov/nccr

United States Food and Drug Administration (USFDA) (2007) National Shellfish Sanitation Program (NSSP) 2007 Chapter IV—Shellstock Growing Areas. National Shellfish Sanitation Program Guide for the Control of Molluscan Shellfish 2007. Section II. Model Ordinance, Chapter IV Shellstock Growing Areas. http://www.fda.gov/Food/FoodSafety/ProductSpecificInformation/Seafood/FederalStatePrograms/NationalShellfishSanitationProgram/UCM046988

Vascetta M, Kauppila P, Furman E (2004) Indicating eutrophication for sustainability considerations by the trophic index TRIX: does our Baltic case reveal its usability outside Italian waters? In: Peer conference, 17 Nov 2004

Vincent CH, Heinrich A, Edwards K, Nygaard K, Haythornthwaite K (2002) Guidance on typology, reference conditions and classification systems for transitional and coastal waters. Produced by: CIS Working Group 2.4 (COAST), Common Implementation Strategy of the Water Framework Directive, European Commission, 119 pp

Vollenweider RA, Giovanardi F, Montanari G, Rinaldi A (1998) Characterization of the trophic conditions of marine coastal waters with special reference to the NW Adriatic Sea: proposal for a trophic scale, turbidity and generalized water quality index. Environmetrics 9:329–357

Xiao Y, Ferreira JG, Bricker SB, Nunes JP, Mingyuan Z, Xuelei Z (2007) Trophic assessment in Chinese coastal systems—review of methods and application to the Changjiang (Yangtze) Estuary and Jiaozhou Bay. Estuar Coasts 30(6):901–918