

RECOMMENDED INDICATORS OF ESTUARINE WATER QUALITY FOR GEORGIA

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Abstract. Increasing nutrient input and subsequent eutrophication and hypoxia are concerns in many estuaries, and the U.S. EPA has mandated the development of numeric nutrient criteria to assess the status of U.S. coastal waters. However, they recognize the need for regionally appropriate criteria, as previous national-level efforts have often relied on criteria that are not equally relevant in all waters. Two pathways to eutrophication have been suggested to exist in Georgia waters: the classic phytoplankton-mediated pathway in stratified waters and an alternate pathway in which excess nutrients stimulate microbial respiration directly, resulting in low dissolved oxygen throughout a well-mixed water column. We propose a suite of seven indicators, as well as basic ancillary data (water temperature, salinity, specific conductance), that are intended to help classify and understand the causes of water quality degradation in Georgia. We recommend two immediate indicators of poor water quality (pH and dissolved oxygen) that may indicate that a stressful and potentially lethal condition is already in progress. The remaining five (nitrogen, phosphorus, chlorophyll *a*, transparency, and biochemical oxygen demand (BOD)) are “early warning” indicators of potentially poor water quality that should be measured in order to anticipate problems and make appropriate management decisions. These indicators, which cover the progression of eutrophication from nutrient over-enrichment to algal overgrowth (if present) to enhanced microbial respiration and hypoxia, will help to ensure that problems will not be missed due to limited sampling frequencies. We present the rationale for choosing these indicators and the considerations for developing evaluation criteria.

INTRODUCTION

Increasing nutrient input is a prime concern for coastal systems worldwide (Bricker et al. 1999; Howarth et al. 2000; NRC 2000). Excess inputs of nitrogen and phosphorus can lead to eutrophication, which is the accelerated production of organic matter and the potential development of areas of low dissolved oxygen concentration (hypoxia). The consequences of hypoxia can include death of benthic organisms, fish kills, reduced growth and reproduction, physiologic stress, forced migration, reduction of spawning grounds and nursery habitats, increased vulner-

ability to predation, and disruption of life cycles. Other symptoms of eutrophication include the stimulation of nuisance and toxic algal blooms, increases in turbidity, losses of submerged aquatic vegetation, and changes in the food web (Howarth 1988; Rabalais 2002).

There have been several national-level efforts to assess the status of U.S. coastal waters. The National Estuarine Eutrophication Assessments (NEEA, NOAA) found that approximately two-thirds of the U.S. estuaries for which data were available exhibited moderate to high expressions of eutrophic conditions, with most estuaries being highly influenced by human-related activities (Bricker et al. 1999, 2007). Georgia estuaries included in these studies rated low to moderate in eutrophic conditions, but the criteria were not always appropriate (e.g. the status of sea grass is irrelevant because sea grasses are not found in Georgia waters). The National Coastal Condition Reports (NCCR, led by U.S. EPA) have consistently rated water quality in continental U.S. estuaries as “fair” overall, while the southeast as a whole has been rated on the high side of “fair” (U.S. EPA 2001a, 2004, 2008). Assessments for individual states are not generally provided, but a report by the Georgia Dept. of Natural Resources, Coastal Resources Division (CRD) using data collected for the EPA National Coastal Assessment program classified 80% of Georgia estuarine waters as having “fair” water quality, 18% as “poor”, and only 1% as “good” based on the NCCR indicators (Guadagnoli et al. 2005).

The EPA’s water quality regulations require States to develop quantifiable targets for nutrients in order to ensure that waters meet their designated uses. The EPA is currently working with the States to establish numeric nutrient water quality standards for U.S. waters (Grumbles 2007). Georgia’s criteria will be developed and adopted under agreement with EPA in 2014.

Two pathways to eutrophication have been suggested to exist in Georgia waters (Figure 1). In the classic pathway, nutrients stimulate phytoplankton growth. As this material gets consumed or dies, it sinks to the bottom where it is decomposed by microbes. The decomposition process uses up oxygen via respiration; hence, enhanced decomposition can result in a reduction of the oxygen concentrations in bottom water. In the alternate pathway, excess nutrients stimulate microbial respiration directly, resulting in low dissolved oxygen throughout a well-mixed water column (Verity et al. 2006).

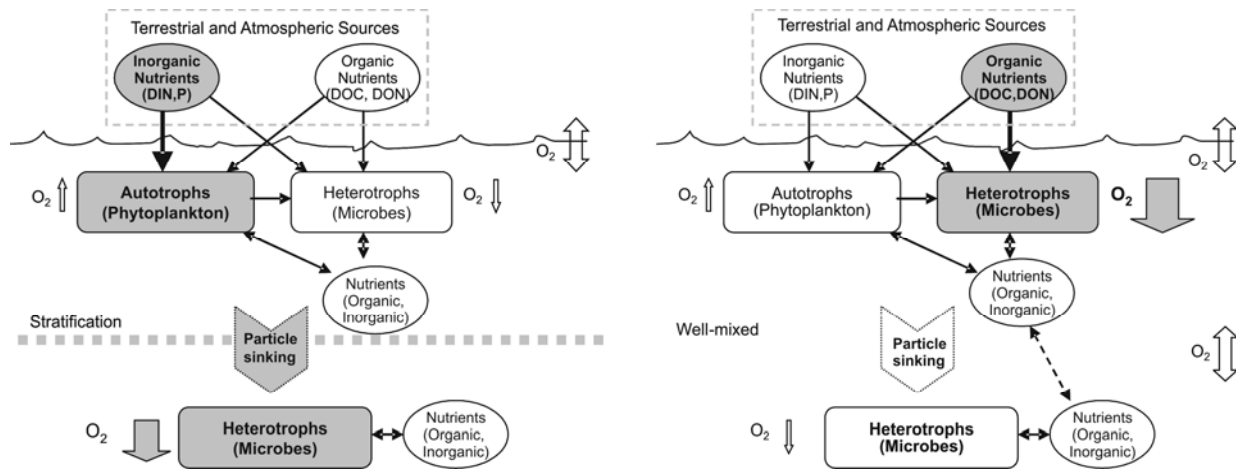


Figure 1. Pathways of eutrophication. (left) The classic pathway, wherein inorganic nutrients fuel phytoplankton production, which then sinks to the bottom in a stratified water column where it is consumed by microbes, leading to decreased oxygen concentrations in bottom water. (right) An alternative pathway, wherein organic nutrients fuel microbial activity, which leads to decreased oxygen concentrations throughout a well-mixed water column. Modified from Verity et al. 2006.

State water quality indicators should be relevant to Georgia habitats, sensitive to change, well-correlated with status, and readily measured. As part of an evaluation of water quality monitoring conducted by CRD (Sheldon and Alber 2010), we have proposed a suite of indicators that are intended to help classify and understand the causes of water quality degradation in Georgia estuaries and coastal waters. They should also help to inform efforts to establish numeric nutrient water quality standards for Georgia waters, as required by EPA.

RECOMMENDED INDICATORS

The seven recommended indicators of water quality for Georgia estuaries are pH, dissolved oxygen, nitrogen, phosphorus, chlorophyll *a*, transparency, and biochemical oxygen demand (BOD), along with some basic ancillary data (water temperature, salinity, specific conductance). At this time, the suite does not include measurements made to evaluate human uses of water bodies (i.e. for recreation, fishing, and shellfishing) because those indicators, which are aimed at protecting human health, are generally mandated separately by State and federal agencies.

Several recent national and regional studies were taken into consideration when selecting these water quality indicators, including the NEEA (Bricker et al. 1999, 2007), the NCCR (U.S. EPA 2001a, 2004, 2008), the South Carolina Estuarine and Coastal Assessment Program (SCECAP) reports (Van Dolah et al. 2002, 2004, 2006; Bergquist et al. 2009), and the recommendations of the Nutrients Workgroup of the National Water Quality Monitoring Council (Caffrey et al. 2007). The EPA guidelines for developing numeric nutrient criteria were also consid-

ered (U.S. EPA 2001b). Current guidance calls for criteria that address nutrient pollution in terms of both causal (nitrogen, phosphorus) and response variables (chlorophyll *a*, transparency), with the addition of dissolved oxygen in systems that have already experienced hypoxia. While there may be some latitude in the choice of indicators used in individual states, the use of indicators preferred by the EPA would facilitate regional and national comparisons.

The following subsections discuss the rationale for choosing each indicator and the considerations for developing evaluation criteria. Recommended criteria for classifying observations as good, fair, and poor are summarized at the end, in Table 1. Application of these recommendations to data collected by CRD in order to evaluate the status of Georgia coastal water quality is described in a companion GWRC paper (Alber and Sheldon 2011).

pH. The buffering capacity of seawater is often thought to protect estuaries and coastal waters against pH changes large enough to affect organisms, so pH is not always used as an indicator in coastal waters. However, there is mounting evidence that estuaries do experience pH changes that are stressful to their inhabitants (Knutzen 1981; Fabry et al. 2008).

pH varies with salinity along the length of an estuary, so pH criteria are best described in terms of deviations from normal. In Georgia estuaries, pH has a log-linear relationship with salinity, with different relationships for different estuary types (Figure 2). Blackwater systems, represented by the Satilla River/ St. Andrew Sound and St. Marys River/ Cumberland Sound, have low pH in low-salinity waters. Alkaline blackwater systems, represented by the Ogeechee River/ Ossabaw Sound, are influenced by both blackwater and carbonate-rich water, and the low-

salinity areas of these systems have slightly higher pH than blackwater systems. Most other alluvial and tidewater systems have near-neutral pH in low-salinity waters.

The log-linear regression lines in Figure 2 are considered “normal” pH conditions at any given salinity for each estuary type. Deviations of greater than 0.5 or 1 unit from these relationships are considered fair or poor, respectively, based on literature reports suggesting that decreases from normal pH of 0.5 units or less appear to be tolerated well by most organisms, whereas a decrease of 0.5-1 units or more can result in stress responses and more serious deleterious effects (Knutzen 1981; Fabry et al. 2008). Both annual minimum and annual median values should be compared to these criteria in order to assess both acute episodic and chronic conditions. These criteria may be refined as new information becomes available.

Dissolved Oxygen. Low dissolved oxygen (DO) concentrations can result in reduced growth, disruption of life cycles, migration to avoid poor conditions, and death of benthic organisms (reviewed in Vaquer-Sunyer and Duarte 2008). DO is used as an indicator in most water quality studies and is suggested by EPA as an additional primary response variable in systems that have already experienced hypoxia (U.S. EPA 2001b). 69% of sites sampled coastwide by CRD during 2000-2008 experienced $DO \leq 3 \text{ mg L}^{-1}$ at least once (Sheldon and Alber 2010), so the need to include DO as a water quality indicator is clear.

The U.S. EPA (2000) derived a value of 2.3 mg L^{-1} as the limit of survival of juvenile and adult fish, crustaceans, and bivalves in coastal waters of the Virginian province, and 4.8 mg L^{-1} as the chronic protective value for growth. These are close to the criteria of 2 and 5 mg L^{-1} used to define the “fair/poor” and “good/fair” boundaries in the NEEA and NCCR studies. However, Sheldon and Alber (2010) revealed some confusion in the literature over the units used to describe oxygen concentrations: the often-incorrectly cited criterion for hypoxia of $2 \text{ mL O}_2 \text{ L}^{-1}$ (Diaz and Rosenberg 1995) is equivalent to approximately $2.85 \text{ mg O}_2 \text{ L}^{-1}$. We take these observations into account by suggesting slightly higher criteria than were used in the other studies: 3 and 5.5 mg L^{-1} as the “fair/poor” and “good/fair” boundaries, respectively. These criteria align with those identified in literature reviews as being protective of most taxonomic groups (Vaquer-Sunyer and Duarte 2008), and they reflect the fact that CRD samples surface waters during the day whereas lowest DO tends to occur in bottom waters and early in the day. Both annual minimum and annual median values should be used to assess both acute episodic and chronic conditions.

Nitrogen and Phosphorus. Virtually all coastal water quality studies recommend measuring at least some fractions of both the nitrogen and phosphorus pools. Inorganic

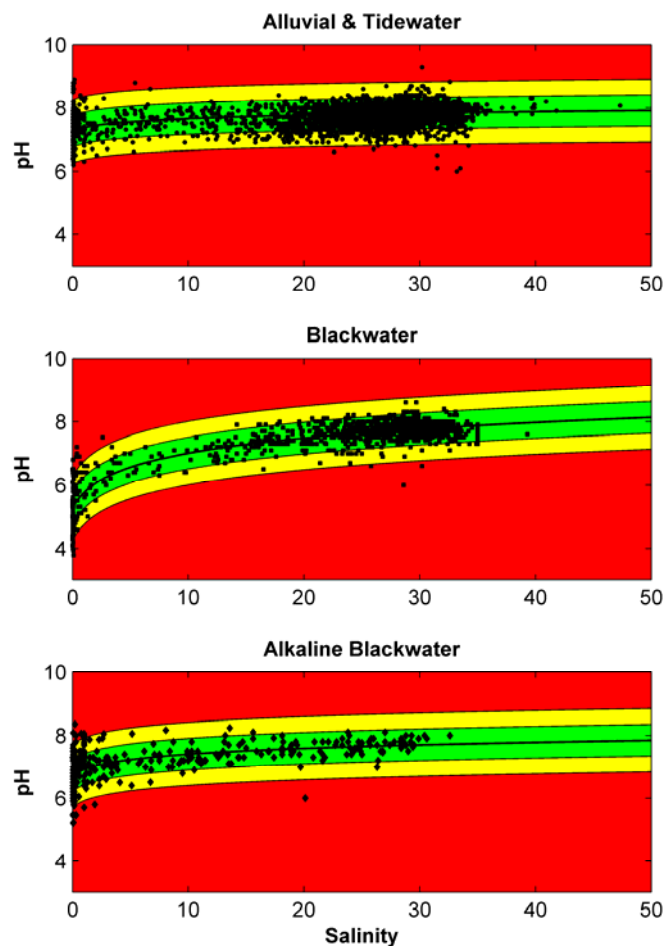


Figure 2. Recommended pH criteria for GA estuarine and coastal waters depending on site salinity and system type. Green denotes “good” water quality values, yellow denotes “fair”, and red denotes “poor”. Black dots are observations from the GA DNR CRD dataset.

nutrients can cause eutrophication through stimulation of algal blooms, but studies in Georgia have shown that organic nutrients can directly stimulate bacteria (Verity et al. 2006). Measurements of total nitrogen (TN) and total phosphorus (TP) are recommended by both the U.S. EPA (2001b) and the National Water Quality Monitoring Council (Caffrey et al. 2007), whereas two recent panels have recommended measuring total dissolved nitrogen (TDN) and total dissolved phosphorus (TDP) (Bricker et al. 1999, 2007; DiDonato, in press). We suggest that TDN and TDP are the single most important components of the nitrogen and phosphorus pools to measure regarding eutrophication, but we also recommend collecting data on particulate fractions (PN, PP) and calculating TN and TP for comparison with national standards. Analysis of the dissolved inorganic vs. dissolved organic fractions would also aid in interpretation of potential causes of eutrophication, so limited collection of samples for these analyses is also suggested.

Regardless of which fractions are measured, establishing criteria for nutrients is problematic. It would be best to link loads and concentrations of nutrients to the expected subsequent values of other indicators such as chlorophyll or DO, but these linkages are dependent on a variety of estuary-specific characteristics including transit time, temperature, light availability for photosynthesis, and grazing pressure. Until more localized criteria can be developed, we recommend using the NEEA criteria in Georgia coastal waters: 1 and 0.1 mg N L⁻¹ as the “fair/poor” and “good/fair” boundaries, respectively, for TDN; and 0.1 and 0.01 mg P L⁻¹ for TDP. Since chronically high nutrients are generally the larger concern, annual median values should be evaluated against the criteria as general indicators of water quality.

Chlorophyll *a*. Excess algal biomass (indicated by high chlorophyll concentrations) is the most obvious symptom of classic eutrophication, and it frequently leads to other problems. Chlorophyll *a* is on the U.S. EPA (2001b) list of core parameters and was used in every national and regional survey of water quality that was examined by Sheldon and Alber (2010); therefore, it will likely be required for compliance with national programs.

We recommend using the NEEA criteria of 20 and 5 µg L⁻¹ as the “fair/poor” and “good/fair” boundaries, re-

spectively, to evaluate chlorophyll data until sufficient data have been collected in Georgia coastal waters to support a detailed analysis. The annual median value is recommended for comparison against these criteria as an indicator of chronic problems, but the annual maximum value should also be evaluated since it is possible that a single bloom could cause symptoms severe enough to cause lasting damage. Furthermore, if a harmful algal bloom is suspected, additional sampling and analysis should be undertaken to identify the causal organism.

Transparency. It is usually desirable to measure some aspect of water clarity as an indicator of light availability for photosynthesis by phytoplankton. Light limitation can also change the balance between nutrient uptake by autotrophs and heterotrophs, with consequences for the potential pathway of eutrophication and the severity of symptoms. Water clarity can be measured in several ways. Secchi depth and percent light transmission are both measures of transparency that account for light attenuation due to both absorption and scattering, whereas nephelometric turbidity is a measure of light scattering only and is insensitive to light absorption. There are no general relationships between turbidity and measurements of transparency: these must be established for different water bodies. We recommend using a measure of transparency such as

Table 1. Proposed indicators, criteria, metrics, and ancillary data for assessing the general quality of Georgia coastal and estuarine waters. TBD = to be determined.

Indicator	Units	Good	Fair	Poor	Metric
pH: 3 system types: Alluvial & Tidewater Blackwater Alkaline Blackwater	pH unit deviation from established relationship between pH and salinity for system type	<0.5	0.5 - 1	>1	Annual minimum Annual median
Dissolved oxygen (surface, daytime)	mg L ⁻¹	>5.5	3 - 5.5	<3	Annual minimum Annual median
Total dissolved nitrogen	mg L ⁻¹	<0.1	0.1 - 1.0	>1.0	Annual median
Total dissolved phosphorus	mg L ⁻¹	<0.01	0.01 - 0.1	>0.1	Annual median
Chlorophyll <i>a</i>	µg L ⁻¹	<5	5 - 20	>20	Annual maximum Annual median
Transparency	A: % transmission at 1m B: Secchi depth (m)	A: >10 B: >0.5 or TBD	A: 5 - 10 B: 0.3 - 0.5 or TBD	A: <5 B: <0.3 or TBD	Annual median
Biochemical oxygen demand	mg L ⁻¹	TBD	TBD	TBD	Annual median
Ancillary Data					
Salinity	PSU				
Specific Conductance	mS cm ⁻¹				
Temperature	°C				

% transmission of photosynthetically active radiation or Secchi depth, in keeping with U.S. EPA (2001b) recommendations.

NCCR I (U.S. EPA 2001a) used a single criterion of 10% light transmission at 1 m to differentiate between “good” and “poor” for all regions. Later NCCR studies (U.S. EPA 2004, 2008) acknowledged the naturally high turbidity of southeastern U.S. estuaries and established separate, more lenient criteria for states that do not expect to support submerged aquatic vegetation (including SC and GA). Those criteria are 10% and 5% light transmission at 1 m as the thresholds for “good/fair” and “fair/poor”, respectively. We recommend use of these criteria for Georgia coastal waters. Annual median values should be evaluated against these criteria as general indicators of water quality.

Biochemical Oxygen Demand

While not included in many indicator suites, the measurement of BOD would be uniquely useful in Georgia because of the potential for non-photosynthetic pathways to eutrophication (Verity et al. 2006). This parameter provides information on the potential for microbial respiration to break down the organic material present in the water, which can lead to low DO and is a suggested cause of hypoxia in coastal Georgia waters. Although there is well-developed guidance in wastewater management applications for permissible loads of oxygen-consuming substances to receiving waters, there are no clear guidelines or standards for concentrations in coastal waters. We suggest that an analysis be undertaken to relate the BOD during a 5-day incubation to subsequent observations of DO minima in the estuaries to use as guidance for establishing criteria for this parameter. We also encourage a focused study comparing 5- and 20-day BOD incubations to ascertain the relative importance of labile and refractory components of the BOD in Georgia estuaries (Mallin et al. 2006). Comparisons of annual median values with criteria are recommended as general indicators of water quality.

Ancillary Data

Measurements of salinity and temperature are required for interpreting the other parameters. Salinity is a general descriptor of coastal habitats, and it is also a reflection of freshwater input to the site. Temperature is likewise an important habitat characteristic, an index of seasonality, and an important moderator of the rates of estuarine processes. Specific conductance is part of the normal instrument readout and a necessary factor, along with temperature, in the calculation of salinity. These parameters are not generally evaluated as being “good” or “poor” unless they are well outside their normal ranges of variability, and they are not generally regulated except in the case of

effluents that would be substantially different from their receiving waters.

SUMMARY

Regular monitoring of water quality in estuarine and coastal waters is vitally important to understand coastal processes, their relationships to important coastal resources, and the potential effects of long-term alterations such as coastal development and climate change. Many of the indicators proposed here are measured nationwide, and indeed, some may be required to meet EPA mandates. However, local relevance of both the indicators and the numeric criteria defining water quality status is key to successful implementation of the program. We recommend that all of the parameters listed here be monitored on a regular basis. However, studies to refine and localize the proposed criteria would be useful.

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