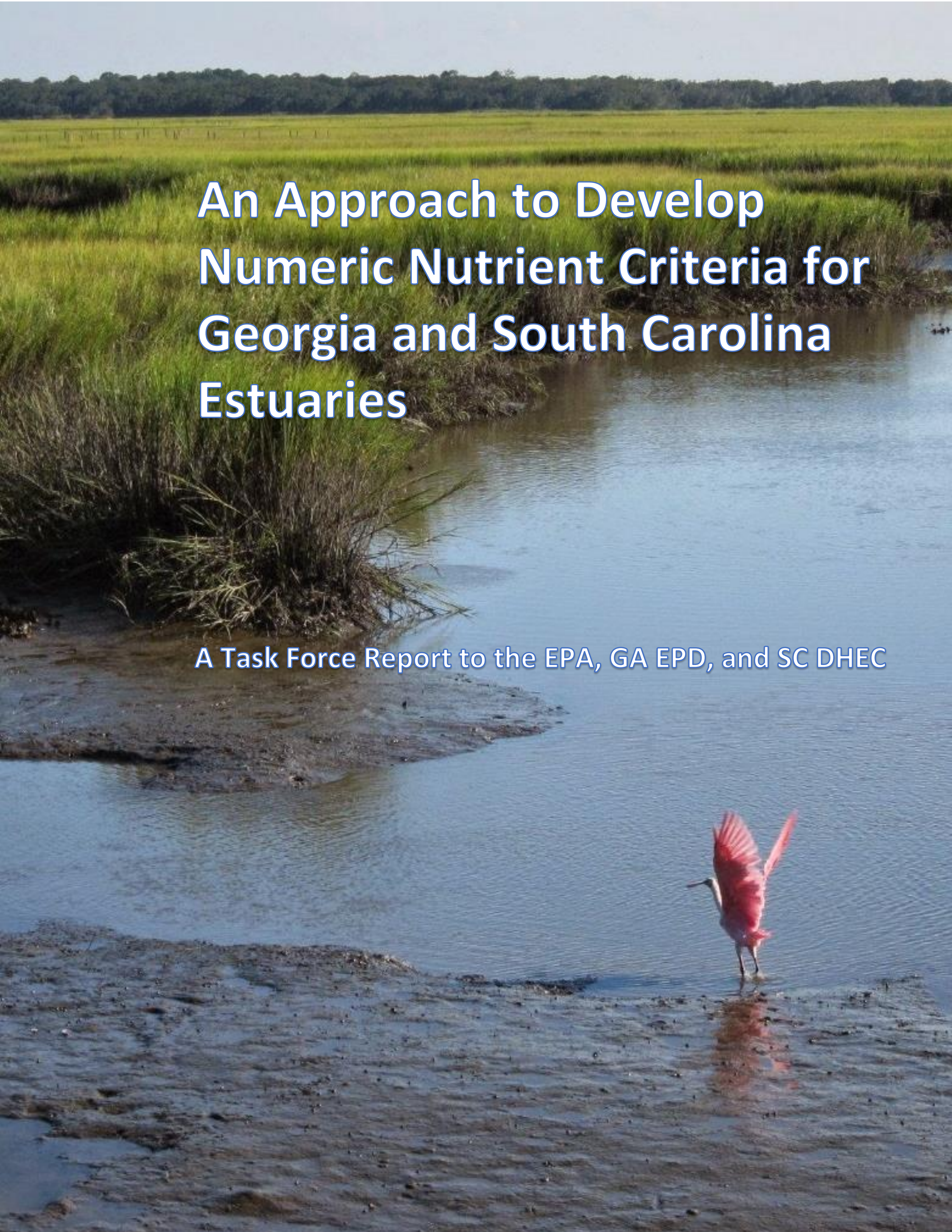

An Approach to Develop Numeric Nutrient Criteria for Georgia and South Carolina Estuaries

A Task Force Report to the EPA, GA EPD, and SC DHEC

Contributing Authors

ordered by last name

Dr. Merryl Alber	*University of Georgia*
Dr. Marc Frischer	*Skidaway Institute of Oceanography*
Dr. Dianne Greenfield	*Belle W. Baruch Institute for Marine and Coastal Sciences, University of South Carolina; Marine Resources Research Institute, SCDNR*
Dr. James D. Hagy III	*U.S. Environmental Protection Agency*
Joan E. Sheldon	*University of Georgia*
Dr. Erik Smith	*University of South Carolina and Belle W. Baruch Institute for Marine and Coastal Sciences*
Dr. Robert F. Van Dolah	*Former Director SC DNR Marine Resources Research Institute*
Dr. C. Brock Woodson	*University of Georgia*

Agency Participants

ordered by affiliation

Dr. Elizabeth Booth	*Georgia Environmental Protection Division*
Victoria Adams	*Georgia Environmental Protection Division*
Dominic Guadagnoli	*Georgia Coastal Resources Division*
David Graves	*South Carolina Department of Health & Environmental Control*
David E. Chestnut	*South Carolina Department of Health & Environmental Control*
Dan Liebert	*South Carolina Department of Health & Environmental Control*
Celeste Journey	*U.S. Geological Survey*
Joel Hansel	*U.S. Environmental Protection Agency*
Stephen Maurano	*U.S. Environmental Protection Agency*
Dr. Katherine Snyder	*U.S. Environmental Protection Agency*

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Disclaimer

This report was prepared by Georgia Environmental Protection Division (GEPD) and South Carolina Department of Health and Environmental Control (SCDHEC), in cooperation with the US Environmental Protection Agency (EPA), and local scientists, to support the development of numeric nutrient criteria for estuaries in Georgia and South Carolina. The information contained herein is intended to provide Georgia and South Carolina with a compilation of the existing literature and other scientific information that can be used as a line of evidence in deriving numeric nutrient criteria for the estuaries evaluated within this report.

Abbreviations and Acronyms

BMP	best management practice
BOD	biological oxygen demand
C	carbon
CA	California
CBOD	carbonaceous biochemical oxygen demand
CFR	Code of Federal Regulations
Chl-*a*	chlorophyll *a*
CWA	Clean Water Act
DO	dissolved oxygen
DOC	dissolved organic carbon
DOP	dissolved organic phosphorus
ECOHAB	Ecology and Oceanography of Harmful Algal Blooms project
EFDC	Environmental Fluid Dynamics Code
EPA	United States Environmental Protection Agency
ERA	environmental risk assessment
FDEP	Florida Department of Environmental Protection
FL	Florida
GA	Georgia
GA EPD	Georgia Environmental Protection Division
GA DNR	Georgia Department of Natural Resources
GA CRD	Georgia Coastal Resources Division
GLUT	Georgia Land Use Trends
HAB	harmful algal bloom
HSPF	Hydrological Simulation Program—Fortran
HUC	hydrologic unit code
LSPC	Loading Simulation Program in C++
LTER	Long Term Ecological Research
MODIS	Moderate Resolution Imaging Spectroradiometer
N	nitrogen
NASA	National Aeronautics and Space Administration
NAWQA	National Water-Quality Assessment Program
NCA	National Coastal Assessment Program
NED	National Elevation Dataset
NERR	National Estuarine Research Reserve
NH_3	ammonia
NH_4^+	ammonium
NHDPlus/NHD^+	National Hydrography Dataset Plus
NLCD	National Land Cover Data
NO_3^-	nitrate
NO_3-NO_2	nitrate+nitrite

NOAA	National Oceanic and Atmospheric Administration
NRCS	National Resources Conservation Service
NPDES	National Pollutant Discharge Elimination System
NWIS	National Water Information System
ORW	Outstanding Resource Waters
P	phosphorus
PAR	photosynthetically active radiation
PO_4^{3-}	phosphate
POP	particulate organic phosphorus
ppb	parts per billion
psu	practical salinity units
SAV	submerged aquatic vegetation
SC	South Carolina
SC DHEC	South Carolina Department of Health and Environmental Control
SC DNR	South Carolina Department of Natural Resources
SCECAP	South Carolina Estuarine and Coastal Assessment Program
SeaBASS	SeaWiFS Bio-optical Archive and Storage System
SeaDAS	SeaWiFS Data Analysis System
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SFH	Shellfish Harvesting Waters
Si	Silicon
SOD	sediment oxygen demand
SPARROW	SPAtially Referenced Regression On Watershed attributes model
STA	stormwater treatment area
STORET	STOrage and RETrieval Data Warehouse
TKN	total Kjeldahl nitrogen
TMDL	total maximum daily load
TN	total nitrogen
TP	total phosphorus
TSS	total suspended solids
USGS	United States Geological Survey
WASP/WASP7	Water Quality Analysis Simulation Program
WCA	Water Conservation Area
WQ	water quality

Summary

Excess inputs of nitrogen or phosphorus can harm aquatic ecosystems. Development of numeric nutrient criteria under the Clean Water Act helps to quantify water quality needed to prevent these effects and supports scientifically defensible management actions. Numeric criteria provide targets for setting National Pollutant Discharge Elimination System permit limits, total maximum daily load restoration, best management practices, waterbody assessment, land stewardship, wetlands protection, voluntary collaboration, nutrient trading, and urban stormwater runoff control.

Georgia and South Carolina's estuaries are characterized by their high turbidity, widely varying residence times associated with high tidal amplitudes, lack of seagrasses, high ratios of tidal wetland to estuary surface area, and relatively low coastal anthropogenic land use. They generally can be classified into Piedmont riverine systems (headwaters above the fall line, with large inflow), blackwater systems (headwaters in the coastal plain with significant terrestrial contributions of organic matter), and coastal embayments (ocean-dominated systems with only freshwater contributions from land stormwater runoff and subterranean (e.g., shallow water aquifer) sources). Conceptual models of estuarine eutrophication established for other U.S. estuaries are often based upon hypoxia below the pycnocline, production dominated by phytoplankton, and seagrass endpoints – none of which apply well to Georgia and South Carolina's estuaries, which tend to be well-mixed, mediated by heterotrophs, and have light-limited phytoplankton production.

An alternative conceptual model is presented here to derive nutrient targets (total nitrogen and total phosphorus), via measures (ecosystem primary production, chlorophyll *a*, dissolved oxygen, and indices of biological integrity) that are surrogates for designated use endpoints (aquatic community structure and function). The suite of indicators provides a flexible framework where a lack of data, or insensitivity of an indicator in a given location, can be overcome by using the remaining indicators to develop defensible criteria for that estuary. Criteria can be derived based on reference conditions, stressor-response relationships, and water quality simulation modeling. A reference condition approach may be particularly viable given that a number of estuaries have natural land-uses in their catchments. Protective criteria will help maintain the designated uses, which may be indicated by their trophic status, thereby ensuring that the beneficial services of Georgia and South Carolina's estuaries to humans are sustained.

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1 Introduction

1.1 Purpose of the Document

The purpose of this document is to present an approach for numeric nutrient criteria development for Georgia and South Carolina's estuarine and coastal waters. These criteria will help quantify the harmful effects of nutrients, defined here as excess inputs of nitrogen or phosphorus. These criteria can be adopted by the states for Clean Water Act (CWA) purposes pursuant to Section 303(c) of the Act, providing targets for numerous water quality management programs including:

- CWA § 303(d) Total Maximum Daily Load (TMDL) waterbody restoration
- CWA § 305(b) Waterbody assessment
- CWA § 319 Non-point source (NPS) best management practices (BMP) and related programs such as land stewardship, voluntary collaboration, wetlands protection, stormwater runoff control, and nutrient trading
- CWA § 401 Water Quality Certification
- CWA § 402 National Pollutant Discharge Elimination System (NPDES) permits

Estuaries along Georgia and South Carolina's coasts exhibit unique combinations of characteristics and a great deal of diversity among systems. In particular, Georgia and South Carolina appear to be the two coastal States in the U.S. where a combination of freshwater inflow, high turbidity and tidal amplitude prevent the occurrence of seagrasses (Foncesca et al. 1998). Estuaries in the region are dominated by shallow bar-built systems interspersed with shallow sounds and drain both low flow coastal plain and high flow Piedmont rivers (Dame et al. 2000). Many systems have high ratios of intertidal *Spartina alterniflora* salt marsh relative to estuary surface area; some are distinguished by significant terrestrial contributions of organic matter; and some feature ocean dominated or freshwater inputs dominated by submarine groundwater discharge. This effort aims to characterize these differences, develop effective conceptual models, identify sensitive assessment and measurement endpoints, identify relevant methods for criteria derivation, and outline frameworks for criteria development for Georgia and South Carolina's estuaries.

1.2 Document Organization

Chapter 1 describes the purpose, organization and background of the document, including the nature of nitrogen and phosphorus in estuarine waters and the purpose of this effort.

Chapter 2 describes the general approach for developing numeric criteria, including methods for numeric nutrient criteria development for estuarine waters, geographic scope, applicable conceptual models, potential assessment and measurement endpoints, and data sources.

Chapter 3 describes an approach for estuarine nutrient criteria development for Georgia and South Carolina's estuaries. The proposed approach considers the natural variation among estuarine ecosystems (e.g., water quality and biological communities in estuaries are affected by a combination of basin shape, tides, and the magnitude, location, and quality of freshwater inflows). This methodology first delineates the estuaries into discrete, relatively homogenous, areas for the purpose of organizing the criteria development process. Each of these discrete areas will then be evaluated to determine the appropriate assessment endpoints and measurement endpoints. The measurement endpoints for use in the development of numeric criteria (as a water quality indicator variable, like TN or TP) in estuaries include benthic IBI, dissolved oxygen, primary production and respiration rates, and chlorophyll *a*. The rationale that may be used for selecting specific water quality variables for each of the estuaries is discussed. This framework can be applied to three different criteria derivation approaches: (1) reference conditions, (2) stressor-response relationships, and (3) water quality simulation modeling, that could be used independently or in combination to develop numeric criteria for total nitrogen (TN), total phosphorus (TP), chlorophyll *a*, and dissolved oxygen.

Chapter 4 provides recommendations for prioritizing estuaries for numeric nutrient criteria development based on available data, attributes, or other relevant factors.

1.3 Clean Water Act Requirements

The Clean Water Act (CWA) established a basis for water quality protection in section 101(a): "The objective of this Act is to restore and maintain the chemical, physical, and biological integrity of the Nation's waters." Under CWA section 101(a)(2) "it is the national goal that wherever attainable, an interim goal of water quality which provides for the protection and propagation of fish, shellfish, and wildlife and provides for recreation in and on the water be achieved." This goal is commonly referred to as fishable and swimmable.

To meet the fishable and swimmable goal, the CWA defines a structure of interlinked programs and identifies the establishment of water quality standards as the key component necessary to achieve that goal. In many ways, water quality standards provide the common mechanism by which the other parts of the CWA (such as NPDES permits and TMDLs) work together to accomplish the overall goals and objective of the CWA.

Water quality standards consist of designated uses of the navigable waters and water quality criteria that are protective of those designated uses. The state specifies the designated use that must be achieved or protected. When designating uses, the state must consider the use and value of water for public water supplies, protection and propagation of fish, shellfish and wildlife, recreation in and on the water, agricultural, industrial, and other purposes including navigation (CWA section 303(c) and 40 CFR 131.10(a)). Designated uses can be general, such as aquatic life use protection or primary contact recreation, or more specific, such as warm water or cold water fisheries. In general, states adopt water quality criteria into water quality standards to protect the designated uses from the discharge of pollutants. These criteria are expressed as either narrative statements or numeric values. Georgia and South Carolina waters have been already classified by designated use, and to protect the designated uses from excess nitrogen and phosphorus, the States have adopted narrative criteria, as described below:

1.3.1 Georgia Water Quality Standards for Estuaries

Chapter 391-3-6-.03 of Georgia's Rules and Regulations for Water Quality Control describes the uses and criteria applicable to the State's estuaries, and is excerpted below.

Section 2(a) describes the aim of the regulations as, "(a) The purposes and intent of the State in establishing Water Quality Standards are to provide enhancement of water quality and prevention of pollution; to protect the public health or welfare in accordance with the public interest for drinking water supplies, conservation of fish, wildlife and other beneficial aquatic life, and agricultural, industrial, recreational, and other reasonable and necessary uses and to maintain and improve the biological integrity of the waters of the State." As a basis for the applicable criteria and policies, Section (4) describes Georgia's six Water Use Classifications, "(a) Drinking Water Supplies," "(b) Recreation," "(c)

Fishing, Propagation of Fish, Shellfish, Game and Other Aquatic Life," "(d) Wild River," "(e) Scenic River," "(f) Coastal Fishing." The table at Section (14) lists the Specific Water Use Classifications by waterbody and is displayed spatially in **Figure 1-1**. Section (6)[1] provides the specific criteria that apply to each of these specific uses, including bacteria and physiochemical parameters such as dissolved oxygen, temperature, and pH[2]. These criteria augment the general criteria for all waters given in Section (5) for the protection of aquatic life and human health.

In addition to numeric criteria for metals, toxics, and other parameters, Section (5) includes narrative criteria, including the requirements:

- (c) All waters shall be free from material related to municipal, industrial or other discharges which produce turbidity, color, odor or other objectionable conditions which interfere with legitimate water uses.
- (e) All waters shall be free from toxic, corrosive, acidic and caustic substances discharged from municipalities, industries or other sources, such as nonpoint sources, in amounts, concentrations or combinations which are harmful to humans, animals or aquatic life.

Further specificity is provided by the definitions in Section three, of note for marine systems are:

- (b) "Biological integrity" is functionally defined as the condition of the aquatic community inhabiting least impaired waterbodies of a specified habitat measured by community structure and function.
- (d) "Coastal waters" are those littoral recreational waters on the ocean side of the Georgia coast.
- (h) "Natural conditions" are the collection of conditions for a particular waterbody used to develop numeric criteria for water quality standards which are based on natural conditions. This is commonly the case for temperature and natural dissolved oxygen standards. For this purpose the Division defines "natural conditions" as those that would remain after removal of all point sources and water intakes, would remain after removal of manmade or induced nonpoint sources of pollution, but may include irretrievable effects of man's activities, unless otherwise stated. Natural conditions shall be developed by an examination of historic data, comparisons to

[1] The criteria at 6(b)i1 were revised and approved by the GA DNR Board on August 25, 2015, but have not been approved by EPA Region 4 as of the publication of this document.

[2] For example:
<u>6(b) Recreation:</u> i Bacteria 1. Coastal waters: Culturable *Enterococci* not to exceed a geometric mean of 35 CFU (colony forming units) per 100 mL. The geometric mean duration shall not be greater than 30 days. There shall be no greater than a ten percent excursion frequency of an *Enterococci* statistical threshold value (STV) of 130 CFU per 100 mL in the same 30-day interval.
<u>6(c) Fishing:</u> iii Bacteria 2. For waters designated as shellfish growing areas by the Georgia DNR Coastal Resources Division, the requirements will be consistent with those established by the State and Federal agencies responsible for the National Shellfish Sanitation Program. The requirements are found in National Shellfish Sanitation Program Guide for the Control of Molluscan Shellfish, 2007 Revision (or most recent version), Interstate Shellfish Sanitation Conference, U.S. Food and Drug Administration.
<u>6(f) Coastal Fishing:</u> This classification will be applicable to specific sites when so designated by the Environmental Protection Division. For waters designated as "Coastal Fishing", site specific criteria for dissolved oxygen will be assigned. All other criteria and uses for the fishing use classification will apply for coastal fishing.

reference watersheds, application of mathematical models, or any other procedure deemed appropriate by the Director.

- (i) "Naturally variable parameters." It is recognized that certain parameters, including dissolved oxygen, pH, bacteria, turbidity and water temperature, vary through a given period of time (such as daily or seasonally) due to natural conditions. Assessment of State waters may allow for a 10% excursion frequency for these parameters.
- (k) "Secondary contact recreation" is incidental contact with the water, wading, and occasional swimming.
- (l) "Shellfish" refers to clams, oysters, scallops, mussels, and other bivalve mollusks.
- (o) "Areas where salt, fresh and brackish waters mix" are those areas on the coast of Georgia having a salinity of 0.5 parts per thousand and greater. This includes all of the creeks, rivers, and sounds of the coastal area of Georgia and portions of the Savannah, Ogeechee, Altamaha, Satilla and St. Marys Rivers where those rivers flow into coastal sounds. Mixing areas are generally maintained by seawater transported through the sounds by tide and wind which is mixed with fresh water supplied by land runoff, subsurface water and riverflow. Mixing areas have moving boundaries based upon but not limited to river stage, rainfall, moon phase and water use. (For the purposes of this rule salinity shall be analyzed by in situ measurement using a properly calibrated multiparametric probe connected by hard line to a deck display or by measuring electrical conductivity according to one of the methods specified in Title 40, Code of Federal Regulations, Part 136 and applying the guidance for conversion to salinity in the same volume. Collection of salinity samples must consider riverflow, precipitation, tidal influences and other variables of the estuarine environment and must conform to the National Coastal Assessment-Quality Assurance Project Plan 2001-2004 (EPA/620/R- 01/002). Measurements at each sampling location must be made in a distribution in the water column according to the Quality Assurance Project Plan, with the minimum observations at each station including surface, mid-depth and near-bottom readings. In situ salinity analysis must comply with the Quality Assurance Project Plan and the manufacturer's guidance for the specific instrument used).

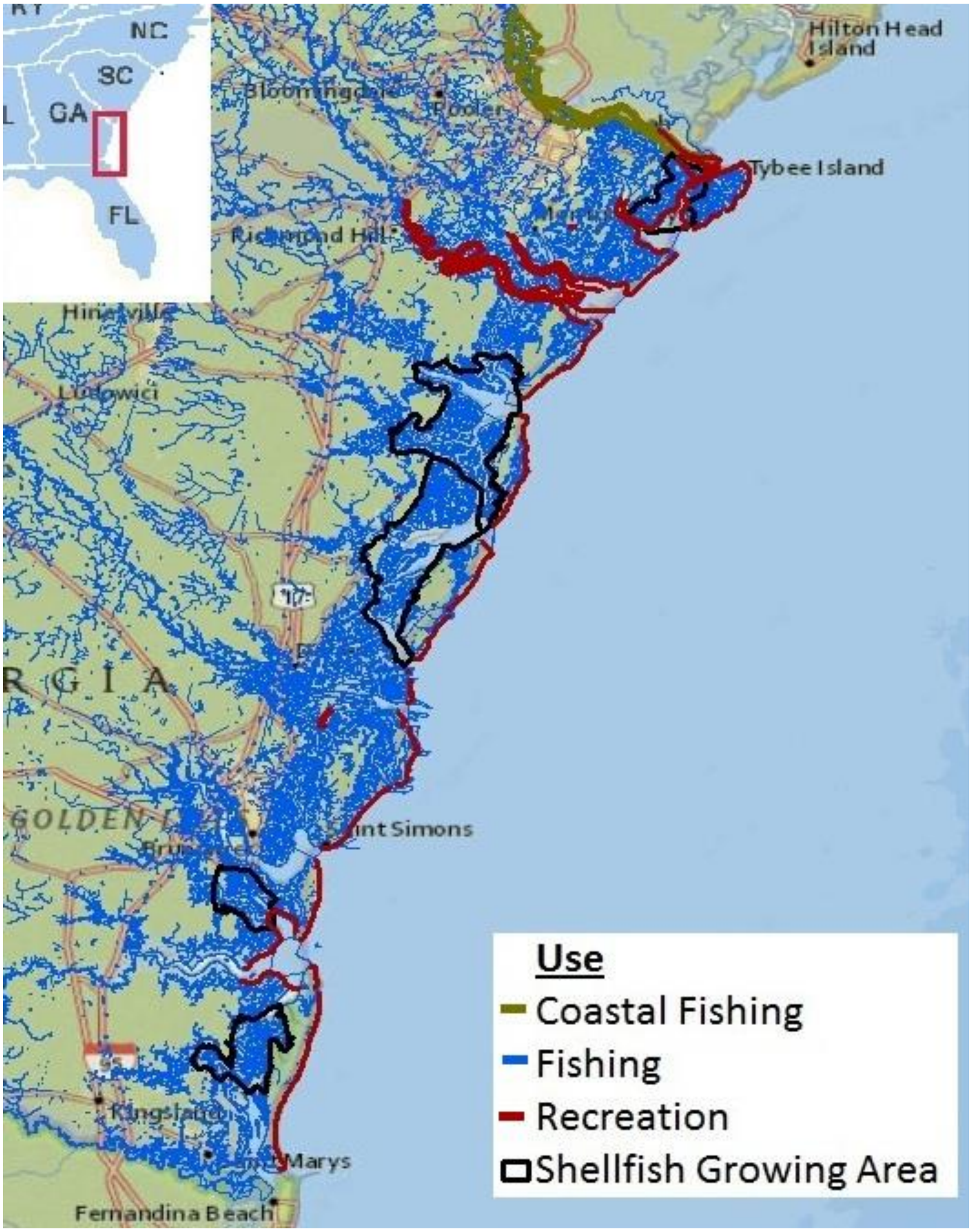

Figure 1-1. *Designated Uses of Georgia's Estuaries. Reaches not specifically listed in Georgia's standards are classified with a default use of Fishing.*

1.3.2 South Carolina Water Quality Standards for Estuaries

Chapter R.61-68 of South Carolina's Water Classifications & Standards describes the uses (**Figure 1-2**) and criteria applicable to the State's estuaries, and is excerpted below.

Section A defines the purpose and scope of the standards, including number 4, "It is a goal of the Department to maintain and improve all surface waters to a level to provide for the survival and propagation of a balanced indigenous aquatic community of flora and fauna and to provide for recreation in and on the water. It is also a goal to provide, where appropriate and desirable, for drinking water after conventional treatment, shellfish harvesting, and industrial and agricultural uses." Section G describes the designated uses of the State for recreation, drinking water, aquatic life, agriculture and industry, and ground waters. Specific to salt waters, it outlines:

- Outstanding Resource Waters (ORW) are freshwaters or saltwaters which constitute an outstanding recreational or ecological resource or those freshwaters suitable as a source for drinking water supply purposes with treatment levels specified by the Department.
- Shellfish Harvesting Waters (SFH) are tidal saltwaters protected for shellfish harvesting and uses listed in Class SA and Class SB. Suitable for primary and secondary contact recreation, crabbing, and fishing. Also suitable for the survival and propagation of a balanced indigenous aquatic community of marine fauna and flora. The dissolved oxygen criteria requires a daily average not less than 5.0 mg/l with a low of 4 mg/l.
- Class SA are tidal saltwaters suitable for primary and secondary contact recreation, crabbing, and fishing, except harvesting of clams, mussels, or oysters for market purposes or human consumption and uses listed in Class SB. Also suitable for the survival and propagation of a balanced indigenous aquatic community of marine fauna and flora. The dissolved oxygen criteria requires a daily average not less than 5.0 mg/l with a low of 4 mg/l.
- Class SB are tidal saltwaters suitable for primary and secondary contact recreation, crabbing, and fishing, except harvesting of clams, mussels, or oysters for market purposes or human consumption. Also suitable for the survival and propagation of a balanced indigenous aquatic community of marine fauna and flora. The dissolved oxygen criteria is not less than 4.0 mg/l

For the SFH and SA uses, the dissolved oxygen criteria requires a daily average not less than 5.0 mg/l with a low of 4 mg/l. For the SB use, the dissolved oxygen criteria is not less than 4.0 mg/l. For ORW use, numeric and narrative criteria for Class ORW shall be those applicable to the classification of the waterbody immediately prior to reclassification to Class ORW, including consideration of natural conditions.

Section C. Applicability of Standards includes the following language, "Because of natural conditions some surface and ground waters may have characteristics outside the standards established by this regulation. Such natural conditions do not constitute a violation of the water quality standards; however, degradation of existing water quality is prohibited unless consistent with Section D.4. of this regulation."

Along with these use-specific standards, Section E includes standards applicable to all waters, including the narrative requirements that:

- Paraphrased from Section E.5: All ground waters and surface waters of the State shall at all times, regardless of flow, be free from… sewage, industrial, or other waste which produce taste or odor or change the existing color or physical, chemical, or biological conditions in the receiving waters or aquifers to such a degree as to create a nuisance, or interfere with classified water uses (except classified uses within mixing zones as described in this regulation) or existing water uses…
- Paraphrased from Section E.11: In order to protect and maintain lakes and other waters of the State, consideration needs to be given to the control of nutrients reaching the waters of the

> State. Therefore, the Department shall control nutrients as prescribed below… Discharges of nutrients from all sources, including point and nonpoint, to waters of the State shall be prohibited or limited if the discharge would result in or if the waters experience growths of microscopic or macroscopic vegetation such that the water quality standards would be violated or the existing or classified uses of the waters would be impaired. Loading of nutrients shall be addressed on an individual basis as necessary to ensure compliance with the narrative and numeric criteria… In evaluating the effects of nutrients upon the quality of lakes and other waters of the State, the Department may consider, but not be limited to, such factors as the hydrology and morphometry of the waterbody, the existing and projected trophic state, characteristics of the loadings, and other control mechanisms in order to protect the existing and classified uses of the waters.

It should be noted that that this is not an all-inclusive list, but just two of the ways that nutrients can be controlled by the State of South Carolina.

Section F makes general statements regarding narrative biological criteria, including that, "In the Class Descriptions, Designations, and Specific Standards for Surface Waters Section, all water use classifications protect for a balanced indigenous aquatic community of fauna and flora." Section B provides definitions adding specificity to aforementioned language, including several relevant to nutrient criteria:

- 12. Balanced indigenous aquatic community means a natural, diverse biotic community characterized by the capacity to sustain itself through cyclic seasonal changes, presence of necessary food chain species and by a lack of domination by pollutant tolerant species.
- 19. Biological criteria, also known as biocriteria, mean narrative expressions or numeric values of the biological characteristics of aquatic communities based on appropriate reference conditions. Biological criteria serve as an index of aquatic community health.
- 21. Chlorophyll *a* means a photosynthetic pigment present in all types of green plants. It is used as a measure of algal biomass and is an indicator of nutrient enrichment.
- 46. Nutrients mean an element or chemical essential to life including, but not limited to, nitrogen and phosphorus.
- 52. Propagation means the continuance of species through reproduction and growth in the natural environment, as opposed to the maintenance of species by artificial culture and stocking.
- 56. Shellfish mean bivalve mollusks, specifically clams, mussels, or oysters.

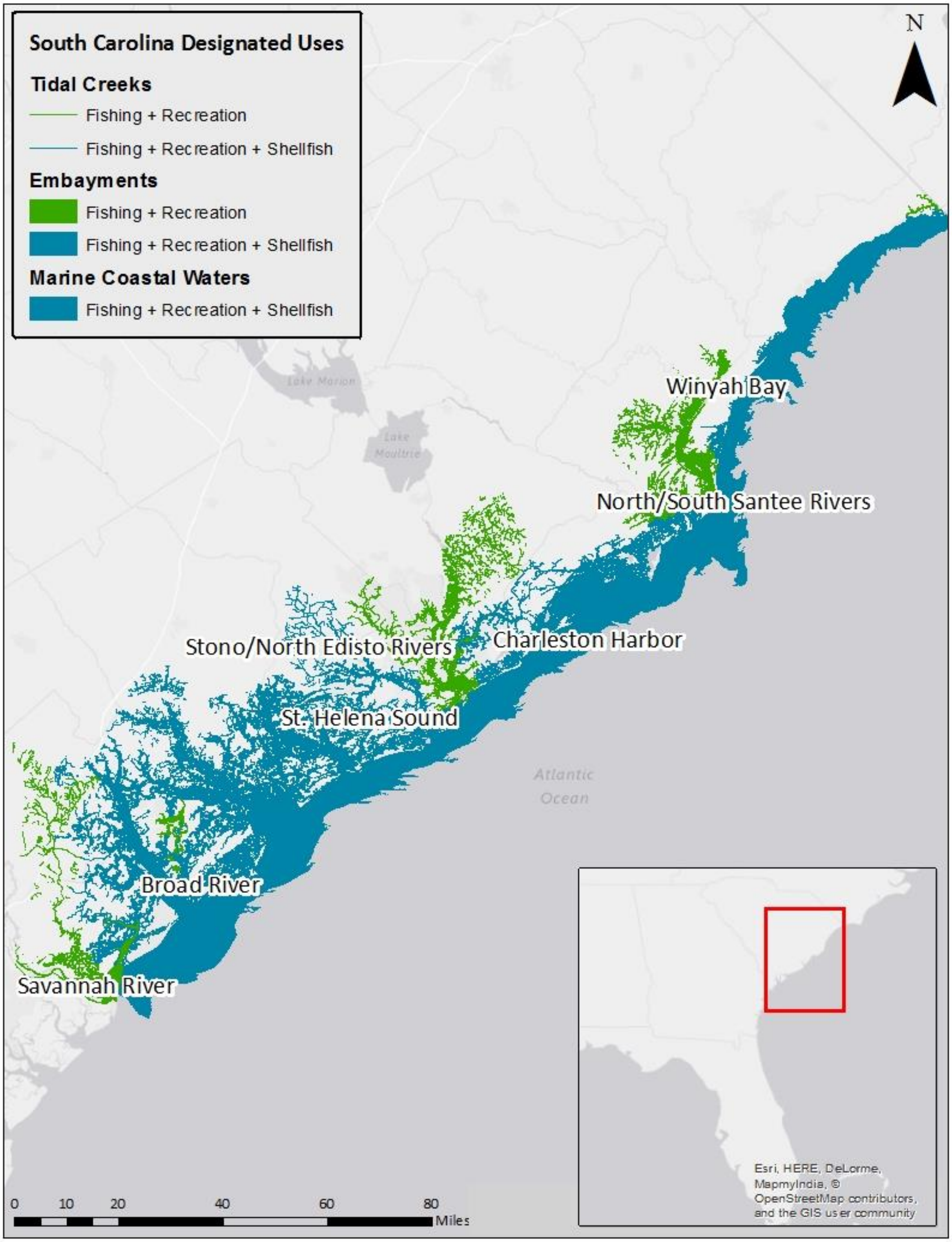

Figure 1-2. *Designated Uses of South Carolina's Estuaries.*

1.3.3 Summary of GA and SC Nutrient-Related Water Quality Standards for Estuaries

Georgia and South Carolina’s standards are sufficiently similar so that the states can collaborate in formulating approaches for nutrient criteria development. A summary of key nutrient criteria standards currently applied to Georgia and South Carolina's estuaries is provided in **Table 1-1**.

Table 1-1. *Summary of key nutrient related water quality standards in Georgia’s and South Carolina’s Estuaries (underlined emphases added to highlight particular areas of similarity).*

<table>
<tr><th></th><th>Georgia</th><th>South Carolina</th></tr>
<tr><td>Biological Integrity Definition</td><td>“ ‘Biological integrity’ is functionally defined as the condition of the aquatic community inhabiting least impaired waterbodies of a specified habitat measured by community structure and function.”</td><td>“Balanced indigenous aquatic community means a natural, diverse biotic community characterized by the capacity to sustain itself through cyclic seasonal changes, presence of necessary food chain species and by a lack of domination by pollutant tolerant species.”</td></tr>
<tr><td>Narrative Water Quality Criteria</td><td>“All waters shall be free from material related to municipal, industrial or other discharges which produce turbidity, color, odor or other objectionable conditions which interfere with legitimate water uses.”

“All waters shall be free from toxic, corrosive, acidic and caustic substances discharged from municipalities, industries or other sources, such as nonpoint sources, in amounts, concentrations or combinations which are harmful to humans, animals or aquatic life.”</td><td>“All ground waters and surface waters of the State shall at all times, regardless of flow, be free from… Sewage, industrial, or other waste which produce taste or odor or change the existing color or physical, chemical, or biological conditions in the receiving waters or aquifers to such a degree as to create a nuisance, or interfere with classified water uses (except classified uses within mixing zones as described in this regulation) or existing water uses…”

“It is a goal of the Department to maintain and improve all surface waters to a level to provide for the survival and propagation of a balanced indigenous aquatic community of flora and fauna and to provide for recreation in and on the water. It is also a goal to provide, where appropriate and desirable, for drinking water after conventional treatment, shellfish harvesting, and industrial and agricultural uses.</td></tr>
<tr><td rowspan="2">Dissolved Oxygen Criteria</td><td>Fishing & Recreation – A daily average of 5.0 mg/L and no less than 4.0 mg/L at all times.

Coastal Fishing – as above, but if it is determined that the “natural condition” in the waterbody is less than the values stated above, then the criteria will revert to the “natural condition” and the water quality standard will allow for a 0.1 mg/L deficit from the “natural” dissolved oxygen value. Up to a 10% deficit will be allowed if it is demonstrated that resident aquatic species shall not be adversely affected. (Designated for Savannah River Seaboard from the Coastline RR Bridge (Mile 27.4) to Fort Pulaski (Mile 0).)</td><td>Shell Fish Harvesting & Tidal Saltwaters “SA” – A daily average not less than 5.0 mg/l with a low of 4 mg/l.

Tidal Saltwaters “SB” Dissolved Oxygen: Not less than 4.0 mg/l.</td></tr>
<tr><td colspan="2">Coastal Fishing (GA) & All Uses (SC) Allows 0.1 mg/l for lowering in waters with dissolved oxygen levels naturally below the default criteria. Criteria in some situations can be 90% of the natural condition, if it can be demonstrated that resident aquatic species will not be adversely affected.</td></tr>
</table>

1.4 Nature of the Chemical Stressors: Nitrogen and Phosphorus

Excess anthropogenic inputs of nitrogen and phosphorus in surface waters can result in excessive primary production and other consequences in a waterbody. An increase in the rate and/or supply of organic matter is referred to as eutrophication.

1.4.1 Stressor Source and Distribution

Nitrogen and phosphorus in water bodies comes from many point and nonpoint sources, which can be grouped into the following five major categories:

1) urban and suburban stormwater runoff,
2) municipal and industrial waste water discharge (e.g. sewage effluent, landfill leachate),
3) row crop agriculture (e.g. commercial fertilizer and manure applications),
4) animal husbandry, and
5) atmospheric deposition (and fossil fuel combustion) (SENITG 2009).

These sources are often direct inputs to estuaries and coasts because of the large populations that reside very close to their shores. It should be noted that urban and suburban stormwater runoff is largely, a conveyance of other nutrient sources, including atmospheric deposition, septic tanks, and soil erosion, but it does not include nutrient input from some anthropogenic sources such as fertilizer applications to lawns. Loss of pervious surface and vegetative land cover reduces retention of nutrients, resulting in increased losses of nutrients to surface waters. Estuaries and coastal waters are especially vulnerable to excess nitrogen and phosphorus because they receive these compounds from multiple natural and anthropogenic upstream sources and have a natural tendency to retain and recycle nutrients and organic matter.

1.4.2 Aquatic Ecosystem Effects of Nitrogen and Phosphorus

The biennially published National Water Quality Inventory Report to Congress indicates that excess nitrogen and phosphorus are consistently a major source of water quality impairment in the Nation's waters. Since the 1992 report, nitrogen and phosphorus compounds have consistently ranked in the top five causes of US water quality impairment. These compounds cause major changes to aquatic ecosystems and disrupt the natural populations of flora and fauna (Dodds et al. 2009; Howarth et al. 2002; National Research Council 2000). Imbalances in natural communities can adversely affect aquatic life as well as human health.

Nitrogen and phosphorus can adversely affect aquatic life in many different ways (see **Figure 1-3**). The effects of nitrogen and phosphorus include direct changes to aquatic systems (e.g., increased algal growth, changes in algal species composition, and increased organic matter production) and indirect effects (e.g., loss of submerged aquatic vegetation (SAV), nuisance algal blooms, and low dissolved oxygen) (USEPA 2006, 2008a). The eutrophication process has resulted in large "dead zones" of low dissolved oxygen found in many coastal areas, such as the Gulf of Mexico and Chesapeake Bay (Ecological Society of America 2009) and reduced seagrass beds, a foundation species for many estuarine waters (Hughes et al. 2009; Tomasko et al. 2005).

Environmental consequences from changes in primary production (e.g., increases in phytoplankton) can include increased turbidity and decreased light penetration (Boyer et al. 2009; Bricker et al. 2007; Bricker et al. 2008; McPherson and Miller 1994). In some estuaries, this can reduce light availability necessary for the growth of submerged aquatic vegetation (Lee et al. 2007; Dennison 1987; Duarte

1991). Although seagrasses are critical components of many estuarine and coastal systems and are used as feeding, spawning, and nursery grounds for many aquatic species (Waycott et al. 2009), Georgia and South Carolina appear to be the two coastal States in the U.S. where a combination of freshwater inflow, high turbidity and tidal amplitude prevent their occurrence (Foncesca et al. 1998).

Imbalances in primary producer dynamics can cause changes in habitat and available food resources that can induce changes affecting an entire food web (Bricker et al. 2003b; Vitousek et al. 1997). Increased phytoplankton abundance has also been linked to composition shifts to less desirable species (Paerl 1988). Because these changes affect natural processes at the lowest levels of the ecosystem, they can cause a cascade of problems.

Eutrophication has also been shown to increase the incidence of disease in aquatic animals and wildlife (Johnson et al. 2010). Although nitrogen and phosphorus may not always be the trigger, excess nutrients can contribute to blooms of nuisance or toxic algae (Glibert et al. 2006; Heisler et al. 2008) or may extend bloom duration (Vargo 2009). Called harmful algal blooms (HABs), the causative species can damage or clog the gills of fish and invertebrates, produce toxins and/or reactive oxygen species (ROS), and cause illness or death to animals and humans (Falconer 1999; NOAA 2010). Direct effects to humans result from exposure to HAB toxins or consumption of toxic shellfish or finfish. Examples of marine algal species that are considered HABs and/or nuisance algal species in SC and GA estuaries and coasts include diatoms (e.g., *Pseudo-nitzschia pseudodelicatissima*) dinoflagellates (*Alexandrium monilatum*, *Heterocapsa rotundata*, *Karlodinium venificum*, *Gambierdiscus toxicus*), raphidophytes (*Chattonella subsalsa, C. marinus, Fibrocapsa japonica, Heterosigma akashiwo), and cyanobacteria (Microcystis aeruginosa, Anabaena, Anbaenopsis, Aphanizomenon spp., Oscillatoria limosa*) (Lewitus et al. 2008; Greenfield et al. 2014, and others). HABs are responsible for 1 in 4 (26%) of coastal fish kills in SC, making them second only to hypoxia as the leading cause of fish kills (Greenfield et al. unpublished data).

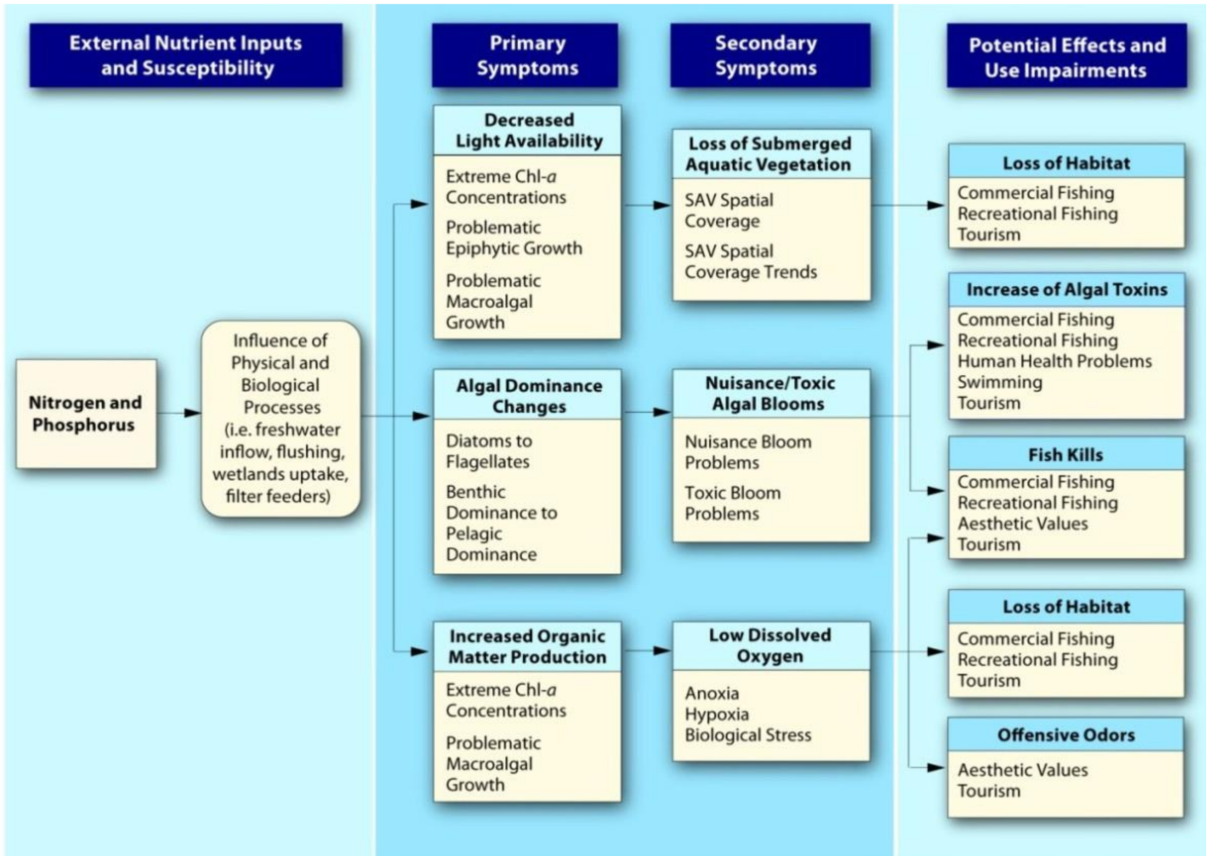

Figure 1-3. *A model of primary and secondary symptoms of excess nitrogen and phosphorus and the potential effects and impairments (Bricker et al. 1999; Bricker et al. 2003b).*

Excessive algal growth contributes to increased oxygen consumption by way of the eventual decomposition of the algae, potentially reducing oxygen to levels below those needed for aquatic life to survive (NOAA 2010; USGS 2010). This is the commonly applied eutrophication paradigm wherein the primary pathway is nutrient stimulation of autotrophic production, which can shade out submerged aquatic vegetation and decompose below the pycnocline causing hypoxia. In Georgia and South Carolina's estuaries, natural factors such as turbidity, high tidal amplitude, and large inflows can suppress both algal production and submerged aquatic vegetation; nevertheless, undesirable effects on aquatic life, such as hypoxia, may still occur because of stimulation of the microbial community (Verity et al. 2006). This could occur even in the absence of elevated phytoplankton levels, especially if alternate organic carbon sources are available for microbial respiration (Discussed further in **Section 2.5** and **Figure 2-5**).

Low oxygen concentrations, or hypoxia, can occur in episodic "events," which sometimes develop overnight. Migration to avoid hypoxia depends on species' mobility, availability of suitable habitat, and adequate environmental cues for migration. For example, mobile species, such as adult fish, can sometimes survive by moving to areas with more oxygen availability. Sessile species are susceptible to low oxygen because they cannot migrate to escape exposure (Ecological Society of America 2009). While certain mature aquatic animals can tolerate a range of dissolved oxygen (DO) levels, younger life stages of species like fish and shellfish often require higher levels of oxygen to survive (USEPA 2000a). Sustained low levels of DO cause a severe decrease in the amount of aquatic life in hypoxic zones and affect the ability of aquatic organisms to find necessary food and habitat. In extreme cases, anoxic conditions occur when and where there is a complete lack of oxygen. Since most plants and aquatic organisms cannot live without sufficient oxygen, hypoxic and anoxic areas are sometimes referred to as dead zones (Ecological Society of America 2009). Periodic hypoxia and anoxia has been reported within a number of SC coastal habitats, though the causes vary from nutrient loading to physical forcing (Sanger et al. 2012; Reed et al. 2015 and In Review) Economic consequences of nutrient pollution include potential adverse impacts on commercial fisheries or restrictions on recreation (such as boating, swimming, and kayaking) due to closures of areas to recreational uses to avoid exposure to algal blooms, and reduction or elimination of recreational fishing, shellfish harvest, and diving due to loss of biological resources.

1.4.3 Trophic Conditions of Georgia and South Carolina Estuaries

The trophic conditions of Georgia and South Carolina estuaries have been evaluated by a number of agencies over the past three decades. As part of the national estuarine eutrophication assessment conducted by NOAA from 1992-1997, estuaries in Georgia and South Carolina were classified as having low to moderate levels of eutrophication (Bricker et al. 1999). A re-assessment of the same estuaries was generated by NOAA in 2007 using data through 2004 submitted to NOAA by assessment participants. In the reassessment, the estuaries and were again found to exhibit low to moderate levels of eutrophication, with only the Charleston Harbor showing improvement since the 1999 assessment (Bricker et al. 2007). The South Carolina DNR and DHEC monitored estuarine and coastal conditions during 1999-2000 and found that 92% of the open water habitat and 88% of the tidal creek habitat had good water quality while the remaining waters had marginal water quality. These assessments were based on a multi-metric measure that integrates measures of water quality, sediment quality, and biological impairment (Van Dolah et al. 2002). Sheldon and Alber (2013) used data collected by GA CRD during 2000-2010 to evaluate water quality of Georgia's estuaries according to a suite of available indicators (Sheldon and Alber 2010). Water quality thresholds used in the analyses were based on extensive literature review, and the methods used for collection, analysis, and interpretations of these data were different from either the NOAA or SCECAP studies. Status of water quality indicators such as dissolved oxygen and nutrients varied coast wide and inter-annually during this period and were generally classified as fair or good based on the criteria set out in the report. Instances of poor dissolved oxygen status tended to be episodic rather than chronic. Sheldon and Alber (2010) pointed out the difficulty in linking N and P concentrations to water quality in their study: while oxygen criteria have been established with reasonable confidence for broad groups of organisms, the nutrient criteria that might correspond to those oxygen criteria are difficult to establish and need refinement. Since that time, analyses of certain estuaries, such as the Ashepoo-Combahee-Edisto (ACE) Basin, have identified several regions of high TN and TP levels within this system, suggesting the influence of surrounding land (Keppler et al. In Press).

1.5 Purpose of this Effort

This document is the product of a panel of experts in estuarine and marine ecology, hydrology, water quality, and biogeochemistry, focusing on the estuaries of Georgia and South Carolina. The expert panel was tasked by environmental management agencies to recommend an approach for developing numeric nutrient criteria for estuaries in these States. The conclusions from these charge questions are integrated into the document at the locations referenced:

1.5.1 Charge Questions Addressed by the Expert Panel

(1) Are Georgia and South Carolina's estuaries adequately homogenous (hydrologically and ecologically) to build a consistent causal model for excess nutrients? Is the response of biology to nutrients similar in each system along the coast in this area? If not, what sub-classifications are needed?
Addressed in Section 2.4 "Geographic Scope" on page 16.

(2) What conceptual model best describes the pathways of nutrient response in Georgia and South Carolina's estuaries?
Addressed in Section 2.5 "Conceptual Model" on page 19.

(3) What endpoints are representative of estuarine designated uses in Georgia and South Carolina's estuaries (based on the respective State water quality standards) and sensitive to nutrients (particularly in light-limited systems)?
Addressed in Section 2.6.3 "Measurement Endpoints for Georgia and South Carolina Estuaries" on page 27.

(4) What data sets exist in the Georgia and South Carolina estuaries for these endpoints? Which endpoints have sufficient data to conduct analyses? Which endpoints could be useful with more data? Of the endpoints, are certain ones easier to monitor than others?
Addressed in Section 2.7 "Potential Data Sources" on page 28.

(5) What recommendations would assist the State in the prioritization of estuaries for numeric nutrient criteria development?
Addressed in Section 4 "Prioritization of Estuarine Criteria Development" on page 41.

2 Approach

2.1 Overview

The EPA's 1976 publication entitled Quality Criteria for Water (also known as the Red Book) contains ambient water quality criteria for nitrates and elemental phosphorus. For domestic water supplies, the maximum contaminant level for nitrate was set at 10 mg/L to protect human health from exposure to this pollutant through domestic drinking water. The phosphorus criterion was set at 0.10 µg/L elemental phosphorus to protect against the toxic effects of elemental phosphorus to estuarine and marine organisms. Note that neither of these criteria was set to reduce the potential for eutrophication, although the Red Book does present a rationale for supporting a total phosphorus criterion.

The EPA has published peer-reviewed technical guidance for states to develop numeric nutrient criteria for lakes and reservoirs (USEPA 2000b), for rivers and streams (USEPA 2000c), for estuarine and coastal waters (USEPA 2001), and for wetlands (USEPA 2008b). These guidance manuals are intended to help states, tribes and others in establishing scientifically defensible nutrient criteria for classes of water bodies. The agency has also published supplemental peer reviewed technical guidance for states using stressor-response relationships to derive numeric nutrient criteria (USEPA 2010).

Additionally, the EPA has recommended CWA section 304(a) water quality criteria for nutrients with the aim of reducing and preventing eutrophication on a national scale, although the 26 peer-reviewed ecoregional criteria documents that were published in 2001 and 2002 cover waterbody types other than estuaries (lakes and reservoirs, rivers and streams, and wetlands). Since none of these available recommended numeric criteria apply to Georgia and South Carolina's estuaries, the States must derive numeric values using the best available data and sound scientific rationale.

2.2 Nutrient Criteria Development Guidance

As noted above, the EPA published peer reviewed technical guidance for developing numeric nutrient criteria for rivers and streams in July 2000 (USEPA 2000c), and estuaries and coastal marine waters in October 2001 (USEPA 2001). These technical guidance documents describe the factors to be considered when deriving numeric criteria for use in state water quality standards. They provide background information on classifying water bodies, selecting criteria variables, designing monitoring programs, analyzing nutrient and algal data, deriving regional criteria, and implementing management practices. The documents describe three general approaches that could be used to develop numeric nutrient criteria (USEPA 2000c):

(1) Identification of reference conditions for each waterbody type based on best professional judgment or percentile selections of data plotted as frequency distributions
(2) Use of predictive relationships (e.g., trophic state classifications, empirical and mechanistic models, biocriteria)
(3) Application and/or modification of established nutrient/algal thresholds (e.g., nutrient concentration thresholds or algal limits from published literature)

The EPA's technical guidance documents suggest that each of the above analytical approaches is appropriate for deriving scientifically defensible numeric nutrient criteria. However, the EPA recognized each approach has different data requirements, and these differences should be considered in the context of individual situations and available information.

2.3 General Approach to Derive Criteria

The general approach the EPA followed for each of the waterbody system types as outlined in the estuarine waters guidance document (USEPA 2001) is summarized below:

(1) Establish a panel of technical experts.
(2) Review the scientific and regulatory basis – **Chapter 1** of this document describes the scientific and regulatory basis for developing numeric criteria for Georgia and South Carolina estuarine and coastal waters.
(3) Develop a segmentation scheme – this step subdivides the population of waterbodies for which numeric criteria are developed. For this effort, waters will first be defined as estuarine or coastal. Waterbody specific units can be delineated, for example, based on salinity, to create areas that consider homogeneity, ecological relevance, and future management.
(4) Select indicator variables – causal (e.g., TN and TP) and response (e.g., chlorophyll *a* and others) variables will need to be selected for the development of numeric criteria.
(5) Data collection and assessment – data will be compiled from potential sources including STORET, state data sets, and remote sensing data.
(6) Establish methodology – **Chapters 3** describes potential methodologies.
(7) Criteria development – the EPA guidance Nutrient Criteria Technical Guidance Manual: Estuarine and Coastal Marine Waters (USEPA 2001) outlines the following process for developing numeric nutrient criteria:
    a. Examination of the historical record or paleoecological evidence for evidence of a trend.
    b. Determination of a reference condition using one of several alternative approaches. Remember that the reference condition, however derived, is only one of the three approaches of the criteria development process.
    c. Use of empirical modeling (or surrogate data sets, where available, in those instances where insufficient information exists). This may be the case especially in estuaries with insufficient hydrological data, or significantly developed or modified watersheds.
    d. Objective and comprehensive interpretation of all information by the established panel of technical experts.
    e. Finally, develop criterion for each variable that reflects the waterbody nutrient condition to protect the designated use. Second, review the criterion to ensure that the proposed level do not entail adverse nutrient loadings to downstream waterbodies.

2.4 Geographic Scope

Georgia and South Carolina's estuaries are an "alternating series of riverine and ocean dominated bar-built systems," are mesotidal, and often have extensive intertidal marshes dominated by *Spartina alterniflora* (Dame et al. 2000). These estuaries can generally be classified into three types of systems based upon hydrology and ecology: Piedmont riverine systems, blackwater systems, and coastal embayments (**Figure 2-1**). Piedmont riverine systems are distinguished by their origin in the Piedmont ecoregion, above the fall line. This generally correlates with the estuaries with largest drainage areas of these three classifications and moderate to large freshwater inflows. In blackwater systems estuaries, the streams in the watershed originate in the Coastal Plain, have a moderate freshwater surface inflow, may have considerable fresh groundwater inflow (Moore 1996, Crotwell and Moore 2003), and are distinguished by significant terrestrial contributions of organic matter. Coastal embayment estuaries are high-salinity, isolated bar-built systems, dominated by ocean water and have freshwater inputs that are dominated by groundwater discharge. Many of Georgia and South Carolina's estuaries have extensive lateral marshes and residence time can vary greatly among waterbodies. Examples of these classifications are provided in **Table 2-1**, and these groupings can be further analyzed and refined via statistical classification or clustering techniques. Segments within each of these estuary systems can be delineated based on characteristics such as salinity, as well as monitoring and management considerations.

Table 2-1. *Georgia and South Carolina estuaries can be classified into at least three types of system types based on hydrology, water quality, and ecology.*

System	**Distinguishing Characteristic**	**Examples**
Piedmont Riverine	Piedmont origin, moderate to large inflow	Winyah Bay/Pee Dee River North/South Santee Rivers Savannah River Altamaha River
Coastal Embayment	Tidally driven	Murrells Inlet Clubhouse Creek Pawley's Island Creek Pawleys's Inlet North Inlet Cape Romain Harbor/Muddy Bay/Oyster Bay/Key Inlet Sewee Bay Copahee Sound Clark Sound Folly River Story River Harbor River St. Catherines Sound/Medway River/Laurel View River/ North and South Newport Rivers Sapelo Sound/Sapelo River St. Simons Sound/Turtle River
Blackwater	Significant terrestrial carbon contributions	Charleston Harbor/Wando/Cooper/Ashley Rivers Stono River South Edisto River St. Helena Sound/S. Edisto/Coosaw Rivers Ossabaw Sound/Ogeechee River St. Andrew Sound/Satilla River Cumberland Sound/St. Marys River

Figure 2-1. *Georgia & South Carolina NOAA Coastal Drainage Units. Major units are labelled, but not delineated due to the scale of this map.*

2.5 Conceptual Model

The aquatic life to be protected in a waterbody ideally should be characterized in a way that captures the structure and function of the biological community that the public expects to be protected. To restore and/or maintain water quality, it is necessary to determine the health of the system and to understand the range of conditions, both physical and chemical, that sustain that health. To accomplish this, one can select suitable surrogates or indicators closely correlated with overall system health and expected to be sensitive to stressors. **Figure 2-2** illustrates the conceptual relationship between the objective, which is the support of the aquatic life designated use, appropriate biological assessment endpoints, and indicators (the causal and response variables, or measurement endpoints, for numeric criteria). To support the aquatic life designated use through effective implementation of CWA programs, the states may need to develop and establish numeric criteria for causal variables, TN and TP, as well as the response variables: dissolved oxygen, chlorophyll, indices of biotic integrity, and/or measures of ecosystem primary production and respiration rates. Ideally, this framework will be applicable across Georgia and South Carolina estuaries so that even in a given estuary where a biological endpoint is insensitive to nutrient loadings or data are lacking, the remaining endpoints can be considered and analyzed for criteria derivation.

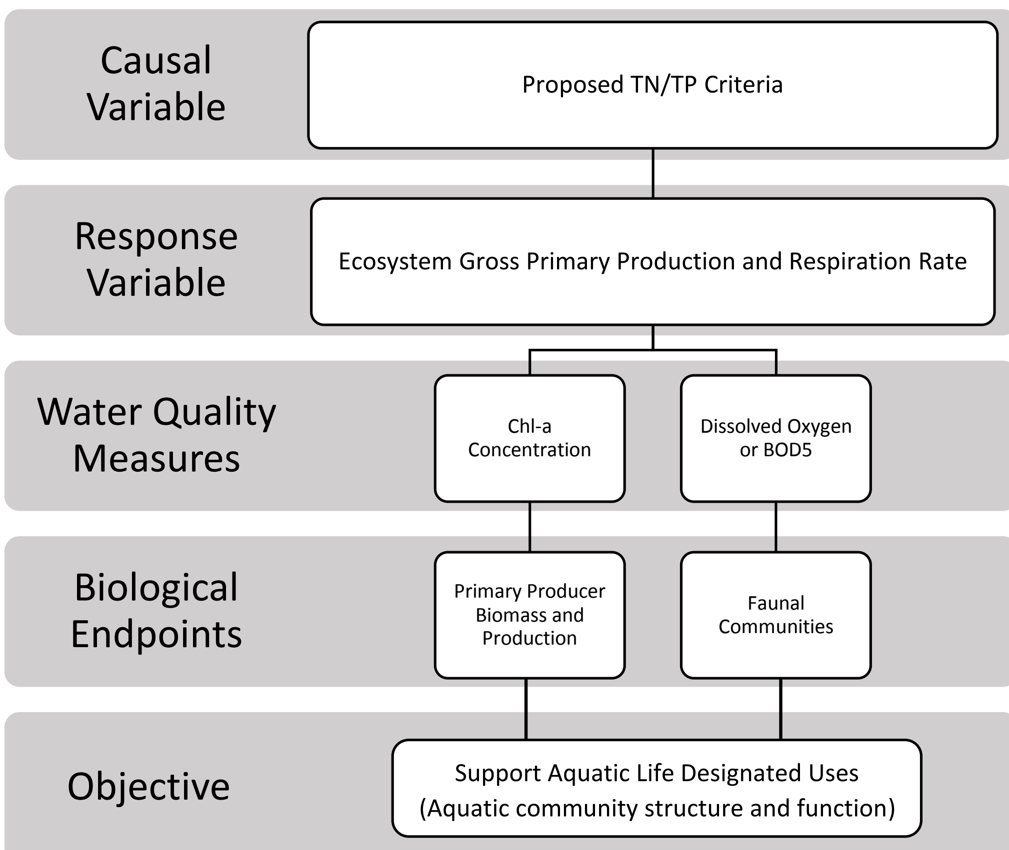

Figure 2-2. *Generalized pathways for nutrient effects on aquatic life designated uses in Georgia and South Carolina's estuaries.* Ecosystem primary production rate refers to primary production resulting from all sources in the estuary, including benthic microalgae, macroalgae, and production associated with intertidal marsh habitats.

Eutrophication can influence a number of biological processes, including a change in the amount of primary production in the water column versus the benthos (**Figure 2-3**). This shift in primary production has the potential to alter trophic transfers and biogeochemistry of nutrient cycling. For example, increased nutrient loading in shallow coastal lagoons from anthropogenic sources generally leads to a shift in primary producers from benthic microalgae and macrophytes to pelagic phytoplankton (Cloern 2001).

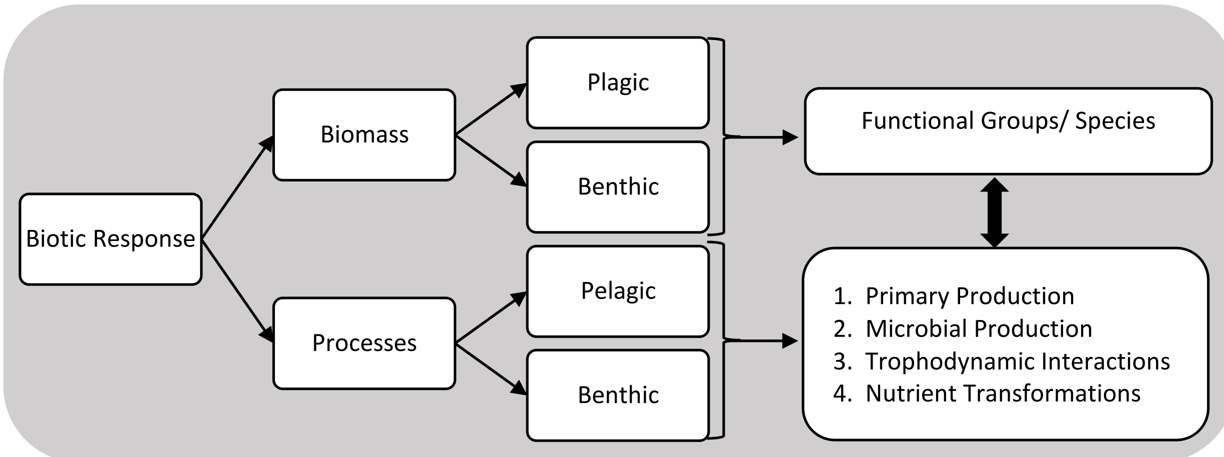

Figure 2-3. *Conceptual model of the effects of eutrophication on changes in primary production in the water column versus the benthos, also altering trophic transfers and nutrient cycling. Adapted from Nutrients in Estuaries, Nutrients in Estuaries "A Summary Report of the National Estuarine Experts Workgroup 2005–2007," US EPA, November 2010.*

A number of case studies have been presented illustrating different marine eutrophication conceptual models for estuaries, including San Francisco Bay, Pensacola Bay and Skidaway Estuary (**Figure 2-4**). For San Francisco Bay, a river-dominated estuary draining a heavily populated area in central California, Sutula et al. (2007) describe processes responsible for the development of hypoxia and possible mechanisms affecting estuarine phytoplankton biomass. Pensacola Bay, a river-dominated estuary located on the western panhandle of Florida, is not heavily urbanized but drains considerable agricultural land. The conceptual model developed by Hagy et al. (2008) for this waterbody highlights the important ecological processes and major environmental stressors of the ecosystem, as well as the historic, ecologic, and socioeconomic factors of potential importance for developing and evaluating water quality management options. Verity et al. (2006) contrast hypoxia in stratified versus well-mixed southeastern estuaries (e.g., Skidaway Estuary, GA). Skidaway Estuary is a tidally-dominated subtropical estuary in Georgia that is surrounded by extensive *Spartina* salt marshes. Due to nutrient enrichment from anthropogenic sources, this estuary has experienced steady increases in nutrients, which is related to cultural eutrophication. Related changes include increased chlorophyll, and particulate matter along with a concurrent decline in dissolved oxygen.

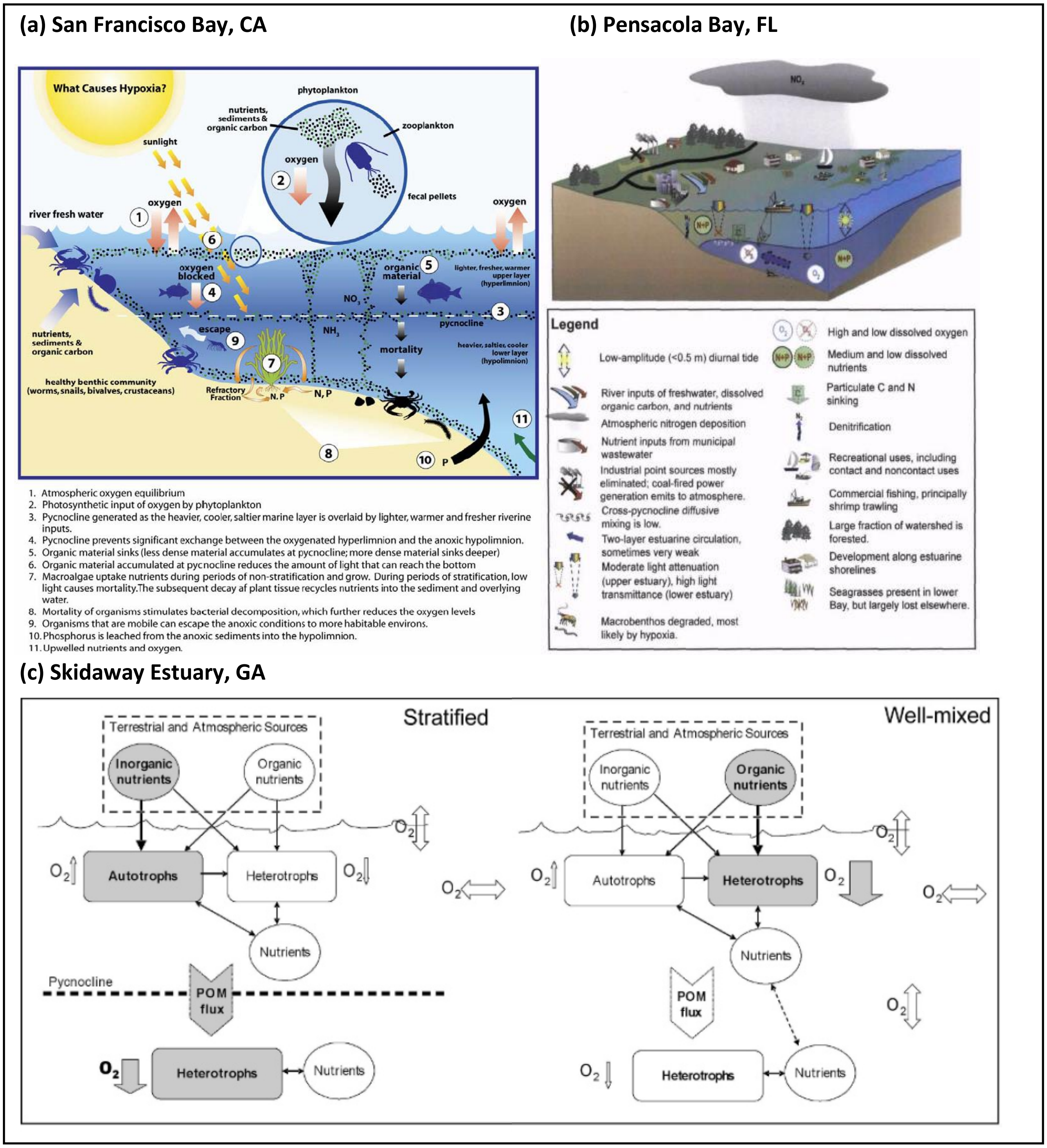

Figure 2-4. *Examples of a marine eutrophication conceptual models: (a) Top Left: Sutula and colleagues present conceptual diagrams for San Francisco Bay, California describing processes responsible for the development of hypoxia, and possible mechanisms affecting estuarine phytoplankton biomass. Top Right: Hagy, Kurtz, and Greene present a conceptual model for Pensacola Bay, Florida, illustrating historic, ecologic and socioeconomic factors of potential importance for developing and evaluating water quality management options. Bottom: Verity and colleagues contrast hypoxia in stratified versus well-mixed southeastern estuaries.*

The conceptual model presented here for Georgia and South Carolina's estuaries describes pathways by which nitrogen and phosphorus can affect ecosystem structure (chlorophyll *a*, benthic index of biotic integrity) and function (dissolved oxygen and ecosystem primary production rates). These effects are diagrammed in **Figure 2-5**, representing pools as boxes and fluxes as arrows.

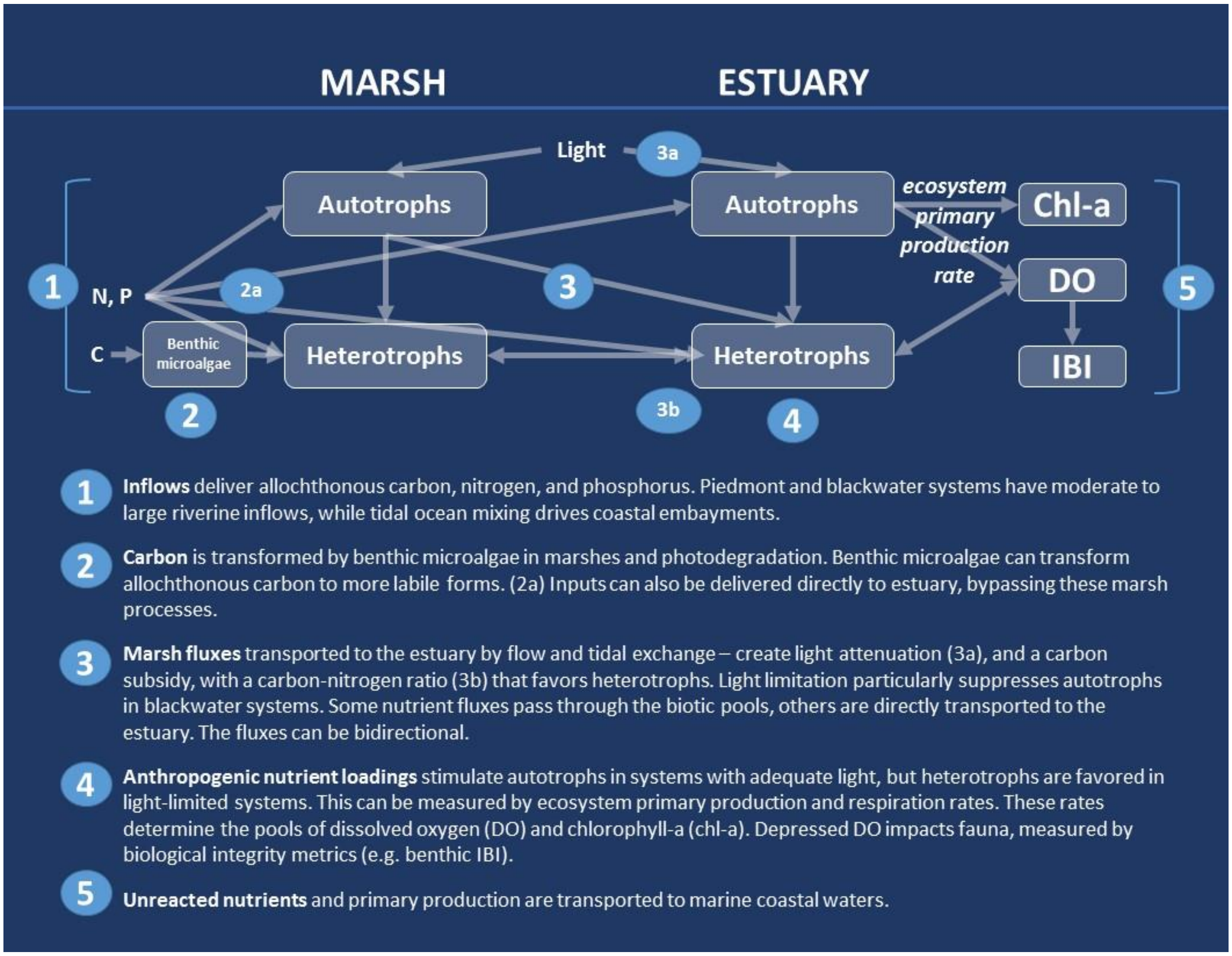

Figure 2-5. *Conceptual model for effects of nitrogen and phosphorus on Georgia and South Carolina's estuaries.*

This process is initiated when inflows deliver allochthonous carbon, nitrogen, and phosphorus to Georgia and South Carolina marshes and estuaries. Piedmont and blackwater systems have moderate to large riverine inflows, while coastal embayments are driven by primarily by tidal ocean mixing. The speciation of the nutrients (organic or inorganic, or for nitrogen, oxidized or reduced) affect the ecosystem differently. Carbon can be transformed by benthic microalgae in the marsh (as well as photodegradation) to more labile forms. As a result, when marsh fluxes are transported to many Georgia and South Carolina estuaries by flow and tidal exchange, the resulting light attenuation, carbon subsidy, and carbon-nitrogen ratio, favors heterotrophs (Taylor and Townsend 2010). This dynamic is reinforced in blackwater systems, where light limitation further suppresses autotrophs. Fluxes can be bidirectional, as matter is exchanged between the marsh and estuary and between the estuary and marine coastal waters. Ongoing research in Georgia is examining the degree to which the marshes are net nutrient sources or sinks, and how they may alter the magnitude, timing, or forms of nutrients delivered to the estuary.

Nutrient loadings to the estuary can stimulate autotrophs in systems with adequate light, but heterotrophs are favored in light-limited systems. This effect can be measured by ecosystem primary production and respiration rates. These rates determine the pools of dissolved oxygen and chlorophyll *a* in the estuary. Depressed dissolved oxygen affects fauna, and the impact on biota can potentially be measured by biological integrity metrics, such as South Carolina's benthic IBI. Ultimately, unreacted nutrients and primary production may be transported further from shore and into marine coastal waters where they may affect those downstream systems.

Applying this conceptual model to cultural eutrophication, it is anticipated that anthropogenic nutrient loadings to Georgia and South Carolina's estuaries may stimulate either autotrophic or heterotrophic community metabolism, thereby depressing dissolved oxygen and, in turn, potentially impairing fauna. Excessive nutrients in Georgia and South Carolina's estuaries could adversely affect estuarine structure at multiple trophic levels and alter basic functions such as normal levels of ecosystem productivity and respiration.

2.6 Potential Assessment and Measurement Endpoints

True assessment endpoints are the valued ecosystem characteristics that are desired to be protected. Assessment endpoints can also encompass the typical structure and function of biological communities or ecosystems associated with a site (USEPA 1998). In a regulatory context, the designated uses of a waterbody and their associated narrative criteria may be considered as assessment endpoints. These assessment endpoints (such as shellfish propagation and harvesting) are often difficult to predict or measure directly. Therefore, development of water quality criteria usually proceeds through the evaluation of operationally defined endpoints (referred to as measurement endpoints) that serve as surrogate measures to link stressors and outcomes.

A measurement endpoint is defined as "a measurable ecological characteristic that is related to the valued characteristic chosen as the assessment endpoint" (USEPA 1998). For water quality criteria development, a measurement endpoint can be translated to a nutrient criterion value for protecting a specific use at a given site. For this effort, criteria will be the numeric value of a measurement endpoint that supports a balanced natural population of aquatic flora and fauna in Georgia and South Carolina's estuaries and coastal areas. Salient aspects of the literature review and the EPA's basis for selecting assessment endpoints and the proposed water quality measurement endpoints to protect those assessment endpoints are discussed in subsequent sections of this chapter.

2.6.1 Potential Assessment Endpoints for Georgia and South Carolina Estuaries

This report reviews the scientific literature to identify candidate endpoints that are ecologically important, widely applicable in Georgia and South Carolina estuaries, and sensitive to nutrients.

2.6.1.1 Balanced Phytoplankton Biomass and Production

Healthy biotic communities often depend on normal, balanced levels of phytoplankton abundance (Bricker et al. 1999; Bricker et al. 2003b). Chlorophyll *a* concentration is the measurement endpoint most often used to indicate balanced phytoplankton biomass and production (Boyer et al. 2009; Hagy et al. 2008). To determine the appropriate water quality criteria, a variety of factors influencing the response of chlorophyll *a*, should be considered. Shifts in the composition of phytoplankton and zooplankton assemblages have been observed in estuarine and freshwater ecosystems in which nutrient loading rates are increased (Arhonditsis et al. 2007; Armitage and Fong 2004; Cloern 1996, 2001).

Although informative studies of phytoplankton assemblage composition are relatively uncommon, unusually high phytoplankton biomass (and thus, chlorophyll *a*) has been associated with proliferation of toxic or otherwise harmful species (Cloern 2001; Reed et al. In Review). Increases in biomass is often associated with elevated levels of N. Specifically, incubation studies have shown that phytoplankton biomass increases in response to organic N (such as urea), and this effect is augmented in developed or developing coastal regions (Reed 2014; Reed et al. 2015 and In Revision). One reason is that such species are not effectively controlled by planktonic grazers, allowing their biomass to increase. Species shifts may involve an increase in the abundance of unpalatable, toxic, or otherwise nuisance species that disrupt grazing and may negatively affect the estuarine food chain from the bottom up. Some species shifts occur in response to a change in the relative abundances of different nutrients. Increased abundance of nitrogen and/or phosphorus sometimes results in silica limitation, which favors non-diatom species because they do not require silica (Cloern 2001). Chlorophyll *a* can serves as a sensitive indicator of the changes in phytoplankton species composition. Subsequently, numeric criteria for TN and TP can be computed using the relationship between chlorophyll *a* and TN or TP.

2.6.1.2 Balanced Faunal Communities

The health of estuarine and coastal biological communities, from fish to benthic macroinvertebrates to plankton, depends critically on sufficient DO (e.g., Diaz 2001; Diaz and Rosenberg 2008). In estuaries and coastal waters, low DO is one of the most widely reported consequences of nitrogen and phosphorus and one of the best predictors of a range of biotic impairments (e.g., Bricker et al. 2003a; Bricker et al. 1999). The effects of low DO on marine life range from mass cross-species mortality to chronic impairment of growth and reproduction, although in some instances low DO is the result of natural conditions and the biological community is composed of species tolerant of such environments. Thus, DO is a measurement endpoint proxy for the marine life for which DO requirements for survival, growth.

Estuaries may exhibit large, diurnal DO fluctuations characterized by high concentrations during the daylight hours, and periods of low (potentially hypoxic or anoxic) concentrations during the night. Furthermore, highly productive systems tend to have large amounts of detritus that deposit to sediments and is re-mineralized by bacteria, consuming oxygen and resulting in sediment nutrient releases (Cloern 2001). Water column stratification due to salinity and/or temperature gradients reduces the mixing of oxygen-rich surface waters (where oxygen can diffuse into the water from the atmosphere) with oxygen-poor bottom waters (where oxygen is generally consumed due to net heterotrophic metabolic), increasing the tendency for net heterotrophic bottom waters to become oxygen depleted.

In the case of DO, the States of Georgia and South Carolina have established DO standards for estuarine and coastal waters. In both States the majority of coastal waters require that the average DO shall not be less than 5.0 mg/L in a 24-hour period and shall never be less than 4.0 mg/L, with normal daily and seasonal fluctuations maintained. In South Carolina there is also a class that only requires that DO shall never be less than 4.0 mg/L. In South Carolina there is an allowable exception to the DO standard when the cause of low DO is due exclusively to natural conditions. In Georgia Coastal Fishing designated use also allows for the consideration of natural conditions. Subsequently, numeric criteria for TN and TP can be computed using the relationship between DO and TN or TP.

2.6.2 Review of Potential Measurement Endpoints

For water quality regulatory purposes, the designated use of a waterbody can be interpreted as its assessment endpoint. Selecting measurement endpoints to protect aquatic life represents a potential tradeoff between environmental sensitivity to excess nitrogen and phosphorus and available data. To develop numeric criteria, it is important to select measurement endpoints that are sensitive to excess nitrogen and phosphorus, so that one can infer that the numeric criteria will protect less sensitive endpoints. Additionally, it is important to choose measurement endpoints with sufficient data that would allow quantitative relationships to be developed either through stressor-response relationships (e.g., empirical or regression models) and/or water quality simulation models.

There are numerous endpoints that can, at a minimum, be qualitatively related to nutrients (e.g., Bricker et al. 2008). For example, endpoints selected by the State of Florida included phytoplankton, macroalgae, epiphytes, seagrass, benthic macroinvertebrate and fish indices, HABs, and coral (US EPA 2010). For Georgia and South Carolina, seagrass and coral endpoints are not applicable, and therefore not considered. Thus, the major measurement endpoints considered for Georgia and South Carolina, and linkage to, or effects of, nutrients are summarized in **Table 2-2**.

Table 2-2. *Measurement endpoints for evaluating the magnitude and effects of nutrients, including advantages and disadvantages.*

	Importance	Linkage to, or Effects of, Nutrients	Advantages	Disadvantages
Phytoplankton	• Primary producers and important component of marine food web • Excess growth affects clarity, DO, habitat, aesthetics, and overall food web productivity.	• Nutrients are key limiting factors for algal growth rates and assemblage composition.	• Responsive to nutrients, well-established basis for use as indicator • Biomass data in estuarine waters are routinely monitored and data are generally abundant	• Other factors can interfere with evaluating stressor-response relationships • Differences in field sample and taxonomic methods may increase uncertainty • Field-collected biomass data in coastal (offshore) waters are limited • Most estuaries lack species composition models developed for nutrient response, but data for incorporation in to models are emerging.
Harmful Algal Blooms	• Often associated with toxins leading to faunal kills, shellfish contamination, economic effects, decline in aesthetic value, environmental and ecological damage.	• HAB species may be less studied.	• Foul odor and reduced aesthetics can lead to public awareness.	• Data exist in the SC coastal zone for HABs

	Importance	Linkage to, or Effects of, Nutrients	Advantages	Disadvantages
Invertebrates	• Reliable indicator of biological conditions	• Invertebrate community changes from increased phytoplankton food base and reduced benthic food base • Severe community changes with hypoxia	• Established indicator of biological conditions • Existing monitoring programs	• Many confounding factors (e.g., habitat loss, sediment toxicity, overfishing, indirect effects of nutrients)
Fish	• Indicator of biological condition	• Nutrient loading may affect habitat quality for fish (e.g., due to hypoxia) HABs can cause fish mortality or reduced fish growth • Excess nutrients can also stimulate fisheries production by increasing prey abundance	• Highly visible • Substantial public concern	• Many confounding factors (e.g., overfishing, stocking, habitat loss, indirect effects of nutrients)
Clarity	• Affects growth of plants and phytoplankton	• Nutrient enrichment enhances phytoplankton growth, reducing clarity	• Easy to measure (photosynthetically active radiation [PAR], Secchi) • Clear linkage to important aquatic life	• Confounding factors (e.g., inorganic particles, dissolved organic carbon [DOC]).
Dissolved Oxygen	• Hypoxia kills fish and invertebrates • Hypoxic or low DO areas nullified as suitable habitat	• Nutrients affect organic loading through algal growth, depleting oxygen • Nutrients accelerate decomposition rates by microbial stimulation, consuming oxygen	• Existing criteria • Well established basis for protection of aquatic life • Clear linkages to nutrient enrichment • Extensive database	• Need to model relationship between nutrients and DO
Chlorophyll *a*	• Chlorophyll is an indicator of phytoplankton biomass	• Nutrients are key limiting factors for algal growth	• Responsive to nutrients • Biomass data in estuarine waters are routinely monitored and data are generally abundant	• Establishing protective concentrations for non-seagrass uses is less well studied • Other factors can interfere with evaluating stressor-response relationships • Field-collected biomass data in coastal (offshore) waters are limited

	Importance	Linkage to, or Effects of, Nutrients	Advantages	Disadvantages
Total Nitrogen	• N is typically more limiting of algal growth than P in estuarine systems	• N directly related to phytoplankton production in N-limited systems • Coastal GA and SC are generally N-limited	• Estuarine water quality best predicted in the short term by antecedent TN loading rates or freshwater discharge • TN concentration is associated with TN loading over the long term	• Nutrient transport and transformation processes complex. • Production may be more responsive to dissolved inorganic nitrogen (although those pools turnover rapidly between water column and intracellular concentration, so total measures may be more spatially/temporally stable and therefore more feasible for assessment purposes).
Total Phosphorus	• Algal production can be P-limited in areas with less soil P.	• P directly related to phytoplankton production in P-limited systems	• TP loading best predicts water quality response in P-limited systems • TP concentration is associated with influent TP loading over the long term	• Water quality response relationship less strong in N-limited systems

2.6.3 Measurement Endpoints for Georgia and South Carolina Estuaries

This report reviews the scientific literature to identify candidate endpoints that are ecologically important, widely applicable in Georgia and South Carolina estuaries, and sensitive to nutrients.

2.6.3.1 Ecosystem Primary Production and Respiration Rates

Within the conceptual model presented in **Section 2.5**, the measurement of ecosystem gross primary production and respiration provides an integrative measure of energy flow and material cycling within the ecosystem. Variations in the net production-respiration balance among different estuaries have been shown to be a reflection of their nutrient to organic carbon loading ratio (Kemp et al. 1997). Shift in ecosystem production and respiration rates from a reference condition could thus serve as an integrative measure of ecosystem perturbations resulting from changing nutrient loading conditions. Direct measures of production and respiration, as determined by short-term “light-dark bottle” techniques and high precision oxygen measurements (e.g., Hopkinson and Smith 2005), are rather labor intensive, however, and generally outside the scope of routine regulatory monitoring programs. The indirect estimate of estuarine production and respiration derived from in situ time-series of dissolved oxygen is also gaining promise (e.g., Caffrey et al. 2014), although this approach must contend with the complicated tidal mixing environment found in most estuaries (Beck et al. 2015). None the less, measurements of ecosystem gross primary production and respiration quantify an important functional aspect of estuarine health, providing a process-oriented context to compliment the structural measures of estuarine health that are more commonly implemented for regulatory purposes (Palmer and Febria 2012), and thus warrant further effort and attention. To that end, one possible line of research may be an examination of the extent to which measure of 5-day Biochemical Oxygen Demand (BOD5), a fairly common regulatory program monitoring parameter, can serve as a functional measure of estuarine condition that can be related to production-respiration dynamics.

2.6.3.2 Chlorophyll a

Chlorophyll *a* is a candidate measurement endpoint because proliferation of phytoplankton, including nuisance algal species may be the most apparent nutrient effects in some estuaries. If nutrient loadings to coastal systems increase, phytoplankton biomass and bloom incidences could increase as well. The magnitude, duration, and frequency of algal blooms can be informative in identifying the sources of nutrients. The responses to nutrients may depend on the form (organic or inorganic, NO_3^- or NH_4^+) of the nutrient contribution. Chlorophyll *a* can serve as an indicator of some changes in the phytoplankton community, particularly total biomass. Relationships between chlorophyll *a* and TN or TP could be used to establish nutrient criteria in systems where the relationship is not confounded by other factors such as light limitation.

2.6.3.3 Dissolved Oxygen

Dissolved oxygen is a candidate measurement endpoint because excess nutrients trigger autotrophic or heterotrophic processes, which drive dissolved oxygen dynamics. Large amounts of algal growth can increase organic matter availability, which when it decomposes can promote dissolved oxygen depletion in some waterbodies. Alternatively, and of particular importance in Georgia and South Carolina's estuaries, nutrient response can be mediated by heterotrophic communities, placing a demand on available dissolved oxygen. Dissolved oxygen is easily measured and tracked to establish adequate regulatory datasets. Although dissolved oxygen response is not specific to nutrient input, it can be implemented as one indicator of nutrients. Continuous measures of dissolved oxygen can be particularly diagnostic when analyzing the trophic status of a waterbody. Dissolved oxygen is a useful indicator for numeric criteria development because ecological modeling approaches can be used to predict the response of dissolved oxygen to nutrient loading.

2.6.3.4 Benthic Index of Biotic Integrity (IBI)

A benthic Index of Biotic Integrity (IBI) measurement endpoint refers to communities of benthos (bottom-dwellers) exhibiting a healthy community composition and biomass. Low dissolved oxygen resulting from nutrients is a key mechanism by which nutrients may affect this measurement endpoint, because pollution sensitive species tend to become less abundant and pollution indicative species become more abundant. In addition, species composition may change due to changes in algal communities and organic matter. The response of an IBI is not specific, but rather indicates a stressor present in the system. An IBI is a potentially useful tool to demonstrate the presence of stressors in the system, but it will likely require additional lines of evidence to demonstrate that the stressor is due to nutrients.

2.7 Potential Data Sources

Significant data may be available from state and local governmental agencies, multiple Federal agencies, including the EPA, USGS, NASA, and NOAA, and public and private research institutions. Data can be accessed via existing online data portals and other means (e.g., e-mail, FTP, mail). Because this document considers water quality simulation models as one of the analytical approaches, the number of different kinds of data that could be needed is very broad and extends well beyond water quality monitoring data. The paragraphs below describe in further detail major data sets that may be available, the sources of the data including internet sources for the data or information about the data, and which aspects of criteria development the data may support.

2.7.1 Water Quality Monitoring Data

These data may be used in almost every aspect of criteria development and pertain to both freshwater and marine water quality.

Georgia Data Sources:

- GA Coastal Ecosystems Long Term Ecosystem Research Program (LTER) – since 2000 (Altamaha River, Doboy Sound, Sapelo Sound, http://gce-lter.marsci.uga.edu/)
- Skidaway River Monitoring Program – since 1986
- GA Rivers Land Margin Ecosystem Research (LMER) program (1994-2000, data available through GCE-LTER and at http://lmer.marsci.uga.edu/)
- GA EPD special studies (Laurel View River, Ogeechee River, Turtle Creek estuary)
- GA EPD photic zone data
- GA CRD estuary data
- Sapelo Island NERR (see below for NERR data descriptions)

South Carolina Data Sources:

- Special studies (SC DNR, USGS, USC)
- NERRs data: North Inlet (sondes, TN, TP species, etc.), ACE (sondes, Chl-*a*, DO, inorganic N & P), ACE Basin and Sapelo NERRs have sondes (temp, salinity, DO, pH, turbidity at 15 min intervals) plus Chl-*a* and inorganic N & P at monthly intervals; North Inlet NERR has those data plus TN, TP and TSS data at monthly intervals. At each NERR, at least one monitoring location includes tidal sampling (13 discrete samples collected with an automated water sampler over the full semidiurnal cycle) at each monthly sampling event.
- DHEC: Estuarine sites: Base Sites are sampled bi-monthly, Statistical Survey sites sampled monthly for one year and moved every year. Every site every visit: instantaneous dissolved oxygen, pH, water temperature, specific conductance, salinity at surface bottom, and mid-depth. Every site every visit, surface grab only: turbidity, Enterococcus bacteria, five-day biochemical oxygen demand, nitrate/nitrite nitrogen, ammonia nitrogen, total Kjeldahl nitrogen, and alkalinity. Every site quarterly, surface grab only: cadmium, chromium, copper, iron, manganese, mercury, nickel, and zinc. Statistical Survey sites, monthly May – October, Chlorophyll *a* surface grab.
- SCECAP and DHEC data. SCECAP is a collaborative partnership between SCDHR and SCDHEC. Piedmont Rivers, Coastal Embayments, & Tide Creeks. Annually SCDNR conducts a collection for macroinvertebrate benthic index of biological integrity, calibrated to toxic pollutants, and sediment contaminants.
- Dianne Greenfield laboratory database (long-term data since 2001, a variety of monitoring and research studies on HABs, nutrients, chlorophyll, toxin, and others).

Shared Data Sources:

- USGS historical continuous WQ (including DO) in GA and SC
- GA and SC have dissolved N and P (National Coastal Assessment data)

2.7.2 Land Use Data

Land use data is one input to water quality simulation models (i.e., mechanistic watershed models). Data for Georgia are from Georgia Land Use Trends (GLUT) 2008 (http://narsal.uga.edu/glut.html) and for both States, from the National Land Cover Database (http://www.epa.gov/mrlc).

2.7.3 Meteorological Data

Meteorological data, including precipitation, evaporation, relative humidity, air pressure, air temperature, solar radiation, cloud cover, wind speed, and wind direction are inputs to mechanistic watershed, hydrodynamic, and water quality models for estuaries. These data may be obtained from the National Centers for Environmental Information (formerly National Climatic Data Center) or the Georgia Automated Environmental Monitoring Network (GAEMN), which reports data for numerous stations. The data are available at http://www.ncdc.noaa.gov and http://www.georgiaweather.net/, respectively.

2.7.4 General Hydrology

General hydrology data is contained within the National Hydrography Dataset Plus (NHDPlus, http://www.horizon-systems.com/nhdplus), which provides subwatershed and flow line delineations that can be used in watershed models. Stream discharge data and flow velocity data are available from the US Geological Survey, available through the National Water Information System (NWIS, http://waterdata.usgs.gov/nwis). These data could be used to parameterize, calibrate and evaluate mechanistic watershed models. The National Elevation Dataset 1/3 arc-second (10 meter by 10 meter) can be used for computing elevations and slopes. The National Elevation Dataset is available from the USGS (http://ned.usgs.gov). Water surface elevation data from NOAA tide gauges can be used for determining boundary conditions, calibration, and evaluation data for hydrodynamic models (Chapter 3). These data are reported by NOAA's Center for Operational Oceanographic Products and Services (http://www.tideandcurrents.gov). Bathymetric data for estuaries and coastal areas can be obtained from the NOAA National Geophysical Data Center (http://map.ngdc.noaa.gov).

2.7.5 NPDES Point-Sources and Water Withdrawals

NPDES-permitted point sources and water withdrawals can be obtained from the respective state's NPDES system for use in water quality simulation models.

2.7.6 Ocean Color Satellite Data and Field Validation

NASA satellite-borne ocean color sensors have been used in other states for development of numeric criteria for offshore coastal waters -- although their application may be more limited in Georgia and South Carolina's turbid estuarine waters. These sensors include the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and the Moderate Resolution Imaging Spectroradiometer (MODIS). The period of record for both sensors is more than 10 years (note that SeaWiFS was decommissioned in December 2010). Possible sources of shipboard data to compare with satellite data include the Ecology and Oceanography of Harmful Algal Blooms project (ECOHAB), the Monitoring and Environmental Response of Harmful Algal Blooms (MERHAB) project and SeaWiFS Bio-optical Archive and Storage System (SeaBASS, http://seabass.gsfc.nasa.gov).

3 Numeric Nutrient Criteria Development in Georgia and South Carolina Estuaries

An estuary is a part of a stream[3] or other body of water that has an unimpaired connection with the open sea and where seawater is measurably diluted with freshwater derived from land drainage. This document describes methods for developing numeric criteria for nitrogen and phosphorus in Georgia and South Carolina's estuaries on a system-specific basis. A system-specific approach allows the consideration of the individual characteristics of these estuarine ecosystems in groups with common characteristics. For example, water quality and biological communities in estuaries are affected by a combination of basin shape, tides, and the magnitude, location, and quality of freshwater inflows. The semi-enclosed basins that define the spatial extent of estuarine areas may also create sub-regions within estuaries with differentiated water quality and assessment endpoints.

This chapter describes the approaches to derive numeric criteria for estuarine waters in Georgia and South Carolina. We describe an approach for delineating estuaries into discrete areas for the purpose of organizing the criteria development process. We also discuss the concepts of assessment endpoints and indicator variables, and the specific endpoints and indicators for use in development of numeric estuarine criteria. We discuss the rationale that may be used for selecting specific water quality indicator variables for developing criteria. Finally, we discuss three approaches: (1) reference conditions, (2) stressor-response relationships (regression models), and (3) water quality simulation modeling that could be used independently or in combination to develop numeric estuarine criteria.

3.1 Delineating Estuaries

The first step in any approach for developing numeric criteria for nitrogen and phosphorus is delineating the water bodies. Delineating the estuarine waters provides an organizational framework for developing and presenting the scientific approach, applying the methods and approaches most appropriate to each estuary, and ultimately deriving criteria. Natural constrictions between estuarine basins tend to limit water flow and exchange between estuaries, even if exchanges are not eliminated entirely. Natural geographic boundaries can be used for delineating sub-segments within estuaries to achieve the objective of homogenous water quality within segments while maintaining a reasonable spatial scale for criteria development (e.g., not an excessive number of very small segments).

3.2 Water Quality Indicator Variables for Expressing Criteria

Based on the EPA guidance (USEPA 2001) and an assessment of the available literature, the numeric criteria for Georgia and South Carolina estuarine and coastal waters should consider addressing the following indicator variables: TN concentration (as mg/L), TP concentration (as mg/L), chlorophyll *a* concentration corrected for pheophytin (chlorophyll *a* as µg/L), ecosystem primary production and respiration, benthic index of biotic integrity, and dissolved oxygen (as mg/L). Appropriate numeric

[3] For the purpose of this effort, a stream has been defined as free-flowing, predominantly fresh surface water in a defined channel, and includes rivers, creeks, branches, canals, freshwater sloughs, and other similar water bodies. Predominantly fresh waters have been previously defined as surface waters in which the chloride concentration at the surface is less than 1500 mg/L (salinity less than ~2.7 psu). Alternative definitions could be considered that are based on conductivity or salinity.

criteria for these variables will help ensure that protection of the biological assessment endpoints is achieved.

While the conceptual model of eutrophication continues to evolve, it is clear that nitrogen and phosphorus are the primary macronutrients that enrich waters and can cause nuisance levels of algae (Elser et al. 2007; Howarth et al. 2002). Conditions that allow phytoplankton to accumulate (i.e., adequate light, optimum velocity or mixing, low loss to grazing, etc.) will not result in high biomass without sufficient nutrient supply (USEPA 2001). Although often either N or P is limiting (and therefore a pollution concern), sometimes the addition of both nitrogen and phosphorus will elicit greater phytoplankton biomass stimulation than either nutrient added separately (Fisher et al. 1992; Flemer et al. 1998), suggesting that nitrogen and phosphorus supply rates were co-limiting phytoplankton production.

3.2.1 Total Nitrogen

Nitrogen is an important limiting nutrient of algal biomass production (USEPA 2001), especially in estuaries. TN consists of organic and inorganic forms. Stimulated algal biomass production has been previously attributed to inorganic nitrogen (Stepanauskas et al. 1999), although some dissolved organic nitrogen may be used for algal growth (dissolved and particulate organic nitrogen are involved in recycling processes) (USEPA 2001). In estuaries, nitrogen concentrations, especially the inorganic forms, typically vary widely on seasonal and interannual time scales and along salinity gradients (USEPA 2001). In those estuaries where nitrogen has been demonstrated to limit algal biomass production, it typically does so at higher salinities. However, the importance of dissolved organic N (DON) is emerging. DON, particularly urea, comprises >50% of commercial fertilizers world-wide (Glibert et al. 2006), and Reed et al. (2015) found that nitrogen additions, particularly those containing DON (as urea), across four different coastal South Carolina systems representing different urbanization levels stimulated phytoplankton biomass (chlorophyll *a*) and DOC levels, suggesting that biogeochemical cycling of DOC may become altered in developing coastal regions. Reed (2014) and Reed et al. (In Review) also describe the specific phytoplankton community responses to N-additions, particularly the sensitivity of HABs to certain forms of N (organic N and nitrate). This underscores the importance of assessing particular forms of N as they relate to total N. Denitrification may remove from a few percent to approximately 50 percent of the TN load entering temperate estuaries annually (Seitsinger 1988; Cornwell et al. 1999) depending largely on residence time of the water, sediment biogeochemical conditions (e.g., benthic macrofauna present to maintain irrigation, oxic conditions in the overlying bottom water), and water column depth. This process helps to modulate extreme dissolved inorganic N concentrations (USEPA 2001).

3.2.2 Total Phosphorus

Phosphorus is often the nutrient that most limits algal production in tidal fresh estuaries, as well as areas with a wider range of salinity in certain subtropical to tropical marine systems (USEPA 2001; Hecky and Kilham 1988), though the SC and GA coast and replete in orthophosphate and generally not P-limiting (Abrams and Jarrell 1995; Litke 1999; Greenfield et al. 2012; Reed et al. 2015 and In Review). In instances where phytoplankton are most likely limited by phosphorus, the discharge of raw or untreated wastewater, agricultural drainage, or certain industrial wastes may stimulate the growth of algae (USEPA 2001). Phosphorus occurs in natural waters and in wastewaters almost solely as phosphates. These are classified as orthophosphates, condensed phosphates, and organically bound phosphates.

Common analytes are TP and dissolved or particulate organic phosphorus (DOP, POP). These compounds may be soluble, in particulates or detritus, or incorporated as organic phosphorus in organisms. Some fraction of phosphorus may be strongly embedded in a mineral matrix, rendering that fraction relatively inert to biological utilization except by algae that have the capability to break down DOP with alkaline phosphatase (algal and free phosphatases) and utilize the phosphate as inorganic phosphate (Huang and Hong 1999).

The Southeastern Coastal Plain has considerable naturally occurring phosphates (**Figure 3-1**). In the form of nodules that formed in Miocene sediments, phosphate has been mined in South Carolina since the mid-nineteenth century (Rogers 1913) and continues to be mined today in similar geologic formations of coastal North Carolina and Florida (Jasinski 2015). While by 1913 South Carolina phosphates were only 4% of total U.S. production, South Carolina produced over 95% of the national total until 1885 when Tennessee and Florida exceeded South Carolina production (Rogers 1913). In fact, South Carolina was the world's leading producer of mined phosphate (Rogers 1913). Despite the 12,826,713 long tons produced in South Carolina from 1867 to 1912, Rogers (1913) points out that "there are probably at least 5,000,000 tons of 60 percent phosphate still in the ground." It should be unsurprising then that South Carolina estuaries with headwaters originating on the Coastal Plain are naturally high in phosphate. Naturally occurring phosphate concentrations in the Southeastern United States were interpolated via the USGS Spatially Referenced Regression on Watershed Attributes (SPARROW) model (**Figure 3-1**). Management of eutrophication in other estuaries that are naturally rich in phosphorus, such as Tampa Bay, Florida, has focused principally on limiting nitrogen pollution, while still setting numeric limits on phosphorus.

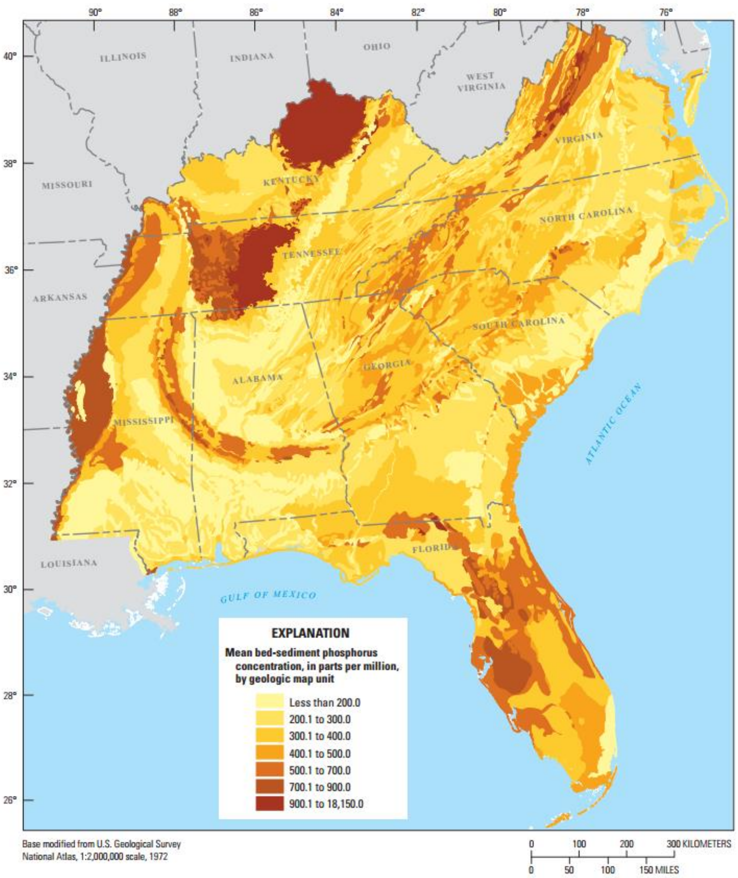

Figure 3-1. *Mean values of bed-sediment phosphorus concentration within geologic map units. Bed-sediment samples collected from headwater streams draining relatively undisturbed areas, 1976–2006. Figure 5 from Terziotti et al. 2010.*

3.2.3 Chlorophyll *a*

Chlorophyll *a* is an indicator of phytoplankton biomass in the water column and is often correlated with the productivity and trophic status of aquatic ecosystems. Chlorophyll *a* reflects the standing biomass, which is the integral of algal growth and mortality. The benefits of chlorophyll *a* as an indicator variable are its relevance to the condition of estuarine and coastal ecosystems, its sensitivity to stressors such as nutrients, and ease of monitoring (Boyer et al. 2009). Elevated concentrations of chlorophyll *a* suggest enhanced phytoplankton production. Excess primary production and algal biomass can cause a variety of negative effects (Bricker et al. 2003b; Vitousek et al. 1997). For example, excess high algal biomass can reduce water clarity, resulting in reduced light availability for benthic algae and macrophytes (Boyer et al. 2009; Bricker et al. 2008), and lead to HABs. Excess production of phytoplankton also contributes to the organic matter supply, which fuels respiration and may lead to decreased DO, including hypoxic and anoxic conditions (Vitousek et al. 1997).

3.2.4 Dissolved Oxygen

Although dissolved oxygen response is not specific to nutrient input, it can be implemented as one indicator of excess nutrients. Excessive algal growth in response to nutrient loads often results in increased organic matter followed by decomposition and decreased dissolved oxygen levels in the affected waterbody. However, nutrient response can also be mediated by heterotrophic communities (of particular importance in Georgia and South Carolina's estuaries) placing a demand on available dissolved oxygen, and this may happen in the absence of elevated chlorophyll *a*. Dissolved oxygen is easily measured and is usually included in routine monitoring of aquatic ecosystems. Continuous diel measurements of dissolved oxygen can be particularly diagnostic when analyzing the trophic status of a waterbody. Dissolved oxygen is also a useful indicator for numeric criteria development because ecological modeling approaches can be used to predict the response of dissolved oxygen to nutrient loading via either autotrophic or heterotrophic pathways.

3.2.5 Not Selected for Numeric Criteria Development

The following nutrient-sensitive biological endpoints were not selected for criteria development: (1) HABs, (2) coral, (3) epiphytes, (4) macroinvertebrate and fish indices, (5) macroalgae, (6) *Spartina* marshes (salt-marshes), and (7) Eastern oysters (*Crassostrea virginica*). In general, these endpoints were not selected because there was either an absence of sufficient data to assess the effects of measured nitrogen and phosphorus concentrations, or there was an alternative endpoint available that was more sensitive to excess nitrogen and phosphorus.

3.3 Numeric Criteria Approaches

This report outlines three basic approaches to derive numeric criteria for estuaries. These approaches include (1) reference condition approaches, (2) stressor-response relationships, and (3) water quality simulation models. Associated with each approach are specific strengths and weakness, factors indicating it could be used and factors indicating another approach may be needed (**Table 3-1**). These factors will be considered to determine which approaches should be used given the ecological details pertinent to each estuary as well as the different types and quantities of data available. Georgia and South Carolina could consider several different types of models and information to derive numeric criteria for different estuaries and could simultaneously consider more than one approach for a single estuary.

Table 3-1. *Strengths, weaknesses, indications (situations where approach is most applicable), and contraindications (situations where another approach may be needed) for each of the three categories of criteria development described.*

	Strengths & Weaknesses	Most Applicable When	Least Applicable When
Reference Condition Approaches	*Strengths* • Simple, direct and understandable; provides information to quantify criteria. *Weaknesses* • Need quantitative data to characterize the reference condition that reflects support of the designated use.	• Substantial water quality data are available and the estuary is minimally impacted by nitrogen and phosphorus sources. • Substantial water quality data are available from a historical period when the estuary was minimally impacted by nutrients. • The estuary is very similar to another estuary to which one of the above conditions applies	• The estuary is impacted by nitrogen and phosphorus sources and is likely impaired by nutrients. • Little or no data are available from a historical period when the estuary was not minimally impacted by nutrients. • The estuary is considered relatively unique.
Stressor-Response Relationships (Regression Models)	*Strengths* • Easy to understand and visualize; uncertainty may be quantified, provides linkage between criteria and aquatic life uses, can quantify relationships between different criteria values. *Weaknesses* • Regressions can be affected by covariates; may not address additive or interacting effects of more than one causal factor.	• Extensive data are available, spanning multiple years and spanning a range of nutrient loading rates and water quality response. • Simple regression relationships exist and quantify relationships between nutrient loading and/or nutrient concentrations and water quality responses. • Response is consistent across many estuaries.	• Little or no data are available • Complex relationships between nutrients and water quality responses involve multiple interacting causes, including physical- biological coupling. • Key ecological processes and interactions are different or unique compared to other estuaries.
Water Quality Simulation Models	*Strengths* • Can provide detailed simulation results for many variables, addressing magnitude, frequency and duration; addresses physical-biological coupling. *Weaknesses* • May not address important ecological processes; many unknown model parameters including boundary conditions; may not be valid for unobserved conditions.	• Important ecosystem processes are well-understood • Available data are from process studies or other isolated studies, rather than consistent monitoring over multiple years. • Interactions are complex, involve physical-biological interactions, or are spatially structured. • Relatively little site-specific data are available.	• Mechanisms governing interaction among nutrient sources, water quality, and biological responses are not well understood. • Critical inputs to model are completely unknown (e.g., large open boundaries) • Linkages between possible model outputs and use attainment are not well-defined. • Adequate data are not available as model input.

3.3.1 Reference Condition Approaches

Reference condition approaches can take a variety of forms, defined by the source of the reference condition. The EPA has previously recommended (e.g., USEPA 2000c) that a percentile of water quality measurements in a sample of minimally-impacted waterbodies, which are known to be fully supporting designated uses (i.e., not impaired), could serve as numeric criteria in similar waterbodies. In this case, a reference condition is derived from a reference population of waterbodies. A reference condition approach is most applicable when (1) historical data adequately describe water quality conditions when the estuary was minimally-impacted by nitrogen and phosphorus and was supporting balanced natural populations of aquatic flora and fauna (i.e., historical reference condition) or (2) when the estuary is currently minimally-impacted by nitrogen and phosphorus and currently supporting balanced natural populations of aquatic flora and fauna (i.e., current-conditions reference condition). In either case, interpretation of the status of reference conditions could be based on examining the assessment and measurement endpoints previously identified (**Section 2.6.3**). A reference condition can also be modelled via mechanistic, process-based water quality models that allow the simulation of conditions in the absence of anthropogenic landuse or hydrologic modifications.

To evaluate assessment endpoints and associated water quality indicator variables, 303(d) listings should be considered, along with peer-reviewed literature, reports, and other data sources. To derive criteria from current water quality conditions, two statistical reference points from the water quality observations could include (1) an average or median concentration and (2) an upper percentile concentration. By simultaneously considering both an indicator of central tendency and a measure of higher concentrations, the criteria could ensure that future water quality conditions remain similar to present conditions (i.e., the conditions associated with support of balanced natural populations of aquatic flora and fauna). As an alternative, the criteria could be expressed as an annual geometric mean. The criteria (which may use the statistical reference points to describe a distribution of allowable values) should be defined in such a way that waters known to be supporting designated uses will not be improperly classified as impaired.

3.3.2 Stressor-Response Relationships

Regression models usually express a stressor-response relationship between one or more explanatory variables and a single response variable. Regression models can encompass more complex linear statistical models such as analysis of covariance models (i.e., models involving both continuous and categorical explanatory variables), as well as non-linear regression models.

Two major strengths of regression models as approaches that could be used for development of numeric criteria are that they are closely grounded in environmental data and, in the case of a single explanatory variable, easy to communicate, often by simple graphics (e.g., bi-variate plots). Accordingly, they can be easy to understand and less dependent upon assumptions and other analytical decisions made by investigators. Additionally, statistical methods for fitting regression models often permit estimation of limits of uncertainty for predictions, even for complex regression models (e.g., Hoos and McMahon 2009). Regression models require adequate data to develop. Additionally, other environmental variables that covary with explanatory variables of interest can introduce uncertainty in estimates of regression model parameters. It may be difficult to find highly predictive regression models for complex ecological systems that include many interacting factors that affect the dependent variable. This is especially true when important processes occur on different temporal and spatial scales. However, useful regression models do exist and have been applied successfully to quantify relationships among water quality indicator variables in estuaries. Examples of regression models that could be useful for development of numeric criteria include (1) models relating a "causal variable" such as TN or TP loading or concentration to a response variable such as chlorophyll *a* or dissolved oxygen, (2) models relating TN or TP loading to average concentration in estuarine waters, and (3) models quantifying relationships between other environmental variables.

3.3.3 Water Quality Simulation Models

Water quality simulation models can be used as tools for developing numeric criteria for estuaries. Specifically, hydrodynamic models coupled to water quality models can be used to simulate coupled physical, chemical, and biological processes in estuaries. Mechanistic or process-based watershed models can provide daily estimates of freshwater and nutrient loading to estuaries as inputs to hydrodynamic-water quality models. Such coupled models are widely accepted and have been previously utilized for water quality management purposes.

Although water quality models are fundamentally different from regression models, the conceptual approach to numeric nutrient criteria development can still be very similar. The water quality model can be used to determine TN and TP levels that would result in water quality conditions (e.g., average chlorophyll *a*, estuarine TN and TP concentrations, and dissolved oxygen) necessary to support balanced natural populations of aquatic flora and fauna. Criteria, including magnitude, frequency and duration, can be derived for the nutrient parameter simulated by the model that results in attainment of the quantitative endpoint.

The process for development of numeric criteria using water quality simulation models involves estimating the current conditions, characterizing natural conditions, and finally developing numeric criteria. Simulations of observed or “current” water quality conditions are necessary to calibrate the watershed and estuarine water quality models. Typically, data from one or more years is used to calibrate the water quality models, and data from one or more different years is used to evaluate the performance of the model. In the case when aquatic life uses are impaired under existing water quality conditions, “natural conditions” is developed to estimate the TN and TP loading rates and associated water quality responses that could be expected to occur in the absence of anthropogenic disturbance. To characterize natural conditions, the watershed model is run with all anthropogenic sources removed to determine the concentrations of nutrients, absent any human disturbance. This includes returning all land uses to a natural condition and removing any point sources of nitrogen and phosphorus. The resulting TN and TP loading rates are then utilized within the hydrodynamic water quality model to simulate the water quality expected to occur in the estuary if TN and TP loading were returned to background levels. Different numeric criteria are then evaluated to determine the highest loading rates that can occur while still maintaining water quality conditions that support the assessment endpoints previously identified. Because simulation models can provide spatially and temporally-resolved outputs, simulated water quality under compliance scenarios can be used to compute spatially-resolved (i.e., estuary segment-specific) estimates for criteria magnitude, frequency and duration.

3.3.3.1 Watershed Models

Some watershed models have been developed using either Hydrological Simulation Program—Fortran (HSPF) or Loading Simulation Program in C++ (LSPC). These models are nearly identical in terms of the algorithms used to simulate water flow and water quality, but differ in their software architecture. LSPC has been updated to relax certain computation limitations associated with HSPF, making it easier to apply it to larger watersheds. Aside from HSPF and LSPC, the Watershed Assessment Model (WAMView) has been previously used most often.

3.3.3.2 Hydrodynamic and Water Quality Models

Coupled hydrodynamic-water quality models using the Environmental Fluid Dynamics Code (EFDC) for hydrodynamics and the Water Quality Analysis Simulation Program (WASP) for water quality have been applied to many water quality management projects throughout the southeast United States. EFDC and WASP are both publicly available (http://www.epa.gov/athens/wwqtsc/).

3.3.3.2.1 EFDC

The EFDC model is an advanced, three-dimensional surface water modeling system for hydrodynamic and reactive transport simulations of rivers, lakes, reservoirs, wetland systems, estuaries, and the coastal ocean. The modeling system was originally developed at the Virginia Institute of Marine Science as part of a long-term research program to develop operational models for resource management applications in Virginia's estuarine and coastal waters (Hamrick 1992). EFDC is currently used by universities, governmental agencies, and engineering consultants. EFDC can be used to simulate hydrodynamics (i.e., three-dimensional advective transport and mixing) in Georgia's and South Carolina's estuaries.

3.3.3.2.2 WASP

The Water Quality Analysis Simulation Program (WASP) is an EPA-developed and supported water quality model that is routinely applied throughout the United States and worldwide to investigate water quality issues. WASP is a dynamic compartment-modeling program for aquatic systems. It can simulate processes in both the water column and underlying benthos. The time-varying processes of advection, dispersion, point and diffuse mass loading and boundary exchange are represented in the basic program. Water quality processes are represented in special kinetic subroutines that are either chosen from a library or written by the user. WASP is structured to permit easy substitution of kinetic subroutines into the overall package to form problem-specific models. WASP comes with two such models—TOXI for toxicants and EUTRO for conventional water quality. WASP is capable of simulating four classes of algae, each targeting a specific ecological "niche" defined by distinctive characteristics of the class and the role those characteristics play in ecosystem function. WASP is able to simulate sediment-water oxygen and nutrient exchanges by simulating sediment processes using a sediment diagenesis model. This approach entails substantial data requirements, as well as a need for adequate data to calibrate the model.

3.3.4 Evaluating Water Quality Simulation Models

Because simulation models are complex computational constructs with many parameters that must be specified, they require systematic and quantitative approaches to calibrate models, verify their performance against independent data, and evaluate uncertainty associated with model predictions. A variety of quantitative performance metrics have been proposed (e.g., Stow et al. 2009) and previously applied in regulatory environmental modeling (e.g., Wool et al. 2003).

Model calibration for watershed models proceeds from physical properties, to chemical properties and ultimately to biological properties and evaluation of specific model outputs that define the model endpoints or objectives. For example, the calibration sequence for LSPC watershed modeling begins with water balance and then proceeds to water temperature and finally water chemistry (e.g., TN and TP). The calibration sequence for EFDC/WASP begins with water levels, salinity, and water temperature (EFDC), and proceeds to water quality simulations within WASP, including nutrients, chlorophyll *a* and/or DO, which are modeling endpoints. Typical model evaluation procedures involve evaluating models across a range of temporal and spatial scales.

3.3.5 Numeric Criteria Development

This modeling framework can be applied to nutrient criteria development. Watershed models can be used to simulate daily freshwater and nutrient inputs to the estuary over multiple decades. Outputs from LSPC can then be used as inputs to the EFDC/WASP model. Hydrodynamic water quality estuary models can then simulate the effect of TN and TP loading on TN and TP concentrations, chlorophyll *a*, water clarity, and dissolved oxygen in the estuary. Estimates of current conditions could be used for model calibration and evaluation. Natural conditions would utilize LSPC to simulate loading rates, with natural variability in flows and load that would be expected in the absence of a significant anthropogenic contribution. If water quality targets cannot be met without reducing TN and/or TP loading to below the natural background, then TN, TP and chlorophyll criteria could be based on the characterization of natural conditions from LSPC. On the other hand, if water quality targets can be achieved, then nitrogen and phosphorus loading rates can be varied, ultimately developing a numeric value, which would simulate the highest nitrogen and phosphorus loading rates that could occur while maintaining water quality targets in the estuarine receiving water. Development of criteria for TN and TP loading, estuarine TN and TP concentrations, and chlorophyll *a* concentrations could then be based on the simulated water quality under these conditions. Using time series outputs from the model, there are a variety of approaches for expressing the criteria. For example, time series output could be evaluated in the same manner as data from a reference condition. Because the model output is highly spatially resolved, criteria could be developed for subsegments of the estuary by averaging outputs from model grid cells within the subsegment.

4 Prioritization of Estuarine Criteria Development

4.1 Prioritizing Locations

Prioritization of estuarine criteria development could begin with estuaries that have the largest available datasets to inform criteria development. These areas are typically in locations where large research facilities already exist including National Estuarine Research Reserves located at North Inlet-Winyah Bay (SC), ACE Basin (SC), and Sapelo Island (GA). In addition, large data sets also exist for highly researched and managed estuaries, such as the Savannah River.

4.2 Prioritizing Approaches

The reference condition approach could provide a useful line of evidence, and potential candidate nutrient criteria, for Georgia and South Carolina's estuaries. Spatial references (i.e. least impacted sampling sites) may be easier to identify in a region with relatively less coastal development (compared to some other regions in the region). Temporal references (i.e. historic data), could be available in areas with long term monitoring programs and research stations. Finally, mechanistic modelling of estuaries has already been undertaken in some locations, and these tools could potentially be leveraged to model nutrient loadings to waterbodies without the confounding factors of various anthropogenic land uses. Harmonizing datasets between states, research groups, and other sources could be a productive enterprise.

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