7. Recommendations

Continued monitoring of water quality in estuarine and coastal waters is vitally important to understand coastal processes, their relationships to important coastal resources, and the potential effects of development. The Indicators section contains our main recommendations for water quality indicators to be used in Georgia estuaries, but here we have collected and summarized all our recommendations including those for parameters to be measured, sampling strategy, quality control procedures, and studies that are needed to refine and localize the criteria proposed here. Data needed to improve the *Enterococcus* studies were also outlined in the sanitary survey reports (Sheldon 2009a-c).

Parameters

The measurement of a suite of parameters is required in order to characterize the multi-faceted concept that we describe as "water quality". Eutrophication problems and subsequent hypoxia may proceed through two pathways in Georgia, and indicator criteria were developed to address both pathways. We recommend that GA DNR CRD continue to measure dissolved oxygen (DO), pH, ancillary data (salinity, specific conductance, and water temperature), and nutrients, although we recommend changes to the nutrient monitoring protocols as described below. We also recommend the addition of three new parameters (chlorophyll *a*, 5-day BOD, and transparency) in order to monitor the progression of eutrophication symptoms through either the phytoplankton bloom or microbial respiration pathways.

Continue measuring DO, pH, and ancillary data

CRD now has a 10-year record of dissolved oxygen (DO) for the Georgia coast. It is critical that this continue, as DO is one of the key measurements of water quality, and the record to-date provides evidence that potentially problematic conditions have already occurred. pH is important in its own right (as pH outside normal boundaries can directly harm organisms) and can provide insight for interpreting other observations. Ancillary data (salinity, conductivity, and water temperature) are easy to collect and provide important information about habitat as well as required information for interpreting other parameters. All of these measurements should be continued at recommended sites on a regular basis.

Measure total nitrogen and total phosphorus using dissolved and particulate fractions

We recommend that CRD switch its nutrient protocols to measure both total dissolved (TDN and TDP) and particulate (PN and PP) material, and then use this information to calculate total nitrogen (TN = TDN + PN) and phosphorus (TP = TDP + PP). This approach accomplishes several things. First, it is dissolved nutrients that get taken up by phytoplankton and microbes, so information on TDN and TDP is probably the best indication of the potential drivers of eutrophication. Second, it allows for the estimation of TN and TP. These are listed as core parameters in the EPA guidance documents, and monitoring of these parameters is likely to be required in the near future. A third advantage to measuring TN and TP via their components is that it includes the direct estimation of PN and PP, which will be useful in Georgia where high and variable particulate N and P can greatly affect TN and TP measurements. A fourth advantage is that similar measurements (e.g. dissolved, total) of both N and P could be used to calculate N:P ratios, which would add to our understanding of nutrient limitation in Georgia estuaries and the roles of N and P in triggering eutrophication pathways. These measurements should be made at recommended sites on a regular basis.

Measure dissolved inorganic nitrogen and phosphorus at selected sites

We recommend measuring DIN (nitrate+nitrite, ammonium) and DIP (orthophosphate) at selected sites. This would provide direct information on the nutrients available to phytoplankton, and also allow the organic fractions to be determined by subtraction (DON = TDN – DIN, DOP = TDP – DIP). In our analysis we found that DIN dynamics can be complex because not all the components of DIN change in synchrony. If, in the future, only TDN (encompassing both DIN and DON) is measured, it may be difficult to deduce the causes of any TDN changes. Given the two potential pathways to eutrophication in coastal Georgia waters, decaying algal blooms and direct stimulation of microbial heterotrophy, information on the relative importance of organic and inorganic nutrients would provide the greatest understanding of eutrophication and its potential causes. We suggest doing these additional measurements at least quarterly at selected sites. Another approach would be to collect and store extra filtered water for each sample, and then determine the inorganic and organic fractions only if TDN and/or TDP are higher than the "good" level criteria.

Add chlorophyll **a** *as an indicator*

We strongly recommend adding chlorophyll *a* to the GA DNR CRD monitoring programs. Chlorophyll *a* is on the EPA list of core variables and may well be required in the future. It is also used in every national and regional survey of water quality that we examined. Chlorophyll is a critical response variable that can be use to evaluate whether algal biomass increases in response to nutrients. If a harmful algal bloom is suspected, additional sampling and analysis should be undertaken to identify the causal organism. These measurements should be made at recommended sites on a regular basis.

Add 5-day BOD as an indicator

We recommend that 5-day biochemical oxygen demand (BOD_5) be added as an indicator of the hypoxic potential of Georgia coastal waters. This will provide information on the potential for the microbial pathway of eutrophication. These measurements should be made at recommended sites on a regular basis.

Measure transparency instead of turbidity

The difficulty of comparing the GA DNR CRD turbidity data with other studies leads us to recommend that CRD switch to a measure of transparency, such as % light transmission or Secchi depth. Another reason for this recommendation is that the Nutrient Criteria Technical Guidance Manual for Estuarine and Coastal Marine Waters (U.S. EPA 2001b) specifically mentions water clarity as a required parameter, so it may well be required in the future. These measurements should be made at recommended sites on a regular basis.

Sampling Strategy

We reviewed the sampling strategy in terms of both the frequency and spatial coverage of the sites included in the different programs.

Collect samples monthly

CRD's strategy of monthly sampling allowed us to see a sequence of events (N, P rise followed by DO decline) that we would have missed with less frequent sampling, as the timescales of the processes that lead to hypoxia may be as short as days to weeks. In previous communications with CRD we recommended bimonthly sampling of nutrients during odd-numbered months as a bare minimum during the budget crisis, rather than eliminating sites or parameters. Sampling during the odd-numbered months gives the best chance of observing annual extreme events such as winter low temperatures, summer high temperatures, salinity extremes, low DO, and high nutrient conditions themselves (high N, high P), based on the monthly data. However, bimonthly sampling severely limits what can be gleaned from the data and leaves little room for error (we need to allow for the inevitable occasional missing sample or analytical error). 5-6 observations is barely enough data to estimate an annual median or mean; is insufficient for characterizing sub-annual variation; and may miss extreme events. The GA EPD 2010 305(b)/303(d) Listing Assessment Methodology states that the preferred minimum dataset for DO, pH, and water temperature is 12 samples per year. Therefore, we recommend at least monthly sampling of all parameters at all sites.

Continue River and Sound programs, and add sites in the lower Savannah and Satilla Rivers

The River and Sound monitoring programs together constitute a good selection of sites that spans the salinity range in riverine estuaries and also includes sites from more lagoonal estuaries less influenced by freshwater input. However, two major east coast rivers, the Savannah and Satilla rivers, have not been included in these programs. The lower Savannah River is heavily industrialized, and sampling there could prove informative if consistent water quality problems were to emerge in the smaller estuaries to the south (although these estuaries did not stand out as problematic in this study (see the Status section)). The Satilla River has approximately twice the flow rate of the St. Marys River, has a watershed contained entirely with the State, and represents the largest source of inputs to St. Andrew Sound, yet sampling there has been extremely limited. The Georgia Rivers LMER Program found the Satilla River estuary to be a valuable system for comparison with the Altamaha River estuary because of the close proximity and yet very different characteristics of the two. If the River program were to be expanded, we suggest that the Satilla River would be a valuable addition.

Continue monitoring at selected Shellfish sites

The Shellfish sites are, by definition, located in areas where shellfish occur in large enough numbers to sustain commercial and recreational fishing. Although only fecal coliform sampling is required by FDA regulations, CRD has measured other water quality parameters at these sites. Nutrients have been analyzed at 66 Shellfish sites, but these analyses were cut back due to funding constraints starting in 2003; by December 2006 nutrients were being measured at only 30 sites. We used Wilcoxon rank sum tests to compare parameter measurements at the 36 discontinued and 30 currently sampled Shellfish nutrient sites. There were no significant differences between the two groups for temperature, DO, NH_3, NO_2, TDP, and pH. We did find differences ($p<0.05$) in salinity, NO_3, PO_4, fecal coliform, and silicate, but all these differences between the medians of the two groups were at the level of the MDL or the recording precision for the parameter except for silicate. Even in this case, the small difference in silicate concentrations was due to a few outliers rather than a consistent difference. Therefore, we conclude that the Shellfish sites that are currently being monitored for nutrients do not differ from those that were discontinued. We did, however, find several instances where the relationships among parameters at Shellfish sites differed from those found at River and Sound sites (see the Correlations section), indicating that these are unique habitats that add to our understanding of water quality relationships and may require different management strategies from nearby Sound sites in order to maintain good water quality. We recommend continuing to monitor all the indicator parameters at selected Shellfish sites.

Continue monitoring at Beach sites

In addition to the requirement to monitor *Enterococcus* abundance at coastal beaches, CRD has measured salinity, specific conductance, temperature, dissolved oxygen (DO), pH, and turbidity at Beach sites. Our statistical analyses for sanitary survey reports of Tier 1 beaches (Sheldon 2009a-c) found that *Enterococcus* abundance may be influenced by freshwater input conditions at most sites and may be related to turbidity at some sites. Therefore, we recommend continued monitoring of salinity, specific conductance, temperature, and the new measure of transparency at all Beach sites to support similar analyses in the future. We found that pH and dissolved oxygen are not important explanatory variables for *Enterococcus* abundance but, as general water quality parameters, both scored fair to poor (as measured by annual minima) at some beach sites (see Section 6). This indicates that beach sites are not always flushed well enough by wave action to eliminate the threat of hypoxia. Hypoxic conditions were also documented in open waters of Long Bay, SC in 2004 (Sanger et al. in press). Therefore, we recommend monitoring all the indicator parameters at least at selected sites within each beach area. Selected sites should be those deemed to be the least well flushed, using prior dissolved oxygen (reported here) as a guide.

Continue with a fixed-site sampling approach

Probability-based stratified sampling designs (e.g. NCA, SCECAP) are designed to answer only very specifically targeted spatial questions (i.e. what percent of the state's total waters are good/fair/poor at the time of sampling?). We recommend letting NCA address that question and keeping Georgia's sampling programs focused on fixed-site sampling. We believe that the relevant questions in the near future are going to be primarily temporal in nature (i.e. are individual locations getting better/worse? Is climate change having a detectable impact?) These questions can best be addressed by minimizing spatial variability in the sampling and focusing on the sources of temporal variation in water quality. Only by having relatively high-frequency (temporal) sampling will we be able to distinguish long-term signals (e.g. climate, sea level rise) from natural variability at shorter time scales.

Monitor over the long-term

There is a lot of value in a long-term data set. In this study we found many correlations between salinity and other parameters, suggesting that variability in freshwater delivery to the coastal zone may be one important driver of water quality. However, we simply need more years of data in order to be able to detect long-term trends of this type in the presence of sub-annual, annual, and interannual variability due to seasonality and climatological cycles. Sheldon and Burd (unpubl.) have found seasonal links between two large-scale climate signals, the Bermuda High Index and the El Niño/Southern Oscillation, and Altamaha River discharge, but we would need a dataset the length of several ENSO cycles (3-5 years each) to even begin to address whether such linkages exist between climate variability and coastal water quality. We recommend that monitoring continue so that we can evaluate long-term changes.

Quality Control

Through our analyses, we found several inconsistencies among measured parameters and brought them to CRD's attention. We also have several suggestions regarding transitioning between labs or protocols.

Review protocols as necessary

In the report we noted the poor correlation between salinity and specific conductance, and orthophosphate values that were higher than total dissolved phosphorus values. We recommend that protocols be examined and modified to correct these problems. Disagreements between the reported salinity and a salinity value calculated from the reported specific conductance that are larger than 0.1-0.4 PSU must be due to factors other than reporting precision. Procedures should be checked to see if the instrumentation is reporting incorrect values or if transcription errors might be to blame. Errors in the beach data appear to be larger than those in other programs, and there is an annual cycle in the mismatch that may indicate a problem with temperature compensation in some of the instruments. We also identified a potential explanation for the high orthophosphate relative to TDP concentrations, but CRD must determine which procedure is in error.

Log instrument use to aid quality control

The poor correlation between salinity and specific conductance, as noted above, points to potential problems with field instrument calibration. In addition, individual bad data values were identified and removed from the database based on extreme values; however, we cannot know how many errors may have gone undetected because their values were within the expected range. It would help to be able to identify individual instruments and sensors that may not have been operating properly during a sampling event, so that all questionable values can be flagged for examination. Therefore, we recommend that CRD record which instrument is used at each station and provide this information for future updates to the database.

Institute consistent procedures for missing or non-detectable data

Another problem that we identified was the use of potentially valid data values (e.g. 0, 1) in CRD's records to indicate missing data. This practice adversely affects data analysis and can lead to erroneous conclusions. We recommend that CRD develop new data entry procedures to incorporate information on missing data and non-detects so that these values may be clearly separated from measured values. The use of the MDL or similar fixed values to represent data below a detection limit is potentially less serious but should also be avoided in the future. We would have preferred to have the actual measured values and accounted for the MDL using statistical procedures. Mixed use of the MDL and the actual measured value in the database is an inconsistent practice that should be discontinued.

Ensure data continuity when protocols are altered or analytical labs are changed

The types of procedural changes that occur in long-running programs, such as changes in processing laboratories or methodology, can make it difficult to evaluate long-term trends. In this report we identified two changes in processing laboratories (fecal coliform methods and *Enterococcus* processing laboratories) that hampered our ability to analyze the data. In order to ensure comparability of data before and after such transitions, we recommend that any change in methods or laboratories include a period of overlap during which samples are processed by both the old and new protocols. The number of samples that should overlap partly depends on the system dynamics during the transition. One strategy is to use the correlations among parameters to guide the sampling plan to ensure that both low and high concentrations are processed by both labs or protocols. For example, a parameter that is related to salinity (and hence freshwater inflow) should be compared under both low and high freshwater inflow conditions. This may necessitate overlapping protocols for several months to a year, at least for selected sites, in order to establish good relationships between newer and older data. This is particularly important if the nutrient parameters are altered (as we have proposed) and/or different processing labs are used.

Compare turbidity with light transmission

In keeping with the above recommendation, if CRD switches from turbidity measurements to one of light transmission (as we have suggested), then we recommend that they continue to measure nephelometric turbidity along with the new method at all sites for at least several months. This would allow the establishment of statistically significant correlations that are relevant for Georgia coastal waters (e.g. see Smith et al. 2006). It would then be possible to relate the turbidity data already in hand to clarity criteria established for other methods. If the cost of light meters is prohibitive, then we suggest borrowing one for a period of time for comparison with Secchi depths and establishment of site-specific relationships between the two.

Studies Needed

We have several recommendations regarding studies that are needed in order to make better use of the data in hand and to transition to the new recommended indicator parameters. We identified several knowledge gaps that limited our ability to set indicator criteria, as well as investigations that would improve our understanding of the potentially unique pathways of eutrophication in southeast U.S. coastal waters.

Develop improved criteria for pH

The pH criteria that we recommended are based on deviations from established normal pH/salinity relationships using literature surveys of the pH change tolerances of major taxonomic groups. These criteria could be improved in two ways. First, reference waters of each estuarine type should be identified, making sure that the locations chosen are not influenced by effluents. These reference sites should span the range of salinity to ensure that the pH/salinity relationships can be established with statistical confidence. Second, the effects of pH and changes in pH on estuarine organisms should be investigated in greater detail. We do not know if effects reported in the literature for major taxonomic groups apply to most of the species found in Georgia coastal waters.

Examine the effects of low DO on native fauna

The dissolved oxygen criteria could also be improved through investigation of the susceptibility of species in Georgia coastal waters to deleterious effects in the presence of low DO. There is extensive examination of hypoxia effects in the literature (Vaquer-Sunyer and Duarte 2008), and the criteria chosen here are fairly robust across major taxonomic groups, but they could be improved with more localized information.

Collect data necessary to evaluate causal relationships for eutrophication

Ideally, nutrient criteria should be based on relationships between concentrations of nutrients (N,P) and subsequent effects on chlorophyll, BOD, and DO. At this point, however, we lack a good understanding of the various steps by which eutrophication occurs. Nutrient inputs themselves are not well quantified, nor do we understand the relationships between inputs and concentrations, the relative importance of the two pathways of eutrophication (microbial vs. phytoplankton), and the timeframe for observed effects. Once we have more data in hand, a more complex model of these parameters is warranted. One question we need to address is whether the scale of sampling (monthly-bimonthly) is missing important dynamics and obscuring short-term relationships. A limited period of higher-frequency sampling at selected sites may help to address this. Another question is whether the weak relationships we found between nutrients and DO nearly a year later persist in a longer dataset. If so, this implies that processes that operate at temporal scales much longer than the flushing times of the estuaries are important. Focused studies of marsh-estuary interactions at multi-year timescales should help to address the potential causes of any such long-term relationships. The sources of nutrients to Georgia coastal waters is also an important question regarding the management of eutrophication and potential hypoxia, and modeling efforts to link nutrient loads to in-estuary concentrations are needed.

Investigate nitrite dynamics in Georgia coastal waters

Although nitrite is usually a minor component of the nitrogen pool, some of the relationships that we found suggest that nitrite dynamics in Georgia estuaries may be different from what is observed in most other places. This study and others (e.g. Jahnke et al. 2003) found nitrite peaks in mid-salinity waters in Georgia estuaries. This is counter to the usual pattern found in estuaries where a nitrite maximum, if one exists, is usually in lower salinity water (Morris et al. 1985; Uncles et al. 1998; Iriarte et al. 1998). Furthermore, low salinity waters generally have increased diversity of ammonia-oxidizing bacteria (which produce nitrite) (Bernhard et al. 2005), but this has not been evaluated in Georgia estuaries. There is also a slight elevation in nitrite at low pH in the low-salinity zones of blackwater estuaries, which suggests that at least part of the difference in nitrite dynamics observed in Georgia may be due to differences in estuaries fed by blackwater vs. neutral-pH streams. This warrants further investigation as it may provide insights into nitrogen cycling that will allow us to develop a better understanding of water quality.

Compare BOD_5 with BOD_{20} as an indication of the relative availability of organic matter

BOD_5 is listed in the U.S. EPA's (2001b) suggested methods and is what we recommend here for comparison with other programs. However, as described in the Indicators section, we also encourage a focused study comparing BOD_5 with BOD_{20} (a 20-day analysis) to ascertain the relative importance of labile and refractory components of the BOD in Georgia estuaries. Given the observed importance of BOD in coastal blackwater streams (Mallin et al. 2004), we suggest that this study should address differences in BOD_5 and BOD_{20} in the three estuary types that we identified for pH criteria: blackwater, alkaline blackwater, and alluvial and tidewater estuaries. This information would be useful for developing a more complete understanding of eutrophication in Georgia waters, as management approaches may differ depending on the relative availability of the organic matter in the system.