4. Correlations among Parameters

In order to discern relationships among parameters that could be useful in understanding coastal processes and developing meaningful indicators for Georgia estuaries, we investigated the correlations among all parameters measured by CRD. We first looked for correlations that existed across all sites, as these would be the most useful for understanding coastwide processes and would be generally applicable for decision-making. Next, we evaluated the data to see whether there were differences in the relationships at different site types (e.g. Shellfish vs. River/Sound sites).

The results in this section are divided into two parts: the first discusses correlations that we expect to find due to the known physical relationships among some of the parameters. Departures from these expected relationships can help to diagnose potential instrumentation and methodological problems or to indicate when biological processes may be changing concentrations from what would be expected based on strictly physical or chemical processes. The second part is a broader exploration of relationships among parameters that can be used to describe coastwide patterns and to indicate where further investigation of ecological processes may be warranted.

Methods

Relationships among most parameters were examined using linear regression. Although the frequency distributions of some of the parameters approximated the normal distribution (dissolved oxygen; salinity, specific conductance, and pH (slight skew)) or the uniform distribution (temperature) and therefore could be analyzed without further manipulation, many parameter distributions were skewed to some degree (all nutrients, turbidity, fecal coliforms, and *Enterococcus*). No transformations were needed in cases where similarly distributed variables were compared. However, when highly skewed parameters (e.g. fecal coliforms) were compared to parameters with less skew, we used a natural log transform to normalize the skewed parameter prior to linear regression analysis. Analyses involving *Enterococcus* required nonparametric statistical procedures because of the extreme skewness in many of the variables examined. Details are given in the section relating *Enterococcus* to other parameters.

Expected Correlations between Related Parameters

Salinity and Specific Conductance

Salinity is calculated from conductivity and temperature; therefore, the relationship between salinity and specific conductance (conductivity normalized to 25 °C) should be well defined. While there was general agreement between the parameters at most stations, many large mismatches were observed, with frequent differences of up to 5 PSU and occasional differences as high as 10-20 between the reported salinity and a salinity value calculated from the reported specific conductance (Figures 4-1, 4-2). These differences are far larger than what might be expected based on the reporting precision of the data. Beginning 3/14/2000, salinity was generally recorded to 0.1 precision and specific conductance was usually recorded to 0.1 mS cm^{-1} precision, which could result in a

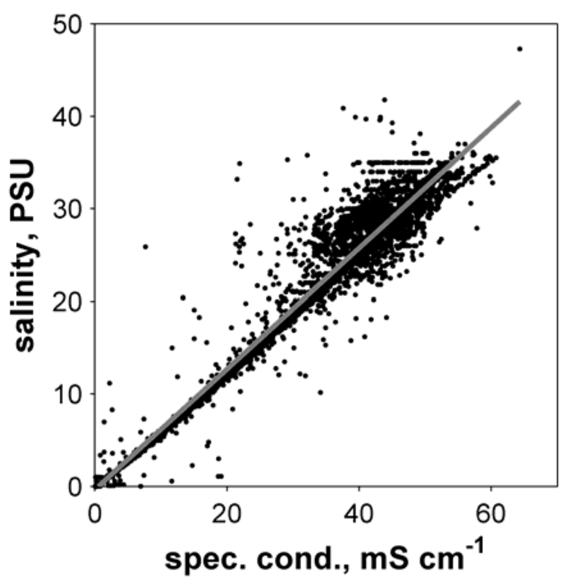

Figure 4-1. Relationship between salinity and specific conductance at all stations when both parameters were sampled. Gray line represents best linear fit.

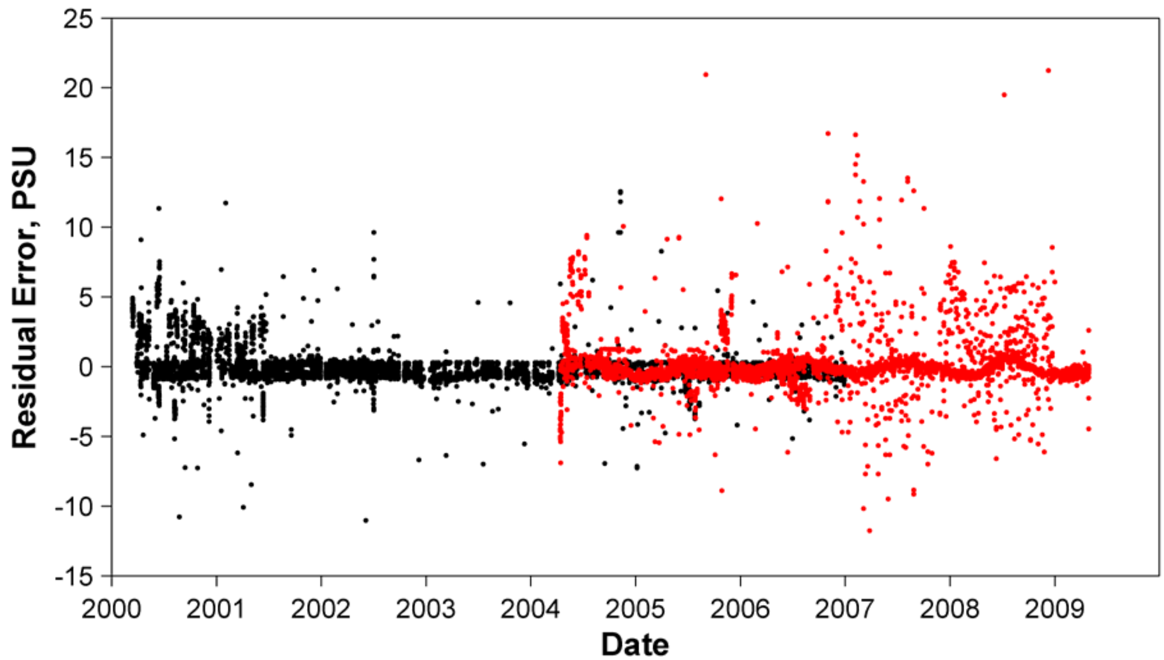

Figure 4-2. Residual error in the relationship between salinity and specific conductance. Black points are Shellfish, River, and Sound stations; red points are Beach stations.

potential error of approximately 0.08 PSU. The recording precision of specific conductance was occasionally better (0.01-0.0001) or worse (whole numbers) than this, leading to a potential error of approximately 0.4 PSU in cases where conductance is reported as whole numbers. Disagreements between the parameters that are larger than 0.1-0.4 PSU must be due to factors other than reporting precision. We suggest that CRD check their protocols to see if the instrumentation is reporting incorrect values or if transcription errors might be to blame. When the errors are plotted over time (Figure 4-2), one can see that they were generally worse in 2000 and the first half of 2001, but large differences persist in later data as well, particularly in the beach data. There is also an annual cycle in the mismatch that may indicate a problem with temperature compensation in some of the instruments.

Total Dissolved Phosphorus and Orthophosphate

Orthophosphate (PO_4) is a component of total dissolved phosphorus (TDP): orthophosphate levels should therefore be lower than TDP, by definition. Instead, we found that 25% of the samples had PO_4 >TDP (Figure 4-3). This indicates that there is an analytical problem in one or both methods, and that some of the reported concentrations must be in error. Neal et al. (2000) found problems with some common hot

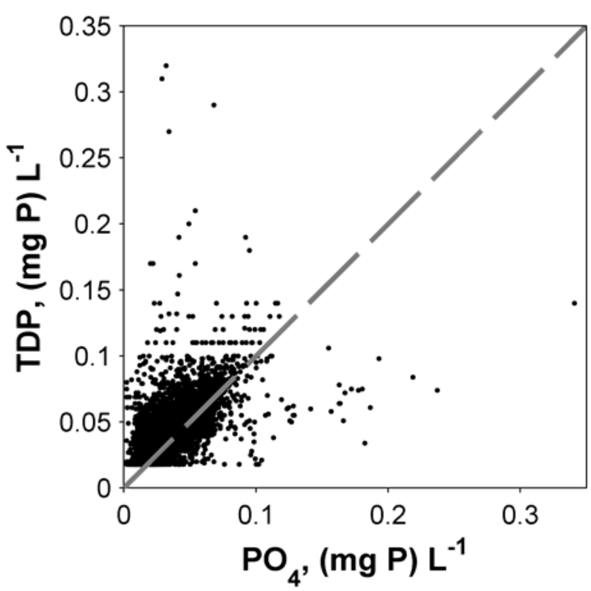

Figure 4-3. Relationship between total dissolved phosphorus and orthophosphate at all stations when both parameters were sampled. Gray dashed line represents a 1:1 relationship: all dots should be above this line. 8 outliers not shown.

temperature PO_4 methods that resulted in apparent PO_4 concentrations about twice the level found by other methods. If PO_4 is measured by a hot method and TDP is measured on the same sample by an ambient temperature PO_4 method (after digestion), apparent PO_4 concentrations are frequently higher than TDP. We need more details on the methods that are being used to measure PO_4 and TDP on the CRD samples, but if the methods exhibit the problems described by Neal et al. then actual PO_4 concentrations may be only half of what was reported. If we cut reported PO_4 values by half then PO_4 concentrations would be greater than TDP in less than 2% of the samples. This observation needs to be followed up so we can have reliable phosphorus data in the future.

pH and Salinity

pH is expected to have a relationship with salinity, as the increasing buffer capacity along the length of an estuary changes the usually lower and more variable pH of freshwater to the higher and more stable pH of seawater. Our situation in Georgia is unique in that we have at least three different types of estuarine systems with respect to expected pH characteristics. As in other southeastern states, some Georgia estuaries are fed by blackwater streams that originate in the Coastal Plain, with clear but dark-colored water stained by humic substances. The humic substances also cause the pH of these streams to be much lower (by about 2 units) than most other freshwater streams. In the GA DNR CRD dataset, blackwater systems are represented by sites in the Satilla River, St. Andrew Sound, St. Marys River, and Cumberland Sound. There are two other types of estuaries in Georgia with respect to pH. The Ogeechee River, which flows into Ossabaw Sound, is also a blackwater stream but it represents a special case because it receives a large input of carbonate-rich water from a limestone spring, so its pH is higher than that of most other blackwater streams (Meyer et al. 1997). We refer to this system as the sole representative of an "alkaline blackwater" type. All other sites in this study appear to fall into a single group with similar pH-salinity relationships, even though these are a diverse group of sites including estuaries fed by alluvial streams and tidewaters with little freshwater input. We refer to these as "alluvial and tidewater" systems.

We evaluated the relationship between pH and salinity for all three of the Georgia estuary types. The relationships were non-linear, at least for the blackwater and alkaline blackwater systems (Figure 4-4). Since pH is on a $\log_{10}$ scale, we log-transformed the salinity values ($\log_{10}$(salinity+1) to avoid taking the log of 0) and found that this effectively linearizes the relationship even though it oversimplifies the chemical relationship between pH and salinity. Thus, we have equations that relate pH and salinity for each estuary type (Figure 4-5). This correspondence helps to explain the correlations of many other parameters with pH. We only note (below) when correlations with pH are opposite the correlations with salinity.

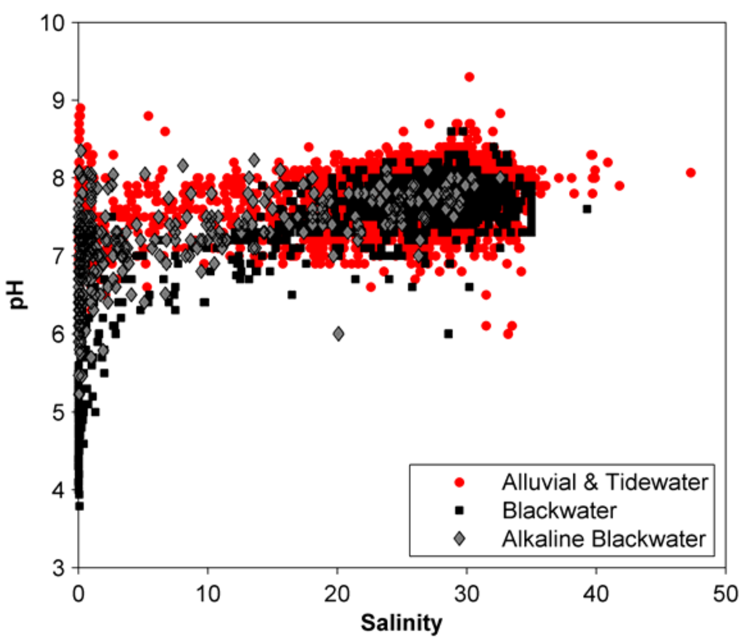

Figure 4-4. pH vs. salinity collected at all sites and times by GA DNR CRD. The relationship is different for estuaries fed by blackwater streams than it is for most other coastal locations (tidewaters and estuaries fed by alluvial streams.) Alkaline blackwater streams (i.e. the Ogeechee River) represent a special, intermediate case.

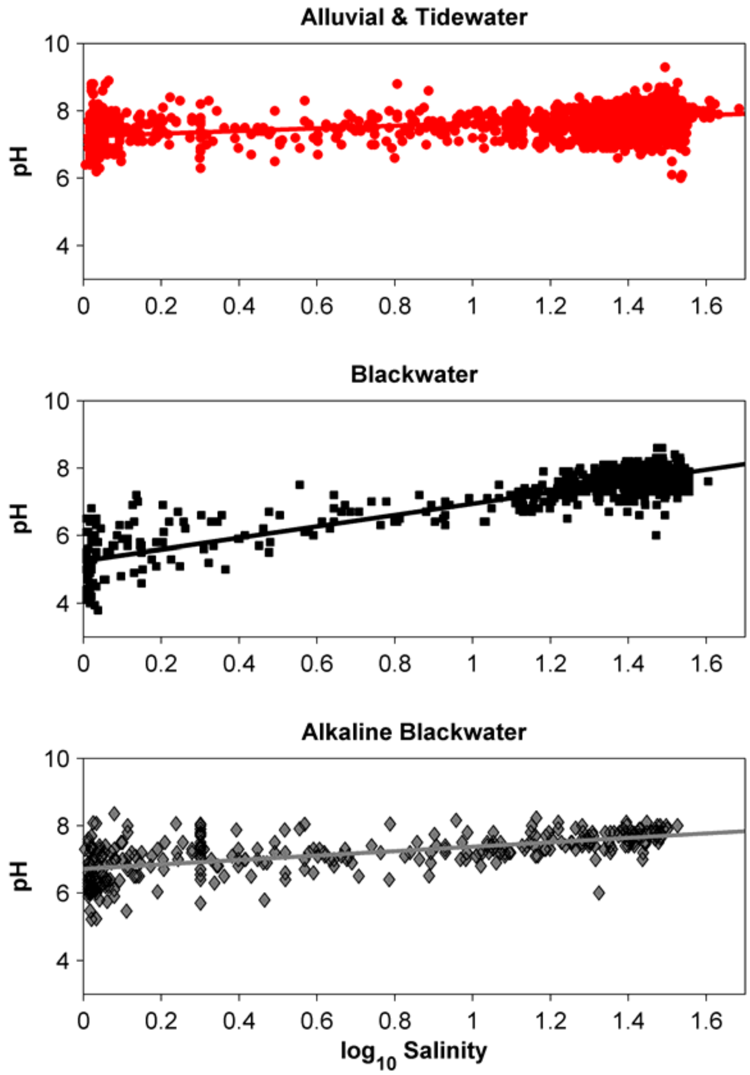

Figure 4-5. Relationships between pH and $\log_{10}$(salinity+1) for sites in alluvial and tidewater, blackwater, and alkaline blackwater-fed estuaries. Least-squares linear regression lines reflect "normal" pH as defined in this study.

Dissolved Oxygen, Temperature, and Salinity

The solubility of dissolved oxygen (DO) varies in a predictable way in response to changes in temperature, pressure and salinity. Percent saturation compares the measured DO with what it would be if DO were saturated under the same physical conditions. Changes that deviate from this expected concentration may be attributed to biological or chemical processes, including photosynthesis and respiration. We calculated oxygen saturation levels (Sea-Bird Electronics 2002) and compared measured dissolved oxygen to these saturation values (Figure 4-6). It is clear from the deviation of points from the 1:1 line in the figure that DO levels are rarely at their saturation point. At most stations DO is well below saturation, but in some cases oxygen is supersaturated. A large proportion of the most undersaturated observations were at River sites, indicating that other processes are reducing oxygen levels. Most of the supersaturated observations were at Beach sites, as might be expected from the entrainment of air in breaking waves in these areas, but some Shellfish and Sound observations and a few River observations were also supersaturated. We next compared the % oxygen saturation with both salinity and temperature to see if there were relationships beyond those already accounted for in the calculation of % saturation. DO % saturation showed a slight but significant increase with salinity at all site types (Figure 4-7). In contrast, DO % saturation showed a significant decrease with increasing temperature, although Beach stations tended to be closer to saturation than other types of sites at any given temperature (Figure 4-8). A decline in % saturation at warmer temperatures may be attributable to increased biological activity. We explore other factors that may influence the dissolved oxygen concentrations below.

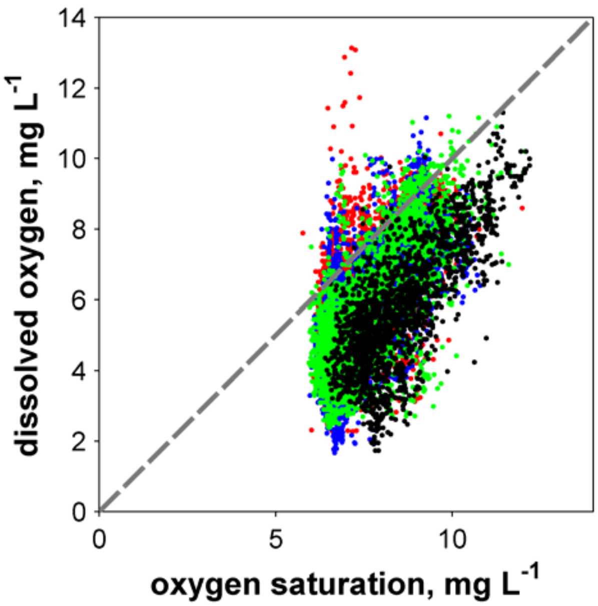

Figure 4-6. Relationship between dissolved oxygen and its saturation level based on temperature and salinity at all stations when all parameters were sampled. Colors are: red, Beach; blue, Shellfish; green, Sound; and black, River sites. Gray dashed line represents a 1:1 relationship.

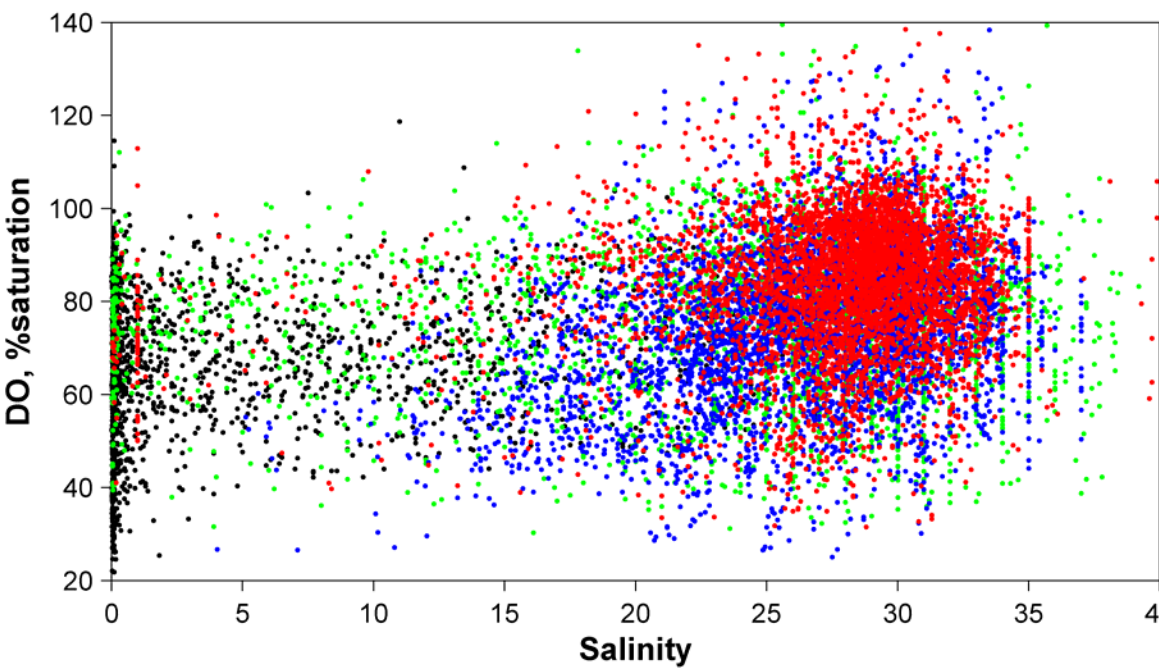

Figure 4-7. Relationship between dissolved oxygen (percent saturation) and salinity. Colors are: red, Beach; blue, Shellfish; green, Sound; and black, River sites. 23 outliers not shown.

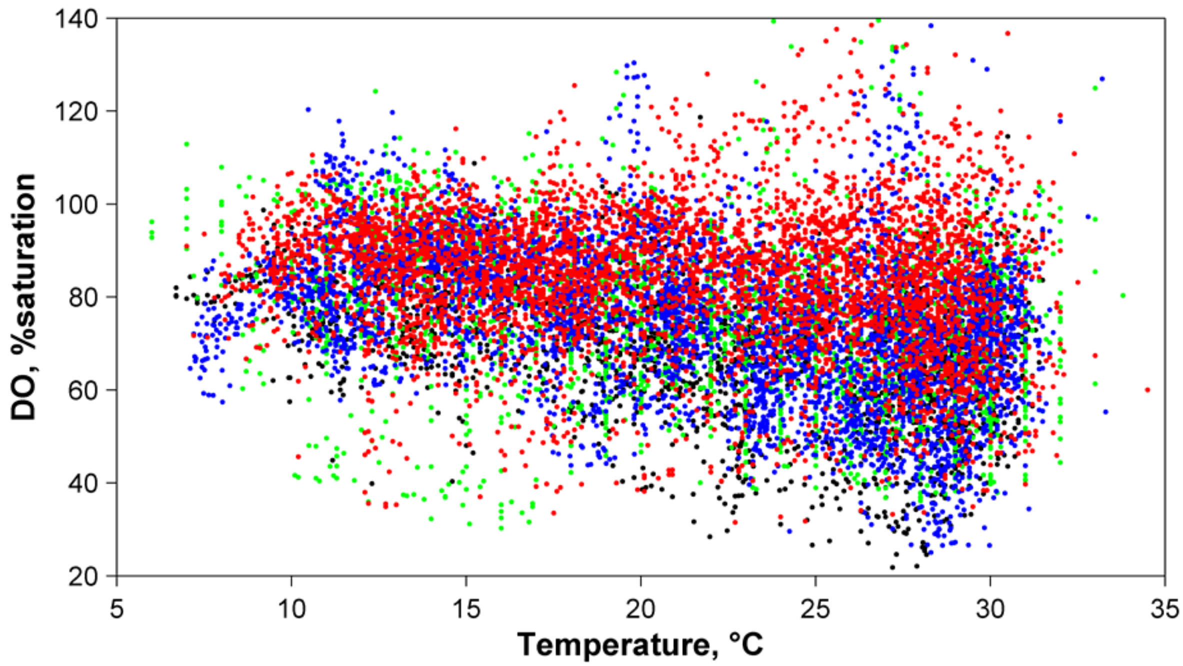

Figure 4-8. Relationship between dissolved oxygen (percent saturation) and temperature. Colors are: red, Beach; blue, Shellfish; green, Sound; and black, River sites. 19 outliers not shown.

Correlations among Other Parameters

Temperature and Salinity

The seasonality observed in both temperature (Figure 3-2) and salinity (Figure 3-5) is an expected consequence of the normal seasonal variations in weather. Therefore, it is not surprising that observations of these two parameters are correlated (Figure 4-9), with higher salinities during the hottest summers (due to evaporation and less rain) and lower salinities during cooler (and rainier) times. The seasonalities in these two important physical parameters as well as the correlation between them must be kept in mind when interpreting patterns in other parameters (below); trends associated with salinity and temperature may indicate an inherent seasonality in a parameter, but they may also confound evaluations of the potential causes of observed relationships.

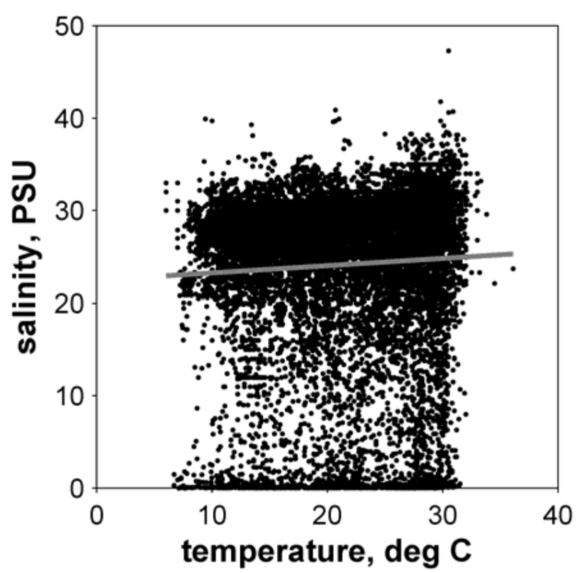

Figure 4-9. Relationship between salinity and temperature at all stations when both parameters were sampled. Gray line represents best linear fit.

Silicate, Salinity, and Temperature

Silicate concentrations may vary significantly in different freshwater sources, in which case they can be useful for determining the sources of water to a given location. We first evaluated silicate concentrations in samples collected in low-salinity waters flowing into the sounds to determine whether there were identifiable differences in source waters. Only four sounds in the CRD data

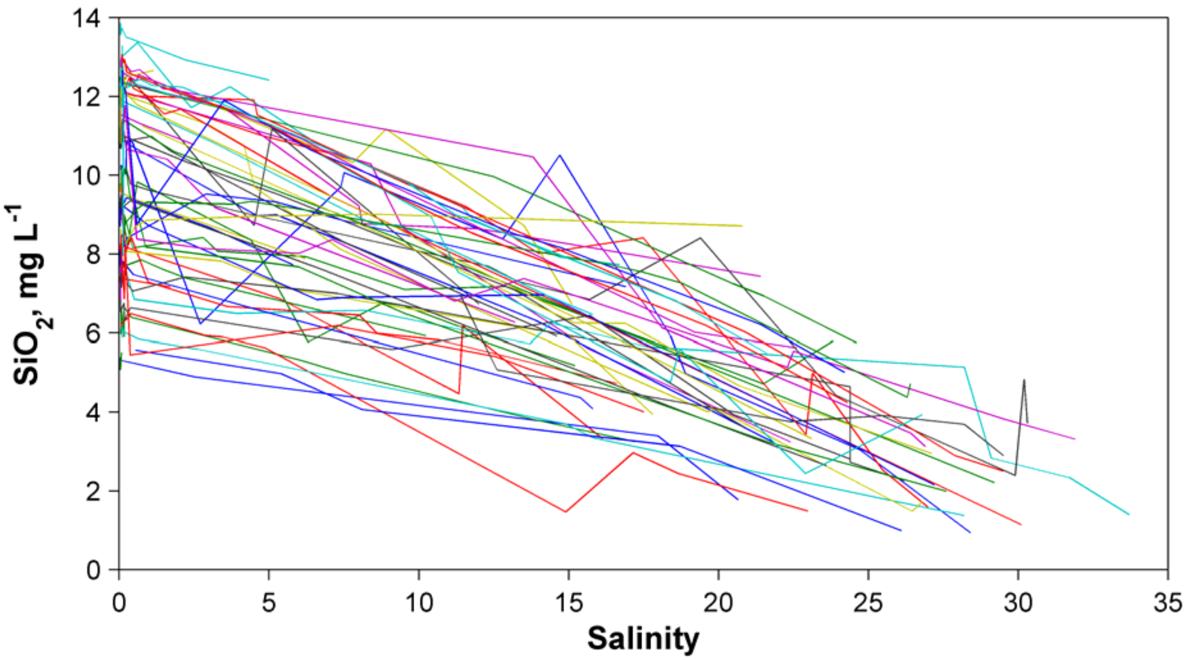

Figure 4-10. Paired silicate and salinity observations in the Altamaha River estuary. Lines represent different sampling transects, each on a different day.

set had silicate observations at upstream sites when salinity was less than 0.1 (Ossabaw, Doboy, Altamaha, and Cumberland), and these concentrations were not consistently different.

We next evaluated the relationships between silicate concentrations and salinity. This allows us to determine whether silicate that is entering with freshwater is being diluted with seawater through simple mixing (in which case we would expect a linear relationship between silicate and salinity, called

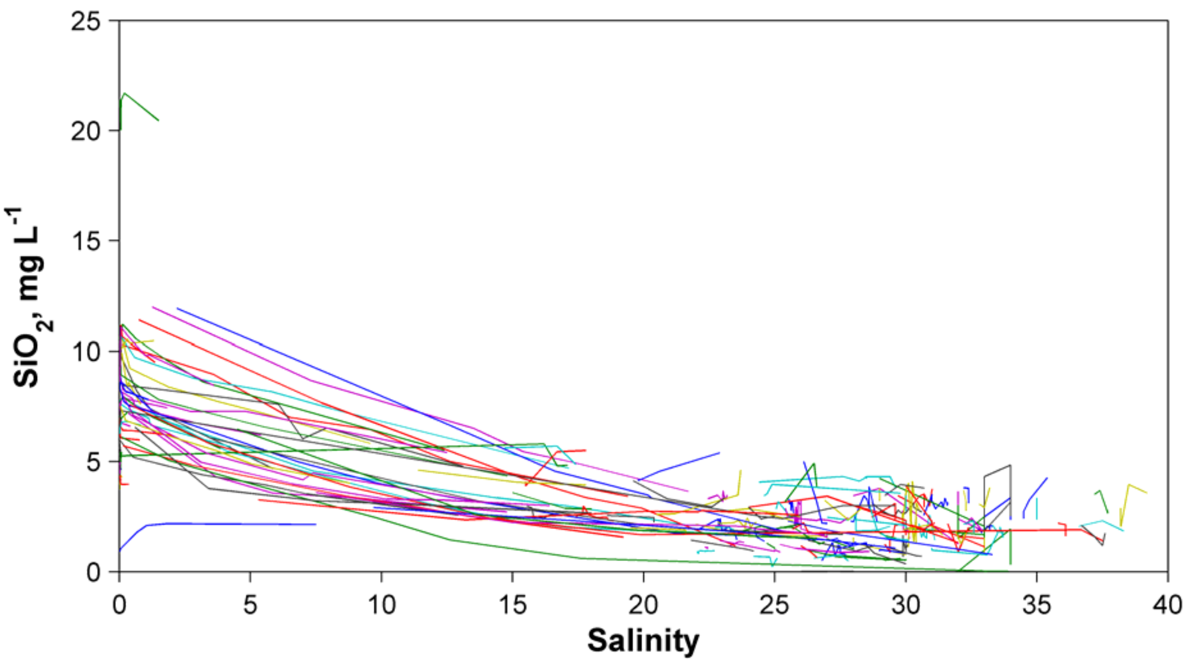

Figure 4-11. Paired silicate and salinity observations in the St. Marys River/Cumberland Sound. Lines represent different sampling transects, each on a different day.

"conservative" mixing) or is being consumed or added (in which cases we would expect concentrations below or above the simple mixing line, respectively; this is called "nonconservative" mixing). Deviations from the expected conservative mixing line are therefore useful in identifying areas of potential consumption of silicate (e.g. uptake by diatoms) or input (e.g. lateral inputs of water). Although all the sounds had a tendency for decreasing silicate with increasing salinity, this relationship was less apparent and more variable in sounds with few low-salinity observations (Wassaw, St. Catherines, Sapelo, and St. Andrew). In sounds with stronger correlations and/or frequent low-salinity observations (Ossabaw, Doboy, Altamaha, St. Simons, and Cumberland), silicate concentrations varied over time at the head of the estuary as well as along the salinity gradient. The sounds exhibited different mixing patterns. The Altamaha River estuary is an example of generally conservative mixing (Figure 4-10): on any given day silicate concentrations tended to decrease linearly with increasing salinity (although individual sites sometimes deviated from the overall decreasing trend). Cumberland Sound (Figure 4-11) is the only sound that showed consistently curved silicate/salinity relationships (below the mixing line), indicating possible uptake of silicate along the estuary. Ossabaw Sound varied between conservative and apparently non-conservative mixing. These differences may be due to differences in the transit times of these systems, which vary from several days in the Altamaha estuary to a few weeks in the Ogeechee/Ossabaw estuary to 1-2 months in the St. Marys/Cumberland estuary (Alber and Sheldon 1999). It may be that mixing is conservative at faster transit times, while slower transit times allow for more uptake.

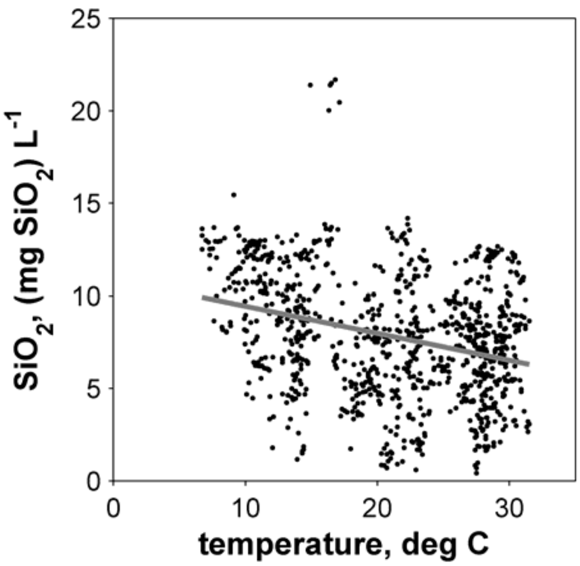

Figure 4-12. Relationship between dissolved silicates and temperature at River sites. Gray line represents best linear fit.

We also evaluated the relationship between silicates and temperature and found that there were differences among programs. River sites showed decreasing silicate concentrations with increasing temperature (Figure 4-12). However, this relationship is potentially confounded by salinity, given that increased temperature also indicates increased salinity (Figure 4-9). When we performed a stepwise regression we found that salinity was indeed the better predictor of silicate concentration, but temperature explained some additional variability In contrast, Shellfish sites showed decreased silicate concentrations at decreased temperatures (Figure 4-13). We postulate this may be explained by increased uptake of silicate in winter by benthic diatoms, especially those associated with oyster reefs (Thoresen and Alber, submitted). Although Sound sites also showed decreasing silicate concentrations with decreasing temperatures (Figure 4-14), the scatter in the relationship suggests that some sites may actually be following the River pattern and others the Shellfish pattern.

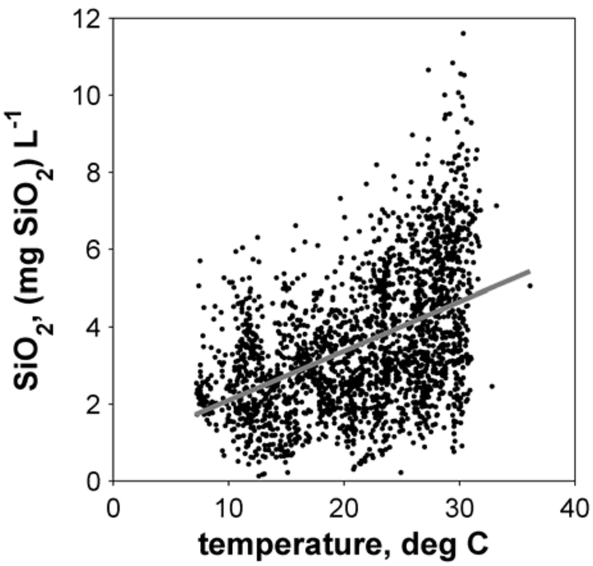

Figure 4-13. Relationship between dissolved silicates and temperature at Shellfish sites. Gray line represents best linear fit.

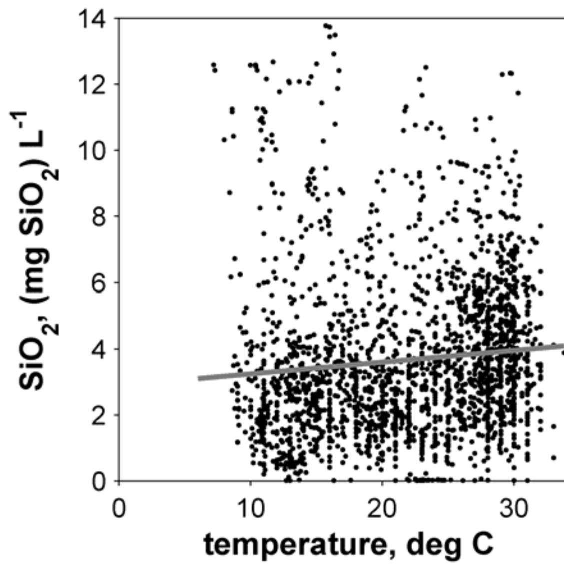

Figure 4-14. Relationship between dissolved silicates and temperature at Sound sites. Gray line represents best linear fit.

DIN Components

We performed an analysis of the individual components of the DIN pool (ammonia, nitrite, and nitrate) to determine whether they are varying in unison, which would indicate that their concentrations are driven by similar factors. When data from all sites were pooled we did not find any significant relationships among concurrent measurements of these parameters. There were, however, some significant relationships when evaluations were done by program: River sites show a slight negative relationship between NO_2 and NO_3, and Shellfish sites show a slight positive relationship between NH_3 and NO_3; however, these relationships are weak (r^2<0.06) and dependent on extreme values (not shown). The overall lack of correspondence among these parameters suggests that the components of the DIN pool are being produced, interconverted, or consumed by independent processes rather than a balanced delivery of all components through one process such as streamflow.

DIN Components, Salinity, and Temperature

We also evaluated the relationships between salinity, temperature and each component of DIN for potential insights into the sources and processes that may be affecting them. In all cases we looked at all site types combined as well as individual programs. Ammonia concentrations were not significantly related to salinity, which suggests that high ammonia is not associated with certain types of sites or streamflow conditions. However, they were positively related to temperature (Figure 4-15), which suggests there

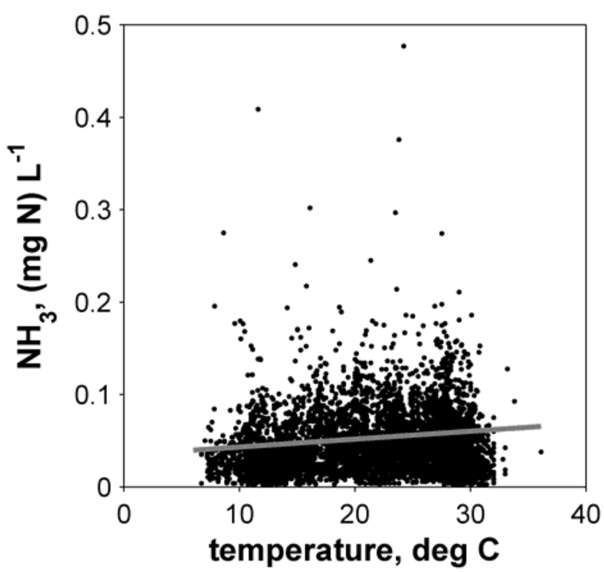

Figure 4-15. Relationship between ammonia and temperature at all stations when both parameters were sampled. Gray line represents best linear fit. 17 outliers not shown.

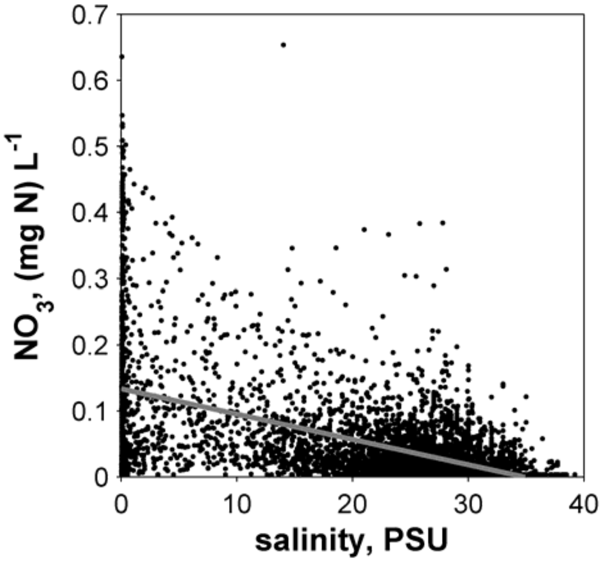

Figure 4-16. Relationship between nitrate and salinity at all stations when both parameters were sampled. Gray line represents best linear fit. 3 outliers not shown.

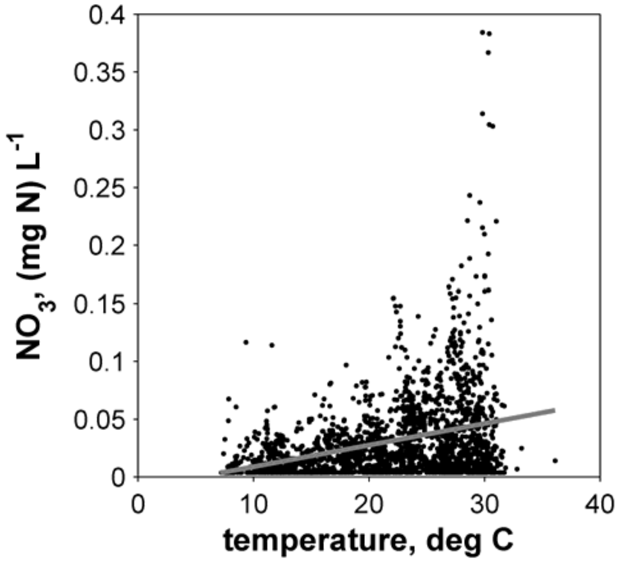

Figure 4-17. Relationship between nitrate and temperature at Shellfish stations. Gray line represents best linear fit. 1 outlier not shown.

may be a relationship between ammonia production and biological and/or chemical processes that are enhanced at warmer temperatures. Nitrate concentrations decreased significantly with increased salinity, highlighting that rivers and runoff are the major sources of nitrate to the coastal waters (Figure 4-16). Nitrate concentrations showed a significant increasing relationship with temperature, but only at Shellfish sites (Figure 4-17). The fact that this trend is opposite in sign from the salinity relationship indicates that this is not due to the correlation between salinity and temperature and instead reflects an independent relationship between nitrate concentration and temperature. The observation that nitrate concentrations are lower at low temperatures is consistent with the notion, suggested above, that benthic diatom production results in decreased silicate concentrations at shellfish sites during winter (Figure 4-13). If benthic diatom production is important during winter (Thoresen and Alber, submitted), it would result in decreases in both silicate and nitrate.

Nitrite concentrations have a non-linear relationship with salinity, with a peak in mid-salinity waters (between10 and 30 PSU) (Figure 4-18). A mid-salinity peak in nitrite concentration was also observed in the Satilla River estuary in 1998 (Jahnke et al. 2003). 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, studies have shown that the diversity of ammonia-oxidizing bacteria in estuaries often decreases with increasing salinity (Bernhard et al. 2005). This suggests that patterns of nitrogen dynamics in Georgia estuaries may be different from what is observed in most other places. If this is the case it would be an important topic for further research. Finally, there is an increasing relationship between nitrite and temperature (Figure 4-19). Although this could be confounded with the salinity relationship, the sharp increase in nitrite concentrations above 20 °C coupled with nitrite's role as an intermediary in both nitrification and denitrification suggest that this may be a real temperature effect on nitrite production within the estuary. Substrate availability does not seem to explain this pattern, because both ammonia and nitrate are present at lower temperatures.

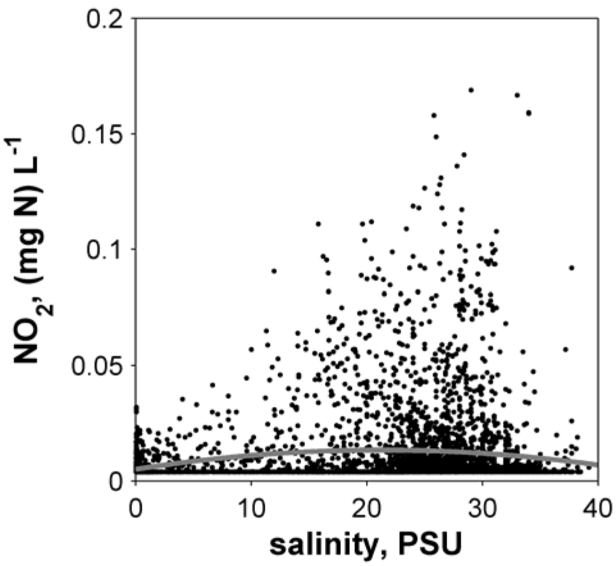

Figure 4-18. Relationship between nitrite and salinity at all stations when both parameters were sampled. Gray line represents best quadratic fit. 10 outliers not shown.

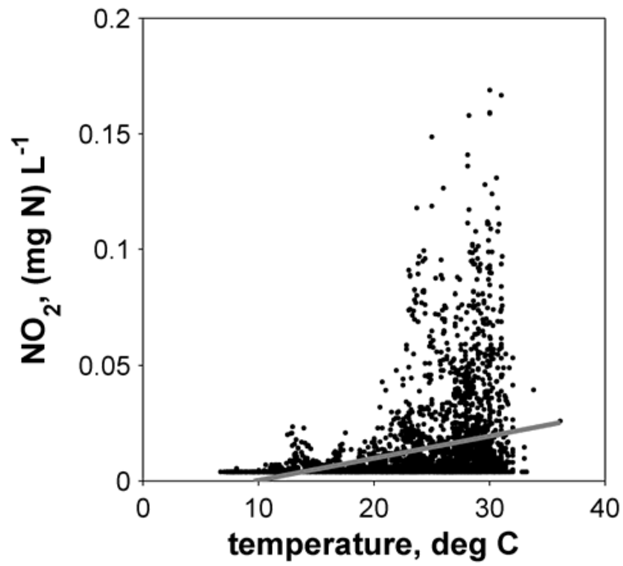

Figure 4-19. Relationship between nitrite and temperature at all stations when both parameters were sampled. Gray line represents best linear fit. 9 outliers not shown.

Phosphorus, Salinity, and Temperature

There are significant increasing relationships between phosphorus and both salinity and temperature, indicating potentially confounding effects. We used stepwise regression to determine if salinity or temperature was the better explanatory variable. In the case of orthophosphate, both variables were about equally useful (Figures 4-20, 4-21). When broken down by program, salinity was a slightly better predictor for River sites while temperature was slightly better for Sound and Shellfish sites, probably

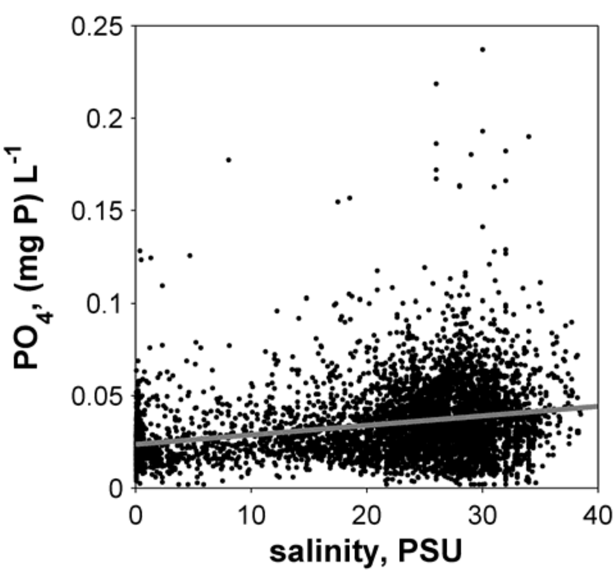

Figure 4-20. Relationship between orthophosphate and salinity at all stations when both parameters were sampled. Gray line represents best linear fit. 6 outliers not shown.

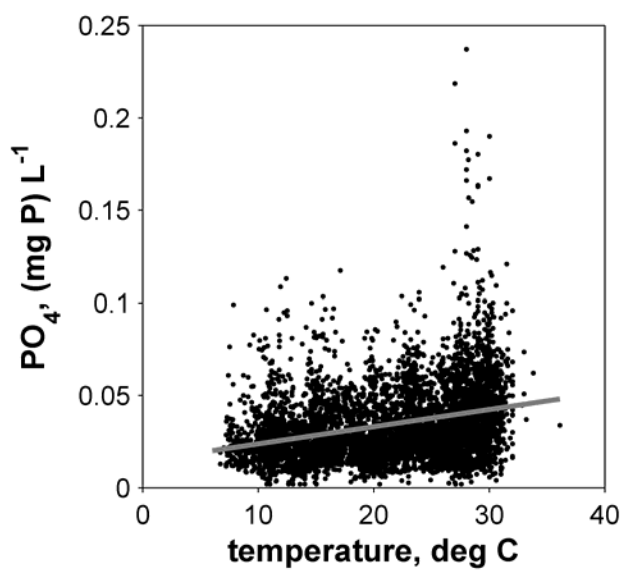

Figure 4-21. Relationship between orthophosphate and temperature at all stations when both parameters were sampled. Gray line represents best linear fit. 4 outliers not shown.

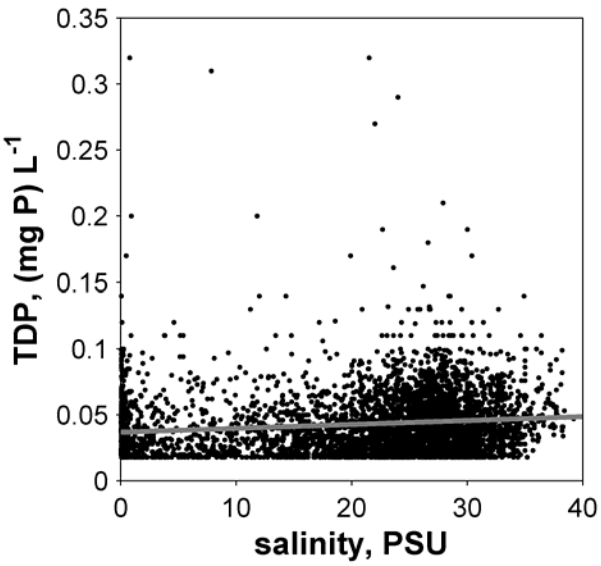

Figure 4-22. Relationship between total dissolved phosphorus and salinity at all stations when both parameters were sampled. Gray line represents best linear fit. 7 outliers not shown.

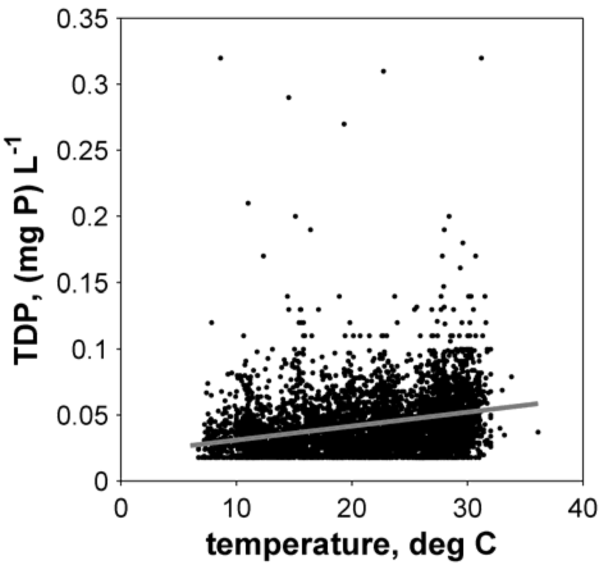

Figure 4-23. Relationship between total dissolved phosphorus and temperature at all stations when both parameters were sampled. Gray line represents best linear fit. 6 outliers not shown.

reflecting the parameter with the greater variability in each case. The orthophosphate/salinity relationship for all pooled sites (Figure 4-20) is virtually the same when broken down according to program. In the case of TDP, temperature was a better predictor for all pooled sites (Figure 4-23) and individual program groups, with salinity helping to explain additional variability only for Shellfish sites. The TDP/salinity relationship (Figure 4-22), is driven by higher concentrations occasionally found at Shellfish sites; River and Sound sites have more uniform concentrations below 0.1 mg P L^{-1} most of the time. The methodological problems in phosphorus measurements need to be resolved, but these different patterns may indicate differences in sources or dynamics of orthophosphate and organic phosphorus compounds.

DIN, Phosphorus, and Silicates

There were few notable correlations among concurrent measurements of nitrogen, phosphorus, and silicates. Ammonia showed no correlations with any other nutrient. Silicates correlated only with nitrate (Figure 4-24), which reflects the fact that freshwater is the primary source for both. Nitrate and nitrite were both positively correlated with orthophosphate and TDP. Relationships with TDP are shown as examples (nitrate, Figure 4-25; nitrite, Figure 4-26). The relationships are weak, driven mainly by the tendency for low concentrations of both nitrogen and phosphorus to co-occur. Phosphorus concentrations are still quite modest when inorganic nitrogen concentrations are high. Of perhaps more interest is the tendency

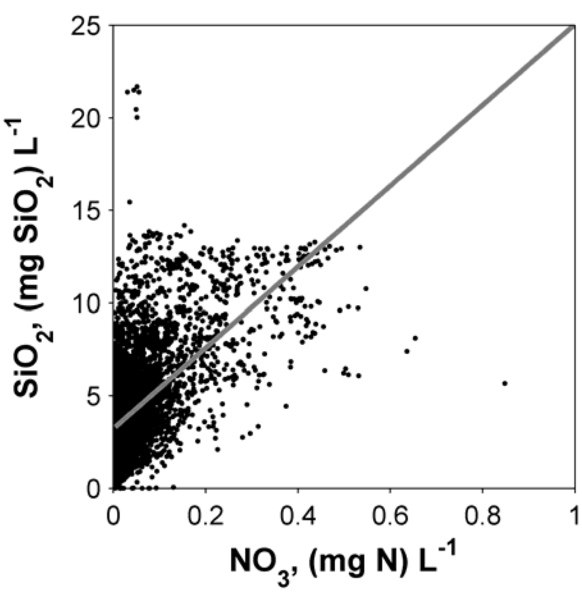

Figure 4-24. Relationship between dissolved silicates and nitrate at all stations when both parameters were sampled. Gray line represents best linear fit.

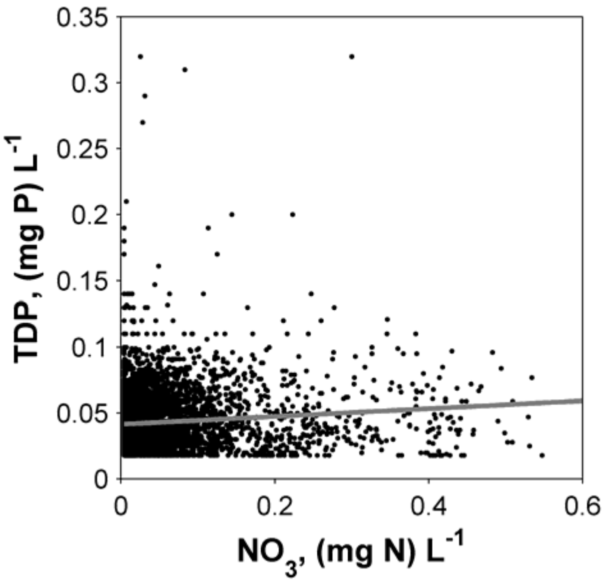

Figure 4-25. Relationship between total dissolved phosphorus and nitrate at all stations when both parameters were sampled. Gray line represents best linear fit. 7 outliers not shown.

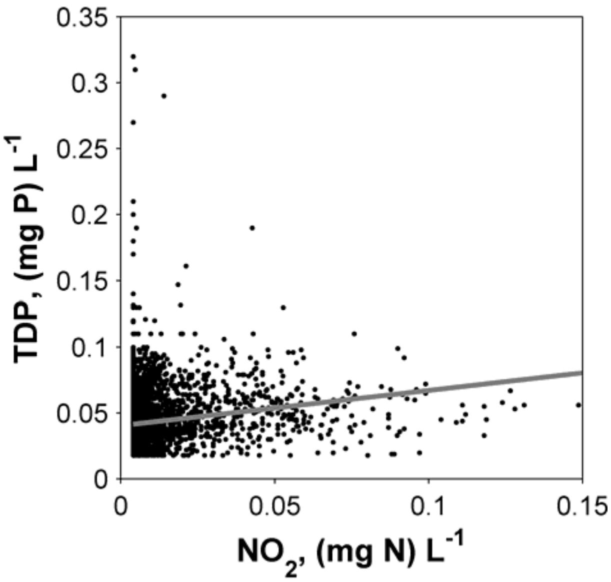

Figure 4-26. Relationship between total dissolved phosphorus and nitrite at all stations when both parameters were sampled. Gray line represents best linear fit. 6 outliers not shown.

for the highest phosphorus concentrations to occur when nitrogen concentrations are low: this may indicate nitrogen limitation of the phytoplankton or microbial community. We were unable to explore N:P ratios in any meaningful way, however, because of the methodological problems in phosphorus measurements and the lack of total dissolved nitrogen (TDN) observations to pair with TDP.

Low pH and Other Parameters

For most parameters, correlations with pH are either nonexistent or follow the same trend as the parameter/salinity relationship (which is not surprising given the relationships between pH and salinity). Three pH relationships are notable, however, for their differences from the salinity relationships. Dissolved oxygen is positively correlated with pH (Figure 4-27), whereas the DO/salinity relationship was very weak (Figure 4-7). Nitrate has a negative correlation with salinity (Figure 4-16) but a positive correlation with pH (Figure 4-28). Nitrite was generally higher when salinity>10 and that is still reflected in highest nitrite values at pH>7, but there is a slight elevation in nitrite at low pH as well (Figure 4-29). In all three cases, the trend with pH is due to samples with pH<6. These are upstream samples in blackwater streams, where DO and NO_3 tend to be lower than in freshwater with near-neutral pH. The slight elevation of NO_2 in these same samples indicates a difference in N dynamics in blackwater vs. neutral-pH streams that is not apparent from the salinity relationships shown above.

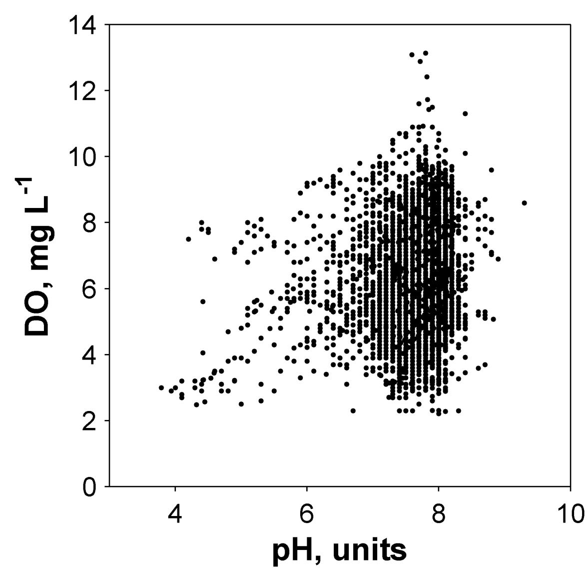

Figure 4-27. Relationship between dissolved oxygen and pH at all stations when both parameters were sampled.

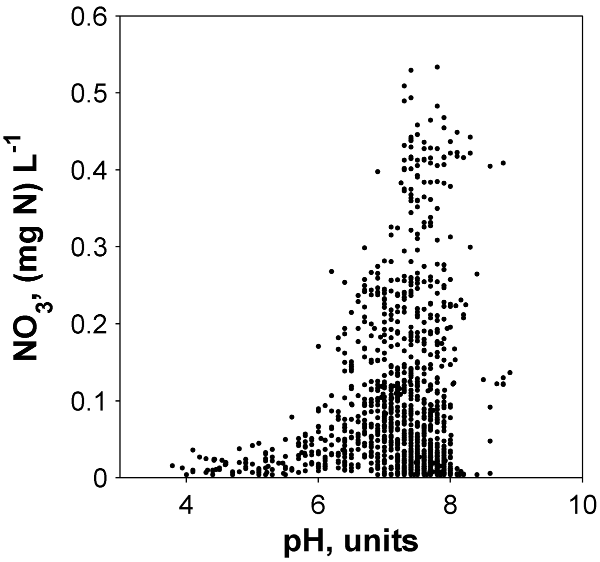

Figure 4-28. Relationship between nitrate and pH at all stations when both parameters were sampled. 2 outliers not shown.

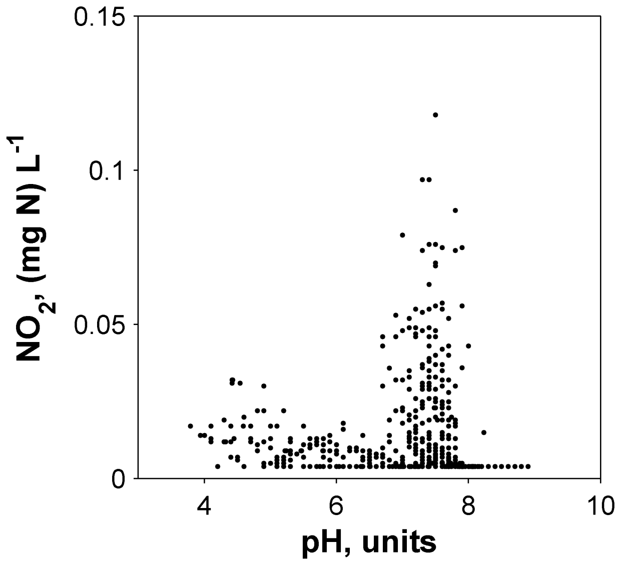

Figure 4-29. Relationship between nitrite and pH at all stations when both parameters were sampled.

Dissolved Oxygen and Nutrients

The relationship between nutrients and dissolved oxygen (DO) is dynamic: nutrient uptake or release and DO production or consumption are affected by the progression of growth and decay and the balance of photosynthesis and respiration in the system. Sampling at different times in the progression of uptake, growth, and decay may find nutrients and DO in various ratios during this dynamic process. For example, a negative relationship may be the result of nutrient uptake by phytoplankton and the production of DO

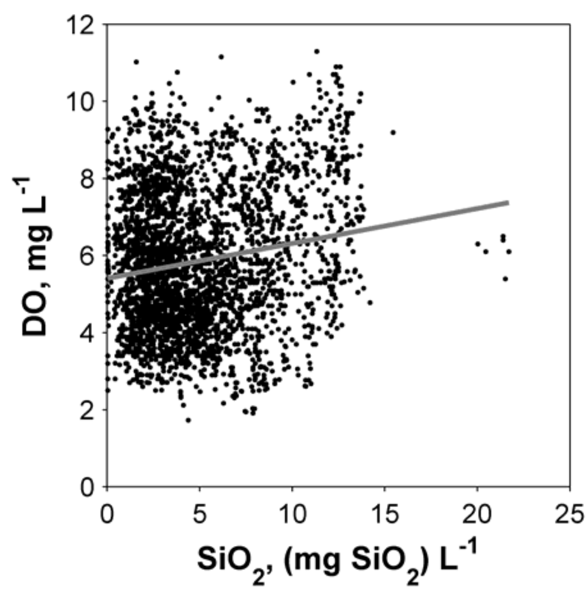

Figure 4-30. Relationship between dissolved oxygen and silicates at River and Sound stations. Gray line represents best linear fit.

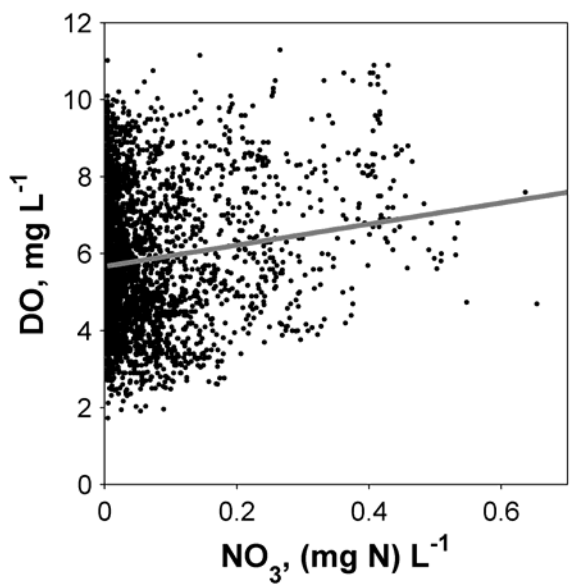

Figure 4-31. Relationship between dissolved oxygen and nitrate at River and Sound stations. Gray line represents best linear fit. 1 outlier not shown.

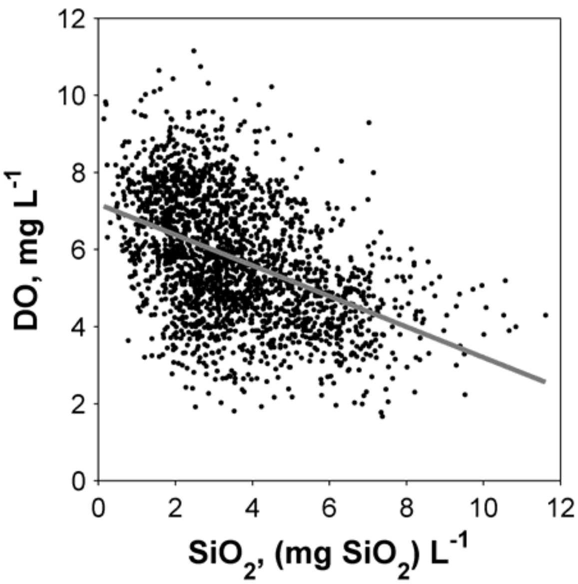

Figure 4-32. Relationship between dissolved oxygen and silicates at Shellfish stations. Gray line represents best linear fit.

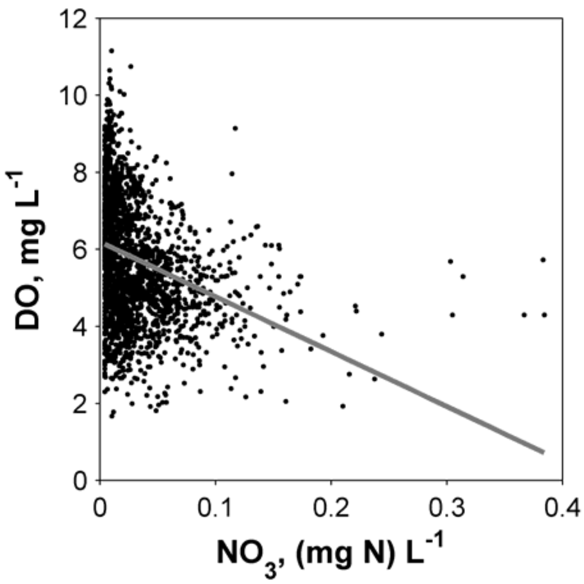

Figure 4-33. Relationship between dissolved oxygen and nitrate at Shellfish stations. Gray line represents best linear fit.

by photosynthesis. However, if the phytoplankton bloom is followed by microbial degradation then nutrients may remain low while DO is consumed, resulting in a positive relationship. Relationships between DO and nutrients can therefore be difficult to interpret because they can change over time.

We first explored the relationships among concurrent measurements of nutrients and DO. Silicates and nitrate show similar patterns, with positive relationships at River and Sound sites (Figures 4-30, 4-31) and strongly negative relationships at Shellfish sites (Figures 4-32, 4-33). The positive relationships at River and Sound sites are driven primarily by Altamaha River sites, which tend to have higher nitrate and silicate concentrations and slightly higher DO than other River and Sound sites. The higher DO concentrations in the Shellfish sites correspond to low temperature (winter) stations, where silicates (Figure 4-13) and nitrates (Figure 4-17) tend to be lower. This could be an indication of benthic diatom production at these sites, as speculated above; enhanced production would lead to an increase in DO as a result of photosynthesis. Nitrite was negatively related to DO at all types of sites (Figure 4-34). Although the linear fit is poor, it is clear that DO is low at all stations when nitrite is elevated. As indicated above, nitrite concentrations increase with temperature (Figure 4-19), so the decrease in DO may be an indication of increased biological activity at these stations (although this may be independent of nitrite per se). No consistent relationships are evident between DO and TDP, orthophosphate, or ammonia.

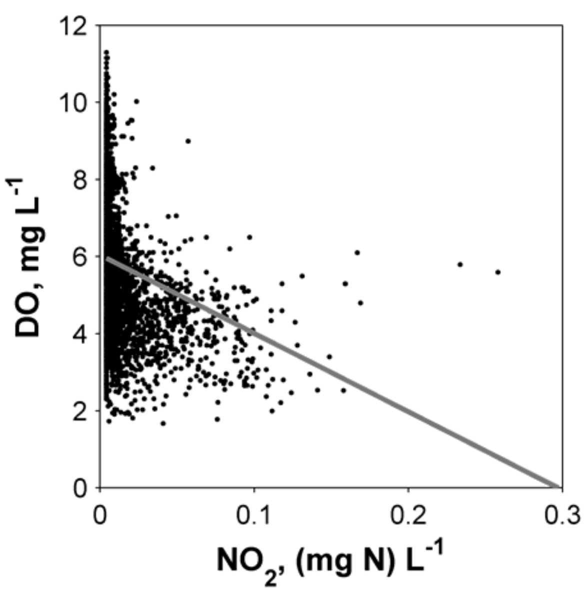

Figure 4-34. Relationship between dissolved oxygen and nitrite at all stations. Gray line represents best linear fit. 4 outliers not shown.

The relationships shown above suggest that both very low and very high DO concentrations can be found when nutrients are at their lowest levels, but this analysis did not allow for the time lags that would be expected during the processes of uptake, growth, and decay. We therefore undertook a special study of 76 River, Sound, and Shellfish sites with consistent sampling timeframes to try to determine the cause of the exceptionally low DO in 2003 and to generally explain the time series of DO during the study period. The sites chosen for this analysis had observations of DO, salinity, and temperature beginning in March 2000 and nutrients beginning in 2001-2002 and continuing through December 2006; span the Georgia coast (Figure 4-35, compare with Figure 2-1); and do not appear to behave differently than sites that were omitted from the analysis. Figure 3-10 showed that dissolved oxygen varied in unison, with temporal variation being more pronounced than spatial variation, and Figure 3-11 showed that this variation was not entirely due to seasonal changes in oxygen solubility. Oxygen concentration data are repeated in Figure 4-36 with observations from the 76 chosen sites highlighted in green to show that they represent the coastwide DO variation.

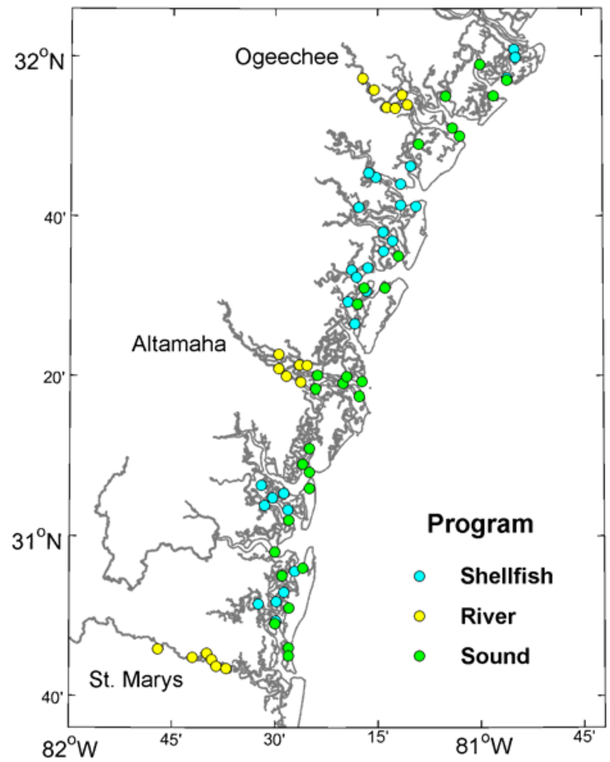

Figure 4-35. 76 sites in the CRD database that were used for the DO study.

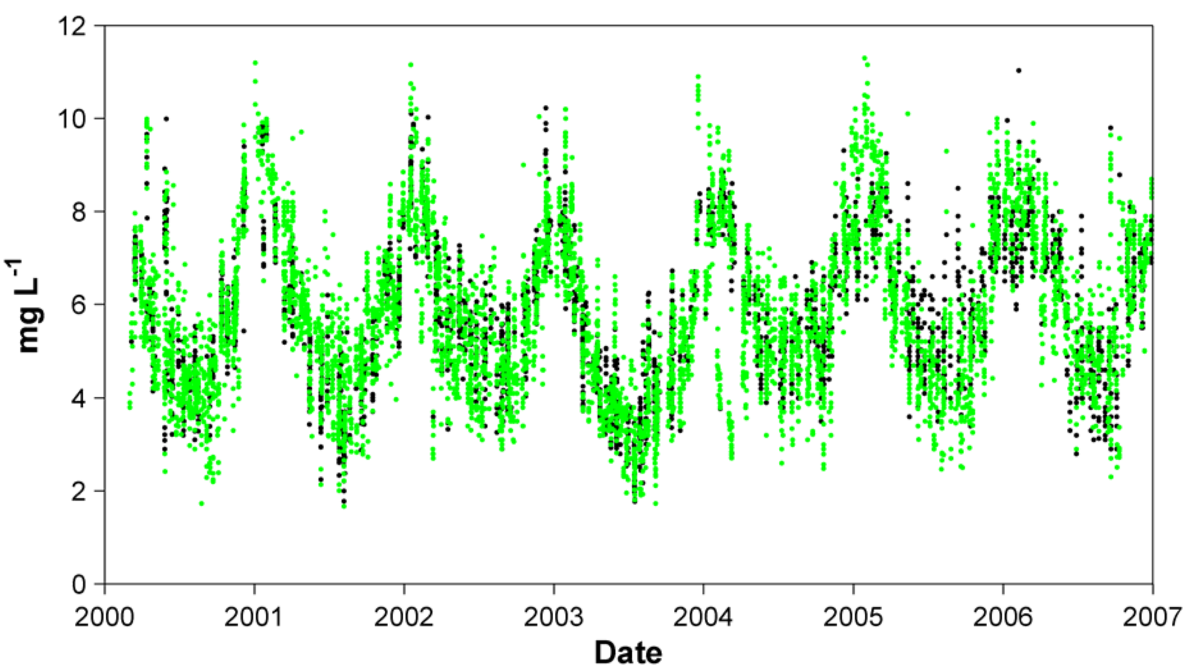

Figure 4-36. Dissolved oxygen concentration at Shellfish, River, and Sound sites, 2000-2006, with observations from the 76 sites for the DO study highlighted in green.

We set out to determine whether we could construct a reasonable scenario of uptake, production, and decay to explain the observed patterns of DO concentration at these sites. As has already been shown, salinity patterns reflected the greater freshwater input in 2003 and, to a lesser extent, 2005 (Figure 3-5). We also found that nitrate concentrations correlate with salinity (Figure 4-16) and tend to be highest at River sites (Figure 3-53). Thus our working hypothesis was that higher nutrient loads, delivered by increased runoff and streamflow in early 2003, could have stimulated phytoplankton and microbial activity coastwide and resulted in higher than normal respiration and subsequently lower than normal summer DO.

As noted earlier, sampling frequencies were not regular enough to permit most types of time series analysis. This affected this study as well, since we could not impose a given time lag (e.g. 30 days) and expect that most observations would have a corresponding earlier observation. Since most observations were collected on a monthly basis, we converted the dataset into a quasi-monthly timeframe by considering each data point as representative of the month it was collected. When more than one observation was available for a given site in a month, we took the median of the available observations. This choice affected very little of the data: of 6232 potential month x site combinations for each parameter (82 months x 76 sites), 625 entries (10%) had no observations and were left as NaN; only 12 entries had 3 observations; 376 entries (6%) had 2 observations; and the remaining 5219 (84%) had just one observation. The large number of cases with only one observation per month limited this study to seasonal-scale processes because only lags of whole months could be considered. This temporal resolution is not guaranteed to coincide with the timeframes of the processes that would affect nutrient and DO concentrations.

In 2003, the lowest salinity in March-April preceded the lowest DO in July by 3-4 months. We therefore explored the salinity and dissolved oxygen observations to see if applying such a time lag would result in a significant relationship between these parameters. Although individual lags of 3-5 months can align low salinity with low DO in each year, no one lag time results in a significant correlation over the whole time range of the data. When we compared the annual minimum DO at each site with minimum salinity for that year, thus avoiding shifts in the time lag, only 4 of the 76 sites showed significant correlations over the study period. (These were all Shellfish sites: 4092 in Sapelo Sound and 3319, 3255, and 3291 in St. Catherines Sound.) We therefore conclude that, even though there are cases where low DO episodes do follow times of lower salinities (and hence increased freshwater inflow) by a few months, there is not evidence for a broad relationship between them.

The above analysis indicates that decreased DO is not well-related to the input of nutrients via freshwater. However, if nutrients are entering the water from other sources (e.g. intertidal areas or the bottom) then it is possible that low DO is still the result of increased respiration stimulated by nutrient input. Indeed, the observed minimum in DO in 2003 was preceded by elevated concentrations of both nitrogen and phosphorus (NH_3, NO_3, PO_4, and TDP were all higher than was observed in later years (Figures 3-17, 3-21, 3-25, 3-27)). We investigated the relative timing of high concentrations of each of these nutrients and subsequent decreases in DO. NO_3, which might be expected to be the best predictor of phytoplankton growth in estuaries since it is usually the largest component of DIN, was poorly correlated with DO. At the best short-term lag (3 months), the amount of variability explained is quite low (r^2=0.03). Moreover, the correlation is positive, indicating that, if anything, low NO_3 concentrations precede low DO. The best-fit lags for the other three components (NH_3, PO_4, and TDP) were each 11 months. Although the correlations were negative (which is in keeping with the notion that nutrients fuel respiration), 11 months is much longer than would be expected from water column processes. In fact, all the estuaries would have turned over their water volumes many times during such a timeframe. The amount of variability in DO explained by prior NH_3 was quite low (r^2=0.01) whereas those for PO_4 (r^2=0.12) and TDP (r^2=0.10) were a bit higher. Sitewise comparisons of maximum PO_4 each year with minimum DO the next yielded significant negative correlations at only 3 widely spread sites (3255 in St. Catherines, 404 in Altamaha, 922 in Cumberland). Comparisons with TDP yielded a different set of sites (6218 in Cumberland, 5199 in

St. Andrew, 4178 in Sapelo, 3275 and 3285 in St. Catherines). Clearly, these patterns are not very consistent within any sound, let alone coastwide.

If correlations with such long lags are indeed a feature of DO dynamics in Georgia estuaries, then longer-term processes (perhaps the marsh grass growth and decay cycle) would have to be invoked to account for them. Stronger correlations with P than with N may indicate stimulation of microbial activity rather than photosynthesis. However, these correlations may just be a consequence of one very extreme drought/flood event in a rather short time series.

The correlations above seem to indicate that a flush of nutrients with the heavy rains immediately after the prolonged drought was followed by a sharp decline in DO months later. We note that high precipitation in 2005 had much less effect (Figures 3-10, 3-17, 3-21, 3-25, 3-27). The difference, and a potential reason for the poor correlations, may be attributable to buildup of nutrients in watersheds during the prolonged drought that were flushed out in 2002-2003 and did not have time to build up again before 2005. If such interannual-scale dynamics can help to explain patterns in nutrients and DO, then a much longer dataset will be required. We would need to study multiple episodes of drought followed by wet years to establish such a pattern.

Fecal Coliforms and Other Parameters

The watershed is considered the primary source of fecal coliform bacteria to coastal water (but see Harwood et al. 1999). Coupling this with the fact that survival of fecal coliforms in seawater is limited (Anderson et al. 2005), we would expect fecal coliform concentrations to be correlated with parameters such as salinity that indicate the degree of runoff from the watershed. Although log-transformed fecal coliform estimates were in fact significantly negatively correlated with salinity (Figure 4-37), most variability remains unexplained (r^2=0.05). We also found a slight negative correlation with temperature (not shown), which may simply reflect the correlation between salinity and temperature (Figure 4-9). We found a barely discernable negative correlation with DO (not shown), which was so slight that it may be influenced by the limited precision of the MPN method. Finally, there was a positive correlation with NH_3 (Figure 4-38), which may indicate some common sources of NH_3 and fecal coliform bacteria to shellfish waters. There were no significant correlations between fecal coliforms and any other nutrients.

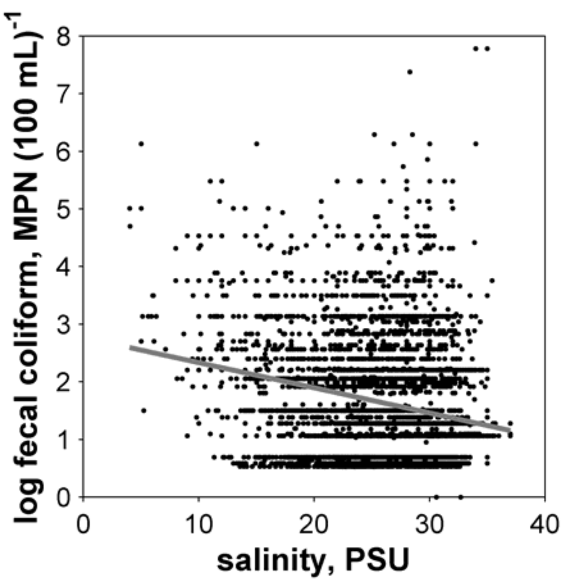

Figure 4-37. Relationship between ln(fecal coliform bacteria) and salinity at Shellfish stations. Gray line represents best linear fit.

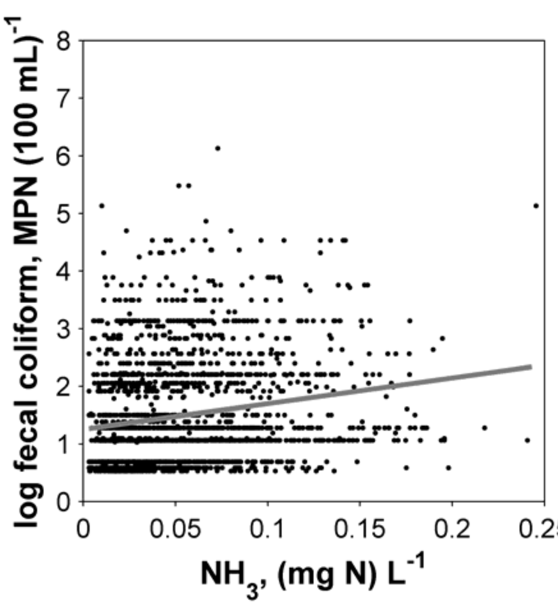

Figure 4-38. Relationship between ln(fecal coliform bacteria) and NH_3 at Shellfish stations. Gray line represents best linear fit.

Enterococcus and Other Parameters

As part of a separately funded study (Sheldon 2009a-c), we investigated associations between *Enterococcus* abundance at Georgia's Tier 1 coastal beaches and other parameters measured by CRD as well as tide, rainfall, streamflow, and drought index. Separate analyses were performed using data from Jekyll, St. Simons, and Tybee Island beaches, but we found that patterns were similar among the beaches. These are summarized below; additional details are available in Sheldon (2009a-c).

We first compared the distributions of *Enterococcus* abundance measurements at the individual sites at each beach location (Jekyll, St. Simons, Tybee) to see if there are significant differences among them. Anderson-Darling k-sample (ADK) and Kruskal-Wallis (KW) tests indicated that there were differences among the sites at Jekyll and St. Simons beaches but not at Tybee beaches (Table 4-1). Results of other tests are presented in the rank order of median *Enterococcus* abundances from these tests.

Table 4-1. Sites sorted by mean rank (lowest to highest) in Kruskal-Wallis test, with shared letters within each beach area indicating nonsignificant differences.

Jekyll Island

JIWY	JIM	JIN	JISD	JIS	JICC	JISA
A	A	A	A			
	B	B	B	B		
					C	C

St. Simons Island

SIMA	SIM	SIF	SIS	SIN
A	A	A	A	
			B	B

Tybee Island

TYN	TYM	TYST	TYS	TYP
A	A	A	A	A

Enterococcus abundance is analyzed by an outside laboratory. As described in Section 2, CRD switched from Altamaha Laboratories, Blackshear, GA to Chatham County Health Department Laboratory, Savannah, GA in May 2006, after which time values appeared to be lower (Figure 3-31). We evaluated this potential effect using two non-parametric tests (ADK and KW). All sites showed a significant lab effect using both tests with one exception: site TYM showed no difference in the KW test. Summer 2006 also marks the beginning of the most recent drought, which means that the change in labs will confound any conclusions that may be drawn regarding freshwater conditions at the sites, including rainfall, streamflow, salinity, and Palmer drought indices, until more samples from normal and wet years are processed using the current lab.

Although many correlations were found between *Enterococcus* abundance and other variables, most of them were weak (Table 4-2). Furthermore, no single parameter that we evaluated explained a great deal of the *Enterococcus* abundance patterns consistently across sites. Of the parameters collected by CRD, only turbidity and salinity showed any consistent correlations across several sites using Spearman rank correlation tests with no lags. Turbidity showed positive correlations with *Enterococcus* abundance at some sites at each beach, but the site pattern was different: it was correlated at the higher-abundance sites on Jekyll and Tybee Islands and the lower-abundance sites on St. Simons Island. In a limited study focused on site JISA in April/May 2004, Hartel et al. (2004) found no significant correlation between turbidity and fecal enterococci measured by Most Probable Number (MPN). Correlations with salinity, where they exist at some of the higher-abundance sites at each beach, generally mirror the correlations found with other variables related to freshwater delivery to the site (below). The few correlations with pH are probably just an artifact of the general pH/salinity relationship. It therefore appears that water temperature, pH, and dissolved oxygen are not important explanatory variables for *Enterococcus* abundance at these beaches.

Table 4-2. Summary of correlations (Spearman rho) or KW test (tide stage only) where p<0.05. For rho, +, ++, +++ indicate weak, moderate, or strong positive correlations, and -,--,--- indicate negative correlations. For tide stage, + indicates significant differences were found among tide stages in the KW test.

Jekyll Island

	JIWY	JIM	JIN	JISD	JIS	JICC	JISA
Turbidity				+		+	+
Water temperature							
pH					-		-
Dissolved oxygen			+				
Salinity		-	-	-	--		-
Tide stage at sampling						+	+
Antecedent tidal range	+	+	+	+	+		
Rainfall	+	+	+	+	+	+	+
Streamflow		+	+		+		+
Palmer Z Index	+	++	++	+	++	++	++

St. Simons Island

	SIMA	SIM	SIF	SIS	SIN
Turbidity	+	+	+	++	
Water temperature					
pH					-
Dissolved oxygen					
Salinity			-		-
Tide stage at sampling		+		+	+
Antecedent tidal range	+	++	++	++	+
Rainfall	+	+	+	+	+
Streamflow		+	+	+	+
Palmer Z Index	+	++			+

Tybee Island

	TYN	TYM	TYST	TYS	TYP
Turbidity					+
Water temperature					
pH					
Dissolved oxygen					
Salinity					-
Tide stage at sampling		+			+
Antecedent tidal range	+	+	+	+	+
Rainfall	+	+	+	+	
Streamflow	+	+		+	+
Palmer Z Index	++		++	+	

Enterococcus abundance was also compared with a suite of additional factors compiled from other sources (summarized in Table 4-2). Tide conditions appear to be important, both for understanding the controlling factors for *Enterococcus* abundance and for interpreting grab samples collected at different stages of the tide. A few sites at each beach showed effects of tide stage at sampling, with a tendency for higher *Enterococcus* abundances on ebb tides at sites with higher overall abundances, although this was by no means a consistent pattern. Antecedent tidal range was characterized as the maximum range (highest high water – lowest low water) over a period prior to sampling. The best overall antecedent period (best fit as judged by Spearman rho) was 75 hours (approximately 3 tidal days) for Jekyll sites, 25 hours (1 tidal day) for St. Simons sites, and 50 hours (2 tidal days) for Tybee sites. Using these periods, *Enterococcus* abundances were correlated with antecedent tidal range at all sites except for the two highest-abundance sites on Jekyll Island (Table 4-2). Further analyses showed generally higher *Enterococcus* abundances on spring tides than on neap tides at most sites and confirmed the generally monotonic relationship between *Enterococcus* abundance and antecedent tidal range (neap/spring cycle) (not shown, see Sheldon 2009a-c). Other studies have found a tendency toward higher *Enterococcus* values on ebb tides and on high spring tides (Boehm and Weisberg 2005). The neap/spring cycle may be important in the actual delivery of enterococci to the sites, as source areas may be flooded to a lesser or greater degree. The tendency for greater *Enterococcus* abundances on ebb tides suggests that a program that samples without regard to tide stage may miss events that may be important for public health.

Variables related to moisture conditions and freshwater delivery all showed similar patterns, with positive correlations indicating tendencies toward higher *Enterococcus* abundances with recent rainfall, higher streamflow, and higher Palmer Z Drought Index (Table 4-2). *Enterococcus* abundances were correlated with antecedent rainfall at all sites except one on Tybee Island. The antecedent period used in these analyses varied among sites according to best statistical fit: the day prior to sampling was used for Jekyll and St. Simons beaches and the second day prior to sampling for Tybee beaches. The lag at Tybee is probably due to having to use a rainfall gauge farther from the beaches. *Enterococcus* abundances were correlated with antecedent streamflow at some, but not all, sites at each beach. We used the streamflow from the Altamaha River at Doctortown on the third day prior to sampling for Jekyll and St. Simons beaches and from the Savannah River at Clyo on the day of sampling for Tybee beaches. These best-fit periods reflect the relative distances from the beach sites to the nearest streamflow gauges. *Enterococcus* abundance values near zero were not generally observed at high flow rates. In the Altamaha and Savannah Rivers, most flows greater than 30000 and 17400 $ft^3\ s^{-1}$, respectively, occurred prior to 2006 so those samples were processed by the earlier lab. This observation may therefore be related to the switch in labs just prior to the drought. Most of the very high *Enterococcus* abundances actually occurred at lower flow rates.

The Palmer Z Index, a monthly drought index variable that is calculated at a regional scale (so it is the same for all sampling sites in this study), was compared with each site's monthly aggregate *Enterococcus* abundance statistics (arithmetic mean, geometric mean, median, maximum, and number of samples exceeding the single-sample regulatory limit of 104 CFU $100mL^{-1}$) using Spearman rank correlation tests with lags ranging from 0 to 3 months (not shown, see Sheldon 2009a-c). No single aggregate statistic and lag stood out as correlating best at most sites, but moderate correlations existed for some statistics (indicated in Table 4-2) even though patterns among sites were not consistent. All correlations were positive, indicating a general tendency for lower *Enterococcus* abundance during drought, but this conclusion may again be confounded by the change in processing labs.

Taken together, these analyses show fairly consistent connections between *Enterococcus* abundance and freshwater delivery conditions across all sites, indicating that further evaluation of this mechanism may be fruitful once more samples from normal and wet years are processed using the current lab.