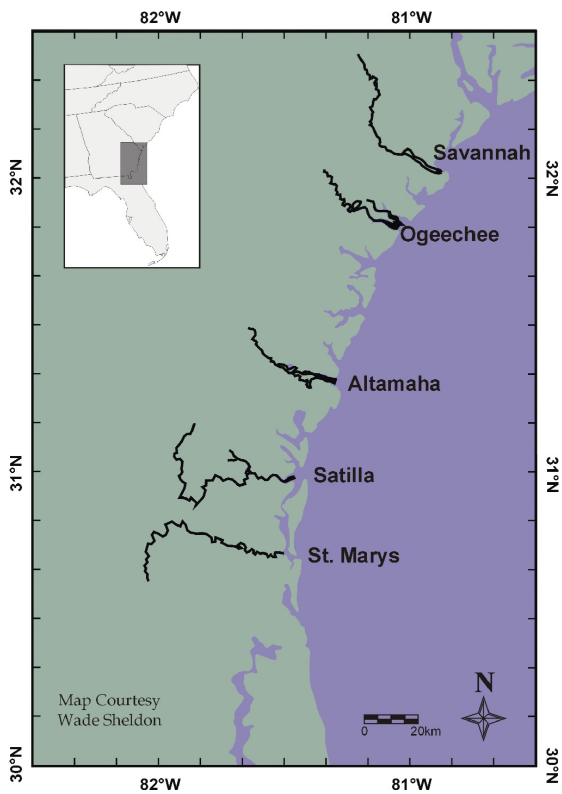
The Effects of Changing Freshwater Inflow to Estuaries:

A Georgia Perspective



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November 2002

Georgia Coastal Research Council

A word about the Georgia Coastal Research Council

The Georgia Coastal Research Council was established to provide mechanisms for improved scientific exchange between coastal scientists and decision makers in the State of Georgia, and to promote the incorporation of best-available scientific information into State and local resource management. The Council is not a policy organization, but rather seeks to provide unbiased, objective information about scientific issues. The Council staff are located in the School of Marine Programs at the University of Georgia, and are supported with funding from a Coastal Incentive Grant from the Coastal Resources Division of the Georgia Department of Natural Resources and the Georgia Sea Grant College Program.

For more information about the GCRC, please contact Janice Flory, project coordinator, at gcrc@arches.uga.edu or see our web site at http://www.marsci.uga.edu/coastalcouncil.

> **"Water may flow in a thousand channels, but it all returns to the sea."**
>
> **African proverb**

Preface

As the human population – and its associated water demand – continues to grow, freshwater delivery to coastal systems will likely decrease. Between 1990 and 2000, Georgia's population grew at a rate of 26.4%, which was twice that of the national average (US Census Bureau), and the coastal counties grew at an even faster rate. In addition to the increased demand for water represented by the increase in population is the recognition that parts of the Floridan aquifer are subject to saltwater intrusion. In 1997 the Georgia Environmental Protection Division (EPD) adopted an "Interim strategy for managing salt water intrusion in the Upper Floridan aquifer of southeast Georgia" (EPD 1997), which imposed caps on groundwater use in several coastal counties to avoid worsening the rate of salt water intrusion and, in some cases, set goals for reductions in groundwater withdrawal. The decreased availability of groundwater, coupled with increased population growth, places tremendous pressure on the surface waters of the state, with unknown consequences for downstream ecosystems.

In its white paper on Water Issues, the Georgia Board of Natural Resources called for "a thorough evaluation of the impacts of possible reduced flows into Georgia's coastal waters as a result of consumptive water uses upstream. Changes in the salinity regime may have impacts on the species composition of plants, animals, and fish in Georgia's estuaries" (GA BNR, 2001). This is a challenge that clearly needs to be addressed in Georgia and is the subject of this report. It is particularly timely now as the State is currently reviewing options regarding a Statewide Water Management Plan (http://www.cviog.uga.edu/water/).

The effect of water withdrawal on estuaries is an issue of national concern. At a recent meeting of the Estuarine Research Federation (held November 2001 in St. Pete Beach, FL), M. Alber, P. Montagna, M. Connor, and P. Doering convened a special session titled "Freshwater inflow: science, policy, management." The papers presented at the session addressed the issue of freshwater withdrawal from the perspective of scientists, managers, and regulators from many parts of the country. This white paper is a modified version of M. Alber's contribution to the meeting and will be included in a dedicated issue of the Journal Estuaries, which is scheduled for publication in December 2002.

This paper is divided into three parts. Part One provides an overview of the scientific information available regarding the connections between freshwater inflow, estuarine conditions, and resources. Part Two presents a conceptual model for inflow management in terms of the types of regulation available and the societal values that must be considered. In this section we categorize management as inflow-based, condition-based, or resource-based, and use this structure as the basis to explore the differing approaches to estuarine inflow management that have been taken in various parts of the country. In Part Three we apply this perspective to Georgia. We describe the inflow policy currently in place in Georgia's rivers and summarize the scientific efforts being undertaken to understand the impact of changing freshwater flow to Georgia's estuaries.

Part One – The Effects of Changing Freshwater Inflow to Estuaries

Background

Most of the world's rivers are affected by dams, interbasin transfers, and surface water withdrawals.

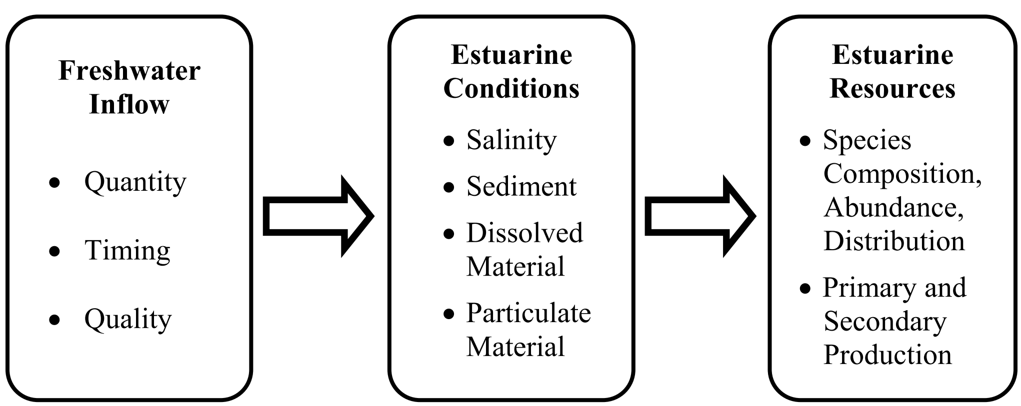
There are very few estuarine systems in the world unimpacted by upstream manipulation of their freshwater inflow. Approximately 60% of the global storage of freshwater is behind registered dams (Vörösmarty and Sahagian 2000), and Dynesius and Nilsson (1994) concluded that 77% of the total water discharged by the 139 largest river systems in the northern third of the world are strongly or moderately affected by dams, interbasin transfers, and surface water withdrawals. Moreover, demand for freshwater is only expected to increase as world population continues to grow (Postel 1998). In light of these pressures, the evaluation of various flow regimes for sustainable river management and the analysis of the environmental effects of hydrologic alteration are both areas of active investigation (e.g. Sparks 1992; Poff et al. 1997). However, it is also important to examine the consequences of freshwater flow regulation for coastal ecosystems.

Decreases in freshwater inflow can have far-reaching, sometimes disastrous consequences downstream.

Changing the amount of freshwater input by any of the perturbations described above can have profound effects on an estuary. For example, construction of the Aswan High Dam in Egypt led to large changes in the discharge of Nile flood water: after the dam was built there was a substantial reduction in overall discharge, a decrease in peak flows, an increase in low flows, and a shift in the timing of the hydrograph (Vörösmarty and Sahagian 2000). Impoundment of water led to a substantial decrease in the loading of nutrients to the Mediterranean Sea, and the sediment load is now virtually nonexistent (Hallim 1991). These changes in inflow have had serious impacts on marine life, resulting in a 95% decrease in phytoplankton and an 80% decrease in fish catch: Sardinella catch dropped from 15,000 tons in 1964 (pre-dam) to 554 tons in 1966 (post-dam) (Aleem 1972; Hallim 1991). In the Seekoei Estuary in South Africa, a drought in 1988-89 coupled with high upstream withdrawal rates made it such that no freshwater entered the estuary at all. Salinities in the upper portion of the estuary reached 98, resulting in massive fish mortality (Whitfield and Bruton 1989). These are extreme cases, but they point out the importance of

The scientific framework for evaluating estuarine inflow involves understanding the linkages between freshwater inflow, estuarine conditions, and resources.

Figure 1. Scientific Framework



establishing the freshwater requirements of estuaries in comparison with other competing needs. A simple overview of the scientific framework for evaluating estuarine inflow is shown in Figure 1. The basic approach is to determine the linkages between freshwater inflow, estuarine conditions, and resources. This information is then used to assess how changes in freshwater input affect estuarine conditions, and how these changes in turn affect different components of the ecosystem. Below we examine the different parts of this model and present information on freshwater inflow, estuarine conditions, and estuarine resources.

Upstream manipulation can affect freshwater input to estuaries.

Freshwater inflow

Input to the estuary begins with freshwater inflow. However, it is important to recognize that the quantity, timing, and quality of these inputs are all determined by events that occur upstream.

- ***Quantity can change.***

Quantity

Human modifications such as dams, diversions, and upstream withdrawals all directly affect the amount of water that reaches the coast, and to the extent that these are consumptive uses there is reduced inflow to the estuary.

> Water quantity is affected by:
> - Withdrawals for upstream use
> - Dams, reservoirs and impoundments
> - Diversions

- ***Timing can change.***

Timing

The timing of water delivery is also subject to upstream modification. Where dams are managed for flood control they tend to dampen the magnitude of flooding and can also result in reduced variations in inflow and modulation of seasonality. In San Francisco Bay, reservoirs capture much of the spring snow melt and store it for use later in the summer when water demand for agriculture and power requirements are highest, effectively truncating the normal spring peak in the hydrograph (Kimmerer and Schubel 1994). Timing of water delivery can also be affected by shifts in land use, such as conversion of land from forested to urban use, that result in changes in runoff patterns. Channelization and the isolation of rivers from riparian buffers can also affect the timing of runoff. For example, in the Kissimmee River basin of central Florida, the annual maximum monthly discharge shifted from October to August as a consequence of channelization (Sklar and Browder 1998).

> The timing of water delivery is affected by:
> - Operation of dams, reservoirs and impoundment
> - Changes in land use

Quality is also affected by decreasing inflow volume…

Quality

To the extent that nutrients, pollutants, sediment, and organic material are all carried along with freshwater, any upstream changes in inflow will affect the amount and timing

> Water quality is affected by:
> - Changes in the quantity and timing of freshwater inflow
> - Changes in upstream conditions

of their delivery to the estuary as well. Ustach et al. (1986) documented how clearing and draining land for agriculture resulted in a 10% increase in freshwater outflow and a consequent increase in nutrients and turbidity. Estuarine concentrations of nutrients, organic matter, pollutants, and sediments have all been correlated with inflow (e.g. Jordan et al. 1991; Mallin et al., 1993; Jassby et al. 1995), and there are numerous examples of how year-to-year changes in river inflow influence the loading of materials to estuaries (e.g. Boynton et al. 1995). Dams can also impact the water quality characteristics of estuarine inflow. Dams tend to trap sediment, and thus decrease the downstream delivery of particles and associated materials such as particle-active metals and pollutants. For example, the presence of upstream dams on the Danube River reduced the load of silt and associated silica to the Black Sea (Ittekkot et al. 2000). Silica concentrations reduced from 140 μmol l^{-1} (pre-dam) to 58 μmol l^{-1} (post-dam), with a concurrent change in the Si:N ratio from 42 to 2.8. The amount of time that water spends behind dams can also affect the age of the water (Vörösmarty and Sahagian 2000), with consequent impacts on the quality and availability of organic matter delivered to the estuary. Townsend et al. (1996) provided evidence for increased photodegradation of dissolved organic material in reservoirs with a longer residence time, and Mousset et al. (1997) measured a higher proportion of humic material in reservoir as compared to river water.

…and by changes in upstream conditions.

It is important to note that loading is the product of inflow and concentration. Although the above discussion focused on changes in inflow, changes in upstream water quality will clearly impact the delivery of materials to an estuary, regardless of flow conditions. A discussion of water quality change is outside the scope of this review, but both point and non-point source discharges can impact downstream water quality. Changes in upstream land use such as deforestation can lead to changes in both nutrient and sediment concentrations (Sklar and Browder 1998), and many coastal systems are showing symptoms of eutrophication as a consequence of increased nutrient concentrations (Rabalais et al. 1996; Howarth 1998). These types of water quality changes, when coupled to changes in discharge, can result in greatly altered patterns of downstream loading to an estuary.

Decreasing the amount of freshwater input by any of the perturbations described above will have profound effects on estuarine conditions.

Estuarine Conditions

Estuarine conditions change as a consequence of altered freshwater input, in terms of salinity patterns and other physical attributes of the estuary as well as in terms of the distribution of dissolved and particulate materials.

Salinity

- ***Salinity increases.***

One of the most obvious consequences of decreased freshwater input is that saltwater may intrude farther upstream, resulting in increased salinity along the estuarine gradient. In extreme cases of high evaporation coupled with low rainfall, the estuary can become hypersaline. For example, the Kariega Estuary in South Africa had no rainfall for more than a year, and salinities in the upper reaches were greater than 40 (Whitfield and Woolridge 1994). In addition to an upstream shift in salinity, decreased outflow can also lead to expansion of the zone of transition from zero salinity to full seawater, hence lengthening the estuary. This can be seen by comparing the upstream extent of the estuarine zone in rivers with high versus low flow. For example, the mouths of the Altamaha and Satilla River Estuaries are located only 37 km apart and experience similar tidal regimes. However, median flow in the Satilla is one tenth that in the Altamaha (25 versus 250 m^3s^{-1}). As a consequence, one typically encounters freshwater only 20 km upstream in the Altamaha as compared to 50 km upstream in the Satilla (Smith et al. 2001).

- ***Mixing patterns are altered.***

Mixing patterns

Alterations in freshwater inflow can also change the hydrodynamic regime of an estuary. Decreases in discharge will serve to increase the influence of the tide on circulation patterns such that a stratified system with well-developed gravitational circulation can shift to a well-mixed system where tidal exchange increases in importance. In the Eastmain River, Quebec, Ingram et al.(1985) reported that diversion of the river led to a 90% decrease in mean flow and a significant increase in tidal amplitude in the estuary. In San Francisco Bay, Cloern (1984) found that the ratio of river discharge to tidal current speed could be used to explain stratification. At high river flows, South San Francisco Bay stratifies, turbidity and nutrient concentrations decline, phytoplankton biomass and production are high, and residual currents accelerate. A change in stratification as the result of changes in inflow can in turn affect bottom water hypoxia, as has been observed in Chesapeake Bay (Malone et al. 1988). Finally, to the extent that circulation patterns interact with local topography, changes in inflow can displace zones of appropriate salinity for specific organisms. This is an example of the overlap concept described by Sklar and Browder (1998), who note that the changing spatial distribution of appropriate habitat is important to consider when evaluating changes in inflow.

> Mixing patterns can be altered, resulting in:
> - Changes in the importance of tidal circulation
> - Changes in the amount of stratification
> - Changes in transit times

- ***Transit times increase.***

Transit times

Another consequence of decreased freshwater inflow is that it results in an increase in flushing or freshwater transit time (Alber and Sheldon 1999; Sheldon and Alber). The transit time provides a measure of the time it takes river water to pass through the system and thus has consequences for the ability of an estuary to flush out materials. As transit times increase, the concentrations of pollutants and pathogens can increase as well. The transit time also sets the time frame for conservative mixing and can thus be compared against the time scales of biogeochemical and other non-conservative processes to determine whether transformations may occur within estuaries. Freshwater transit time has been positively correlated with the amount of nitrogen exported from estuaries (Nixon et al. 1996; Dettmann 2001).

- ***The size and shape of the estuary changes.***

Geomorphology

Changes in inflow can also lead to alterations in estuarine geomorphology (the size and shape of the estuary). Because freshwater is generally also a source of sediment to an estuary, decreased inflow can result in losses for tidal deltas, benthic communities, and intertidal habitat (e.g. Boesch et al. 1994).

- ***The distribution of dissolved and particulate material is altered.***

Dissolved and particulate material

Finally, freshwater is also a source of both dissolved and particulate material to an estuary, as described above. As a consequence, changes in freshwater input can have important effects on the downstream delivery of organic matter, suspended sediments, nutrients, and pollutants. Drinkwater and Frank (1994) summarized data from the receiving waters of six rivers that had significant freshwater flow regulation. In every case, decreased inflow was coupled to changes in nutrient concentrations and sediment delivery. These relationships are generally positive, such that increased inflow brings in more material. For example, Grange et al. (2000) measured a 20-fold increase in the nutrient concentration of the Kariega Estuary in the wet as compared to the dry season. However, in cases where inflow is not the main source of materials, the opposite relationships have been observed. In the estuary of the Fraser River in Canada, decreased inflow led to decreased stratification and increased mixing of benthic nutrients (Beamish et al. 1994). Although these relationships are complicated, the point remains that inflow can have profound effects on water quality, which in turn impacts processes in receiving estuaries.

Table 1. Summary of Responses to Freshwater Flow Regulation.

	Nile	Indus	Black Sea	SF Bay	James Bay Eastmain	James Bay La Grande
Freshwater flow						
Total	D	D	D	D	D	I
Seasonal	M	M	M	M	M	M
Environment						
Salinity	I	I	I	I	I	D
Circulation	M	M	M	M	M	M
Sediments	D	D	D	D	I	I
Nutrients	D	D	I	D	I	I
Biology						
Primary Production	D	D	I	D	I	?
Secondary Production	D	D	D	D	?	?
Fish Production	D	D	D	D	U	U
Fish Distribution	M	M	M	M	M	M

Responses are categorized as increased (I), decreased (D), modified (M), remained unchanged (U), or unsure (?). Redrawn from Table 1 of Drinkwater and Frank (1994).

Changes in estuarine conditions will in turn affect estuarine resources.

Estuarine Resources

Some examples of the types of estuarine resources that are affected by estuarine conditions are shown in the last box of the scientific framework (Fig. 1). Estuarine ecology is almost by definition a study of the linkages between estuarine conditions and the distribution and abundances of estuarine biota and the resultant implications for such things as community structure, food web interactions, rates of primary and secondary production, and material cycling. Rather than provide an exhaustive review of this topic, our purpose is to highlight those changes that result directly from changes in the quantity, quality, and timing of freshwater inflow.

Many estuarine resources are linked to salinity.

Quantity

The effects of quantity of freshwater inflow are often manifested through changes in salinity. Salinity is a critical determinant of the habitat characteristics of an estuary, and changes caused by variations in freshwater inflow can affect the species composition of a given area.

Vegetation can shift in response to changes in salinity.

Vegetation and sedentary organisms. Shifting isohalines caused by decreases in freshwater inflow will affect the distribution of both rooted vegetation and sessile organisms. For example, upstream movement of *Spartina* species in both the Delaware River and Chesapeake Bay have been linked to long term increases in salinity (Schuyler et al. 1993; Perry and Hershner 1999). We have also documented large differences in the distribution of marsh vegetation along two Georgia estuaries with different river flows, as described in Part Three (Smith et al. submitted). As noted above, Sklar and Browder (1998) pointed out the importance of considering the spatial extent of appropriate habitat under various salinity regimes. For example, as a given isohaline moves upstream, the channel width and the extent of intertidal habitat is often changed, with consequent impacts in terms of the suitability of the new location for benthic organisms.

The distribution of mobile organisms can change.

Mobile organisms. Changes in salinity structure affect the distribution of mobile organisms as well. Most of the biota found in estuarine environments occur within focused salinity ranges, and different stages in the life histories of many estuarine organisms have specific salinity requirements. Bulger et al. (1993) found nonrandom discontinuities in the distributions of fish along the estuarine gradients in Chesapeake and Delaware Bays. In their review of the impact of flow regulation, Drinkwater and Frank (1994) found changes in the species composition, distribution, abundance, and health of fish and invertebrates attributable to changes in freshwater flow. They also linked changes in river flow to changes in migration patterns, spawning habitat, and fish recruitment. Whitfield (1994) identified the longitudinal salinity gradient as the single most important factor linked to successful recruitment of larval and juvenile marine fish in South African estuaries and has gone on to develop a fish recruitment index that relates estuarine fish abundance to inflow (Quinn et al. 1999). Recruitment of anadromous fish such as striped bass has also been correlated with changes in inflow (e.g. Rulifson and Manooch 1990).

The timing of freshwater delivery to an estuary can impact the life histories of estuarine organisms.

Timing

In addition to changes in the magnitude of freshwater inflow, changes in the timing of water delivery can also impact estuarine resources. The life histories of many fish and shellfish are cued to high spring runoff, such that changes in timing can affect spawning and nursery cycles. For example, Sutcliffe (1973) found a positive correlation between spring runoff in the St. Lawrence River and lobster landings in the Gulf of St. Lawrence 9 years later. In Sabine Lake, Texas, the presence of a dam affected inflow patterns, reducing the availability of both low salinity nursery habitat for brown shrimp in the spring and high salinity nursery habitat for white shrimp in the summer (White and Perret 1974, referenced in Sklar and Browder 1998). In a study of the impact of salinity variability on estuarine organisms, Montague and Ley (1993) found a negative correlation between the standard deviation of salinity and the density of plants and benthic animals and suggested that frequent salinity fluctuations result in increased physiological stress. On the other hand, Flint (1985) found that episodic freshwater input stimulated production of both benthic infauna and shrimp in Corpus Christi Bay. These conflicting reports suggest that organisms have a complex response to inflow variability, and it is likely that the interaction of salinity and other dynamic characteristics determine habitat suitability in a given area.

Changes in water quality conditions can affect estuarine productivity rates and trophic structure.

Quality

The consequences of changes in freshwater inflow include changes in the distribution of nutrients, organic matter, and sediment in an estuary, all of which have implications for estuarine productivity rates and trophic structure.

The delivery of nutrients and light can affect primary production in an estuary.

Primary production. The relationship between nutrients and inflow is generally positive, and many investigators have found a correlation between nitrogen loading and phytoplankton production (Flint et al. 1986; Nixon 1992; Mallin et al. 1993; Boynton et al. 1995). The converse is also true: decreased inflow can often be linked to decreased rates of both primary and secondary production (Drinkwater and Frank 1994). However, increased inflow usually also brings increased sediments, which can impact the light environment of the estuary via turbidity effects and result in reduced phytoplankton production. For example, a drought in San Francisco Bay was linked to increased water clarity and high chlorophyll concentrations (Lehman 1992). In several studies that compared two South African estuaries with different riverine inflows, investigators found that decreased inflow resulted in better light penetration and a concurrent increase in the importance of aquatic macrophytes, which resulted in a switch from a pelagic to a benthic food web and a change in the balance between detritivory and herbivory (Whitfield and Woolridge 1994; Grange et al. 2000).

Organic matter that comes from upstream can be used by estuarine organisms.

Food web. Freshwater delivery of organic matter can be an important food source in an estuary, and changes in this input can affect downstream food webs. For example, the presence of an upstream dam in the Mbashi Estuary in South Africa led to a reduction in the input of silt and organic detritus, which was correlated with a decrease in fish abundance (Plumstead 1990). The decline in fish was thought to be the result of decreased organic material as a food resource both for the fish themselves and for their prey. Moreover, studies of estuarine food webs that use the stable isotope technique indicate that terrestrially-derived organic matter is used in estuarine food webs, particularly in upstream reaches (e.g. Day et al. 1994; Riera and Richard 1996). In a comparative study of two Maine estuaries, Incze et al. (1982) showed that bivalves had increased dependence on terrestrially-derived material in an estuary with a high river discharge compared with one with little river input.

A good example of the propagation of changes in inflow through an ecosystem was observed in Apalachicola River Estuary in Florida, where decreased freshwater inflow led to an initial increase in primary production (due to reduced turbidity),

Changes in inflow can also have cascading effects on the food web.

followed by a long-term decrease in production, which they postulated was due to decreased delivery of nutrients to the estuary (Livingston et al. 1997). In terms of the food web of the receiving estuary, this study showed little change over prolonged periods as long as flow remained within its natural bounds. However, during a two-year drought in which average river flow decreased approximately 50%, there were dramatic effects on trophic structure. Overall trophic diversity decreased, and there were increases in some groups (herbivores, detritivorous omnivores, primary and secondary carnivores) and decreases in others (tertiary predators were virtually absent). It should be noted that the effects of the drought took two years to make their way through the food web of the estuary (Livingston et al. 1997).

The relationship between inflow and secondary production is difficult to predict.

Considering the interplay of factors described above, it should come as no surprise that the relationship between inflow and secondary production is difficult to predict. In many systems, an increase in inflow results in increased catch of fish (Sutcliffe et al. 1983; Skreslet 1986) and shellfish (Browder 1985; Gracia 1991; Gammelsrød 1992; Galindo-Bect et al. 2000). The mechanisms that underlie these relationships are not always understood, but increased secondary production is generally attributed to increased nutrient inflow resulting in increased primary production. Gammelsrød (1992) suggested three additional mechanisms for the relationship between Zambezi River runoff and shrimp catch: a) strong runoff leads to greater flooding by brackish water, resulting in an increase in the area of habitat suitable for successful recruitment, b) runoff leads to greater dispersion of larvae, or c) runoff increases estuarine turbidity, providing protection from predators. However, negative relationships between runoff and the catch of fish (Sutcliffe et al. 1983; Beamish et al. 1994), shellfish (Turner 1992), and other organisms (Ardisson and Bourget 1997) have also been observed. Again, the mechanisms are not always understood, but they likely involve a decrease in the availability of suitable nursery habitat and/or a negative relationship between inflow and nutrients.

Part Two – Estuarine Inflow Management

It is important to understand the roles of scientists, politicians, managers, and citizens in setting inflow policy.

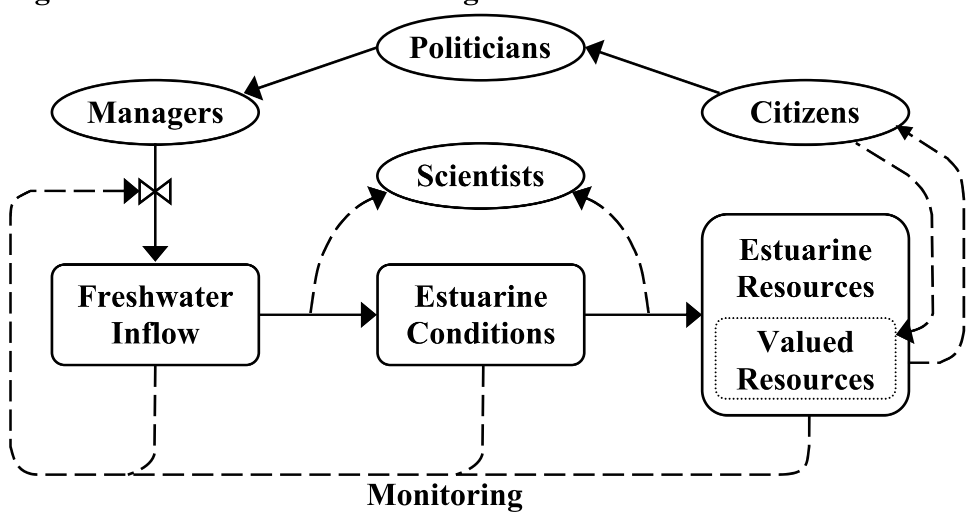
As described in Part One, considerable progress has been made in terms of understanding the consequences of changing inflow patterns to estuaries and the mechanisms that underlie these relationships. However, this information is not always available to aid in making decisions with regard to upstream water utilization, and there is a need to improve the exchange among scientists, politicians, managers, and citizens when it comes to managing estuaries. Here we present a conceptual framework for inflow management that describes the roles of these various groups, and use this model to evaluate inflow management in several parts of the country.

Management model

***The goal of inflow management is to protect valued estuarine resources*.**

A conceptual model for estuarine inflow management is shown in Figure 2. Clearly, this is a simplification and there are more links than are represented in the model, including interactions among different groups (e.g. scientists and citizens; scientists and politicians; managers and politicians, etc.), and links via education. However, what is emphasized here are the primary connections among the various

Figure 2. Estuarine Inflow Management



The model depicts the primary roles of citizens, politicians, scientists, and managers. Solid lines denote direct control; dashed lines denote information transfer; the gate on the arrow between managers and inflow signifies that managers can modify inflow based on the information they receive. Source: Alber, in press.

groups and how they relate to management. Our premise is that the goal of estuarine freshwater inflow policy is to protect those resources and functions that we as a society value in estuaries, and that management measures are geared toward establishing inflow standards that can meet this goal. Below we describe the model more fully and then use it to explore estuarine inflow management in the context of several case studies.

Valued resources are those things that people care about in estuaries.

We begin our discussion of the model with the compartment labeled "valued resources," because a perceived threat to these resources is often the impetus for the development of a freshwater inflow policy. Valued resources are depicted as a subset of the estuarine resources box, as these are the resources and functions that people care about in estuaries. This does not usually include all of the natural resources of an estuary, and what is in this box will not be the same for each stakeholder. Examples of the types of resources that are often identified as valuable in estuaries are shown (see box). Intrinsic value is listed in recognition of the fact that some groups (e.g. many environmental organizations) consider estuaries intrinsically valuable and they are willing to see decisions made on this basis alone. However, other groups value estuaries for their commercially important fisheries or the presence of wildlife habitat. Some of the terms listed in the table connote legal value: For example, through passage of the Endangered Species Act society has asserted that the continued presence of rare and endangered species is valuable. Likewise, the Magnuson-Stevens Act (although as yet untested) assigns value to essential fish habitat.

Valued Resources

- Intrinsic value
- Navigation
- Assimilative capacity
- Fish and shellfish production
- Wildlife habitat
- Aesthetic/recreational value
- Intertidal wetlands
- Rare and endangered species
- Essential fish habitat

***Policies to protect valued resources are instituted in response to pressure from constituents*.**

The reason for the emphasis on societal values is to focus attention on the role that citizens play in setting inflow policy. Policy-making is by definition a political endeavor, and elected officials will respond to pressure from citizens to establish inflow policies that protect those resources that they care about. As long as there is no perceived threat to valued resources, it is difficult to muster the political will to pass legislation or to enforce estuarine inflow requirements. Even with a perceived threat, the effort is unlikely to be successful unless there are stakeholders who are concerned enough to attend public hearings or write to their representatives. In practice, the broader the base of support (e.g. the combined strength of the wildlife lobby, commercial fishermen, and the presence of endangered species), the more likely a requirement will prevail. Note that there are two arrows in Figure 2 connecting citizens and valued resources. This is to denote that on one hand, citizens act to determine which items fall into the valued resources category, and on the other they keep track of the status of these resources and can in turn exert an influence on policymakers in the face of a perceived threat.

There is some overlap between our usage of valued resources and the Valued Ecosystem Component approach used by EPA in the National Estuary Program (see sidebar), which itself was an adaptation of the Valued Environmental Component (VEC) approach of W.C. Clark. Clark defined VECs as "attributes of the environment that some party to the assessment believes to be important" and noted that "Which components are valued will depend on specific social, political, and environmental circumstances." (Clark 1986, p.17). He sought to develop causal relationships between VECs and potential sources of environmental change, and devised a matrix to evaluate

Valued Ecosystem Components (National Estuaries Program)

1. A resource or environmental feature that is important (not only economically) to a local human population, or has national or international profile, or if altered from its existing status, will be important for the evaluation of environmental impacts of development and the focusing of administrative efforts.
2. Any part of the environment that is considered important by the proponent, public, scientists and government involved in the assessment process. Importance may be determined on the basis of scientific concern or based on cultural values.

(SFWMD 2001).

the importance of the various sources of disturbance on the identified VECs. This concept is very much in keeping with valued resources as described here.

In practice, protecting an estuary requires managing inflow.

In order to meet policy goals and protect valued resources, it is important to recognize that freshwater inflow is the primary point where humans exert control over an estuary. The implications of this statement for inflow management are two-fold: first, any regulations that affect upstream flow will affect estuarine inflow, and second, any management actions that are put in place to protect estuaries will be focused on inflow regulation. The factors listed below serve to highlight the components of upstream management that influence the quantity, quality, and timing of freshwater inflow to estuaries. The connection between upstream policies and the downstream delivery of freshwater, although straightforward, is not generally made explicit. Except in situations where there is a dedicated effort to manage estuarine inflow, such as in the case studies discussed below, it is rare for decisions regarding upstream resources to be made in light of potential estuarine effects, and there is little recognition that upstream regulation is, by default, setting estuarine inflow. In addition, the authority to make decisions regarding such things as permits for water withdrawal or point source discharges is given to agencies with jurisdiction over freshwater resources, which are generally independent of those agencies responsible for coastal resource protection. This is unfortunate, because it is primarily on the inflow side that management practices can most influence estuarine conditions. Although there are other regulations that do directly affect estuarine conditions and resources (e.g. regulations affecting dredging, dock construction, fish catch, etc.), these are not considered here because they do not usually influence freshwater inflow

Upstream Regulations

Examples of the types of policies and management decisions that affect freshwater inflow to estuaries.

- Withdrawal permitting
- Discharge permitting
- Instream flow requirements
- Reservoir management
- Diversions and interbasin transfers
- Flood plain modification
- Sediment and erosion controls
- Water quality standards

(although wastewater discharge can be an important source of freshwater to an estuary).

Scientists work to understand the connections between inflow, conditions, and resources.

Management plans that are instituted with the goal of protecting estuarine resources are carried out by regulating inflow, and this is depicted as an arrow in Figure 2 that runs directly from managers to inflow. However, inflow then influences estuarine conditions, which in turn influence resources, as described in the scientific framework (Fig. 1). Scientists are linked to the arrows between the boxes in Figure 2 to indicate that science works on explicating the linkages between inflow, estuarine conditions, and resources. The scientist (whether working in academia or in an agency) seeks both to quantify the relationships among these variables and to understand the causative mechanisms that underlie these relationships. The connection between scientists and managers is drawn as a one-way arrow to underscore the point that understanding the ways in which inflow affects estuarine conditions and resources is critical for the establishment of scientifically-defensible inflow management. As the ones that have to make decisions about upstream flow (e.g. whether to grant permits for increased water withdrawals in a system), managers are on the front lines of the issue and it is important that they have timely access to scientific results.

Monitoring an estuary provides feedback on the effectiveness of a management plan.

The model has numerous routes for information collection that can feed back to managers, causing a potential modification of inflow regulation. Monitoring of either inflow itself, estuarine conditions, or estuarine resources will provide direct feedback, allowing managers to determine if the decisions being made are actually effective in terms of meeting management goals. For example, a minimum inflow level might be chosen that is geared towards maintaining the average high tide salinity below a certain threshold at a specific point in an estuary, and salinity data collected at that point could be used to determine if the target is being met. If average salinity is higher than expected, minimum inflow levels can then be modified accordingly. This is an example of what Johnson (1999) characterized as the "monitor-and-modify" approach to management.

Management approaches

Management can be focused on inflow, conditions, or resources.

In practice, management can be focused on different boxes in the scientific framework, and we therefore distinguish between an inflow-, condition-, or resource-based approach to estuarine inflow management. In an inflow-based approach, flow is kept within some prescribed bounds under the assumption that taking too much away is bad for the resources. A condition-based approach is one in which inflow standards are set in order to maintain a specified condition (e.g. salinity) at a given point in the estuary. In a resource-based approach, inflow standards are set based on the requirements of specific resources. We suggest, however, that connections are usually made, either directly or indirectly, between inflow and valuable estuarine resources. Below we use examples from Florida, California and Texas to support these generalizations.

Many estuaries without an explicit inflow policy are using an inflow-based approach.

<u>Inflow-based approach</u>

Where there is not an explicit freshwater requirement established for an estuary then whatever mechanisms are in place for minimum upstream flow (e.g. the 7-

day 10 year minimum flow, or 7Q10) are what set the lower bounds for estuarine inflow. Although this is adequate for those estuaries that are not experiencing any problems, communication between upstream and downstream regulators is rare, and there is generally no recognition that upstream regulation is, by default, setting estuarine inflow.

The Southwest Florida Water Management District sets upstream withdrawal limits as a proportion of river flow.

A clear example of an explicit inflow-based regulation is the approach taken by the Southwest Florida Water Management District (SWFWMD). In this case, the District established what was called the "10% presumption" to review applications for water withdrawal permits, which stated that: "The District presumes that the withdrawal of water will not cause unacceptable environmental impacts if the withdrawal, combined with other withdrawals, does not reduce the rate of daily flow by more than 10% at any point in the drainage system at the time of withdrawal" (Section 4.2.C.2 of the Basis of Review, SWFWMD). The District had also done studies to demonstrate that reducing inflow by 10% or less had a minimal impact on estuarine conditions and resources. This was an interesting approach in that it linked withdrawal to daily flow, thereby preserving natural streamflow variations (Flannery, submitted). However, the use of the 10% presumption was successfully challenged in an administrative hearing in 1995, in part because it was considered arbitrary. Moreover, opponents argued that the District studies that showed that reducing inflow by 10% did not affect the estuary were limited and might not be appropriate for every system. Although the 10% presumption is no longer in effect, the district still limits withdrawals to a percentage of stream flow (Flannery, submitted).

The inflow-based approach for estuaries is similar to that advocated for river management.

This type of inflow-based management is very much in keeping with the approach that is often advocated for river management, where flow is considered a master variable because it is correlated with many other factors in the ecosystem (Poff et al. 1997; Richter et al. 1997). In this case, the emphasis is on maintaining the natural flow regime with the premise that maintaining inflow will also maintain complex estuarine interactions regardless of whether scientists understand them. Inflow-based approaches are attractive and straightforward. However, their link to resources is weak, which renders them less accessible to the general public and more difficult to sustain in the face of opposition.

Condition-based approach

Freshwater inflow to San Francisco Bay is regulated based on the location of water of a specific salinity in the estuary.

San Francisco Bay provides an example of a condition-based approach to inflow management. In this case the regulatory policy is based on the location of water of a given salinity, rather than directly on either inflow or resources, although it can be linked to both. The inflow policy in place requires that the so-called X_2 (the position of the 2 psu isohaline, measured 1 m off bottom and averaged over more than 1 day) is located a minimum distance downstream of the Golden Gate Bridge. Maintaining the isohaline downstream positions the salinity gradient of the estuary in such a way as to provide suitable habitat for many organisms, and investigators have found significant statistical relationships between the longitudinal position of X_2 and numerous estuarine resources, including the total input of organic carbon; the supply of phytoplankton and phytoplankton-derived detritus; the abundance of mysids and shrimp; the survival of striped bass and striped bass year class strength; the survival of salmon smolts; and the abundance of planktivorous, piscivorous, and bottom-foraging fish (Kimmerer and Schubel 1994; Jassby et al. 1995). Note that these connections are operative and the causal mechanisms remain largely unresolved.

Salinity is related to freshwater inflow.

In addition to relating X_2 to resources, it was also necessary to relate it to freshwater inflow. As might be expected, salinity in San Francisco Bay is related to freshwater inflow, and X_2 can be correlated with estimated outflow from the delta of the Sacramento and San Joaquin Rivers (Kimmerer and Schubel 1994). However, there was considerable debate over whether to set the standard based on freshwater flow or location of X_2. In the end, the location of the isohaline was selected because the geography of the estuary and water delivery prevents direct measurement of flow, resulting in a high degree of uncertainty, particularly at low flows (Kimmerer and Schubel 1994). X_2 is therefore used because it is a direct measure of salinity in the estuary, and hence San Francisco Bay is used here as an example of a condition-based index.

San Francisco Bay provides an example of a science-based policy set with the help of informed citizens.

The scientific basis for the San Francisco Bay inflow policy is reviewed in greater detail elsewhere, along with the process used to utilize this information as part of the regulatory framework (Kimmerer and Schubel 1994; Jassby et al. 1995; Kimmerer, submitted). This represents an excellent example of the joint power of scientific consensus and public education in setting inflow levels. The fact that X_2 was linked to a range of estuarine components at all trophic levels, that there was agreement on the relationship between inflow and salinity, and that there was general understanding among stakeholders that X_2 was a meaningful indicator of habitat quality enabled this to work. This type of consensus-building among all parties provides a useful example for the development of a similar index in other systems.

Resource-based approach

Resource-based approaches can focus on sensitive indicators and/or on resources valued by society.

Resource-based approaches for managing inflow involve providing suitable environmental conditions for an important resource or set of resources. However, there is a distinction to be made between indicators, which are key species or habitat types that are particularly sensitive to estuarine conditions, versus valued resources, as identified by society. Although they can be one and the same, those resources that are sensitive and might be considered good indicators of estuarine conditions are not always the ones that the public values. Conversely, those resources that the public values might be less sensitive to change. Below we use two examples from The South Florida Water Management District (SFWMD) to illuminate this contrast.

Loxahatchee River and Estuary

Proposed inflow to the Loxahatchee River in South Florida was based on the distribution of cypress, a valued resource.

The SFWMD takes a resource-based approach for setting inflow requirements, following the valued ecosystem component method described above. In the Loxahatchee River and Estuary, bald cypress, *Taxodium distichum*, was identified as the key species to be protected against significant harm. The upstream freshwater portion of the river is comprised of largely pristine cypress-river swamps, including a number of trees within the 300-400 year old range (SFWMD 2001). Many people enjoy canoeing and other recreational activities in this part of the river, and identify cypress with the system. The trees serve to stabilize the shoreline and they provide habitat for many other plants and animals, including epiphytic plants and nesting birds (threatened osprey nest in dead trees). Moreover, the cypress and the associated freshwater flood plain community have high plant diversity. In proposing a minimum flow for this system, the assumption was made that maintaining suitable environmental conditions for cypress would also be important for other desirable species (SFWMD 2001).

Proposed inflow standards for the Loxahatchee were chosen to maintain low salinities in cypress stands.

The upstream reaches of the Loxahatchee currently have standing dead cypress trees, which provide evidence of an upstream shift in cypress distribution. This change in distribution has been linked to an increase in salinity and invasion by mangroves (SFWMD 2001). The proposed minimum flow for the Loxahatchee sought to maintain salinities at less than 2 (identified as a critical value for cypress) at a given position in the estuary in order to prevent further upstream encroachment of mangroves. In keeping with the requirements of Florida's legislation for setting Minimum Flows and Levels, this proposal was evaluated by an external scientific review panel. The review panel identified a potential problem in that, although high salinity can kill cypress, their response is not well-quantified. In addition, cypress are long-lived and slow-growing, so it may be many years before they would show a change in response to a change in inflow. Therefore, although cypress is a valued resource, it is not necessarily a good choice for setting management objectives. This proposal is currently under revision by the District.

Caloosahatchee Estuary

Proposed inflow to the Caloosahatchee Estuary in Florida was based on indicator species that are sensitive to salinity.

In contrast to the Loxahatchee River and Estuary, the proposed minimum flow for the Caloosahatchee Estuary was based on the distribution of indicator species. In this case three species of seagrass (*Vallisneria americana*, *Halodule wrightii*, and *Thalassia testudinum*) were identified as key species that provide important benthic habitat for juvenile estuarine and marine species. These seagrasses are sensitive to changes in salinity, and maintaining their distribution patterns along the longitudinal axis of the estuary was proposed as an overall indicator of estuarine health. The SFWMD did a combination of field and laboratory research to determine the salinity sensitivity of the various seagrasses, and their results were then combined with modeling and hydrologic studies to determine the flow rates needed to maintain target salinities within the estuary (Doering, submitted). Although the plants being used are sensitive indicators of estuarine salinity, and do in fact offer protection and foraging for many other organisms, they are not readily identified by the public and do not represent a resource that is highly valued by society. Instead, the case is made that if they are protected, conditions will also be suitable for other organisms, and Chamberlain and Doering (1998) describe how the optimal flows determined for the seagrasses will also be beneficial for fish, shellfish and other resources. Once again, it was necessary to link the resource chosen by the scientists to those valued by society, and to provide this information to the public.

Inflow can also be linked directly to valued resources, rather than via estuarine conditions.

Texas

It is also possible to link inflow directly to valued resources. As described above, there are numerous examples where inflow has been related to the catch of commercial fish and shellfish species. These correlations do not get at mechanisms, but a direct link offers firm ground for establishing inflow requirements. This direct approach forms the basis of the approach taken in Texas, which has evolved over the past 50 years.

Texas law mandates that inflow be maintained so as to protect valued estuarine resources.

It is instructive to begin with the Texas legislation, which mandates that: "For permits issued within an area that is 200 river miles of the coast… the commission shall include in the permit... those considerations necessary to maintain beneficial inflows to any affected bay or estuary" (Texas Water Code 11.147b). Beneficial inflows are defined as "a salinity, nutrient, and sediment loading regime adequate to maintain an ecologically sound environment in the receiving bay and estuary system that is necessary for the maintenance of productivity of economically important and ecologically characteristic sport or commercial fish and shellfish species and estuarine life upon which such fish and shellfish are dependent. " (Texas water code 11.147a).

The resources identified in the legislation formed the basis of the Texas Estuarine Mathematical Programming Model, which seeks to identify those flows that optimize the harvest of valuable fish and shellfish.

The legislation specifically mentions inflow effects on estuarine conditions (salinity, nutrient, and sediment loading), which in turn impact estuarine resources (sport or commercial fish and shellfish species and the life upon which they depend). Note that the identified resources are ones that are generally considered valuable by society. This language was used to guide the development of the Texas Estuarine Mathematical Programming (TxEMP) model, which utilizes a series of relationships between historic monthly inflow and the catch of various fish (black drum, red drum, sea trout), crustaceans (blue crab, white shrimp, brown shrimp) and mollusks (clams, eastern oyster) (Matsumoto et al. 1994; Powell, submitted). The salinity ranges of each organism are considered, and if information on nutrients and sediments is available it can be added as well (Matsumoto et al. 1994). Running the model requires input from managers in terms of which species are included, the relative weighting of the species, fishery harvest targets, and constraints on inflow, salinity, nutrient loading, and sediment loading (Powell and Matsumoto 1994). The model itself is a nonlinear, stochastic, multi-objective model of salinity-inflow and inflow-fishery harvest equations. Model results are in the form of a performance curve, which is a series of solutions that seeks to optimize inflow/harvest relationships. Variability in the inflow/salinity relationship is used to set statistical bounds on salinity. The TxEMP model is now in use as a management tool in Texas (Powell and Matsumoto 1994; Powell, submitted).

The Texas approach is direct and easy to understand, but it is not designed to protect the entire ecosystem.

One of the advantages of the Texas approach is that it is keyed to commercially-important fisheries and thus is easily understood by a range of constituents. It is also straightforward in that it works directly with both inflow and resources, rather than depending on relationships among different compartments. Although these correlations do not get at mechanisms, a direct link offers firm ground for establishing inflow requirements. A disadvantage of this approach is that decisions based on a limited number of species and their habitat requirements can invite solutions that protect the specified resource without regard for the rest of the ecosystem. Conversely, what is good for the ecosystem may not consistently benefit individual species (Sparks 1992). Although it can be argued that the Texas model avoids this in that it simultaneously optimizes the harvest of several species, the focus on commercial and recreational catch may still overlook other resources with different inflow requirements.

Part Three - A Georgia Perspective

Introduction

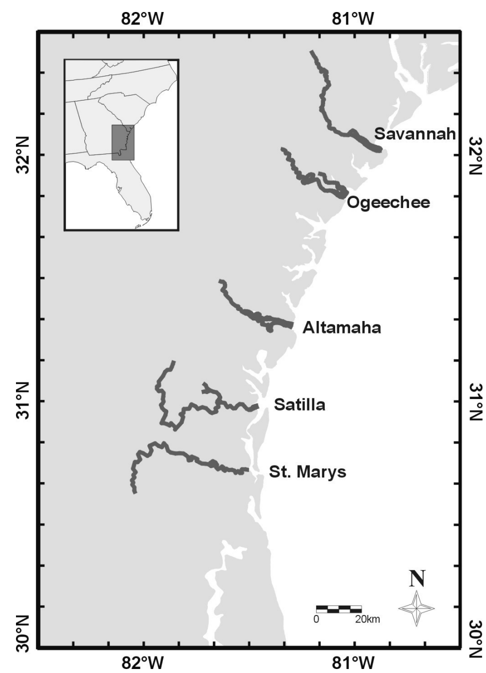
This section provides a brief review of the available information regarding inflow effects on Georgia's riverine estuaries. We present this in the context of the conceptual model presented in Part Two: we first describe the scientific information that addresses freshwater inflow, estuarine conditions, and resources in Georgia, and then provide an overview of the current management framework for regulating inflow.

Georgia has five major riverine estuaries.

Georgia riverine estuaries

Because we are interested in the management of freshwater inflow, this report focuses on the five major riverine estuaries in Georgia. From north to south, they are the Savannah, Ogeechee, Altamaha, Satilla, and St. Marys Rivers (Fig. 3). Substantial proportions of both the Savannah and Altamaha lie in the Piedmont; the Ogeechee lies primarily in the Coastal Plain; and the Satilla and St. Marys rivers lie entirely within the Lower Coastal Plain. These differences in geological setting influence numerous characteristics of the rivers. When compared to Coastal Plain rivers, rivers that originate in the Piedmont tend to be longer, with larger watersheds and steeper gradients in their upper reaches. However, their mouths are located within a 120-mile segment of coast, and thus their estuaries share similar climatic and tidal regimes. The estuaries tend to be vertically well-mixed in all cases except the Savannah, which is routinely stratified. Tides are semi-diurnal, with an average tidal range of 2 m.

Figure 3. Georgia Riverine Estuaries



Freshwater Inflow

Quantity

River discharge is the main source of freshwater to riverine estuaries.

Sources of freshwater for an estuary include river inflow as well as local inputs (precipitation on the estuary surface, local runoff, and groundwater). These additional inputs are usually minimal (e.g. Hagy 1996), and river discharge is generally considered the main source of fresh water to riverine estuaries. Data on river discharge

Disclaimer: This is not meant to be a complete review of the considerable amount of scientific information that has been collected in Georgia estuaries, which is well beyond the scope of this document. Rather, we have worked to identify information that is specifically focused on inflow issues. Even within this narrowed focus, we have undoubtedly missed some material and have relied on examples from our own work because they were readily available. We therefore want to take this opportunity to solicit additional input so that we can update this document as appropriate. This is meant to be a living document, and updated versions will be available in PDF format at the Georgia Coastal Research Council web site (http://www.marsci.uga.edu/coastalcouncil).

into the Georgia estuaries are readily obtainable from USGS Water Resources Data for the State of Georgia (http://ga.water.usgs.gov/). The period of record for the Georgia rivers dates back to at least 1937 in all five rivers, and as early as 1926 in the St. Marys. In order to estimate river inflow into the Georgia estuaries, we routinely use the most downstream discharge gaging stations in the main channels and add, where possible, discharge from gaged tributaries that enter the estuary below the main gages

Table 2. USGS Gaging Stations Used to Estimate Inflow to Georgia Estuaries.

Basin / Sub-Basin	Hydrologic Unit Code	Gage Number	Gage Location	Latitude (N)	Longitude (W)	Drainage Area: Station[1] (km^2)	Drainage Area: Basin[2] (km^2)	Drainage Area: % Gaged	Period of Record (to present)
Savannah									
Lwr Savannah	03060109	02198500	Savannah R. near Clyo	32° 31' 30"	81° 15' 45"	25511			1929
Lwr Savannah	03060109	02198690	Ebenezer Cr. at Springfield	32° 21' 56"	81° 17' 51"	469			1990
Total:						25980	27001	0.96	
Ogeechee									
Lwr Ogeechee	03060202	02202500	Ogeechee R. near Eden	32° 11' 29"	81° 24' 58"	6863			1937
Lwr Ogeechee	03060202	02202600	Black Cr. near Blitchton	32° 10' 04"	81° 29' 18"	601			1980
Canoochee	03060203	02203000	Canoochee R. near Claxton	32° 11' 05"	81° 53' 20"	1437			1937
Total:						8902	11620	0.77	
Altamaha									
Altamaha	03070106	02226000	Altamaha R. at Doctortown	31° 39' 16"	81° 49' 41"	35224			1931
Altamaha	03070106	02226100	Penholoway Cr. near Jesup	31° 34' 00"	81° 50' 18"	544			1958
Total:						35768	36961	0.97	
Satilla									
Satilla	03070201	02228000	Satilla R. at Atkinson	31° 13' 16"	81° 52' 03"	7226			1930
Total:						7226	8965	0.81	
St. Marys									
St. Marys	03070204	02231000	St. Marys R. near Macclenny, FL	30° 21' 31"	82° 04' 54"	1813			1926
Total:						1813	3486	0.52	

[1]Area of basin upstream of gage
[2]Total area of basin above head-of-tide (Alice Chalmers, pers. comm.)

(Table 2). Ungaged area comprises only a small portion of the Altamaha and Savannah rivers (3 and 4%, respectively), relatively more of the Satilla and Ogeechee rivers (19 and 23%, respectively), and 48% of the St. Marys river. Discharge is then corrected for ungaged area within each basin by multiplying gaged discharge by a factor equivalent to the ratio of total to gaged area. There are large differences in the median discharges into the five Georgia estuaries (Table 3).

Table 3. Discharge Statistics for Georgia Estuaries.

River	Min	10^{th}	50^{th}	90^{th}	Max
Savannah	86	182	263	656	2512
Ogeechee	4	14	60	275	1555
Altamaha	41	90	244	957	3907
Satilla	1	4	31	222	1546
St. Marys	1	2	12	85	1486

Minimum, maximum, 10^{th}, 50^{th}, and 90^{th} percentile flows ($m^3 s^{-1}$) were calculated from daily mean discharges at the most downstream USGS gaging stations on each river, corrected for ungaged watershed areas below the gages. Data are for water years 1951-2000..

The five estuaries receive varying amounts of river water.

As expected, discharge is much slower from the two coastal plain rivers, the St. Marys (12 m^3s^{-1}) and the Satilla (31 m^3s^{-1}), than from the larger Piedmont-originating rivers, the Savannah (263 m^3s^{-1}) and the Altamaha (244 m^3s^{-1}), with the Ogeechee (60 m^3s^{-1}) falling in between. (Discharge is highly skewed in these rivers, so medians were used instead of averages as a descriptor of the central tendency.) Corrected discharge for the period of record for each of the Georgia estuaries is presented in Figure 4. Vertical lines represent the years when various dams began operating. There are no significant linear trends in discharge in any of these rivers over time.

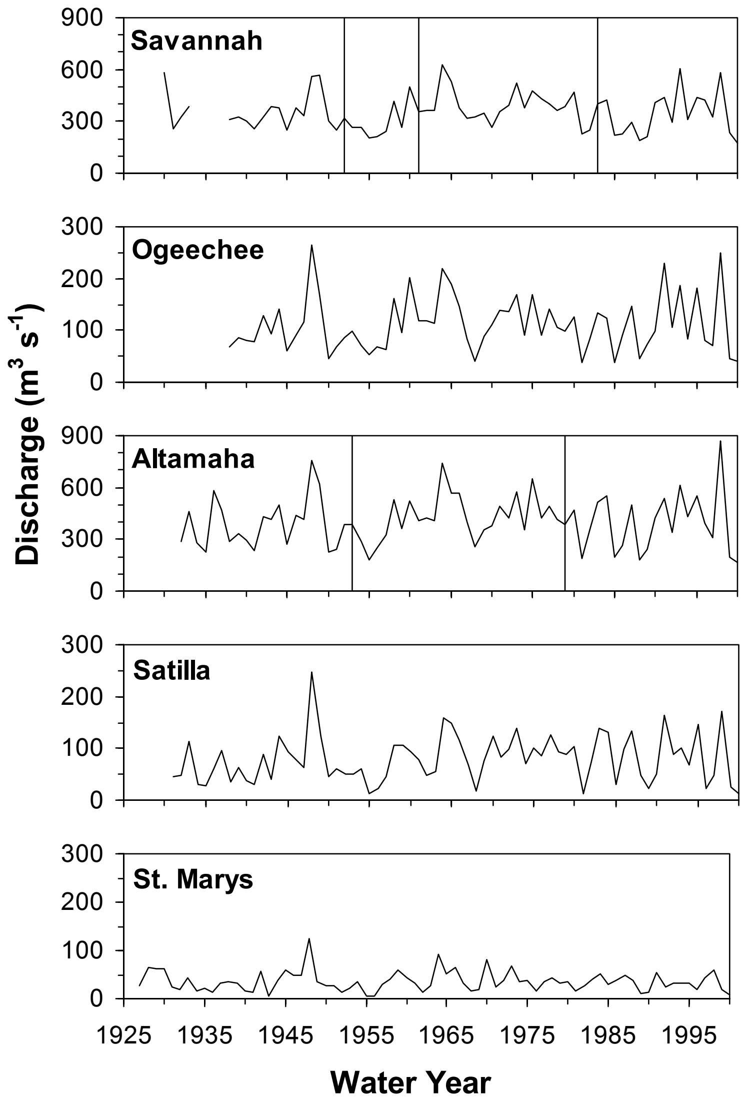
Timing

There is considerable inter- and intra-annual variability in discharge in all of these estuaries, which underscores the importance of evaluating a range of flow conditions rather than ascribing one steady-state median flow to a system. All five estuaries exhibit at least a 29-fold inter-annual difference between minimum and maximum discharge (Table 3). In the record (Fig. 4), drought and flood years can be readily seen (e.g. the beginning of the current drought is seen as a decreased discharge in 1999-2000 in all rivers).

River discharge varies within a year as well as between years.

At the intra-annual scale, freshwater inflow undergoes a regular seasonal cycle. The 50-year monthly median discharge within each estuary is shown in Figure 5. There are seasonal maxima in discharge during the spring and minima in the fall. The discharge patterns change slightly from north to south, with a secondary maximum in August in the

Figure 4. Discharge to Georgia Estuaries.



Graphs depict water-year-averaged discharge for the period of record. Vertical lines indicate years in which dams were completed.

There is evidence that the timing of freshwater inflow to the Altamaha River Estuary has changed.

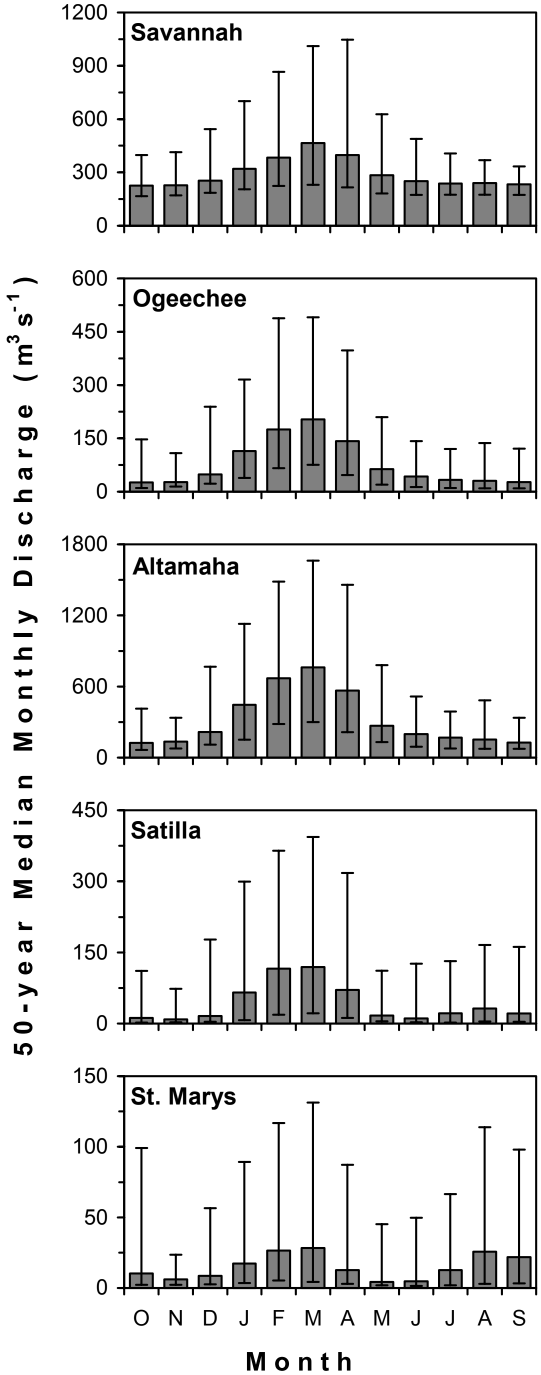
Flow to the Satilla River Estuary may have changed as well.

Satilla and St. Marys. The August peak in discharge coincides with a peak in rainfall in the southeastern part of the state (Plummer, 1983).

There are also more sophisticated analyses that could be performed to evaluate more subtle changes in the timing of freshwater inflow. The Indicators of Hydrologic Alteration (IHA) trend-analysis method, developed by Richter et al. (1996) for The Nature Conservancy, examines daily flows for characteristics such as changes in the timing and magnitude of high and low flows. When applied to the Altamaha, the analysis revealed greater daily water level fluctuations now than in the past, but no alterations in the timing of floods. However, baseflow conditions during the low flow period of the year have dramatically declined. This decline appears to be the result of regional climate variability (Shaw, 2001).

An IHA analysis of the Satilla River flow indicated statistically significant increases in winter maximum and minimum flows and in measures of both the slope of the hydrograph and high-pulse behavior (Elkins, 2000). A second analysis of Satilla River flow, also by Elkins (2001) was performed using a hydrographic yield calculation modeled after the method of Changnon et al. (1996) and Moglen and Beighley (submitted), which can help assess the impacts of urbanization on runoff characteristics for a basin. The hydrographic yield (a ratio of runoff to precipitation) after typical storm events was calculated for storms between 1948 and 1998. The ordered set of these values was then analyzed on a seasonal basis and, again, the most striking results were observed

Figure 5. Monthly Discharge to Georgia Estuaries.



Pattern of monthly river discharge into the Georgia estuaries over 50 water years (1951-2000). Values shown are medians, 10th and 90th percentiles.

for winter storms, which had a marked increase in the variability of yield values. As hydrographic yield is strongly influenced by land use, this pattern suggests that seasonally changing land uses (or land uses in which the land cover changes on a seasonal basis) may significantly affect runoff patterns in the Satilla basin.

Quality

The most complete information on the quality of the river water entering Georgia estuaries is from USGS.

The most complete data set for the quality of water as it enters the Georgia estuaries comes from USGS, and much of this information was compiled on a compact disc produced by EarthInfo (1997). Although sampling programs and analysis protocols varied among rivers and over time, there are at least some measurements of the concentrations of inorganic and organic nutrients (nitrogen, phosphorus, carbon) as well as total suspended sediment for the most downstream station in each of the five Atlantic coast rivers in Georgia (Table 4). This represents a near-complete record of dissolved nutrients for these stations. Sampling was carried out for an additional year in the Satilla and an additional 6 months in the Ogeechee, and then these analyses were discontinued. Total nutrients are still being measured at some of these sites (dissolved plus particulate). The complete data set is available at the USGS web site (http://waterdata.usgs.gov/nwis/qwdata).

Table 4. USGS Water Quality Data

River	Station	Code	Parameter	# Obs	Period
Savannah	02198500	608	NH4 (dissolved)	77	10/04/1979 - 09/30/1994
	Clyo	631	NO3+NO2 (dissolved)	76	10/04/1979 - 09/30/1994
		671	PO4 (dissolved)	54	11/04/1981 - 09/30/1994
		80154	Total suspended sediment	144	01/17/1974 - 09/30/1994
Ogeechee	02202500	608	NH4 (dissolved)	100	10/09/1979 - 11/16/1994
	Eden	631	NO3+NO2 (dissolved)	99	10/09/1979 - 11/16/1994
		671	PO4 (dissolved)	77	10/26/1981 - 11/16/1994
		80154	Total suspended sediment	184	04/02/1974 - 09/01/1992
Altamaha	02226000	608	NH4 (dissolved)	1	06/19/1974 - 06/19/1974
	Doctortown	631	NO3+NO2 (dissolved)	3	05/30/1974 - 06/19/1974
		671	PO4 (dissolved)	1	06/19/1974 - 06/19/1974
		80154	Total suspended sediment	58	04/03/1974 - 10/13/1977
Altamaha	02226010	608	NH4 (dissolved)	0	
	Gardi	631	NO3+NO2 (dissolved)	0	
		671	PO4 (dissolved)	0	
		80154	Total suspended sediment	2	04/06/1976 - 04/27/1976
Satilla	02228000	608	NH4 (dissolved)	73	10/10/1979 - 09/02/1992
	Atkinson	631	NO3+NO2 (dissolved)	74	10/10/1979 - 09/02/1992
		671	PO4 (dissolved)	51	07/09/1980 - 09/02/1992
		80154	Total suspended sediment	156	01/10/1974 - 09/02/1992
St. Marys	02231000	608	NH4 (dissolved)	36	05/16/1978 - 08/19/1986
	Mcclenney	631	NO3+NO2 (dissolved)	37	05/16/1978 - 08/19/1986
		671	PO4 (dissolved)	25	05/16/1978 - 08/19/1986
		80154	Total suspended sediment	96	01/15/1974 - 05/28/1986

Source: EarthInfo, 1997.

Inorganic nutrients

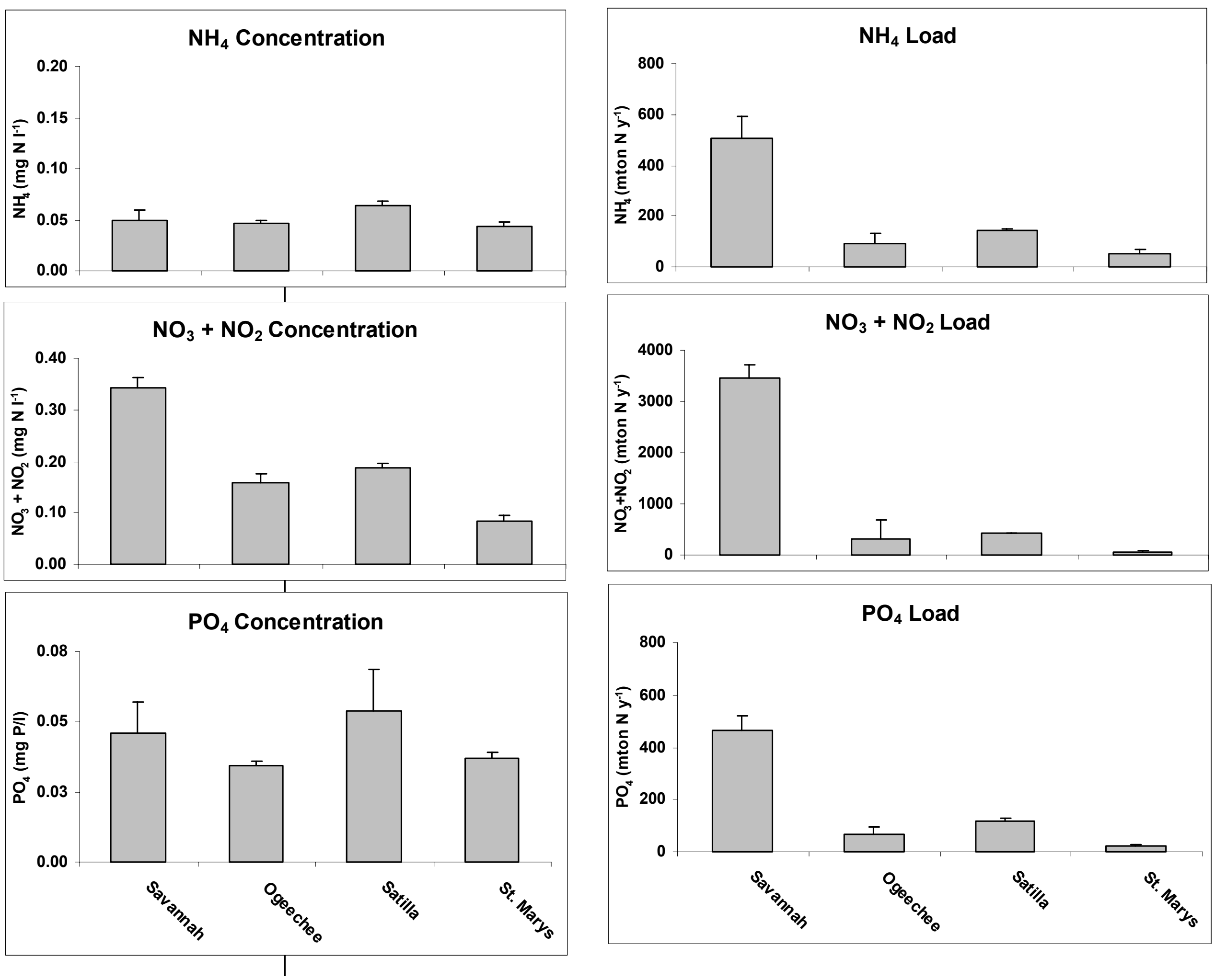
USGS dissolved inorganic nitrogen and phosphorus information was compiled.

Data on dissolved inorganic nutrient concentrations available in the EarthInfo data set were compiled to get information on the concentrations of nutrients entering Georgia estuaries. In the Savannah and the Ogeechee rivers, dissolved inorganic nitrogen (NH_4, NO_3+NO_2) records are available from 1979 through 1994 and dissolved orthophosphate (PO_4) records are available from 1981 through 1994. Sampling for these constituents in the Satilla ended in 1992, and in the St. Marys sampling was even more limited, ending in 1986. In the Altamaha, water quality is sampled at gage #02226010 (near Gardi), but these data were not used in the present analysis because a different methodology is used (total rather than dissolved nutrients are analyzed).

Ammonium and phosphate concentrations were similar among rivers, whereas nitrate was more variable.

Inorganic nutrient concentrations were variable but did not show trends over time, nor were there obvious seasonal differences (data not shown). With the exception of NO_3+NO_2, which was highest at the head of the Savannah and lowest in the St. Marys, there were no differences among rivers in terms of nutrient concentrations (Figure 6). Overall, NH_4 concentrations averaged between 0.04 and 0.06 mg N l^{-1} and PO_4

Figure 6. Dissolved Inorganic Nutrient Concentrations and Loads to Georgia Estuaries.



Source: EarthInfo 1997 (summary of observations described in Table 4.)

concentrations averaged between 0.03 and 0.05 mg P l^{-1} in all rivers. NO_3+NO_2 concentrations ranged from 0.08 ± 0.03 mg N l^{-1} in the St. Marys to 0.34 ± 0.15 mg N l^{-1} in the Savannah.

Nutrient loads were greatest in the Savannah, which has the highest discharge.

Average nutrient concentrations were multiplied by average discharge (obtained from the USGS web site {http://ga.water.usgs.gov/}) to estimate the load of dissolved inorganic nutrients entering each river (Fig. 6). Because nutrient concentrations did not vary greatly among rivers, differences among these loads are driven by differences in discharge. It is therefore not surprising that the largest river represented by these observations, the Savannah, has the highest amount of inorganic nutrients entering the estuary. Although, as mentioned above, the Altamaha River was not included in these data, it would be interesting to compare the nutrient load in the Altamaha with that in the Savannah. As part of the Georgia Coastal Ecosystems Long Term Ecological Research (GCE-LTER) project, measurements of nutrient concentrations entering the Altamaha began in 2001. These data are being compiled for publication (Joye et al., in prep.) and will be available on the GCE-LTER web site (http://gce-lter.marsci.uga.edu/lter/).

USGS information on dissolved organic material was also examined…

Dissolved organic material.

A similar compilation of information on the concentrations of dissolved organic carbon (DOC) and nitrogen (DON) was performed by Alberts and Takacs (1999) (Table 5). They reported average DOC concentrations ranging from 5 ± 2 mg C l^{-1} in the Savannah to 28 ± 12 mg C l^{-1} in the St. Marys. DON concentrations ranged from 0.34 ± 0.24 mg N l^{-1} in the Savannah to 0.66 ± 0.26 mg N l^{-1} in the St. Marys, and represented between 49 and 91% of the total dissolved nitrogen entering these estuaries. When these concentrations were combined with discharge to estimate loads, an overall average of 32.4 ± 8 thousand tonnes DOC per year and 28 ± 10 hundred tonnes DON per year were estimated to enter southeastern estuaries.

Table 5. Dissolved Organic Carbon and Nitrogen Concentrations Delivered to Georgia Estuaries.

River	DOC (mg C/l)	DON (mg N/l)
Altamaha	8.01 ± 2.88	0.35 ± 0.16
Ogeechee - Eden	8.96 ± 4.60	0.52 ± 0.33
Ogeechee - Oliver	8.59 ± 4.43	0.39 ± 0.24
Satilla	19.05 ± 8.03	0.75 ± 0.33
Savannah	5.03 ± 2.20	0.34 ± 0.24
St. Marys	27.94 ± 11.68	0.66 ± 0.26

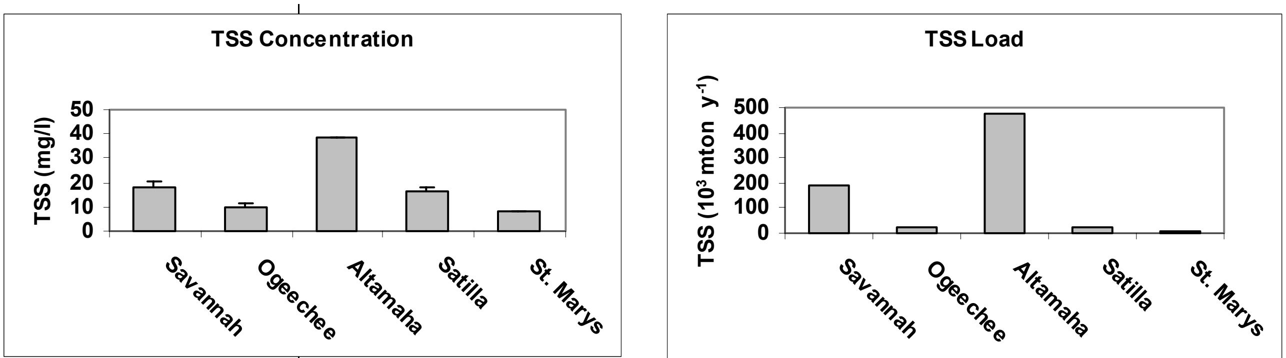
Source: Alberts and Takacs 1999

Suspended sediment.

…as were suspended sediment concentrations.

Finally, total suspended sediment (TSS) concentrations were also measured at these sites. TSS concentrations were again variable, with no obvious trends over time or seasonal differences. Average concentrations ranged from 8 ± 15 mg l-1 in the St. Marys to 38 ± 67 mg l-1 in the Altamaha (Fig. 7). When combined with discharge, sediment loads were highest in the Altamaha, which is a high-discharge river. Those in the Savannah were not quite as high, which is likely the result of upstream flow regulation due to the operation of dams. It should be noted that the observations in the Altamaha were quite limited and only range from 1974 to 1977. It would be extremely useful to obtain updated TSS information for this system.

Figure 7. Total Suspended Sediment Concentrations and Loads to Georgia Estuaries.



Source: EarthInfo 1997 (summary of observations compiled in Table 4).

Estuarine Conditions

Once water enters an estuary, we need to relate that inflow to estuarine conditions. Although many studies look at water quality, sediment type, etc., this information is not usually related to flow. In Appendix A, we provide a list of data sources that are available for the Georgia riverine estuaries, but in this section we focus on the limited work that has been done to relate this information to inflow.

Transit times were calculated for Georgia estuaries.

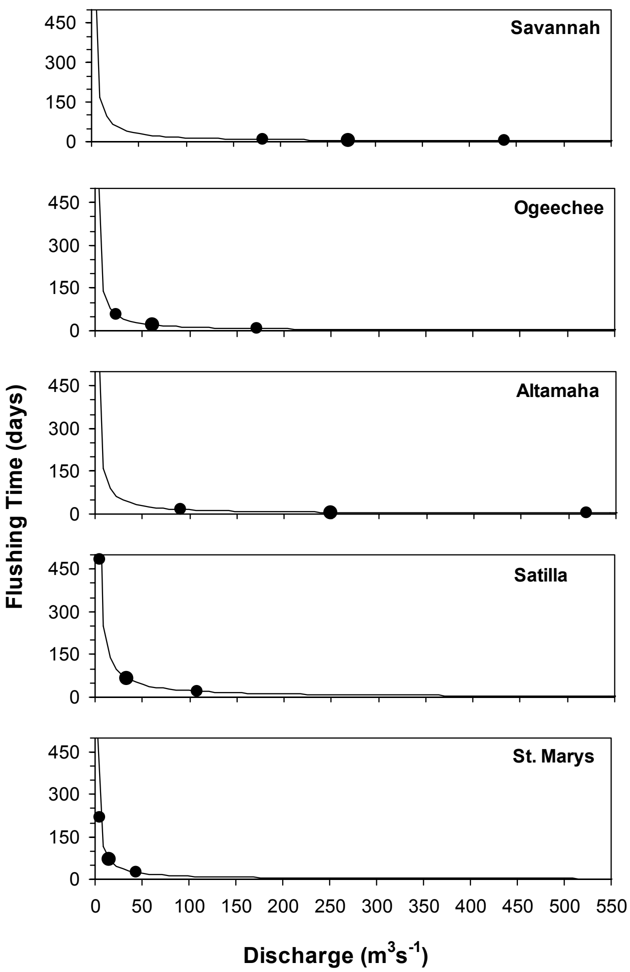
Transit time

The transit (or flushing) time of an estuary is the amount of time fresh water (in riverine estuaries this is primarily river water) spends in the system. As described in Part One, one of the impacts of reducing flow to an estuary is that transit times increase. Flushing times for the Georgia estuaries were calculated by Alber and Sheldon (1999) using a modification of the fraction of freshwater method (Dyer, 1973), which calculates flushing time of an estuary based on the amount of fresh water in the estuary and river discharge. Median flushing times over a 30 year period (1968-1997) were as follows: Savannah (5.6 d), Ogeechee (20.7 d), Altamaha (5.8 d), Satilla (66.8 d), and St. Marys (71.6 d), although there was considerable inter- and intra-annual variability in these estimates.

The transit times of the five estuaries have differing sensitivity to changes in river flow.

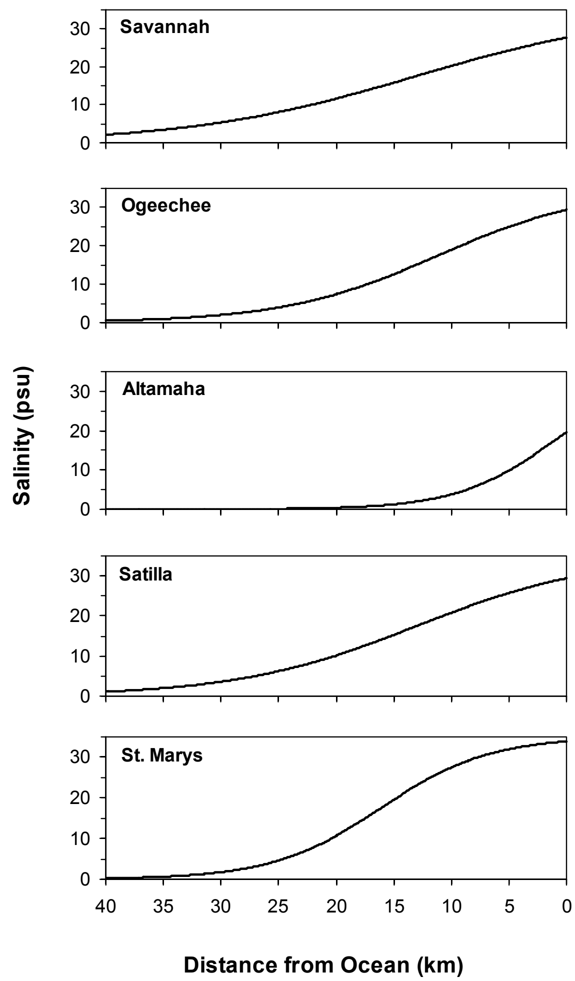
When the flushing times of the five rivers are compared (Fig. 8), what is immediately clear is that the consequences of changes in discharge depend on where the operative discharge range falls on the curve. Flushing times do not change rapidly in the two estuaries with the fastest discharge rates (Altamaha, Savannah), so despite very large ranges in their observed annual median discharge (90 - 519 m^3s^{-1} in the Altamaha), there are only slight changes in flushing time (2.8 - 16 d). In contrast, the operative ranges for the other three estuaries are on the steep part of the curve, so that small changes in discharge (4.6 - 108 m^3s^{-1} in the Satilla) result in very large changes in flushing time (20.8 - 482.9 d). The estuaries with faster discharge rates are therefore less sensitive to changes in flow. Another point that is evident from the shape of these curves is that the flushing time calculation is more sensitive to decreases in discharge than it is to increases. For example, a 20% decrease in discharge results in a 25% increase in flushing time, whereas a 20% increase in discharge results in only a 17%

Figure 8. Transit Times



General theoretical relationships between flushing time and discharge in the five Georgia estuaries. Symbols show minimum, median, and maximum annual-scale median values over 30 water years (1968-1997). Source: Alber and Sheldon.

Figure 9. Average Salinity



Logistic fit of average mid-tide salinities in the five Georgia estuaries based on cruises conducted from 1994-1999.

decrease in flushing. In an absolute sense, however, the observed change in flushing will be smaller at high flows where the curve is relatively flat as compared with low flows.

Average salinity distributions were estimated for each estuary.

Salinity distribution

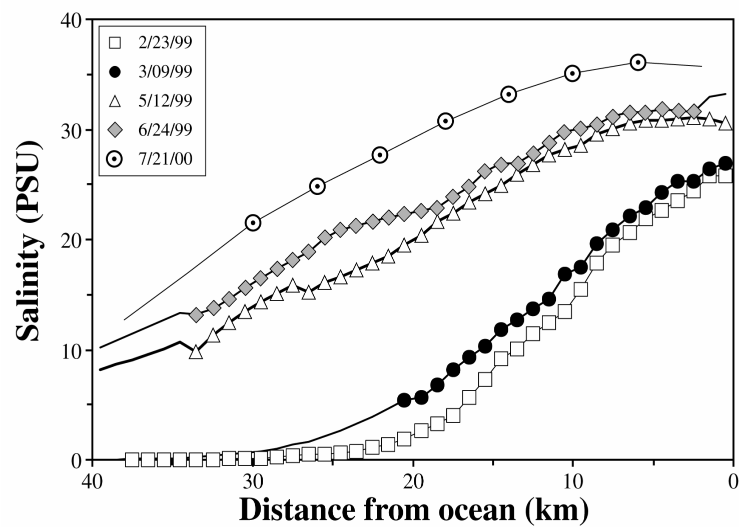
The distribution of salinity along an estuarine gradient is one of the most fundamental descriptors of an estuary because so many other characteristics are linked to salinity. Over the course of the Georgia Rivers Land Margin Ecosystem Research Program (LMER), salinities were measured in each of the five estuaries on cruises conducted over the period 1994 - 2000. Logistic curves could be fitted to the average mid-tide salinities to show the general shape of increasing salinity as one moves upstream in the estuary (Fig. 9). These average curves vary among rivers in terms of their shapes as well as their end-members. Average salinity at the mouth of the St.

Marys River was almost 34 psu over the course of these observations (likely due to dredging of the Kings Bay Channel), whereas salinity at the mouth of the Altamaha was close to 20. Salinity also dropped to 0 fairly quickly in the Altamaha, whereas in the other rivers the salt penetrated considerably farther upstream.

Salinity distribution varies with river flow, as can be seen in the Satilla.

The above paragraph describes average salinity conditions for each estuary. However, the salinity profile of an estuary clearly varies with river flow. A good example of this can be seen in a series of intensive observations conducted in the Satilla River by Blanton et al. (2001). Between February 1999 and July 2000 a series of five intensive surveys were undertaken. Over the course of these observations, freshwater discharge varied 8-fold, from almost 150 m^3s^{-1} in February 1999 (twice the average) to below 10 m^3s^{-1} in May and June 1999, with consequent impacts on the salinity regime of the Satilla River Estuary. The salinities observed during the surveys shifted significantly, with the location of 15 psu varying from approximately 10 km from the mouth during high discharge to further than 35 km during low flow (Fig. 10). Thus, the estuary and its habitats experienced large changes in the salinity regime over a period of a few months. These data also show how different the salinity distribution can be during a drought, as evidenced by the observations obtained in July 2000.

Figure 10. Salinity Distributions in the Satilla River Estuary.



Salinity distributions at mid-tide. All transects represent surface salinities except 7/21/00, which is average water column salinity. Source: Blanton et al., 2001.

There are several new efforts to measure salinity in the Georgia estuaries.

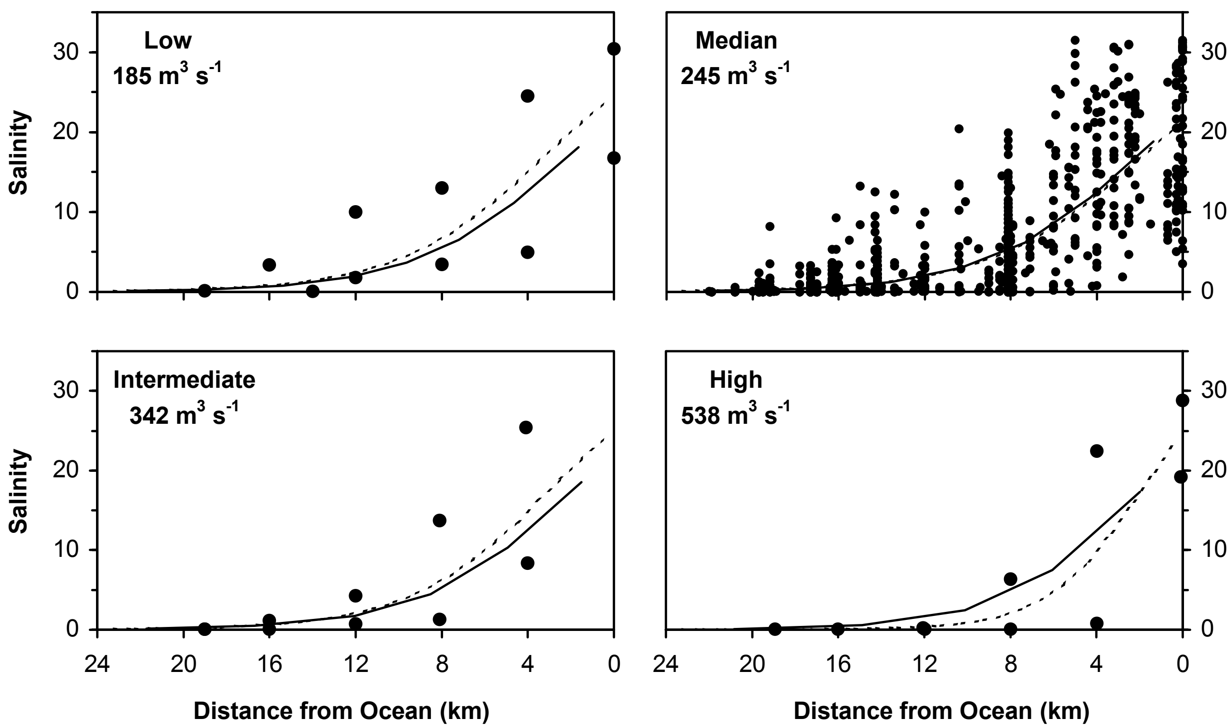
In recent years, there have been several programs that have placed moored instrumentation in the Georgia estuaries. These instruments are gathering continuous data on salinity as well as other oceanographic parameters, all of which will be useful for gaining a better understanding of salinity distributions and their responses under differing conditions. This includes intensive observations conducted in both the Satilla and the Ogeechee Rivers as part of GA Department of Natural Resources -- Coastal Resources Division (CRD)-funded research by Jack Blanton and colleagues at Skidaway Institute of Oceanography; moored instruments and regular surveys conducted by the UGA Marine Extension Program, again funded by CRD; information collected as part of the Georgia Rivers LMER Project: and ongoing monitoring as part of the GCE-LTER. Further information on each of these projects is provided in Appendix A.

Modeling

Models are useful tools to understand how changing inflow affects estuarine conditions such as salinity.

Models are an increasingly common way of linking observations of estuarine conditions to inflow. We have recently developed a desktop modeling tool (SqueezeBox [Alber and Sheldon, 2002]) that provides a readily accessible way to assess how changes in freshwater inflow will affect the salinity in an estuary. Although this is a simple box model, it represents an improvement over traditional models because it recognizes that discharge is variable and it incorporates daily changes in river flow. Model output includes information about salinity and residence time in the estuary, and it can be used to simulate transient conditions such as that following a pulse input of dissolved substances. It also provides information on the transit times and distributions of conservative constituents, which can be compared against observations of non-conservative materials such as nutrients.

Figure 11. SqueezeBox Salinity Predictions for the Altamaha River Estuary



Altamaha River Estuary salinity predicted by SqueezeBox (solid lines) compared with logistic curves (dotted lines) derived from field observations (circles). Source: Sheldon and Alber, in press.

A simple model is now available to relate changes in inflow to salinity in the Altamaha.

SqueezeBox has been applied first to the Altamaha River Estuary, and a comparison of model predictions and field observations of salinity for four different flow cases is shown in Figure 11. This type of salinity distribution can be generated for any given flow, and we are in the process of extending the model so that it can provide salinity information for variable flow as well. We are also working to develop a module for the Ogeechee River Estuary to provide similar types of information for that system.

Another, more sophisticated modeling effort is under way under the auspices of the Georgia Sea Grant College Program. This is a 3-D hydrodynamic model developed by Dr. Changsheng Chen for the Satilla River estuary, which will be extended to other Georgia estuaries as well. The model uses water quality data being collected by the UGA Marine Extension Service, and the development of a water quality layer is planned. More information on this effort can be found on the Georgia Sea Grant web site: http://www.marsci.uga.edu/gaseagrant/pdf/Chen.pdf.

Estuarine Resources

Water quality conditions clearly affect estuarine resources, and there are certainly resource data available for the Georgia estuaries. However, there have been very few direct efforts to tie these observations to inflow. As above, this section focuses on cases where inflow has been related to resources. Additional sources of resource data are listed in Appendix A, and it may be possible to relate this information (e.g. on the distributions of organisms such as oysters, shrimp) to inflow and/or conditions.

***Crab catch can potentially be related to freshwater inflow*.**

Crabs

Rogers et al. (1990) did an analysis of the Georgia blue crab stock in which they gathered crab catch information from several sources, standardized the data, and then did statistical analyses to examine the relationship between crab catch and discharge. Specifically, they looked at the relationship between harvest and cumulative discharge from each of the five Georgia rivers for the nine-month period from September through May when these crabs would have been developing. Although they were able to find some significant relationships, these were not consistent (e.g. annual harvest increased with increasing discharge in the Savannah and decreasing discharge in the Satilla) and were not found for the entire time period examined. These authors concluded that it was potentially possible to relate inflow to crab harvest and proposed a number of further analyses that would help to refine this effort.

Salinity distributions can potentially be related to fish requirements.

Fish

CRD has collected information on shad landings since 1978. The results of 10 years of monitoring the population dynamics of American shad in the Altamaha River (1982-1991) were summarized by Michaels (1993). One of the findings in this report was a statistically significant linear relationship between population estimates of juvenile shad in the river and the average flow of water at Doctortown for the months of May and June. Interestingly, this relationship was not observed for earlier or later months. Michaels (1993) points out that since shad spawn during April, May and June are probably a critical time during which year-class strength is set. It should be noted, however, that there is not a strong relationship between juvenile and adult shad, so flow could not be used to predict the abundance of adults.

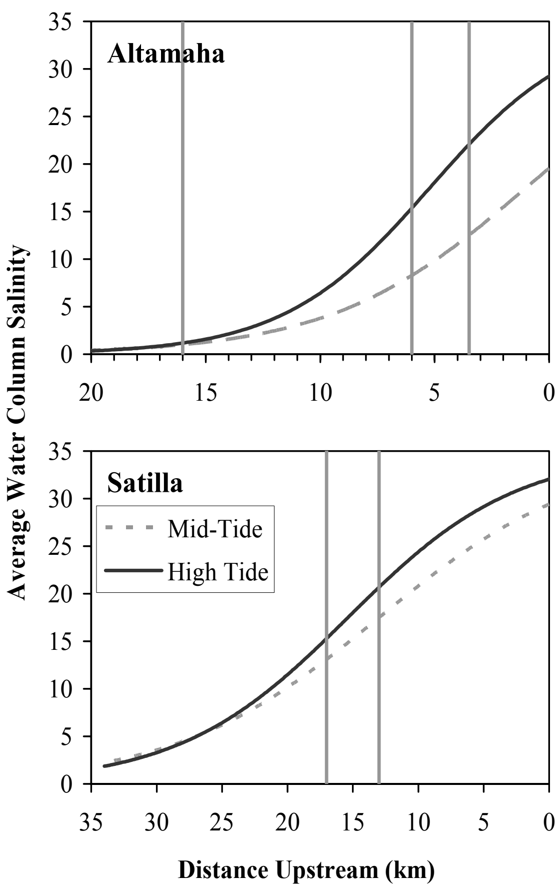
We have recently begun discussions with the Environmental Protection Division of the DNR regarding the potential to use the salinity requirements of fish as a means to understand how changing inflow can affect fish. We have provided them with information on salinity distributions in the Altamaha under various flows (e.g. Figure 11, above), which they may be able to relate to fish habitat. This can be done by using fish survey data (e.g. striped bass and shad surveys), and/or it can be done using literature information on salinity.

***Changes in salinity in the Savannah River Estuary affected marsh plant distribution*.**

Vegetation

Salinity is considered the primary factor controlling the distribution of tidal marsh vegetation in estuaries (Odum 1988), and the growth and production of many marsh plants is inversely related to interstitial salinity (e.g. Nestler 1977). An analysis of the vegetation distribution in the Satilla and Altamaha rivers was conducted using aerial photographs and GIS analysis (Smith et al., 2001). Four vegetation classifications were identified and groundtruthed with field surveys: salt marsh (areas containing primarily *Spartina alterniflora*); brackish marsh (*S. alterniflora* and *S. cynosuroides.*), Juncus (*Juncus roemerianus*), and fresh marsh (*Zizania aquatica*, *Zizaniopsis miliacae*, and others). Although the inland extent of each marsh zone was further upstream in the Satilla than in the Altamaha, the borders between both fresh/brackish marsh and brackish/salt marsh vegetation correlated with tidally-averaged high-water salinities in each estuary (Smith et al., [submitted], Fig. 12).

Figure 12. Distribution of Vegetation with Respect to Salinity in Two Georgia Estuaries.



Altamaha	Vegetation Border Salt Marsh/ Juncus	 Salt Marsh/ Brackish Marsh	 Brackish Marsh/ Fresh Marsh
Dist. (km)	3.5	6	16
Salinity			
Mid-tide	12	8	1
High-tide	22	15	1

Satilla	Vegetation Border Salt Marsh/ Juncus	 Salt Marsh/ Brackish Marsh	 Brackish Marsh/ Fresh Marsh
Dist. (km)	13	17	>34
Salinity			
Mid-tide	17	13	<2
High-tide	21	15	<2

Graphs represent average high and mid-tide salinities versus distance in the Altamaha and Satilla River Estuaries (left). Vertical lines represent location of borders between different vegetation zones, as summarized in the tables.

These observations suggest that the upstream penetration of seawater may be an important factor controlling the distribution of marsh vegetation. If this is the case, changes in freshwater flow would be expected to produce a change in the distribution of marsh vegetation along the estuary.

A dramatic example of the effects of changes in the salinity regime in an estuary is provided by the changes that took place in the Savannah River Estuary as a result of the combined effects of a tide gate and a diversion canal in the Back River near the Savannah River National Wildlife Refuge. As an immediate result of these manipulations, the salt wedge was displaced 6-8 miles upstream, resulting in a shift toward more salt-tolerant marsh vegetation and changes in marsh fauna (Pearlstine et al. 1993). When the tide gate and canal were subsequently removed (in 1991 and 1992, respectively), there was a resultant shift in the vegetation back towards a tidal freshwater community. Although the freshwater plant community has not fully recovered, *S. alterniflora* decreased from 49% in 1986 (during the diversion) to 22% in 1993 (one year post-diversion), and the freshwater marsh plant *Scirpus validus* increased from 27 to 51% during the same period. This study demonstrates that vegetation does in fact respond to changes in salinity, with consequent impacts on those organisms that use these areas for food and shelter.

Management framework

Georgia policy

Georgia takes an inflow-based approach to estuarine inflow management.

Georgia does not have an explicit policy for setting freshwater inflow requirements to estuaries. Rather, the mechanisms that are in place to regulate upstream water withdrawal in streams and rivers implicitly set the limit for flow to estuaries. According to the definitions provided in Part Two, above, Georgia therefore uses an inflow-based approach, based primarily on water withdrawal regulations.

***Water withdrawals are regulated by EPD*.**

Water withdrawal permit applications in the state are regulated by the Environmental Protection Division (EPD) of the Georgia Department of Natural Resources. Surface water withdrawal is regulated separately from groundwater. In this report we focus on surface water, as that is most clearly linked to estuarine inflow. However, it should be noted that groundwater is another source of freshwater to coastal systems (see box).

***A word about groundwater*.** Groundwater occurs as surficial groundwater that is close to the surface as well as in deeper aquifers. The connection between surficial groundwater and surface water needs to be considered when evaluating estuarine conditions, as this water can be a source of nutrients as well as fresh water. For example, surficial groundwater was detected entering the Satilla River estuary via thermal infrared technology (M. Joye, pers. comm.). It should also be recognized that the proportion of water delivered as overland runoff versus via groundwater will change with land use.

In terms of water withdrawal, most wells in coastal Georgia pump from the Floridan aquifer. This is a deep aquifer (more than 500 feet deep in Brunswick, rising to less than 300 feet in Savannah) that is enclosed below an impermeable layer and does not reach the surface within the estuaries, but rather further offshore. However, it is possible that there is still diffuse upward leakage between the Floridan aquifer and surface water, and that the amount of upward leakage and/or input from artesian wells has changed over time due to heavy usage of the aquifer. The data on this phenomenon, as well as potential connections to the Miocene aquifer, are limited. For example, there has been speculation that a groundwater seep at Ebenezer Bend in the Altamaha serves as a thermal refuge for shortnose sturgeon.

New information on groundwater is being generated as part of the Sound Science Initiative currently being conducted by the Georgia Geologic Survey. The results from this effort will be used to support development of a final water management strategy, which is scheduled for implementation January 2006. More information about this project can be found on line at: http://ga2.er.usgs.gov/coastal/.

Surface water withdrawal

Permits are required for surface water withdrawals greater than 100,000 gallons per day.

Surface water withdrawal is regulated according to the Official Code of Georgia Annotated (OCGA) 12-5-20, the Water Quality Control Act, which was first enacted in 1964. Permitting began for some municipal and industrial water uses under the Surface Water Control Act (OCGA 12-5-31, enacted in 1977), with the addition of a requirement for agricultural water withdrawal permits in 1988. Currently, any water uses or diversions in excess of 100,000 gallons per day (monthly average) require a permit, whereas withdrawals less than 100,000 gallons per day have neither permitting nor reporting requirements. Water for municipal or industrial use is regulated differently than water for agricultural use, and these are discussed separately below.

Municipal and industrial withdrawals must comply with EPD procedural requirements during the application process,

Permits for municipal or industrial freshwater withdrawals are issued by the EPD Water Resources Branch/ Municipal and Industrial Program. The applicant is required to have a well-defended, justifiable need for water and must meet procedural requirements. These include supplying information as to the source of the supply, the exact location of the withdrawal, system management details (including water quality protections, such as back-flow devices, and water quantity protections, such as a leak detection plan), a long-range plan (to incorporate water conservation programs), and a drought contingency plan.

***and once the permit is granted*.**

Once a permit is granted, water must be used as specified in the permit and the permit itself may not be transferred to another user. The permit holder is required to file an annual water use report on the quantity of water withdrawn, the source of the water, and the nature of its use. In addition, after the 5th year, the permitee must submit a progress report on "actions and/or improvements made to conserve water and reduce water loss." Permit periods are usually limited to 10-20 years; however, shorter periods are permitted under a temporary permit and longer ones are sometimes issued, for example, to a municipality that requires payment on a water supply construction bond. Permits may be lost due to non-use over a two-year period, and during a water shortage the EPD may levy restrictions or modifications on the permitted uses.

Streamflow is also evaluated when considering permit applications for surface water withdrawal…

In addition to the above requirements, EPD also takes streamflow into consideration when evaluating permit applications. State code requires municipal and industrial users to maintain a minimum inflow according to written standards on Low Flow Protection (Rules and Regulations for Water Quality Control 391-3-6-.07), and as long as other conditions are met, EPD will allow permits to be granted until conditions are reached where flow drops below the specified instream flow limit for that stream (see box). However, any additions to these existing withdrawals are subject to regulation.

***…which requires an estimate of streamflow*.**

To determine whether water withdrawal in a given stream is below minimum flow standards, EPD relies on gaged flows for that stream. If the stream is not gaged, it is necessary to extrapolate flows from nearby gaged streams, correcting for differences in watershed area, stream length, etc. There is an effort underway to improve this capability by developing hydrologic models for the river basins in the state.

Georgia's Instream Flow Requirements for Surface Water Withdrawals

"The applicant will be required to pass instream flow at or immediately downstream of the point of withdrawal, diversion or impoundment so long as it is available from upstream. When instream flows drop below the required instream flow at the point of withdrawal, diversion or impoundment, the applicant will be required to pass that upstream flow. The Instream Flow required for new or modified permits in this subsection shall be:

I. The 7Q10 flow, if no unreasonable adverse effects to the stream or other water users will occur from the withdrawal, diversion or impoundment; or
II. The Non-Depletable Flow, as established by the Director, if probable impacts of the withdrawal, diversion or impoundment would occur to other water users; or
III. Other appropriate instream flow limit, as established by the Director"

Definitions

7Q10 – lowest average stream flow expected to occur for seven consecutive days with an average frequency of once in ten years.

Non-Depletable Flow – instream flow consisting of the 7Q10 flow plus an additional flow needed to ensure the availability of water to downstream users. Non-depletable flow is normally calculated by adding the 7Q10 flow to the pro rata share of the downstream withdrawal using the drainage area ratio method.

Withdrawals for agricultural use are subject to different regulations than those for municipal and industrial use.

Agricultural freshwater withdrawal is managed by the EPD Water Resources Branch/ Basin Analysis and Agricultural Program. There are significant differences between the permits issued for agricultural and non-agricultural uses: agricultural permits require no conservation plan during the application process, are transferable, do not expire, are not lost under conditions of non-use, and have no reporting requirements. Although new agricultural permits are subject to low flow protection plans, those granted before June 30, 1991 were grandfathered in and do not have to meet instream flow requirements.

"Farm uses" are defined by the state as:

"…irrigation of any land used for general farming, forage, aquaculture, pasture, turf production, orchards, or tree and ornamental nurseries: provision of water supply for farm animals, poultry farming, or any other activity conducted in the course of farming operations."

"…processing of perishable agricultural products and the irrigation of recreational turf, except in the Chattahoochee River watershed upstream from the Peachtree Creek confluence, where irrigation of recreational turf shall not be considered a farm use." (391-3-6-.07)

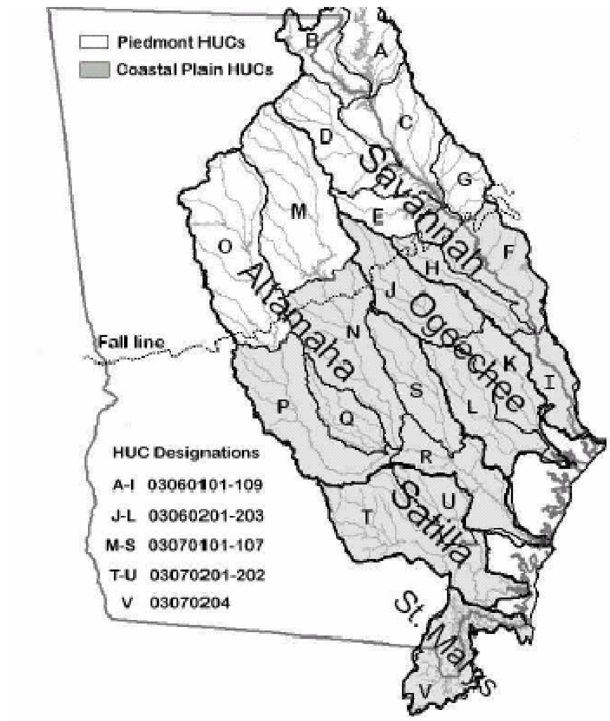
Records of water withdrawals for the state are kept by EPD, and this information is compiled periodically by the Georgia Water Use program, which regularly surveys both water sources (groundwater and surface water) and water uses (domestic, commercial, industrial, mining, irrigation, livestock, thermoelectric, and hydroelectric) as part of the USGS National Water Use Synthesis (http://water.usgs.gov/watuse/).

An analysis of water use patterns in the hydrologic units that comprise the watersheds of the five major coastal rivers in Georgia was done by Alber and Smith

Water withdrawal records are available through the Georgia Water Use program, and these indicate that surface water withdrawals are a small portion of median flow in the five coastal rivers.

(2001 [here, Fig. 13 and Table 6]) using the information available from USGS. Total water withdrawal in the study area was 5749 million gallons per day (mgd) in 1995, with no large changes in either water withdrawal or water use patterns for the last three reporting years (1985, 1990, and 1995). Surface water accounted for 91% of the water withdrawal in the region, and much of this was for thermoelectric use in the watersheds of the Savannah and Altamaha Rivers. However, only 10% of the water withdrawn (from either surface or groundwater sources) was actually consumed, with the remainder returned to the surface water. Excluding thermoelectric use, which is returned immediately, total withdrawals accounted for less than 6% of the median flow of any of the rivers, and some of that is also returned.

Figure 13. Watershed and HUC Boundaries of the Georgia Coastal Rivers.



Water quality

Water quality is also regulated.

In addition to water quantity, water quality is clearly important for estuaries. Upstream water quality in Georgia is regulated primarily by EPD: "…the GAEPD, in cooperation with many local, state, and federal agencies, manages most aspects of water pollution control, including, monitoring; water quality modeling and total maximum daily loads (TMDLs); river basin management planning and the continuing planning process; water quality standards; nonpoint source management; toxic substance monitoring and fish tissue monitoring; aquatic toxicity testing; watershed assessment and the State revolving loan

Table 6 Water Withdrawal from the Watersheds of Georgia Coastal Rivers in 1995.

	Surface Water	Groundwater	Total
Savannah	3685	139	3824
Coastal	1092	118	1209
Piedmont	2593	21	2615
Ogeechee	18	48	66
Altamaha	1494	275	1769
Coastal	129	225	354
Piedmont	1365	50	1414
Satilla	11	32	43
St. Marys	3	44	47
All Watersheds	5211	538	5749
Coastal	1253	467	1720
Piedmont	3958	71	4029

Units are millions of gallons per day.Source: Alber and Smith 2001.

process for funding municipal water pollution control plant construction; the NPDES [National Pollutant Discharge Elimination System] permit and enforcement program for municipal and industrial point sources; the erosion and sedimentation program; stormwater management; industrial pretreatment; and land application of treated wastewater. The GAEPD has designated the Georgia Soil and Water Conservation Commission as the lead agency for dealing with water quality problems caused by agriculture. The Georgia Forestry Commission has been designated by the GAEPD as the lead agency to deal with water quality problems due to commercial forestry operations." (GA DNR 2001).

Additionally, the Coastal Resources Division of the DNR oversees numerous programs that impact water quality, including the Coastal Management Program, the Shellfish Sanitation program, commercial and recreational fishing operations, and the handling of permits required by the Coastal Marshlands Protection and Shore Protection Acts.

Comprehensive water planning

The Comprehensive Planning Process provides an opportunity to review Georgia policy.

In response to the water resource challenges facing Georgia, the General Assembly adopted Senate Resolution 142 during the 2001 legislative session to create a Joint Comprehensive Water Plan Study Committee. The study committee was charged with considering existing policy, laws, rules, and programs to manage water resources; recommending a process and schedule to prepare the details of a comprehensive water plan; developing the principles for such a plan; undertaking a study of water resources issues facing Georgia (including water quality and quantity); and recommending other actions or legislation as appropriate. Complete information on this effort is available through the Carl Vinson Institute of Government at UGA (see http://www.cviog.uga.edu/water/). The list of issues developed by the study committee includes several that are relevant here, including "Protection, conservation and restoration of wetlands, marshes and other aquatic ecosystems; Instream flow protection standards and strategy; and Water quality, quantity and biotic integrity monitoring." Moreover, the proposed goals for a Comprehensive Water Management Plan include the statement that "Georgia's water programs manage water resources as an integrated system" and that they "base water management decisions on accurate and reliable information." The committee completed its work in August 2002, and their recommendations will be brought before the next session of the General Assembly.

Summary and Recommendations

There is a need to improve the exchange of information such that upstream decisions consider downstream impacts on estuaries.

Freshwater inflow to estuaries comes from upstream. Although this point is self-evident, it is often overlooked when it comes to water resource management. Part of this is due to the fragmentation of our management structure, such that different agencies are often responsible for upstream and downstream decisions. This observation applies to the situation in Georgia, as regulations for upstream water management do not explicitly consider downstream effects. Although an application for water withdrawal is evaluated in terms of the minimum flow of a stream, there is no requirement to consider downstream resources, or to consult with relevant coastal agencies such as the Coastal Resources Division. Indeed, one of the findings of the ongoing State Comprehensive Water Planning effort is that water policy is fragmented in the State (findings of the Planning Framework Working Group, http://www.cviog.uga.edu/water/0417/findings-criteria.pdf).

There is also a need for policy coordination.

We need to do a better job of integrating the management of rivers, watersheds, and estuaries, such that upstream policies regarding the quality, quantity, and timing of freshwater inflow are evaluated in the context of estuaries. Moreover, there is a further need for coordination in terms of environmental legislation. Under the Rules for Environmental Planning, the Criteria for River Corridor Protection (ch 391-3-16.04) and the Criteria for Wetlands Protection (ch 391-3-16.03), which otherwise protect the natural resources of the state, specifically exclude coastal areas, as they are covered under the state Coastal Marshlands Protection Act. Similarly, the Marshlands Protection Act *only* regulates activities and structures in coastal marshlands. Therefore, it becomes difficult to apply management standards in a continuous manner throughout an entire watercourse, from the river to the sea.

There is not currently a minimum inflow for Georgia estuaries.

Georgia uses an inflow-based approach to inflow management and does not have an explicit minimum inflow requirement for estuaries. This approach is the one that is generally in place until there is a problem downstream, and it depends on the assumption that if inflow is protected then conditions (and therefore resources) will be protected as well. Current Georgia policy is to use the 7Q10 or a non-depletable flow to set withdrawal limits for a stream. However, as described in Part Two, inflow-based policies in general can suffer from a "disconnect" wherein decisions regarding upstream flow are not made in view of downstream considerations. One way to begin to address this gap is to evaluate proposed withdrawals not only in terms of the target stream itself but also in terms of the impact such a withdrawal would have on the salinity distribution of the downstream estuary, with its consequent implications for estuarine resources. Moreover, the cumulative effect of applying a standard such as the 7Q10 to all streams within a given river should be evaluated in terms of the potential impact on the estuary. As The Board of Natural Resources recently stated: "…although DNR's 7Q10 rule is designed to protect water quality, it is NOT based on the science of how much water should remain in a stream to maintain a healthy aquatic community" (May 2001, Water Issues White Paper, emphasis is theirs). Although this statement was made with regard to freshwater communities, it applies equally well to estuarine resources.

***Maximum flow and timing of inflow should also be considered*.**

Finally, it is not only the minimum flow that is important to aquatic systems. There is ample evidence that periodic flooding is an important requirement in the life cycle of numerous organisms, allowing fish and other organisms access to backwater areas in order to feed and spawn (Richter, 2002). This applies downstream as well, such that maintaining the timing and variability of freshwater flow to an estuary is something that also needs to be considered in terms of the life histories of crabs and shrimp as well as for fish such as striped bass and shortnose sturgeon. Some of this information is being considered as part of an ongoing effort being coordinated by The Nature Conservancy to develop flow recommendations for the Savannah River.

Once inflow controls are in place, there needs to be benchmarking to determine whether they are in fact working.

Successful programs also need a specific statement of measurable ecosystem response and a research and monitoring component to determine whether inflow controls are having the desired results. At a minimum, one must be able to estimate how much freshwater enters the estuary. It is easy to install gages to measure surface water discharge via major streams and rivers, but it is also important to account for ungaged portions of the watershed as well as direct atmospheric and groundwater inputs. It is also straightforward to measure salinity, which is a fundamental characteristic of the estuary and provides a useful index of conditions. Designing an appropriate research program to track estuarine resources is more challenging, and depends on which resources are targeted in inflow management. However, this is necessary in order to be able to determine whether inflow polices are having the desired effects in terms of estuarine resources.

***The Comprehensive Planning Process provides an opportunity to work towards an integrated estuarine inflow policy for the State of Georgia*.**

As described above, the comprehensive water management planning process now underway provides an opportunity to review current management of Georgia's water resources. If the state goes forward with the development of a Statewide Water Management Plan, the type of scientific information provided in this document can contribute towards that effort in terms of estuarine inflow. The better we understand the linkages between estuarine inflow and valued estuarine resources, the better the chances of ensuring that inflow policies are based on sound science.

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APPENDIX A – Sources for Water Quality and Estuarine Resource Data

Listed below is information on water quality and estuarine resource data for the five riverine estuaries under consideration in this report.

- **Historic Data** (Winker Report)

Program Description: Winker et al. (1985) summarized most of the available water quality data, both published and unpublished, collected from the Georgia estuaries between 1961 and 1977. Some of the larger datasets summarized include several from the Georgia EPD, Howard (1971, 1975), Kuroda and Marland (1973), Windom (1973), and Winker (1976).
Parameters Measured: Although individual studies may have included other parameters, this report included salinity, temperature, current velocity and direction, suspended sediment, turbidity, dissolved oxygen, pH, and tide stage.
Estuaries Sampled: The report contains information for all five estuaries considered here (Savannah, Ogeechee, Altamaha, Satilla, St. Marys). Data for each estuary were standardized by translating sampling locations from the various studies to a consistent reference transect.

- **Environmental Protection Division**

Program Description: The Georgia EPD sponsored a monitoring program conducted monthly from September 1973 through December 1982 (Brunswick Junior College, 1975-1983) and then reinstated on a quarterly basis (EPD, 1985-1992. The program currently samples each estuary every 5 years on a rotating basis, with quarterly samples taken during the sampling year.
Parameters Measured: Air temperature, water temperature, conductivity, redox potential, dissolved oxygen, BOD, pH, total alkalinity, turbidity, color, total solids, ammonium, nitrate+nitrite, total phosphorus, total organic carbon, chloride, and total and fecal coliforms. Brunswick Junior College also collected fouling community organisms quarterly, and EPD measured Secchi transparency, total nitrogen, chlorophyll, and a variety of toxic metals and organic compounds.
Estuaries Sampled: Surface water samples were collected at approximately slack low tide at a station close to the mouth of each of the five Georgia Estuaries.

- **United States Geological Survey**

http://waterdata.usgs/ga/nwis/qwdata
Program Description: The GADNR EPD has a contract with USGS to provide water quality information. USGS maintains more than 100 surface water quality sampling stations throughout Georgia. The program involves a core of 53 surface water sites that are sampled every year, and an additional 100-120 sites in five basin groups that are monitored in a five-year rotation.
Parameters Measured: (monthly) turbidity, pH, conductance, alkalinity, total organic carbon, total residue, phosphorus, NH_3, $NO_2 + NO_3$, and dissolved oxygen; (quarterly) fecal coliform; (semi-annually) total metals – cadmium, chromium, copper, nickel, zinc, arsenic, selenium, antimony, thallium, lead, and mercury.
Estuaries Sampled: The Georgia core sites include downstream (although not strictly estuarine) monitoring stations for the Savannah, Ogeechee, Altamaha and Satilla Rivers (the St. Marys River is monitored by USGS in Florida).

- **DNR Coastal Resources Division (CRD) – Water Quality Programs**

http://www.state.ga.us/dnr/coastal/

CRD runs several different water quality sampling programs, each of which is considered below. Data collected for each of these programs will be made available on a website in the near future. The Environmental Protection Agency (EPA) has proposed to have the data collected from year 1 of Coastal 2000 Estuary Assessment online soon. Addresses to these web sites will be included upon completion.

Program Description: **Shellfish Monitoring Program**
Parameters Measured: Fecal coliform bacteria
Estuaries Sampled: 53 sites are sampled monthly along the shores of the Savannah, the Ogeechee, the Altamaha, the Satilla and the St. Marys.

Program Description: ***Pfiesteria* Monitoring Program**
Parameters Measured: Nitrates, phosphorus, silica, presence/absence of *Pfiesteria* organisms
Estuaries Sampled: 18 sites (6 each) in the Ogeechee, the Altamaha and the St. Marys are sampled bi-monthly from March to November. 40 sites (8 each for the five major rivers) are monitored June and August for the presence/absence of *Pfiesteria*.

Program Description: **Nutrient Monitoring Program**
Parameters Measured: Nitrite, nitrate/nitrite, ammonia, orthophosphate, total dissolved phosphorus, and silicates.
Estuaries Sampled: A total of 89 sampling stations are used (including shellfish sampling stations, shrimp trawl assessment stations and nutrient sampling stations). These sites are well-distributed along the coast, and are monitored on a monthly basis.

Program Description: **Beach Water Quality Monitoring Program**
Parameters Measured: Fecal coliform bacteria
Estuaries Sampled: 11 sites on Tybee Island, Sea Island, St. Simons Island and Jekyll Island are sampled weekly, year round.

Program Description: **EPA Coastal 2000 Estuary Assessment**
Parameters Measured: Water quality (dissolved oxygen, salinity, temperature, depth, pH, nutrients, chlorophyll), sediment quality (grain size, total organic carbon, sediment chemistry, sediment toxicity), biota – fish and benthos (community structure, external pathology, and tissue analyses).
Estuaries Sampled: All five major riverine estuaries in Georgia.

- **DNR -- Commercial Fisheries Data**

Several fish and crustacean monitoring programs are managed by DNR (CRD and Wildlife Resources Division). These programs also assess some aspects of water quality.

Program Description: **Young-of-the-Year American Eel Monitoring Survey**
Parameters Measured: Water quality (dissolved oxygen, salinity, water temperature, stream flow, pH), length and catch information on American eels, catch information on all other species.
Estuaries Sampled: One to two sites annually for a minimum of six weeks (4 days per week) are sampled near the head of tide during the recruitment season (December –March). 2000 to present.

Program Description: **Population Dynamics of American Shad in the Altamaha River**
Ron Michaels surveyed Altamaha shad from 1982 to 1993 and since then, Wildlife Resources Division personnel have continued to monitor this population. Two interim reports and one final report are available (Michaels, 1984, 1990, and 1993).
Parameters Measured: 1) From 1982 to 1993: fishing mortality rates and population size of adult spawners. 2) From 1982 to 1991: harvest, effort, standardized catch rates, and age class distribution of adult shad; indices of juvenile shad abundance; salinity, conductivity, and turbidity data; USGS flow records. 3) From 1982 to 1987: size class composition of juvenile shad.
Estuaries Sampled: The entire Altamaha River, from Altamaha Sound to the confluence of the Oconee and Ocmulgee rivers.

Program Description: **Shrimp Assessment Survey**
Parameters Measured: Water quality (dissolved oxygen, salinity, temperature, depth) plus fish and invertebrate catch and length information.
Estuaries Sampled: Cumberland, St. Andrews, St. Simons, Sapelo, Ossabaw, and Wassaw are sampled monthly with six sites in each. Sampling has been conducted since 1975. Other sound systems (Altamaha, St. Catherines, Doboy) have been sporadically sampled in the past.

Program Description: **Juvenile Finfish and Crustacean Monitoring**
Between 1979 and 1985, creeks were sampled from small boats to complement the shrimp assessment survey (above).
Parameters Measured: Water quality (dissolved oxygen, salinity, temperature, depth) fish and invertebrate catch and length information.
Estuaries Sampled: Cumberland, St. Andrews, St. Simons, Sapelo, Ossabaw, Altamaha and Wassaw.

Other DNR Programs:

- Bycatch characterization of various commercial fisheries - ongoing.
- Shortnose sturgeon monitoring of the Altamaha - mid 1990's.

- **DNR/CRD -- Stock Assessment of Recreationally-Important Fishes in Coastal Georgia**

The Marine Fisheries Section of the CRD oversees several monitoring programs for recreational fisheries, some of which include tracking water quality parameters.

Program Description: **Participation in Marine Recreational Fisheries Statistics Survey (MRFSS)**
Parameters Measured: Total number of finfish harvested/released, species identification, length and weight of fish samples, mode of fishing, hours fished, county and state of residency.
Estuaries Sampled: Access sites in each of Georgia's six coastal counties are surveyed each year.

Program Description: **Juvenile Red Drum Survey**
Parameters Measured: Water quality (dissolved oxygen, salinity, temperature), gear type, latitude/longitude of sampling site, date of trip, weather conditions, wind direction and speed, species identification, fish length.
Estuaries Sampled: Wassaw, Altamaha River Delta, and St. Simons

Program Description: **Adult Red Drum Survey**
Parameters Collected: Water quality (dissolved oxygen, salinity, temperature), gear type, latitude/longitude of sampling site, date of trip, duration of sampling effort, weather conditions, wind direction and speed, species identification, fish length, fish weight, gender, sagittal otolith, ovarian tissue sample.
Estuaries Sampled: Altamaha River Delta

Program Description: **Adult Red Drum Tagging**
Parameters Measured: Gear type, latitude/longitude of sampling site, date of trip, water temperature, species identification, fish length, tag number.
Estuaries Sampled: Altamaha River Delta and coastwide by cooperative anglers.

Program Description: **Sportfish Carcass Recovery Project**
Parameters Measured: Angler name, address, number of anglers participating in trip, date of trip, fishing location (estuary), species identification, length, gender, sagittal otolith.
Estuaries Sampled: Coastwide

Program Description: **Entanglement Gear Survey of Recreationally-Important Fishes**
Parameters Measured: Water quality (dissolved oxygen, salinity, temperature), gear type, date of trip, weather conditions, wind direction and speed, latitude/longitude of sampling site, species identification, fish length.
Estuaries Sampled: Wassaw and St. Simons

- **UGA Marine Extension Service** (MAREX)

http://www.uga.edu/marine_advisory/waterquality.html
Program Description: Marine extension has an ongoing program supported by CRD to monitor water quality in the Georgia River Estuaries on a rotating basis (one estuary per year). The data will be used for a water quality model being developed with the support of Georgia Sea Grant.
Parameters Measured: Dissolved oxygen, chlorophyll, salinity, temperature, pH and turbidity are monitored continuously. Total and fecal coliform bacteria, carbon and nitrogen, biological oxygen demand, total suspended solids, ATP, and nutrients (ammonia, nitrate+nitrite, and phosphorous) are monitored monthly.
Estuaries sampled: Satilla River Estuary (measurements were made at 7 stations from 2/2000 – 1/2001); Ogeechee River Estuary (measurements were made at 5 stations from 2/2001-1/2002); Altamaha River Estuary (5 stations, ongoing).

- **Georgia Rivers Land Margin Ecosystem Research Program** (LMER)

http://wiegert.marsci.uga.edu/
Program Description: The GARLMER program was an NSF-funded project conducted in the five Georgia estuaries between 1994 and 1999. During that time period, 9 major cruises and numerous minor cruises were conducted in the five Georgia estuaries.
Parameters measured: Physical parameters (salinity, temperature, CTD profiles, current speed); inorganic material (dissolved inorganic carbon, inorganic nutrients, suspended sediments, bottom sediment); organic

material (dissolved and particulate organic matter); and biological parameters (chlorophyll, bacterial production, microbial respiration). As of February 2002, all data files on the GALMER site are available for public access.
Estuaries sampled: Savannah, Ogeechee, Altamaha, Satilla, St. Marys

- **Georgia Coastal Ecosystems Long Term Ecological Research** (GCE-LTER)

http://gce-lter.marsci.uga.edu/lter/
Program Description: The GCE program is an NSF-funded project that began in 2000. The project domain includes the Altamaha River Estuary.
Parameters measured: At the head of tide (at Doctortown), the GCE has been measuring dissolved inorganic nutrients and particulate carbon and nitrogen concentrations weekly, starting in 2001. At 3 permanent monitoring stations, GCE has continuous information on physical parameters (salinity, temperature), and on quarterly water column cruises, measurements are made of physical parameters (salinity, temperature, CTD profiles); inorganic material (dissolved inorganic carbon, inorganic nutrients); organic material (particulate organic material); and biological parameters (chlorophyll, phytoplankton production). Biological measurements are also made in the marshes (invertebrates, vegetation, fungi).
Estuaries sampled: Altamaha

Other Projects

- **Salinity Response of the Satilla River Estuary to Changes in Freshwater Inflow**

Jack Blanton, Skidaway Institute of Oceanography
http://www.skio.peachnet.edu/faculty/blanton.html
http://www.skio.peachnet.edu/projects/blanton_physics/estuarine.html
Project Description: Several related projects have been supported jointly by the CRD Coastal Incentive Grant program and the state legislature to evaluate the response of the salinity regime in the Georgia estuaries to changes in flow.
Parameters Measured: Physical parameters, such as salinity, temperature, depth, current speed are measured during surveys conducted aboard ship as well as by deployment of field instruments that record data continuously.
Estuaries sampled: Satilla River Estuary -- two intensive field campaigns in 1999 (20 Jan - 20 Mar; 9 Sept - 19 Oct.) and the Ogeechee River Estuary – in progress (2002)

- **Sources and Transport Mechanisms of White Shrimp in Southeastern Coastal Waters**

Jackson O. Blanton, Peter G. Verity (SKIO) and Charles A. Barans, Elizabeth L. Wenner (Marine Resources Research Institute, S.C. DNR)
http://www.skio.peachnet.edu/faculty/blanton.html
http://www.skio.peachnet.edu/faculty/verity.html
http://www.dnr.state.sc.us/marine/mrri/inlet/inlet.htm
Project Description: With funding from the Georgia and South Carolina Sea Grant programs, scientists have been studying how the distributions of postlarval white shrimp are influenced by physical processes during their transport through inlets to their nursery grounds. The study has been conducted over the past 5 years at two

locations: the North Edisto Inlet in South Carolina and the Ogeechee River in Georgia (Georgia Sea Grant project number R/FS-1).
Parameters Measured: Wind velocity, barometric pressure, current, salinity, sea temperature, subsurface pressure, optical backscatter, acoustic plankton distribution and white shrimp (*Penaeus setiferus*) larval sampling (by towed net).
Estuaries Sampled: Ogeechee.

- **Coastal Eutrophication in the Southeastern United States: Nitrogen versus Phosphorus Limitation and the Contribution of Organic Nitrogen**

Deborah A. Bronk and Marta P. Sanderson, (both formerly of the UGA Dept of Marine Science, currently, Virginia Institute of Marine Science, College of William and Mary.)
http://www.arches.uga.edu/~kfield/
http://www.vims.edu/physical/faculty/bronk_da.html
Project Description: This is a nutrient-analysis study of two Georgia rivers, the Altamaha and the Satilla. The research was funded by Georgia Sea Grant (project number R/WQ-10) and had the following objectives: 1) to investigate nitrogen (N) versus phosphorus (P) limitation; 2) to measure uptake rates of organic and inorganic nitrogen; 3) to quantify the potential role of groundwater as a source of eutrophication; and 4) to compare the findings with studies on the utilization of dissolved organic nitrogen in New Jersey and Maryland.
Parameters Measured: Inorganic and organic nitrogen and phosphorus, chlorophyll a, nitrogen flux rates (sampling thrice yearly)
Estuaries Sampled: Altamaha, Satilla

- **Rates and Controls of Sediment Processes Regulating Nutrient Regeneration/Burial in the Satilla River Estuary**

Joel E. Kostka*, Clark R. Alexander, Richard A. Jahnke, (SKIO, *currently, Florida State Univ., Dept of Oceanography)
http://mailer.fsu.edu/~jkostka/people/joel.html
http://www.skio.peachnet.edu/faculty/sed_lab/index.html
http://www.skio.peachnet.edu/faculty/alexander.html
http://www.skio.peachnet.edu/faculty/jahnke.html
Project Description: This Sea Grant-supported research (project number R/WQ-4) aimed to; 1) directly measure rates of nutrient regeneration and burial from a range of sediment types (and salinity conditions) to the water column of the Satilla River in an adjacent tidal creek; 2) characterize the porewater/solid phase geochemistry of a range of sediment types in the Satilla River channel, in an adjacent tidal creek, and in a fringing marsh and 3) utilize sediment incubations to elucidate rates and pathways of the dominant microbial/geochemical processes controlling nutrient flux in sediments of the Satilla River Estuary.
Parameters Measured: Sediment, nutrients.
Estuaries Sampled: Satilla

- **Community Structure, Food Web Analysis, and Organic Matter Dynamics in a Brackish Tidal Creek within the Altamaha River Estuary**

Richard G. Wiegert, Charles N. DeCurtis, Jr., Marirosa Molina (Inst of Ecology, UGA)
http://wiegert.marsci.uga.edu/bios/wiegert.html
http://wiegert.marsci.uga.edu/bios/decurtis.html
http://wiegert.marsci.uga.edu/bios/molina.html
Project Description: The objectives of this research were 1) To determine the interaction of mesohaline-brackish tidal creeks (and adjacent marsh/wetlands) and estuaries with respect to carbon fixation , community metabolism, benthic processes and tidal subsidies: 2) To describe the food web in the mesohaline-brackish zone of the estuary and to examine diversity across the salinity gradient from river to estuary: and, 3) To develop a model of the mesohaline-brackish food web/community that will allow interpretation and assessment of trophic linkages and impacts of perturbations to the chemical environment of these systems: and 4) To link this model with the comprehensive model of the Altamaha Estuary being created as part of the GA-LMER project. The project was funded by Georgia Sea Grant (project number R/EA-21-PD).
Parameters Measured: Phytoplankton, zooplankton, and pelagic detrital matter.
Estuaries Sampled: Altamaha

Additional Resources

- The Georgia Coastal Analysis Partnership (GCAP) is a new initiative of the federal EPA, NOAA and the GA DNR. Dr. Jeffrey Hyland, at the University of Charleston, S.C., is coordinating this partnership.
jeff.hyland@noaa.gov
In order to support research and management goals along the coast of Georgia, sampling information has been inventoried, collected and stored for use by participating scientists. Initial efforts are addressing environmental conditions (benthic and demersal fauna, and pollutant levels) along a series of transects in the Doboy, Sapelo, and Altamaha Sounds.

- NESPAL, The National Environmentally Sound Production Agriculture Laboratory is a unit of the University of Georgia's College of Agricultural and Environmental Sciences located at the Tifton, Georgia campus. Although estuaries are not the focus of this resource, they have compiled a useful listing of water data websites for Georgia.
http://nespal.cpes.peachnet.edu/agwateruse/research/waterdata.htm

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