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A Resource-based Framework for Establishing Freshwater Inflow Requirements for the Suwannee River Estuary

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ABSTRACT: The availability of methods for establishing freshwater inflow requirements for estuaries lags behind those for establishing flow requirements in riverine ecosystems. Some of the basic principles and approaches for establishing riverine flow requirements may be applicable to estuaries. An emerging approach for establishing freshwater inflow needs for the Suwannee River estuary involves maintaining a natural inflow regime (in terms of magnitude, frequency, duration, and timing of freshwater flows) and identifying important habitat targets to be protected. The salinity-river flow conditions needed to sustain the habitat targets in their existing condition are then identified. A variety of tools are employed, such as salinity metrics, biological metrics, limits of distribution of communities or habitats, and landscape-scale characteristics to define the salinity and corresponding flow ranges needed to protect and maintain the resource targets. With this information, combined with use of models to evaluate flow-salinity relationships and various withdrawal scenarios, river flow criteria can be set which address the freshwater inflow requirements to maintain these ranges. Subsequent monitoring and research is undertaken to evaluate the effectiveness of the river flow criteria in protecting the estuarine resource targets. This information can be used to subsequently confirm, refine, or modify the flow criteria.

Introduction

An estuary results from the inflow of freshwater to the sea, and de facto, alterations to freshwater flow affect the ecology and natural resource values of an estuary. Despite the existence of case studies documenting impacts to estuarine structure and function due to freshwater inflow alteration (e.g., Estevez 2002), the conceptual frameworks and methods for setting and managing estuarine freshwater inflows are not well developed. A review by Estevez (2002) indicates that the management and alteration of inflow remains a non-issue in the overall discipline of estuarine ecology. This contrasts with instream flow management in lotic ecosystems where there are well-developed conceptual frameworks (Ward and Stanford 1983; Richter et al. 1997) and a variety of approaches to establishing flow criteria are available (Karim et al. 1995; Richter et al. 1996; Jowett 1997; Instream Flow Council 2002).

In Florida, the five regional Water Management Districts are the principal agencies charged with the setting of instream flows, or minimum flows and levels, in river systems (Chapter 373.042, Florida Statutes). In part, the legislation reads ''. . . the minimum flow for a given water course shall be the limit at which further withdrawals would be significantly harmful to the water resources or ecology of the area . . . .'' This statute is widely interpreted to include providing adequate freshwater inflows to estuaries (Wade 1991). While the statute refers to minimum flows, it adds qualifying language that these flows may reflect seasonal variations. As a matter of policy, all of the Water Management Districts recognize that a dynamic range of flows, approximating the natural seasonal pattern, are necessary to protect rivers and their downstream estuaries, rather than a single minimum flow standard.

All of the Districts are now involved in the setting of minimum flows and levels in one or more major river-estuary systems in Florida. In the Suwannee River Water Management District (SRWMD), we are developing instream flow standards for the lower Suwannee River, which will include consideration of estuarine freshwater needs. I describe our emerging approach to establishing freshwater needs for the Suwannee estuary, using a resource-based framework (sensu Johansson and Greening 2000).

The Resource-based Approach

Our approach is based on four fundamental principles (summarized in Fig. 1).

MAINTAIN A NATURAL RANGE OF FRESHWATER INFLOWS

A current paradigm in river flow management is that maintenance of a natural flow regime is critical to protecting the array of natural resource values in river ecosystems: biodiversity, productivity, and linkages with adjacent floodplains and downstream habitats (Poff et al. 1997; Richter et al. 1997; Instream Flow Council 2002). Because rivers

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SUMMARY OF THE RESOURCE-BASED APPROACH

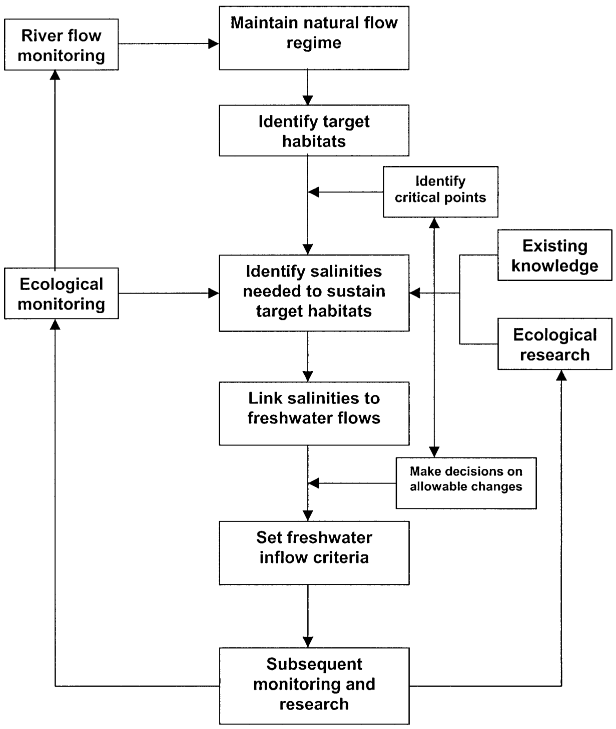

Fig. 1. Flow chart summarizing the resource-based approach to setting estuarine freshwater inflows in the Suwannee estuary.

and their estuaries are linked, this natural flow regime concept can be extended downstream to include freshwater inflows to the estuary. Browder's (1991) conceptual model of estuaries as an overlap of stationary habitat (structural features such as marshes, tidal creeks, SAV beds, etc.) and dynamic habitat (the area of reduced, variable salinity created by freshwater inflow) implies the need for a regime of flows, not a single volume of freshwater inflow. Day et al. (1997) also recognize the importance of a flow regime (their flow pulses from annual and larger floods), rather than a single or narrow range of inflows, in sustainable management of deltaic ecosystems.

Because water use in the Suwannee basin is predicted to increase over the next 20 years, it is recognized that river flows in the Suwannee are likely to decrease over time. The natural flow regime principle assumes that an altered hydrologic regime which is still near-natural in terms of magnitude, frequency, duration, and timing of freshwater inflows would be adequate to protect estuarine structure and function. The important question to answer is What is the minimum freshwater inflow regime (in terms of high, average, and low flows) needed to sustain the estuary?

Identify Critical or Target Habitats to Sustain

The setting of instream flow standards in river ecosystems is often based on identification of the resources to be protected (Beecher 1990; Jowett 1997; Richter et al. 1997). In the approach proposed here, we focus on important estuarine habitats to sustain. Habitat is used to refer to an ecological community, such as a tidal marsh community or oyster reef community. Habitat rather than community is employed to give managers and the public a better indication that these natural features are providing a service; growing fish, oysters, etc., which are of value to humans. Identification and protection of these habitats should support other natural resource values of the estuary (e.g., fish production, wildlife habitat, critical habitat for endangered species, etc.). This approach has precedence; Beck et al. (2000) recommended identifying important target habitats for conservation, in order to protect overall biodiversity in the northern Gulf of Mexico. Two corollaries are important here.

The first is that, given the array of biota present in an estuary, each with its own particular environmental requirements, it is impossible to set inflow criteria that optimally meet the needs of each and every species (Poff et al. 1997). Identifying key habitats, and setting inflow standards that meet the needs of those habitats, should meet the needs of the entire array of biota in the estuary (sensu Beck et al. 2000).

The second corollary is that habitats are easier to measure and quantify than other characteristics such as populations (Stalnaker et al. 1994). Attempts to quantify more obvious resources of concern, such as population sizes of commercial fishery species or endangered birds, are usually estimates at best. Measuring the habitats which support those species is more repeatable, more practical, and more defensible.

Once the target habitats are identified, we use a combination of existing knowledge and new research to determine the range of salinities experienced by these habitats. From this information, we can determine the freshwater inflow regime needed to establish these salinity fields. A main focus of new research is to attempt to discover functional relationships (correlations) between salinity-river flow and one or more biological variables. From this information, critical points are chosen. These are benchmarks used to establish particular river flows or flow ranges (discussed in more detail in the next section). Factors studied in the target

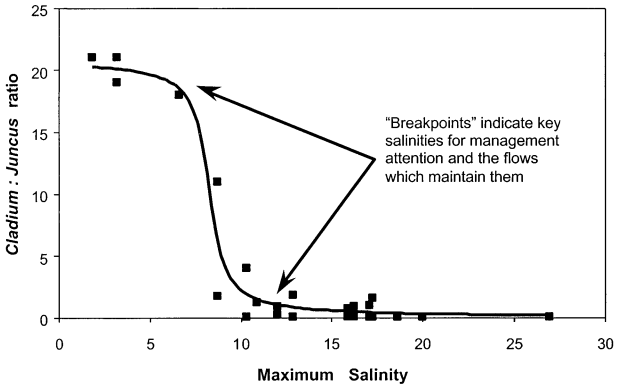

Fig. 2. Relationship between maximum salinity at a location in the Suwannee estuary and the ratio of sawgrass occurrence to black rush occurrence (after Clewell et al. 1999).

habitats include salinity, which is a direct or indirect determinate of many biological characteristics in estuaries (Bulger et al. 1993). For many target habitats, salinity is the key predictor or primary determining variable, even though underlying mechanisms may not be entirely understood (Jassby et al. 1995). Also included are community level measures of the target habitats, such as species composition, relative abundance, frequency of occurrence, or a derived variable such as an index or ratio, and how these vary with salinity. Landscape-level descriptions, such as acreages of particular community types, particularly cumulative acreage as one moves upstream or downstream (Estevez and Marshall 1997) are also included. Landscape-scale features can also include the upstream or downstream limits of a community type. These characteristics are then related back to key salinity fields (Estevez and Marshall 1997).

Link Biological Critical Points to Hydrology

Studies in the target habitats generate information relating various biological response variables to salinity. In many cases, these relationships are non-linear (Fig. 2). The breakpoints in the curve are the critical points or benchmarks which are used to identify important salinities or salinity ranges that need to be maintained or minimally altered. These salinities are then related to river flows using various modelling tools. Flow duration curves are employed as the statistical tool to determine how much flows can be reduced (across the entire hydrologic spectrum or regime), and thus how much water would be available for human use above and beyond estuarine needs. Vogel and Fennessy (1995) and Jacobs and Vogel (1998) describe how this is done in general, and Good and Jacobs (2001) provide hypothetical examples of how this could be done for the Suwannee river system. A

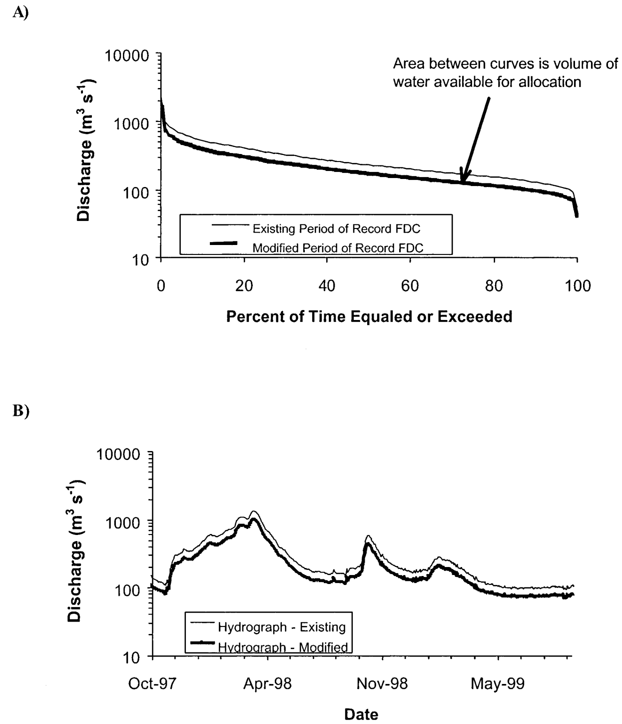

Fig. 3. A) Example of use of flow duration curves to establish availability of water for allocation, showing original and modified flow duration curve determined from critical salinity/flow thresholds. Area between the curves is water available for allocation. B) Effect of withdrawal of amount of water determined in (A) on a portion of the hydrograph of the Suwannee River flow at the Wilcox gauge (USGS HUC Code # 02323500). Modified hydrograph (bold) is flow regime after water withdrawals. Adapted from Good and Jacobs (2001).

flow duration curve is a cumulative summary of all flow measurements from a river gauge, showing the percentage of time a given flow is equaled or exceeded (Fig. 3); it is a type of frequency distribution curve. The area under the curve (derived from integration) represents a volume of water. This is a statistical property of flow duration curves. The area under a curve constructed with flow data from the period of record of a river flow gauge is the average annual flow of the river (Vogel and Fennessy 1995).

Once critical salinities and related river flows are identified from biological studies, information from the literature, and hydrologic modeling, decisions have to be made as to how much these can be changed without resulting in significant impacts to the target habitats. The critical salinities-flows identified from biological information provide the starting points (or benchmarks) from which judgements are made regarding how much flows can be reduced without causing unacceptable change (defined as significant harm in the Florida Statutes). This is done using existing or new information to determine what threshold salinities-flows cannot be exceeded without causing unacceptable change relative to management goals. For the Suwannee estuary, our general goal is to maintain the existing ecological integrity of the ecosystem (existing ecological structure and function). When no data are available to determine these thresholds, we make a best professional judgement, erring on the conservative side (i.e., minimal alteration). Future monitoring and research is critical here to help fill in these knowledge gaps.

Flow duration curves are used to determine the new flow regime after determining allowable reductions in flow (Fig. 3a) based on the critical salinities. The allowable changes in salinity determined in the analysis above are used to determine acceptable reductions in flow, which are then used to construct a new flow duration curve based on these reductions. The area between the original and new or altered flow duration curves represents the allowable water yield of the river system (Fig. 3a). Use of a variety of habitats and measures within those habitats to determine shifts enables us to look at needs during low, intermediate, and high flows. Using this method, water is withdrawn in scale with existing seasonal river flows, and a natural flow regime is maintained (Fig. 3b). Once streamflow criteria are developed, they will be adopted as a rule in the SRWMD water use regulatory program. Through the use of the flow duration curve methods described above, the volume of water (and thus proportion of river flow) available for allocation can be estimated. The main tool for allocating this water is the District's Consumptive Use Permitting authority (Chapter 40B-2, Fla. Administrative Code), which issues permits for most types of water withdrawals.

Monitoring and Research

After establishment and adoption of freshwater inflow criteria, continued monitoring and research are used to evaluate the adequacy of the inflow criteria, which could be modified in the future to reflect this additional knowledge. Continued monitoring of the target habitats, as well as river flows and estuarine salinities, will determine if the flow criteria are sustaining the target habitats and the estuary as a whole. As with other elements of our approach, this is patterned after river flow and watershed management approaches (Frissell and Bayles 1996; Richter et al. 1997), and is in keeping with an adaptive management approach (Walters and Holling 1990). Continued monitoring and research is a critical component to our approach, since in essence the establishment of flow criteria represents a working hypothesis that these criteria will protect the ecological integrity of the Suwannee estuary.

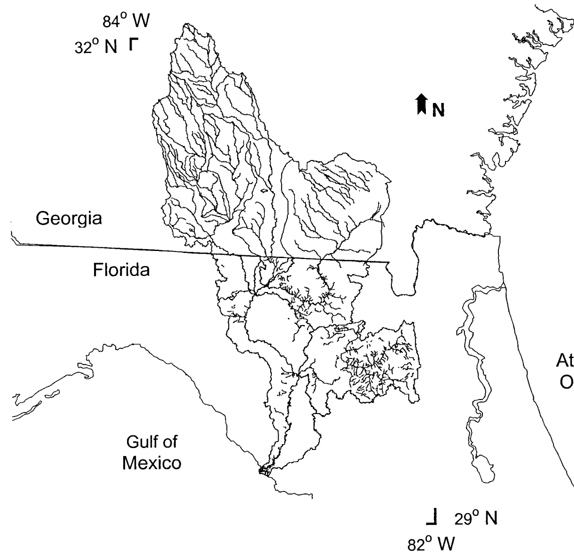

Fig. 4. Map of the Suwannee River drainage in Florida and Georgia, USA.

Study Area Description

The Suwannee River is the second largest river system in Florida, by both drainage area and mean annual flow (Nordlie 1990). The river drainage encompasses 25,770 km^2, of which 57% is in Georgia and the remainder in Florida (Fig. 4). Mean annual flow is 295 m^3 s^{-1} (Franklin et al. 1995). The river has three major tributaries; the Withlacoochee and Alapaha Rivers (both located mostly within Georgia), and the Santa Fe River, located entirely within Florida. The flow of the Suwannee is derived from two main sources. During low or baseflows, much of the river flow is from spring and groundwater discharge from the Floridan Aquifer System. At above-average and flood flows, most of the river flow is derived from surfacewater runoff, mostly from the Georgia portion of the river basin. The Suwannee system is one of the few large river systems in the U.S. which remains undammed and free-flowing (Benke 1990). The low relief and karst geology of the area make the construction of instream reservoirs impractical for this river system. The bulk of water use in the area is from wells withdrawing groundwater from the Floridan Aquifer System. Since much of the baseflow of the Suwannee is derived from groundwater inflow from this aquifer system, groundwater withdrawals can affect surfacewater flows in the Suwannee. The U.S. Geological Survey (USGS) is completing development of a linked groundwater-surfacewater model (MOD-FLOW/BRANCH) which will enable us to evaluate how groundwater withdrawals might affect streamflows.

The flow of the Suwannee accounts for 60% of the total freshwater inflow to the Florida Big Bend coastal region (Montague and Odum 1997), making the Suwannee estuary the largest in the Big Bend region of the state. The estuary is an open, deltaic type consisting of two main branches; West Pass (which divides into Alligator and Wadley passes) and East Pass. These passes encompass the Hog Island/Bradford Island delta complex. The river drains to Suwannee Sound, an embayment semienclosed by a reef system known as Suwannee Reef (Orlando et al. 1993). The influence of the freshwater discharge from the Suwannee extends well beyond Suwannee Sound. Orlando et al. (1993) and anecdotal observations indicate that its influence extends from Horseshoe Cove on the north down to the Cedar Key area on the South. Orlando et al. (1993) recognized three distinct regions of the estuary: the Suwannee River portion, lower Suwannee Sound (extending to Cedar Key), and upper Suwannee Sound and Horseshoe Cove. They characterized river inflow as the dominant force structuring monthly-seasonal and year-to-year salinity variability in the estuary with tides being the major force influencing hourly salinity variation and wind direction and strength having secondary influences on daily and seasonal salinity variation.

Ecologically, the Suwannee estuary is quite different from other Florida Gulf coast estuarine systems, in that the brackish transition zone from fresh to higher salinity conditions (e.g., polyhaline) is much more extensive. This is due to the large volume of freshwater inflow and a relatively large tidal range. This area has one of the largest tide ranges on the Florida Gulf coast (McNulty et al. 1972); about 1 m between mean high and mean low water. Tide range declines to the west, in the Florida panhandle, and to the south along the peninsular west coast (McNulty et al. 1972). This broad, brackish transition zone supports extensive areas of tidal freshwater swamp and marsh, tidal brackish marshes, low-salinity submerged aquatic vegetation (SAV) beds and oyster reefs.

Target Resources and Freshwater Inflow Needs

In this section, I briefly describe the target habitats we have identified for protection of the Suwannee River estuary. Along with the discussion of each habitat, I describe how we are trying to use existing and new knowledge to identify the salinities needed to sustain the target habitats.

Tidal Freshwater Swamps

Approximately 2,692 ha of tidal freshwater swamp occur in the upper Suwannee estuary (Light et al. 2002). These estuarine wetlands are one of the least studied wetland forest types in the southeastern U.S. (Tiner 1993; Clewell et al. 1999). They are not delineated as a distinct community type in most wetland mapping studies. Light et al. (2002) and Wharton et al. (1982) found Suwannee estuary tidal freshwater swamps were dominated by a canopy of *Taxodium distichum, Fraxinus profunda, Nyssa biflora, Sabal palmetto,* and *Magnolia virginiana.* Based on personal knowledge, the Suwannee supports the most extensive stands of this forest type of all the tidal river systems on the penisular Florida Gulf coast. They may represent a significant source of primary production in the form of leaf litter and may provide important habitat for larval and juvenile fishes, but to date no comprehensive ecological investigations have been conducted in them to evaluate this.

These forests would be affected by increased salinity as water withdrawals reduce river flows. Some information is available in the literature on salinity tolerance of some of the tree species found in these forests. Cypress seedlings exhibit reduced net photosynthesis and stomatal conductance and leaf injury when exposed to salinities of 2‰ and higher (Pezeshki et al. 1987) with more severe damage occurring at higher salinities (up to 7‰). Survival of seedlings of *Acer floridanum* (Florida maple; Suwannee tidal swamps support *Acer rubrum,* red maple) was reduced by salinities of 2‰ and higher (Williams et al. 1998). In order to protect the ecological integrity of tidal freshwater swamps in the upper estuary, and prevent upstream retreat of the tree line (boundary between tidal swamps and marshes), a recommendation would be to maintain river flows that keep surface salinities $\leq$ 2‰ in tidal waters flooding the swamps at and near the tree line during seasonal low flow periods (= periods of highest salinity in the upper estuary).

Tidal Marshes

The Suwannee estuary supports extensive stands of tidal fresh, brackish, and salt marshes (Clewell et al. 1999). The salt marshes are dominated by *Juncus roemerianus, Distichlis spicata,* and *Spartina* spp. Brackish marshes support a more species-rich plant community, including the aforementioned plants, plus *Scirpus* spp., *Sagittaria lancifolia, Saururus cernuus, Crinum americanum, Ipomea sagittata,* and others. Highest plant species richness is seen in the tidal freshwater marshes, which include many of the above, plus *Zizania aquatica, Cicuta mexicana, Sium suave, Hydrocotyle* sp., *Typha domingensis,* and other freshwater marsh species. The fisheries habitat value of salt and brackish marshes has been well established (Weinstein 1979; Rozas and Hackney 1983; Boesch and Turner 1984), and the same values probably apply to tidal freshwater marshes as well (Odum et al. 1984). Beck et al. (2000) designated tidal marshes as priority habitat targets for conservation in the northern Gulf of Mexico.

Few studies of the salinity tolerances of the various marsh plants appear to have been conducted. Hackney and de la Cruz (1978) found that low-salinity brackish marshes dominated by *Phragmites* sp. and *Spartina cynosuroides* (both common plants in Suwannee estuary brackish tidal marshes) tolerated up to 14.5‰ soil salinity. Odum et al. (1984) presented information showing that most of the brackish marsh plants are found in a salinity range of 3–10‰. Clewell et al. (1999) conducted investigations in tidal marshes of the Suwannee estuary and found a statistically significant relationship between maximum surface water salinity and the ratio of occurrences of *Cladium jamaicense* (sawgrass, a dominant plant in low-salinity brackish and tidal fresh marshes) and *J. roemerianus* (black rush, a dominant plant in mesohaline and salt marshes; Fig. 2). Below a seasonal maximum salinity of 7‰ (= highest salinity measured based on monthly sampling at high tide), oligohaline and tidal fresh marshes are dominated by *Cladium,* while above 11‰, salt marshes occur and *Juncus* becomes the dominant marsh plant. Sawgrass-dominated marshes in the Suwannee estuary do experience higher salinities (up to 10–12‰) of tidal floodwaters. Lacking specific data on salinity tolerances of various brackish and tidal fresh marsh taxa, our approach would be to recommend that for areas of the estuary vegetated with *Cladium*-dominated brackish marshes, flows should maintain seasonal maximum salinities of < 11‰ in high tide waters flooding the marshes during a normal hydrologic year. Alternatively, we might specify that a particular seasonal maximum salinity (e.g., 7‰) not be allowed to encroach more than some distance upstream (e.g., ≤ 0.5 km) due to withdrawals.

Low-salinity Submerged Aquatic Vegetation

The major aquatic habitat in the upper estuary (East and West Pass of the lower river) are stands of SAV growing on shallow subtidal areas bordering the river channel. Stands of SAV are also found in the many tidal creeks branching off the mainstem of the river and passes. These beds are dominated by *Vallisneria americana, Sagittaria kurziana,* and *Myriophyllum spicatum.* Several other plant species occur as associates in these beds. The value of these beds for fish and invertebrate habitat was established by Rozas and Odum (1987a,b) and Thorp et al. (1997). Beck et al. (2000) designated tidal freshwater SAV as a priority habitat target for conservation in the northern Gulf of Mexico. Mapping studies delineated about 11 ha of this SAV bordering the main channels of East and West Pass (Golder and Associates 2000). This work was conducted during a period of record low ENSO-induced river flows, which elevated salinity and substantially reduced SAV cover in the upper estuary. The downstream limit of SAV in both East and West Passes corresponds to an annual average bottom salinity < 8‰, and average annual surface salinity < 5‰ (SRWMD unpublished data). Odum et al. (1984) characterize *Vallisneria* as occurring in the tidal fresh (< 0.5‰ annual average salinity) and oligohaline (0.5‰ to 5‰ annual average salinity) estuarine zones. Doering et al. (1999), using experimental and field studies, showed that *Vallisneria* had a maximum salinity tolerance of about 15‰, with reduced growth at salinities above 9‰. Based on this, it would be recommended that freshwater flows maintain average annual bottom salinities at the downstream limits of SAV of ≤ 9‰ during seasonal low flow periods.

Oyster Reefs and Bars

Oyster was identified as a priority habitat target for conservation in the northern Gulf of Mexico as a whole, and was also specifically identified as a principal target in Suwannee Sound (Beck et al. 2000). Oyster habitats, dominated by eastern oysters, *Crassostrea virginica,* are the main structural habitat feature in Suwannee Sound and have both ecological value as habitat and economic value as a commercially harvested resource. The Suwannee estuary is the only other commercial oystering area in Florida besides Apalachicola Bay. The best oyster reef development is in areas influenced by freshwater flow (Patillo et al. 1997). Generally optimal salinity ranges for various life stages are (from Patillo et al. 1997): for egg and larval development 10–15‰ (for oysters in mesohaline habitats); for larval growth 10–29‰; for spat settling 16–22‰; and for juveniles and adults 10–30‰. Along the Florida Gulf coast, spat settlement occurs throughout the spring and summer (Patillo et al. 1997). Freshwater flows that maintain salinities < 22‰ in Suwannee Sound (where most of the oyster coverage is found) during this time would be recommended. Livingston et al. (2000), demonstrated that highest oyster mortality was associated with maximum salinities experienced at particular locations in Apalachicola Bay. It appears that these are sites that experience salinity maxima of > 35‰. An additional target criterion based on oyster habitat would be to keep maximum salinities in the Sound < 35‰ during low flow seasons.

SRWMD is currently mapping oyster habitat in the Suwannee estuary. These mapping data will be combined with the output from a hydrodynamic

TABLE 1. Summary of salinity criteria recommended for the target habitats in the Suwannee estuary. Habitats are ordered in roughly an upstream-downstream hierarchy. Note that these salinity criteria may be modified in the future based on additional analyses and review.

Habitat	Factors Considered	Salinity Criteria
Tidal freshwater swamp	Downstream limit of the treeline (= transition from swamp to marsh); salinity tolerances of dominant tree species (adults and seedlings)	≤ 2‰ in surfacewater flooding the swamps at high tide at or near the tree line
Low-salinity SAV beds	Downstream limit of SAV beds; salinity tolerances of dominant plant taxa	≤ 9‰ bottom plant taxa salinity during low river flows at downstream limit of SAV
Brackish tidal marsh	Ratio of *Cladium : Juncus* in marshes; salinity tolerances of dominant marsh plants	< 11‰ in surface-waters flooding marsh surface at high tide during low river flows
Tidal creeks	Fish habitat value; nursery habitat for larval/juvenile fishes; maintain low-salinity SAV habitat	Maintain mesohaline (5–18‰) range of salinities across the Hog Island delta area
Oyster reefs and bars	Spat settlement in spring-summer; mortality (from predation and disease) at high salinities	< 22‰ average in Suwannee Sound during spring-summer; < 35‰ maximum salinity during low river flows

model, also currently being completed for the estuary, to assess the area of oyster habitat which might be affected by unacceptably high salinities if excessive water is withdrawn from the Suwannee.

TIDAL CREEKS

Tidal creeks are the primary fish habitat in tidal marshes (Montague and Wiegert 1990). Many tidal creeks in the Suwannee estuary support dense stands of SAV, which adds to their habitat value (Rozas and Odum 1987a). The Hog Island delta supports the densest network of tidal creeks in the estuary. Depth-integrated salinities at the mouths of East and West Passes, bordering the delta, range from 0–30‰ (Tillis 2000; SRWMD unpublished data). The interquartile range of salinity (75th to 25th percentile) at the Pass mouths is on the order of < 1‰ to 17‰ (Tillis 2000). This range constitutes conditions from fresh to mesohaline (maximum of 18‰) according to the Venice salinity classification system (Odum et al. 1984). The interquartile range is regarded as important because half of the data points used to determine the quartiles falls within this range (Tillis 2000, used continuous measurements of salinity with recorders). In keeping with the conceptual model of Browder (1991), in order to protect the fisheries value of these tidal creek habitats, we would recommend freshwater flows that maintain salinities in the mesohaline range across the Hog Island delta area.

SUMMARY AND CRITIQUE

It is acknowledged that the approach outlined in this paper is just a proposed approach, which has not been tested scientifically nor has it gone through the political approval process. I am presenting our approach at this time to subject it to the scrutiny and review of the estuarine science and management community. If the scientific community is largely supportive, that will strengthen the argument to be made before decision makers to adopt this approach.

Table 1 presents a summary of the target habitats and suggested salinity criteria discussed above. The table orders the habitats in an upstream-downstream hierarchy, showing that lower salinity criteria are associated with more upstream habitats. The USGS is completing development of a hydrodynamic salinity model (Environmental Fluid Dynamics Code), which will enable us to evaluate the river flows needed to meet the salinity targets. Flows will be determined for each target habitat independently. If there is conflict between the flows needed to sustain different habitats (e.g., brackish marshes could tolerate a greater reduction in flow than SAV beds), the more restrictive flow reduction standards associated with SAV would be used. This would ensure protection of these more sensitive habitat(s). The water needs of less sensitive habitats would also be met.

Note that many of the salinity targets have a low flow bias, in that they more frequently specify maximum salinities, which usually occur at the seasonal low river flows. It is recognized that high flows fulfill important ecological functions in estuaries (Day et al. 1997). Upstream, in the riverine portion of the Suwannee, we have identified additional habitats, such as river floodplain wetlands and riparian aquatic habitat, protection of which will be more dependent upon flow criteria set at intermediate and higher flows. Through the use of a river flow model (USGS BRANCH model) linked with the estuarine hydrodynamic model, we will be able to evaluate whether the higher flow criteria, developed using upstream, riverine habitats, are adequate to maintain suitable salinity regimes in the near and offshore areas of the estuary (e.g., maintain the offshore extent of the freshwater plume from the Suwannee during flood flows).

A confounding factor in our approach is sea level rise, which has been well documented in the Suwannee estuary region, and has been shown to be responsible for landward retreat of coastal forests (Williams et al. 1999). There are several ways we would separate sea level rise effects from those caused by flow reductions due to water withdrawals. Effects of sea level rise will probably occur on a scale of decades to centuries. Flow reductions from water withdrawals will occur over a scale of years to decades. SWMD operates a continuous river flow gauging network on the Suwannee cooperatively with the USGS. This network will detect changes in the river's flow regime. The District also regulates the consumptive use of water through a permitting system, which allows for tracking water allocation and use. These data will be supplemented by the hydrologic models, which will enable evaluation of the interaction between water use and changes in streamflow. If we observe ecological changes in the estuary in association with increases in water use and reductions in streamflow, it would be inferred that these changes are due to water use. Monitoring the same types of habitats described here in other river systems, or in similar habitats distant from the Suwannee but within the Big Bend region of Florida, would enable us to evaluate if the ecological changes are unique to the Suwannee or if they are a region-wide phenomenon (and thus probably attributable to sea level rise). The target habitats we have chosen are large-scale features that are fixed in the landscape (there is not an extensive seasonal or year-to-year movement in their locations), so ecological changes will likely be due to changes in key forcing functions such as river flow and salinity.

Our approach has the flexibility to incorporate other factors into the establishment of freshwater inflow criteria with the accumulation of new knowledge. Light is no doubt an important factor influencing the distribution and coverage of SAV in the upper estuary, since during higher flows the Suwannee is characterized by increased water color and reduced light penetration. If future studies were to evaluate the interactions of water withdrawals, river flow, light availability, and SAV growth and production, and show that light was a more important forcing factor than salinity, we would modify the flow criteria accordingly. As a rule, we use the most conservative limiting factor for a particular target habitat. This insures that other habitats, with less restrictive water needs, would be protected.

Epilogue

A New York Times article (Egan 2001, p. 1A) noted that "water will be for this century what oil was for the last." Florida remains one of the fastest-growing states in the U.S. with correspondingly immense pressure placed on its river and estuary ecosystems. Within the state, the counties of Hillsborough, Pinellas, and Pasco, the Southwest Florida Water Management District and the West Coast Regional Water Supply Authority have collectively expended over $3 million of public funds in legal fees disputing the allocation and transfer of freshwater resources in the Tampa Bay watershed (Patton and DeHan 1998). Population growth in adjacent Georgia has brought the interstate water wars of the western U.S. to the southeast, as Florida and Georgia have been struggling for the past several years to work out a formula for the allocation of the freshwater resources of the Apalachicola-Chattahoochee-Flint River system. Much of Florida's concern has to do with providing adequate freshwater inflow to Apalachicola Bay, the estuary of this river system (Leitman personal communication). Because of increasing human demands for freshwater, in Florida, the southeastern U.S. and worldwide, it is correspondingly urgent that we as estuarine scientists and managers develop the conceptual foundations and tools for determining estuarine freshwater needs, as well as ways to communicate these to decision makers in a clear and compelling fashion.

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