COMPARING TRANSPORT TIMES THROUGH SALINITY ZONES IN THE OGEECHEE AND ALTAMAHA RIVER ESTUARIES USING SQUEEZEBOX

Joan E. Sheldon[1] and Merryl Alber[2]

AUTHORS: [1] Research Coordinator and [2]Associate Professor, Dept. of Marine Sciences, University of Georgia, Athens, GA 30602.
REFERENCE: *Proceedings of the 2005 Georgia Water Resources Conference*, held April 25-27, 2005, at the University of Georgia. Kathryn J. Hatcher, editor, Institute of Ecology, The University of Georgia, Athens, Georgia.

Abstract. This study explored differences in the transit times of dissolved substances through salinity zones in the Altamaha and Ogeechee River estuaries under a range of flow conditions. Salinity distributions and transit times were estimated from box models generated using the SqueezeBox modeling framework. The estuaries were compared in spite of the large difference in their river flow ranges by using flow rates ranging from the 10^{th}-90^{th} percentile within each range. In each case, zone lengths and transit times were calculated for the tidal freshwater, oligo-mesohaline, and polyhaline zones. Although the two estuaries have similar lengths, the slower-flowing Ogeechee grades from a zone of tidal freshwater (except at very low flows) through oligo-mesohaline zones to a polyhaline zone inside the mouth whereas the Altamaha always has a fairly long (>25 km) extent of tidal freshwater but only a short (or non-existent) polyhaline zone. Transit times through the whole Ogeechee estuary are 3.3-4.7 times longer than those in the Altamaha, but the lengths of time water spends in the tidal freshwater reaches of the estuaries are comparable whereas there are large differences in the times spent in oligo-mesohaline and polyhaline reaches. These types of predictions may be useful in interpreting nutrient and pollutant dynamics in estuaries as well as in studies that compare the relative susceptibility of estuaries to perturbations.

INTRODUCTION

The total amount of time it takes freshwater to transit through an estuary often controls the extent to which materials carried in the water can be processed within the system. For example, longer transit times allow more time for nitrogen that enters from upstream to be denitrified within the estuary so that less of it is exported to the coastal ocean (Dettmann, 2001). Transit times are therefore a useful way to compare systems with regard to their relative susceptibility to potential perturbations such as increased nitrogen loading, which may lead to eutrophication (Bricker et al., 1999).

Although total transit times are useful, water that flows through a riverine estuary passes from tidal freshwater through sequentially saltier reaches, and some processes occur primarily in specific salinity zones. For example, nitrification is optimal at low to intermediate salinities (Rysgaard et al., 1999). More specific information on how long water spends within relevant reaches of the estuary would therefore allow for a better understanding of the processing of materials.

This study explored differences in the transit times of dissolved substances through salinity zones in the estuaries of the Altamaha and Ogeechee Rivers under a range of flow conditions. The Altamaha River has a three-fold larger watershed area than the Ogeechee River and delivers ~3.7 times as much freshwater to its estuary (median discharges are 240 and 59 m^3s^{-1}). However, the lengths and volumes of the estuaries are similar: the Altamaha is 54 km long with a volume of 157 x 10^6 m^3 whereas the Ogeechee is 61 km with a volume of 190 x 10^6 m^3 (Alber and Sheldon 1999). The differences in discharge relative to estuary volume translate to differences in transit times through the estuaries, which are ~3.5 times longer in the Ogeechee (median transit times are 6 d in the Altamaha and 21 d in the Ogeechee; Alber and Sheldon 1999). This study expands on our previous work by evaluating how transit times through specified salinity zones vary in the two estuaries.

METHODS

SqueezeBox Modeling Framework. Transit times were estimated using box models generated by the SqueezeBox modeling framework for different steady state flow conditions in the Altamaha and Ogeechee River estuaries. SqueezeBox generates tidally averaged 1-dimensional optimum-boundary box models constructed so that simulations of flows among boxes are numerically stable and may be used to estimate mixing time scales and track the transport of inert tracers. It uses smoothed equations for cross-sectional area and upstream flow of seawater vs. distance along the longitudinal axis of the estuary, so that box boundaries may be drawn at any points along the estuary and the characteristics of the resulting boxes (e.g. salinity) may be determined. 1-D models are most appropriate for estuaries that are well mixed both vertically and laterally. This is generally true for the estuaries considered here, although the lower Altamaha River estuary is sometimes stratified.

The SqueezeBox framework is modular: equations and data from external files are used to generate box models for an estuary. The application and results from an earlier Altamaha River estuary module calibrated for a more limited flow range have been described previously (Sheldon and Alber, 2002; 2003), but that module could not predict the higher salinities that occurred during the recent drought (1999-2002). We have now recalibrated the equation for upstream flow of seawater so that it includes salinity observations collected at low flows (obtained from the Georgia Coastal Ecosystems LTER project (D. Di Iorio, pers. comm.) and the Georgia Coastal Resources Division Water Quality Monitoring Program).

We developed a module for the Ogeechee River estuary using the same methods as for the Altamaha (Sheldon and Alber, 2002). Cross-sectional areas at 1-km intervals along the estuary axis were estimated using measurements from National Oceanic and Atmospheric Admin. (NOAA) or U.S. Geological Survey (USGS) charts. Salinity data, in addition to that compiled by Winker et al. (1985), were provided by the Georgia Rivers LMER Program, the Georgia Coastal Resources Division Water Quality Monitoring Program, the Univ. of Georgia Marine Extension Service, L.R. Pomeroy, and J. Blanton. Daily mean river discharges into the estuary were estimated as the sum of the discharges at USGS gauges 02202500, 02202600, and 02203000 (Alhadeff et al. 2003), corrected for the ungaged portion of the watershed (23%).

Model Runs. Box models were generated for each estuary using river flow rates from the 10th-90th percentile of the range (Table 1) for the period of record common to both estuaries (1937-2003). We compared relative rather than absolute flow rates because the flow ranges of the two estuaries are considerably different: comparisons of equal river flows would misrepresent the normal ranges of both estuaries and unfairly compare high flow in the Ogeechee with low flow in the Altamaha River. In addition, the two estuaries are geographically close and their watersheds experience similar rainfall patterns, so that temporal flow patterns are highly correlated (i.e. a peak discharge for the Altamaha occurs about 2 d after one in the Ogeechee). Model time steps were 0.2 d for the Ogeechee and 0.05 d for the Altamaha so that, given the differences in flow rates, numbers of model boxes would be approximately equal and spatial resolutions similar.

Salinity zones were defined as follows: tidal freshwater extended from head of tide (54 km from the mouth in the Altamaha estuary and 61 km in the Ogeechee) to the box boundary where salinity was ≤0.5 on the upstream side; the oligo-mesohaline zone extended from this boundary to the box boundary below salinity 18; and the polyhaline zone extended downstream of the latter boundary. To

Table 1. River Flow Rates Compared in Model Runs and Corresponding Average Transit Times

	Ogeechee		Altamaha	
Percentile	Flow ($m^3 s^{-1}$)	Transit Time (d)	Flow ($m^3 s^{-1}$)	Transit Time (d)
10	14.8	54.0	91.8	11.5
20	22.8	39.7	121.2	9.3
30	31.6	31.1	153.5	7.7
40	43.1	24.5	192.4	6.4
50	58.7	19.3	240.1	5.4
60	81.9	14.8	309.0	4.3
70	116.4	11.0	428.1	3.3
80	166.8	8.1	609.1	2.4
90	273.1	5.2	933.4	1.6

determine transit times through salinity zones, tracers were introduced into the most upstream box of each model by giving the box an initial relative concentration of 1 and all other boxes and boundary inputs initial concentrations of 0. Models were run until 99% of tracer had exited the estuary, and whole-estuary average transit times (average amount of time tracer spends between head of tide and the mouth) were calculated (Sheldon and Alber, 2002). Similarly, tracers were introduced into the boxes below the salinity zone boundaries and average residence times (times to exit the estuary) were calculated. Average transit time through each salinity zone was calculated by subtraction.

RESULTS

Model Validation. Predicted salinity distributions in both the Altamaha and Ogeechee River estuaries agree well with observations of mid-tide averaged salinity obtained for 14 flows in the Ogeechee ranging from the 6th to 84th percentile and for 21 flows in the Altamaha ranging from the 1st to 90th percentile. Direct observations (e.g. physical tracer studies) suitable for validating average transit times are not available, but model estimates corresponding to flows from the salinity calibration data sets are highly correlated with estuary flushing times calculated independently from a long-term data set (Alber and Sheldon, 1999).

Salinity Zonation. Although the Ogeechee and Altamaha River estuaries have similar overall lengths, those of the individual salinity zones vary considerably between the two systems (Fig. 1, left). The Ogeechee estuary grades from tidal freshwater through oligohaline and mesohaline zones (combined in Fig. 1) to a polyhaline zone inside the mouth except at very low flows (<30th percentile), when there is negligible tidal freshwater. The Altamaha estuary always has a fairly long (>25 km) extent of tidal freshwater even at very low flows, but only a short (or non-existent) polyhaline zone. This is due to the large freshwater flows that enter the Altamaha estuary, which can shift the polyhaline zone onto the Continental Shelf.

Transit Times. In both estuaries, average transit times through each salinity zone as a proportion of the total transit time (Fig. 1, middle) are somewhat different than would be expected from the proportional lengths of the zones (Fig. 1, left). A greater proportion of time is spent in higher-salinity zones (and a lesser proportion in tidal freshwater) than might be expected, largely due to the increase in estuarine volume that occurs towards the mouth. These results show that, depending on flow rate, conservatively mixing substances entering at the head of tide would spend 17-44% of the time in tidal freshwater in the Altamaha even though tidal freshwater constitutes 47-80% of the estuary length. In the Ogeechee, substances would spend up to 23% of the time in tidal freshwater even though it constitutes up to 47% of the estuary length.

Although a proportionate view of transit times is useful for comparison, the extent to which materials are transformed depends on the absolute amount of time spent in relevant zones (Fig. 1, right). Average transit times through the Ogeechee estuary are 3.3-4.7 times longer than in the Altamaha estuary (Table 1) but this difference is not uniform over all salinity zones. For example, the length of the tidal freshwater zone in the Altamaha is at least 50% greater than that in the Ogeechee, yet under most flow conditions transit times through this zone are similar or up to twice as long in the Ogeechee. More importantly, transit times through tidal freshwater are short in both estuaries: only 0-2.6 d in the Ogeechee and 0.7-1.9 d in the Altamaha. Likewise, transit times through the Ogeechee oligo-mesohaline zones are up to 4 times longer than those in the Altamaha, even though this reach is only about twice as long. Finally, transit times through the Ogeechee polyhaline zone are up to 8 times as long as those in the Altamaha, when the zone itself is at most 5 times longer. In absolute terms, transit times through the higher-salinity zones in the Ogeechee vary from 3-21 d in the oligo-mesohaline zone and 1.5-33 d in the polyhaline zone, whereas in the Altamaha times range from only 1-10 d in both zones combined.

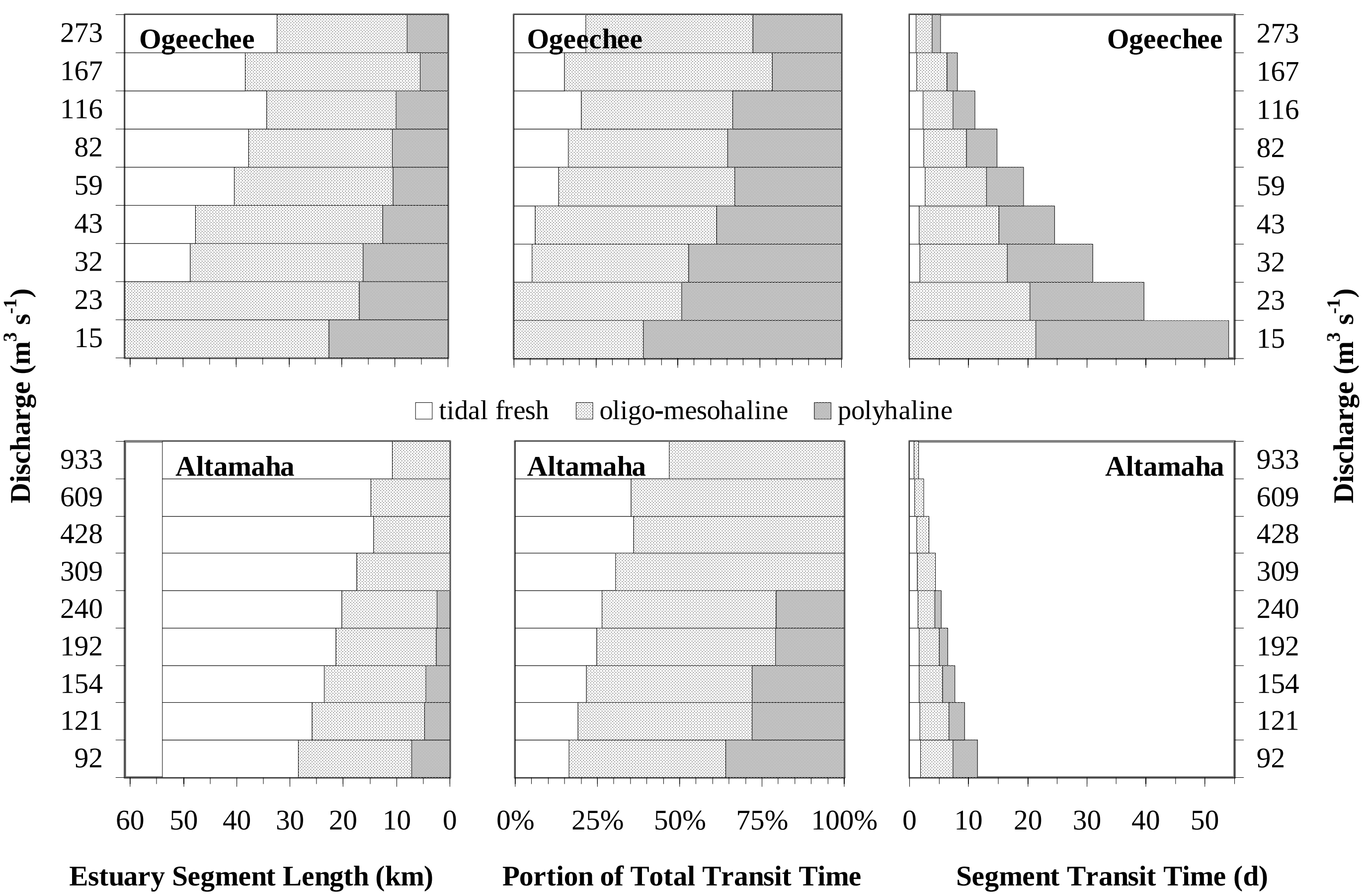

Figure 1. Lengths of salinity zones (left) and average transit times through each zone as a portion of the total (center) and on an absolute scale (right) for flows in Table 1.

DISCUSSION

The SqueezeBox framework is a tool for producing box models of riverine estuaries under specified flow conditions. Having modules for both the Altamaha and Ogeechee River estuaries allows us to make comparisons across the natural ranges of flow, not only with regard to whole-estuary scale parameters such as flushing time (Alber and Sheldon, 1999) but also within estuarine zones.

These results indicate that more than half the length of the Altamaha River estuary is tidal freshwater, whereas the Ogeechee River estuary has a much shorter tidal freshwater zone. However, the lengths of time water spends in the tidal freshwater reaches of the estuaries are comparable, but there are large differences in the times spent in oligo-mesohaline and polyhaline reaches. These types of observations can be compared to the time scale of a process of interest to determine the extent to which transformations might occur. If the lower estuary is stratified then transit times may differ somewhat from these estimates, although the effects of smaller mixing volumes in the upper layer may be offset by decreased estuarine circulation. More importantly, comparisons with process rates should be made with transit times through the appropriate layer.

A potential application of these types of results is in conjunction with efforts by NOAA to address the potential problem of eutrophication in US estuaries. Their approach was to summarize concentrations of parameters of concern (chlorophyll *a*, nitrogen, phosphorus and dissolved oxygen) within broad salinity zones (NOAA 1996 and related reports) and then aggregate this information over all zones and use “Estuarine Export Potential” to assess the relative susceptibility of estuaries to increased nutrient loads (Bricker et al, 1999). Export potential was estimated as a combination of dilution and flushing potential, but it is a qualitative parameter that may not correctly distinguish among estuaries. For example, the Ogeechee estuary (Ossabaw Sound) is listed as less susceptible than the Altamaha estuary but our results show that it always flushes more slowly than the Altamaha, which would make it more susceptible.

Model responses at different river inflow levels show the value of estimating the range of an estuary’s response rather than the mean. For example, susceptibility to excess nitrogen inputs is likely to be higher in summer when flows are generally lower, transit times longer, temperatures higher, and oxygen saturation lower. This may not be apparent using the average flow, especially because river flows are generally skewed. NOAA’s estimation of susceptibility could be improved by using data relevant to the most sensitive time of year, such as median summer flow.

The work presented here combines several elements of NOAA’s approach to eutrophication assessments and demonstrates that susceptibility of estuaries to perturbations may be examined with regard to salinity-sensitive processes using relatively simple models. SqueezeBox requires much the same data as that summarized in the NOAA (1996) survey but provides more detailed information on how materials move through estuaries, which could improve our understanding of estuarine susceptibility to increasing nutrient loads within a framework that is still simple enough to apply to a broad range of estuaries.

ACKNOWLEDGMENTS

Financial support was provided by The Nature Conservancy, the Georgia Coastal Ecosystems LTER Project (NSF OCE 99-82133), and the Georgia Coastal Management Program (NOAA NA17OZ1119).

LITERATURE CITED

Alber, M. and J.E. Sheldon, 1999. Use of a date-specific method to examine variability in the flushing times of Georgia estuaries. *Estuar. Coast. Shelf Sci.* 49:469-482.

Alhadeff, S.J., B.E. McCallum and M.N. Landers, 2003. Water Resources Data-Georgia, 2003. USGS.

Bricker, S.B., and others, 1999. National Estuarine Eutrophication Assessment: Effects of Nutrient Enrichment in the Nation's Estuaries. NOAA, Nat’l Ocean Service, Special Projects Office and the Nat’l Centers for Coastal Ocean Science, Silver Spring, MD.

Dettmann, E.H., 2001. Effect of water residence time on annual export and denitrification of nitrogen in estuaries: a model analysis. *Estuaries* 24:481-490.

National Oceanic and Atmospheric Admin., 1996. NOAA's Estuarine Eutrophication Survey. Vol. 1: South Atlantic Region. Office of Ocean Resources Conservation Assessment, Silver Spring, MD.

Rysgaard, S., and others, 1999. Effects of salinity on NH_4^+ adsorption capacity, nitrification, and denitrification in Danish estuarine sediments. *Estuaries* 22:21-30.

Sheldon, J.E. and M. Alber, 2002. A comparison of residence time calculations using simple compartment models of the Altamaha River estuary, Georgia. *Estuaries* 25:1304-1317.

Sheldon, J.E. and M. Alber, 2003. Simulating material movement through the lower Altamaha River estuary using a 1-D box model. In: Hatcher, K.J. (ed.), *Proc. of the 2003 Georgia Water Resources Conference.* Institute of Ecology, Univ. of Georgia, Athens, GA.

Winker, C.D., L.C. Jaffe and J.D. Howard, 1985. Georgia estuarine data 1961-1977, Volume 1. Tech. Report Series 85-7. Georgia Marine Science Center, Univ. System of Georgia, Skidaway Island, GA.