SIMULATING MATERIAL MOVEMENT THROUGH THE LOWER ALTAMAHA RIVER ESTUARY USING A 1-D BOX MODEL

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Abstract. 1-D optimum-boundary box models were used to simulate the movement of dissolved pollutants or other conservatively mixing constituents through the Altamaha River estuary. Tracers were introduced into the models as point sources at various locations within the estuary and as a non-point input to the entire system. In each case, models were run at four different river flow rates and were used to simulate both the movement of tracer within the estuary and its rate of removal. When tracer was introduced at head of tide, it moved rapidly (from 1-2 d, depending on flow) to the head of the mixing zone 30 km downstream. Tracer released anywhere in the estuary, including farther downstream at 2 km, moved toward an area 4-6 km upstream of the mouth, where it remained centered as overall removal continued. Movement toward this zone was observed regardless of flow rate. Introduction of tracer as a non-point source also resulted in distributions centered at 4-6 km, suggesting that this area is a potential convergence zone in the Altamaha River estuary. Maximum exposure to tracer, measured as the amount of time that concentration exceeds a given threshold, depends on where in the estuary tracer is released. When released at head of tide, maximum exposure is experienced at 6-10 km. Simulations of the type presented here are useful for evaluating the conservative movements of both point- and non-point-source constituents in the estuary.

INTRODUCTION

The movement of water through estuaries is an important factor in determining the distribution of dissolved substances such as pollutants or nutrients and the consequent exposure of estuarine habitats to those substances. The ability to estimate the potential effects of introduced substances on critical habitat may be aided by modeling studies of water movement and mixing within estuaries. For example, fate and transport modeling has been recommended as an aid in estimating exposure of aquatic communities to chemical stressors, a component of ecological risk assessment (Morton *et al.*, 2000).

This study explored the longitudinal movement and distribution of conservatively mixing substances within the Altamaha River estuary using simple box model simulations. The Altamaha River is one of the largest and least developed rivers on the east coast of the USA, although urbanization is increasing. The lower watershed provides critical habitat for more than 130 rare and endangered species and was designated a Bioreserve by The Nature Conservancy in 1991 (The Nature Conservancy, 1998). The estuary is also part of the study area of the Georgia Coastal Ecosystems Long Term Ecological Research (GCE-LTER) project. Information about the movement of water and dissolved substances in this system can aid in the interpretation of other data collected by these projects and in the evaluation of potential management scenarios for this watershed.

METHODS

1-dimensional (1-D) optimum-boundary box models were used to simulate the movement of dissolved pollutants or other conservatively mixing constituents through the Altamaha River estuary. The models were generated using the SqueezeBox modeling application (Sheldon and Alber, 2002), which is based on the method of Miller and McPherson (1991). This application constructs box models using 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 point along the estuary. The cross-sectional area equation is the same for all flow rates, but the upstream flow of seawater increases as freshwater inflow increases, as expected for estuarine circulation. For a given constant freshwater inflow rate specified by the user, box boundaries are chosen so that the ratio of box throughflow during a time step to box volume is within an optimum range for numerical stability (0.2-0.5). In addition to calculating upstream flow of seawater, the model calculates exchange flows between boxes to maintain steady-state balances of water and salt. This results in models with variable-sized sets of boxes that are different for different flow rates. See Sheldon and Alber (2002) for a complete description of the method.

Tracers were introduced into the models as point sources at various locations within the estuary (denoted as km upstream of the mouth) and as non-point inputs to the entire system. Point source locations were head of tide (54 km), the approximate upstream extent of seawater intrusion (24 km), and four points within the mixing zone (12, 6, 4, and 2 km). Point source inputs were modeled by giving the box containing the point source location an initial relative concentration of 1 and all other boxes initial concentrations of 0. For non-point source inputs, all model boxes were given an initial concentration of 1. Inputs at the model boundaries had concentrations of 0, so that as the estuary was flushed with new freshwater and seawater, tracer was progressively reduced. Flushing is the only removal method included in the models.

The models were used to simulate both the movement of tracer within the estuary and its rate of removal for four different river flow rates representing low, intermediate, and high flow field observations plus a median case (Table 1). SqueezeBox models have reproduced the observed salinity distributions associated with these flow rates (Sheldon and Alber, 2002), indicating that the models are adequate 1-D representations of the Altamaha River estuary. A time step of 0.05 d resulted in models with 11-18 boxes with spatial resolutions of 1.4-11.3 km (<4.7 km within the mixing zone). All models were run until 99% tracer removal was achieved. When tracer is introduced as a point source, the time for removal of a given percentage of material is called the pulse residence time (PRT), whereas removal of material introduced throughout the estuary (e.g. as a non-point source) is called an estuarine residence time (ERT) (Miller and McPherson, 1991). In this paper, all estimates of PRT and ERT refer to the time for 99% tracer removal unless stated otherwise. Average transit times, the average amount of time tracer particles spend between entrance at head of tide and exit at the mouth, were also calculated according to the method of Sheldon and Alber (2002).

The models presented here are 1-D simplifications of the Altamaha River estuary. The correspondence between model distances and estuary locations is not exact because the models collapse all side channels into one combined channel, even though they have slightly different lengths and cross-sectional areas. These models also assume the estuary is well mixed both vertically and laterally. Although the estuary usually shows only slight vertical stratification, deviations from these assumptions could result in local concentrations being either higher or lower than those estimated by the model. Model results are useful, however, as a way to help focus further exploration and as an initial indication of areas that are potentially vulnerable.

Table 1. Average Transit Times, Pulse Residence Times (PRT) from Head of tide and Estuarine Residence Times (ERT) for % Tracer Removal

Flow Case	River Flow (m^3 s^{-1})	Transit Time (d)	PRT 58% (d)	PRT 99% (d)	ERT 99% (d)
Low	185	7.2	7.25	17.90	14.85
Median	245	5.4	5.45	13.50	11.20
Intermed.	342	3.9	3.95	9.60	8.00
High	538	2.5	2.55	6.05	5.00

RESULTS

Average transit times in the Altamaha River estuary are rapid: in the cases presented here they range from 2.5 to 7.2 d (Table 1). Transit times of individual tracer particles approximate a Poisson distribution, as expected for simple models of stirred tanks in series (e.g. Wen and Fan, 1975). For identical tanks and unidirectional flow, the predicted cumulative fraction of a tracer pulse escaping over the average transit time would be 53-54% for 11-18 tanks. The boxes in the models presented here are not of equal volume and exchange flows are bi-directional; nevertheless, the fraction of tracer introduced at head of tide that escaped during the average transit time was approximately 58% for all flow cases (Table 1). As expected from the transit time distribution, PRT for 99% removal was approximately 2.5 times the average transit time, regardless of flow rate (Table 1). ERT, although still longer than transit time, was only 83% of PRT because tracer is initially distributed throughout the estuary and so not all of it must traverse the entire estuary before it exits.

Tracer released as a point source anywhere in the estuary or as a non-point source over the whole estuary moved toward the region located 4-6 km from the mouth, regardless of flow rate. When tracer was introduced at head of tide (54 km), the peak moved rapidly to the head of the mixing zone at 24 km (from 1-2 d, depending on flow) and then slowed as it moved farther downstream (Fig. 1 top row). When the peak reached the 4-6 km region, it remained centered there,

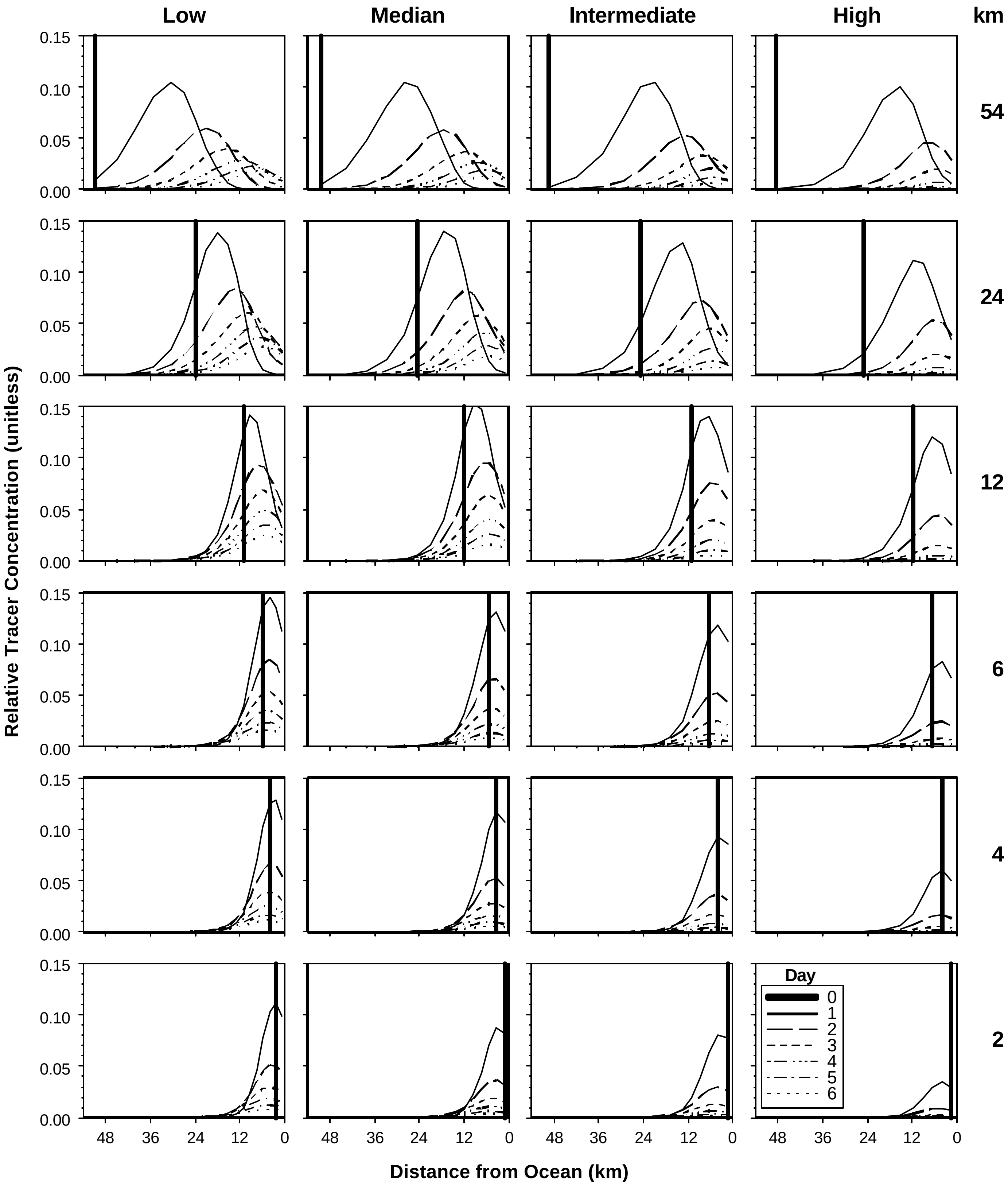

Figure 1. Tracer distribution for 4 flow cases (low, median, intermediate, and high) following introduction of point source inputs at 6 locations throughout the estuary. See Table 1 for corresponding flow rates.

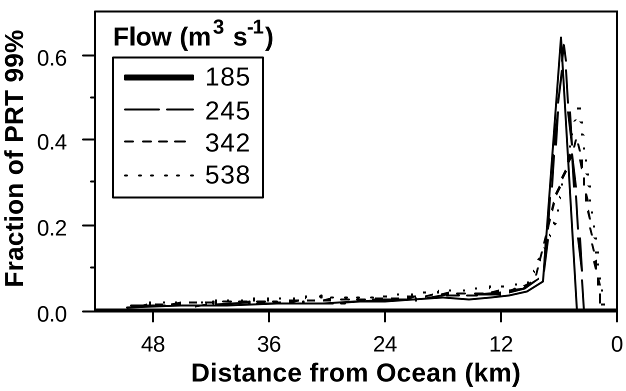

Figure 2. Fraction of PRT 99% spent at locations along the estuary axis by a tracer peak introduced at head of tide.

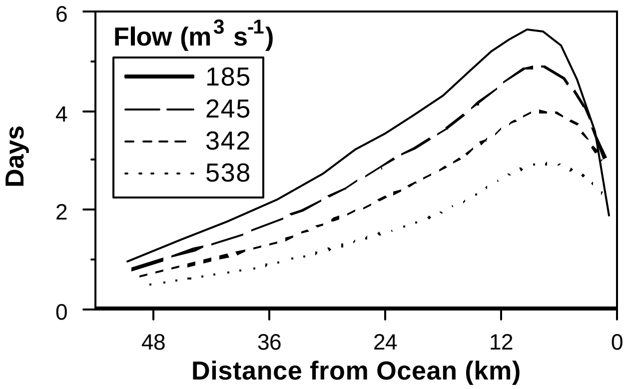

Figure 4. Days that locations along the estuary axis experience tracer concentrations above a threshold of 1% given a tracer input at head of tide.

although the peak height decreased as overall tracer removal continued. For each flow case, the tracer peak was located in this region for 62-69% of the total PRT (Fig. 2). Tracers released as point sources at other locations also moved toward the 4-6 km zone, even when they were released farther downstream at 2 km (Fig. 1). When tracers were introduced as a non-point source, concentrations in the lower estuary upstream of 6 km remained near their original values for 1-2 days because tracer-containing water moved toward the 4-6 km zone from both up- and downstream (Fig. 3). Similar behavior occurred for introductions of tracer either at the head of the estuary or as a non-point source in an optimum-boundary box model of Charlotte Harbor, Florida (Miller and McPherson, 1991).

Another way to evaluate pollutant exposure is to consider the amount of time that a location experiences a pollutant concentration above a minimum level. As an example, Fig. 4 shows the number of days that estuary locations experienced a tracer concentration above an arbitrary minimum of 1% when a tracer concentration of 1 was introduced at head of tide. Although the peak spends the most time at 4-6 km (Fig 1 top row), tracer concentration is lower than it is upstream: the region of maximum exposure in this case is 6-10 km. At locations farther upstream, where maximum concentrations are higher still, peak movement is rapid so total exposure is lower.

The reason for the convergence of tracer at 4-6 km in the model has not been determined, but several possibilities have been eliminated. If convergence zones exist, they are often manifested in persistently high concentrations of refractory materials or particles, such as in estuarine turbidity maxima. Estuarine turbidity maxima (ETMs) typically occur near the head of seawater intrusion, but this is usually above 19 km in the Altamaha River estuary. ETMs might also be expected near topographic features, but the estuarine topography is represented in the model by a curve of cross-sectional area vs. distance, and it does not break sharply at 4-6 km. Finally, the simple balance of forces between down-estuary river flow (Q_R) and up-estuary seawater flow (Q_{sw}) in the model occurs at 1.9 km.

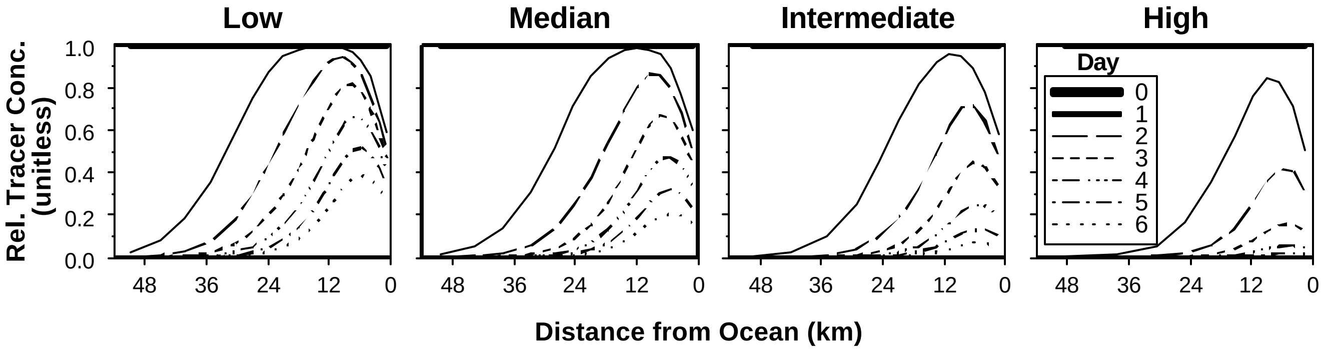

Figure 3. Tracer distribution for 4 flow cases (low, median, intermediate, and high) following introduction of a non-point source input throughout the estuary. See Table 1 for corresponding flow rates.

DISCUSSION

The model runs suggest a potential convergence zone at 4-6 km in the Altamaha River estuary. Convergence zones are areas where materials remain for extended periods of time and thus could experience prolonged exposure to dissolved pollutants and other substances. Some physical evidence exists in support of a convergence zone at 4-6 km in the Altamaha River estuary. Relative concentrations of fluorescent dissolved organic matter (FDOM), adjusted for conservative mixing of fresh- and seawater end-member FDOM, showed consistent peaks at 2, 4, and 6 km during 3 sampling cruises in 1997-1998 (W. Sheldon, pers. comm.). The Little Mud River enters at 4 km, which could account for the extra peak there, but there is no side channel entering at 6 km that could be a source of FDOM input. Hydroacoustic sampling of fish (and other organisms larger than 2 cm) also showed increased density centered at 6 km (D. Di Iorio, pers. comm.). However, optical backscatterance from CTD profiles taken during 12 transects (5 cruises) in 1994-1999 showed inconsistent peaks from 0-12 km, 4 of which were near 4-5 km (Georgia Rivers LMER Program, unpubl.).

The disproportionate amount of time that water may spend in the lower estuary suggests that this region may be vulnerable to prolonged concentrations of dissolved substances such as nutrients or pollutants, even those originating from other locations within the estuary. In the case of nutrients, this could enhance lower estuarine production, whereas in the case of pollutants, this could result in a greater incidence of chronic toxicity among lower estuary organisms. Peaks in dissolved nutrients are not generally observed in this region (W. J. Wiebe and J. Sheldon, unpubl.), but the distribution of labile materials is less likely to reflect simple water movement. Convergence of labile materials may instead be reflected in peaks in process rates, such as production, or in peaks in standing stocks, such as chlorophyll. Chlorophyll is higher in the lower Altamaha River estuary (M. Alber, unpubl.), but sampling was not sufficient to assess whether this narrow region has a consistent peak.

Much of this paper has focused on the movement of tracer toward a potential convergence zone at 4-6 km. Although information of this type is important for locating the region in the estuary that experiences the maximum duration of exposure to a dissolved substance such as a pollutant, it is not the only consideration for evaluating the potential impact of the distribution of material in the estuary. If the primary concern is acute exposure to the maximum concentration of a pollutant, the point of introduction is of principal interest. If the concern is the amount of time a pollutant is above a given threshold (i.e. a water quality standard), the region of primary interest depends on the interaction between pollutant concentration and the movement of the peak through the estuary over time. When a substance is introduced at head of tide, the region of maximum exposure occurs at 6-10 km (Fig. 4), whereas the region of maximum exposure for a substance released at 12 km occurs at 4-9 km, with no exposure above 24 km (data not shown).

Our results suggest that the lower Altamaha River estuary may experience greater exposure to introduced substances than the faster-flushing upper estuary, and there is sufficient anecdotal evidence in support of this to warrant more detailed modeling and field investigations. If this area proves to be a convergence zone, this information can be useful for evaluating the conservative movements of both point- and non-point-source constituents in the estuary and the potential exposure of estuarine habitats to those constituents.

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LITERATURE CITED

Miller, R.L. and B.F. McPherson, 1991. Estimating estuarine flushing and residence times in Charlotte Harbor, Florida, via salt balance and a box model. *Limnol. Oceanogr.* 36:602-612.

Morton, M.G., K.L. Dickson, W.T. Waller, M.F. Acevedo, F.L. Mayer, Jr. and M. Ablan, 2000. Methodology for the evaluation of cumulative episodic exposure to chemical stressors in aquatic risk assessment. *Environ. Toxicol. Chem.* 19:1213-1221.

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.

The Nature Conservancy, 1998. Altamaha River Bioreserve 1997 Conservation Report.

Wen, C.Y. and L.T. Fan, 1975. *Models for Flow Systems and Chemical Reactors*. Marcel Dekker, Inc., New York.