Modeling mixing time scales and transport of dissolved substances in the Altamaha River estuary

Joan E. Sheldon and Merryl Alber, Dept. of Marine Sciences, University of Georgia, Athens, Georgia, 30602

Abstract

This project focuses on 1) estimating flushing (freshwater transit) times and residence times for the Altamaha River estuary, Georgia, by several different methods (fraction of freshwater models and box models) and 2) using 1-D optimum-boundary box models to simulate the movement of dissolved pollutants or other conservatively mixing constituents through the estuary. Freshwater transit time estimates from simple steady-state box models were very similar to flushing times but depended on river flow. As river discharge increases from 185 to 538 $m^3 s^{-1}$, flushing times decrease from 7.2 to 2.7 d. When box models were used to simulate both the movement of tracer within the estuary and its rate of removal, it 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 or the point of tracer introduction, suggesting that this area could be a slowly flushing node 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. Simulations of the type presented here are useful for evaluating the conservative movements of both point- and non-point-source constituents in the estuary.

Objectives

1) To clarify concepts related to flushing, transit, and residence time
2) To compare simple methods for calculating such time scales
   a) Fraction of freshwater (flushing time) model
   b) SqueezeBox model (1-D box model with optimal box boundaries)
3) To simulate the movement of dissolved substances through the Altamaha River estuary using the SqueezeBox model

Definitions of Time Scales

Age: amount of time a particle (of a specified substance) has *already spent* in a reservoir.

Residence Time: amount of time a particle *will remain* in a reservoir.

Transit Time: amount of time a particle spends in a reservoir *between entrance and exit.*

Transit Time = Age + Residence Time

(Zimmerman, 1976; Takeoka, 1984)

However, these time scales are often calculated for a group of particles.

Average transit time of freshwater: average amount of time that freshwater spends in the estuary. It is often estimated by:

Flushing Time or **Freshwater Replacement Time**: time required for freshwater inflow to equal the amount of freshwater originally present.

For residence time, it is important to specify the initial distribution of particles. As an alternative to the average, the fraction of particles to be removed can be specified.

Estuarine Residence Time (ERT): time to remove a specified fraction of particles *initially distributed throughout the estuary.*

Pulse Residence Time (PRT): time to remove a specified fraction of particles *introduced into one subregion or model box, often the most upstream.*

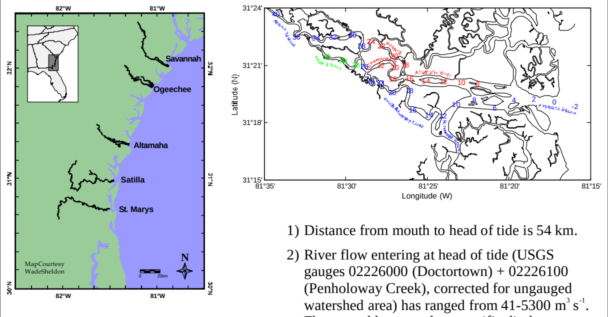
(Miller and McPherson, 1991)

Model Data Requirements

We used both the fraction of freshwater method and 1-D box models to estimate various mixing time scales for the Altamaha River estuary. One of the attractions of these simple models is that they have minimal data requirements:

1) Estuarine dimensions (usually from charts)
2) River flow (usually from discharge gauges)
3) Salinity (routinely measured in scientific studies)

Altamaha River Estuary



Case	Date	River Flow ($m^3 s^{-1}$)
Low:	29 Aug 1998	185
Intermediate:	16 Oct 1995	342
High:	6 Feb 1999	538
Median:	long-term obs.	245

1) Distance from mouth to head of tide is 54 km.
2) River flow entering at head of tide (USGS gauges 02226000 (Doctortown) + 02226100 (Penholoway Creek), corrected for ungauged watershed area) has ranged from 41-5300 $m^3 s^{-1}$. Flows used here are date-specific discharge rates averaged over the flushing time (Alber and Sheldon, 1999).
3) Salinities for the low, intermediate, and high flow cases considered here are from low and high tide observations taken during Georgia Rivers LMER cruises. Salinities for the median case are based on 1297 observations from 10 historical studies (Sheldon and Alber, 2002).

Flushing Time Model

Flushing time or **average freshwater transit time** (τ) sets the time scale for conservative transport of river-borne materials, such as nutrients or pollutants. It is often compared against the time scales of other processes to determine whether transformations may occur within the estuary. It is calculated according to the **fraction of freshwater method** (Dyer, 1973):

$$\tau = \frac{\text{Freshwater Volume}}{\text{Freshwater Input}} = \frac{\sum_{i=1}^{n}\left[\left(\frac{S_{sw}-S_i}{S_{sw}}\right)V_i\right]}{Q_R}$$

n = number of estuary segments
S_{sw} = seawater end-member salinity
S_i = salinity of volume segment i
V_i = volume of segment i
Q_R = freshwater input

Estimating "typical" flushing time of an estuary:

Fraction of freshwater was calculated from the average of many salinity observations, then multiplied by volume to obtain freshwater volume.

Annual *median* discharge was used to estimate median flushing time. Annual *mean* discharge will underestimate the "typical" flushing time, since daily mean river discharge rates are positively skewed (Alber and Sheldon, 1999).

Estimating flushing time for specific conditions:

Fraction of freshwater was calculated from salinity observations from a sampling period.

The appropriate time period for averaging discharge is the flushing time itself. This requires an iterative method in which the averaging period is incremented by 1 day until the resulting flushing time closely matches the averaging period. Arbitrary, fixed prior averaging periods for discharge (e.g. day or month of salinity observation) can give poor estimates of flushing time (Alber and Sheldon, 1999).

Altamaha River Estuary Mixing Times

Average transit times, pulse residence times (PRT) from head of tide and estuarine residence times (ERT) for 99% tracer removal (days).

	Flow Case			
	Low	Median	Intermed.	High
Flushing Time Model				
Transit Time	7.2	5.8**	3.9	2.7
SqueezeBox Model*				
Transit Time	7.2	5.4	3.9	2.5
PRT 99%	17.90	13.50	9.60	6.05
ERT 99%	14.85	11.20	8.00	5.00

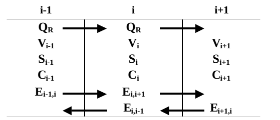
* Sheldon and Alber, 2003
** Alber and Sheldon, 1999

SqueezeBox

A New Desktop Tool for Generating Optimum-Boundary Box Models

Box models are spatially explicit and therefore can be used for a variety of applications, such as calculating expected steady-state distributions of nutrients or pollutants to determine the degree to which observations differ from conservative mixing.

The residence time of the entire estuary can be calculated by considering the estuary as one box; however, a **simulation** is required to calculate residence time while retaining spatial resolution. Simulations involve explicit calculation of flows among boxes and resultant changes in box tracer concentrations. The numerical tracers represent water or a conservatively mixed substance.



Q_R = river flow
V_i = volume of box i
S_i = salinity of box i
C_i = concentration of a conservative substance in box i
$E_{i,i+1}$ = exchange flow between box i and box i+1
(Modified from Officer, 1980)

For other uses, **box boundaries** may be placed arbitrarily (Officer, 1980); *however, for a simulation:*

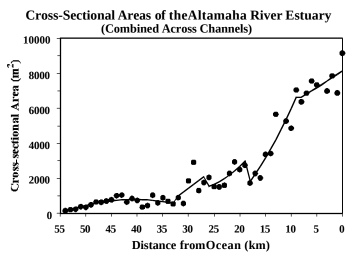
Flow through a box during a time step must not exceed the box volume.

Small flow through a box relative to the box volume will require many time steps (inefficient, possible accumulation of round-off errors)

The optimum ratio of throughflow:box volume (R_i) is between 0.2 and 0.5 (Miller and McPherson, 1991) and may be controlled by selection of box sizes or time step.

Miller and McPherson (1991) outlined a method for creating box models suitable for any chosen steady-state river flow, using continuous equations as smoothed representations of estuarine parameters. We have used a modified version of their method to create the desktop application SqueezeBox and developed the first module for the Altamaha River Estuary.

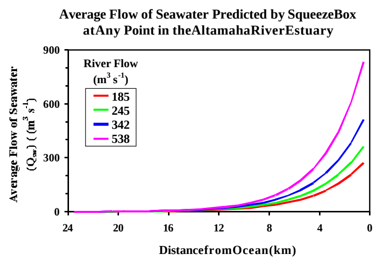
Equations describe cross-sectional area vs. distance along the estuary axis, so that box boundaries can be drawn anywhere as necessary to maintain



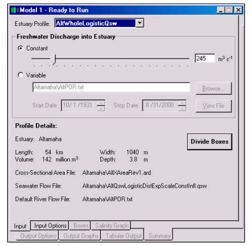
Salinities at the box centers are calculated from simple mixing of river flow with up-estuary seawater flow to that point. When river flow is sufficient to cause estuarine circulation, the tidally-averaged flow of seawater up-estuary should be proportional to the river flow and is calculated as follows:

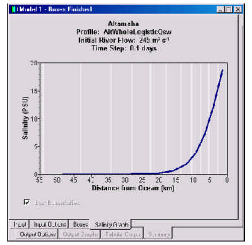
Salinity observations at known locations are paired with prior river flow conditions, and a conservative mixing equation is used to find the flow of seawater (Q_{sw}) that, when mixed with each river inflow, predicts the salinity observations.

A function is fit to Q_{sw} vs. river flow and distance. The form of the function assumes that salinity is a logistic function of distance and that this function's inflection point, scaling parameter, or both may be functions of river flow.



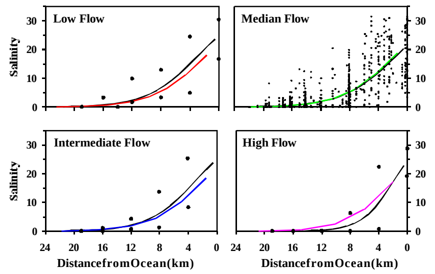
Equations for cross-sectional area and upstream flow of seawater are contained in estuary modules. The user chooses a module and river flow rate and sets other input options such as the time step (panel not shown). Results using constant freshwater inflow are shown here, but we are developing the application for variable freshwater inflow as well.





SqueezeBox sets box boundaries for optimum throughflow:volume ratios and calculates salinity at the center of each box as well as exchange flows between adjacent boxes. This defines a particular box model for this estuary and river flow rate. The example shown is for the long-term median river flow rate.

Salinity predicted by SqueezeBox (colors) reproduces field observations (black)



Box model simulations can be used to calculate a variety of **residence times** (i.e. ERT or PRT) for which the starting distribution and endpoint are specified:

Starting distribution of a conservative tracer may be throughout the estuary or in any one box.

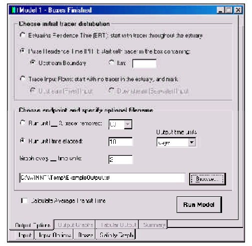
Endpoint may be a fixed runtime or a fixed arbitrary percent removal of tracer.

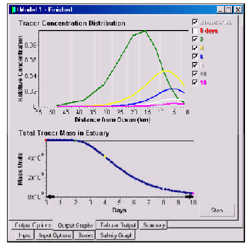
Box model simulations can also be used to calculate **average freshwater transit time**:

Start with tracer in the most upstream box, which is almost entirely freshwater, and run until nearly all tracer (e.g. >99%) has exited the estuary.

At each time step, multiply the fraction of tracer exiting during the time step by the elapsed

This example shows a simulation setup starting with tracer in the most upstream box and running for 10 days. The model time step is 0.1 days but results are graphed every 2 days.

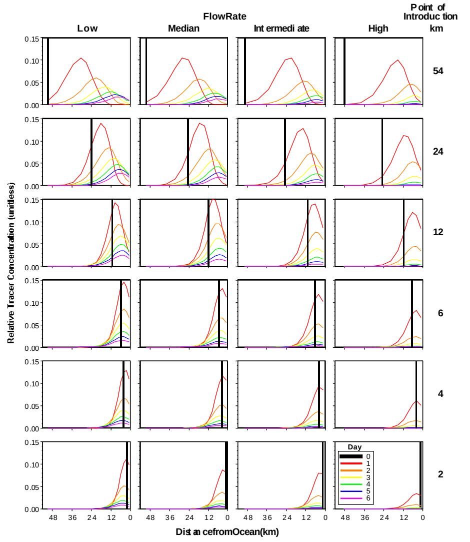




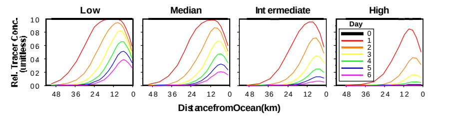
As the simulation runs, graphs show the tracer distribution at specified intervals and the tracer remaining at each time step. After the simulation is finished, summarized results including residence times are shown.

Simulations of the Movement of Dissolved Substances in the Altamaha River Estuary

Tracer released anywhere in the estuary moved toward an area 4-6 km upstream of the mouth, where it remained centered as removal continued.



Introduction of tracer as a non-point source also resulted in distributions centered at 4-6 km.

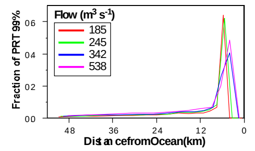


Exposure to Dissolved Substances

Exposure to dissolved substances may be evaluated in several ways:

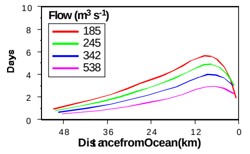
1) Maximum concentration at the point of introduction of the substance.
2) Maximum duration at the location where the peak spends the most time.
3) Duration that a location experiences concentrations above some threshold such as a water quality standard.

The tracer peak spends the most time at 4-6 km, regardless of flow rate.

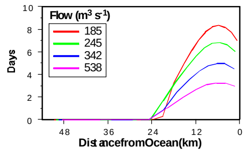


The duration that a location experiences concentrations above a threshold varies depending on the point of introduction.

Tracer released at head of tide; maximum exposure at 6-10 km.



Tracer released at 12 km; maximum exposure at 4-9 km.



Conclusions

1) Flushing and box models agree very well on average transit times in the Altamaha River estuary, which range from 2-7 d depending on flow rate.
2) Box models are spatially explicit and can be used to examine a variety of residence times. For this purpose, they must be constructed differently for different flow rates. SqueezeBox, a desktop tool for creating optimum-boundary models, automates this process.
3) Mixing time scales are non-linearly correlated with river flow.
   a) Average freshwater transit times and pulse residence times are negative power functions of river flow (Alber and Sheldon, 1999; Sheldon and Alber, 2002).
   b) The time scales for the fast-flowing Altamaha River estuary are all short and differences with flow are small on an absolute scale; however, larger ranges would be expected for longer or more slowly flowing estuaries.
   c) Evaluating variability over the range of flow in an estuary is important for characterizing mixing time scales.
4) Different mixing time scales are appropriate for different applications.
   a) Flushing time and average transit time are equivalent
   b) The time to remove 99% of introduced tracer is much longer than the average transit time; therefore "flushing time" should not be considered as the time to flush all of an introduced substance from the estuary.
   c) PRT from head of tide is always longer than ERT for the same % removal because for PRT all the tracer must traverse the whole estuary, whereas for ERT some of the tracer is introduced near the mouth and can exit immediately.
5) There may be a node of slow flushing in the lower Altamaha River estuary.
   a) 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. Introduction of tracer as a non-point source also resulted in distributions centered at 4-6 km. Movement toward this zone was observed regardless of flow rate.
   b) 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 but tends to be in the lower estuary because of the slower peak movement through that zone.
   c) The lower estuary may be more vulnerable than the faster-flushing upper estuary to prolonged concentrations of dissolved substances, 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.
6) Simulations of the type presented here are useful for evaluating the conservative movements of both point- and non-point-source constituents in the estuary.

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. *Estuarine, Coastal and Shelf Science* 49:469-482.

Dyer, K. R. 1973. Estuaries: A Physical Introduction. John Wiley & Sons, London.

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. *Limnology and Oceanography* 36:602-612.

Officer, C. B. 1980. Box models revisited, p. 65-114. *In* P. Hamilton and K.B. Macdonald (eds.), Estuarine and Wetland Processes with Emphasis on Modeling. Plenum Press, New York.

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* K.J. Hatcher (ed.), Proceedings of the 2003 Georgia Water Resources Conference. Institute of Ecology, University of Georgia, Athens, Georgia.

Takeoka, H. 1984. Fundamental concepts of exchange and transport time scales in a coastal sea. *Continental Shelf Research* 3:311-326.

Zimmerman, J.T.F. 1976. Mixing and flushing of tidal embayments in the western Dutch Wadden Sea. Part I: Distribution of salinity and calculation of mixing time scales. *Netherlands Journal of Sea Research* 10:149-191.

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