Any way you slice it: a comparison of residence time calculations using simple compartment models of the Altamaha River Estuary

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Abstract

Residence time and flushing time of estuaries are two concepts that are often confused. Flushing time is the time required for the freshwater inflow to equal the amount originally present in the estuary. It is specific to fresh water (or materials dissolved in it) and represents the transit time through the entire system (e.g. from head of tide to the mouth). Residence time is the average time particles take to escape the estuary. It can be calculated for any type of material (including fresh water), and will vary depending on the starting location of the material. We explored these two concepts in the context of the Altamaha River Estuary, Georgia, and present a comparison of techniques for their calculation (fraction of fresh water models and variations of box models). Freshwater transit time estimates from simple steady-state box models were virtually identical to flushing times for four river-flow cases. Another common approach is segmented tidal prism models, which have data requirements similar to other models but can be cumbersome to implement properly. We are now developing an improved box model that will allow the calculation of a variety of residence times using simulations with daily variable river discharge.

Objectives

1) Clarify concepts related to flushing, transit, and residence time
2) Compare several simple methods for calculating such time scales
   a) Fraction of fresh water (flushing time) model
   b) Classic box model (with arbitrary box boundaries)
   c) “SqueezeBox” model (with optimal box boundaries)

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 fresh water: average amount of time that fresh water 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 fresh water 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 remove 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

One of the attractions of these simple models is that the data are readily accessible:

1) Estuarine dimensions, usually from charts
2) River flow (Q_R), usually from discharge gauges
3) Salinity, usually from scientific studies

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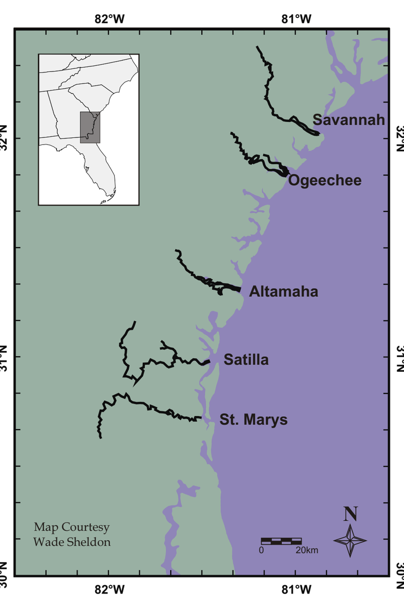
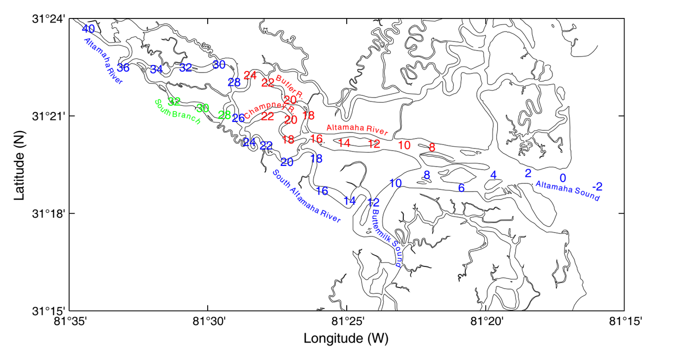
Altamaha River Estuary





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

1) The distance from mouth to head of tide is 54 km, but the models presented are limited to the usual upstream extent of salinity, the lower 24 km.
2) River flow entering at head of tide (corrected for ungauged watershed area) has historically ranged from 42-5300 $m^3\ s^{-1}$, and the average annual daily min-max is 79-1878 $m^3\ s^{-1}$. Date-specific river flows are prior discharge averaged over the flushing time of the entire estuary (Alber and Sheldon, 1999).
3) Salinities for the low, intermediate, and high flow cases are from observations at low and high tide taken during Georgia Rivers LMER cruises. Salinities for the median case are based on 1297 observations from 10 historical studies.

Flushing Time Model

Flushing time or average freshwater transit time sets the time scale for conservative transport of river-borne materials, such as nutrients and pollutants. It is often compared against the time scales of other processes to determine whether transformations may occur within the estuary.

Flushing time ( ) is calculated according to the **fraction of fresh water method** of Dyer (1973) where

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

$$\frac{\text{Freshwater Volume}}{\text{Freshwater Input}} \quad \frac{\sum_{i\ 1}^{n} \frac{S_{sw} \quad S_i}{S_{sw}} V_i}{Q_R}$$

This calculation assumes steady-state freshwater input and is not spatially explicit. (The estuary may be segmented for convenient calculation of freshwater volume but ultimately is considered as one box).

Moreover, the **choice of freshwater input is important,** as river discharge is rarely constant over time scales of interest to investigators.

Estimating “typical” flushing time of an estuary:

Fraction of fresh water is usually calculated from the average of many salinity observations, then multiplied by volume to obtain freshwater volume.

Annual *mean* discharge will underestimate the "typical" flushing time, since daily mean river discharge rates are often positively skewed.

Annual *median* discharge is recommended to estimate median flushing time (Alber and Sheldon, 1999).

Estimating flushing time for specific conditions:

Fraction of fresh water is usually calculated from salinity observations from a defined sampling 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).

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.

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.

Individual box residence times can also be calculated to determine the amount of time that some material (e.g. water) will remain in the box; however, the sum of these does not equal the residence time of a larger, aggregate box or the entire estuary because flows to other boxes are treated the same as flows outside the estuary.

Although the entire estuary could be considered as one box, 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.

Box model simulations can be used to calculate a variety of **residence times** in which the starting distribution and endpoint are specified:

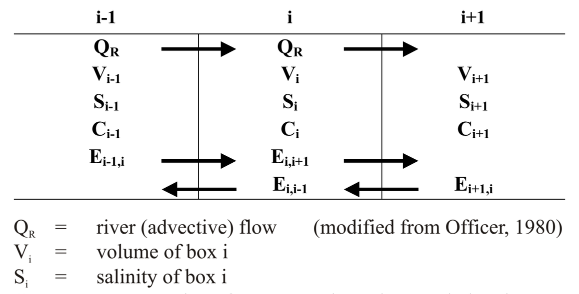
Starting distribution of water (or a conservative tracer) may be throughout the estuary, in any one box, or a more complex distribution

Endpoint may be a fixed runtime or a fixed arbitrary percent removal of tracer (e.g. 99%, 95%, 63% = e^{-1} remaining)

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 fresh water, 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 time (which is the transit time for that fraction). The sum is the average transit time of the tracer.



Q_R = river (advective) flow (modified from Officer, 1980)
V_i = volume of box i
S_i = salinity of box i
C_i = concentration of a conservative substance in box i
$E_{i,i+1}$ = non-advective exchange flow from box i to box i+1

Classic (Arbitrary Boundaries)

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

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

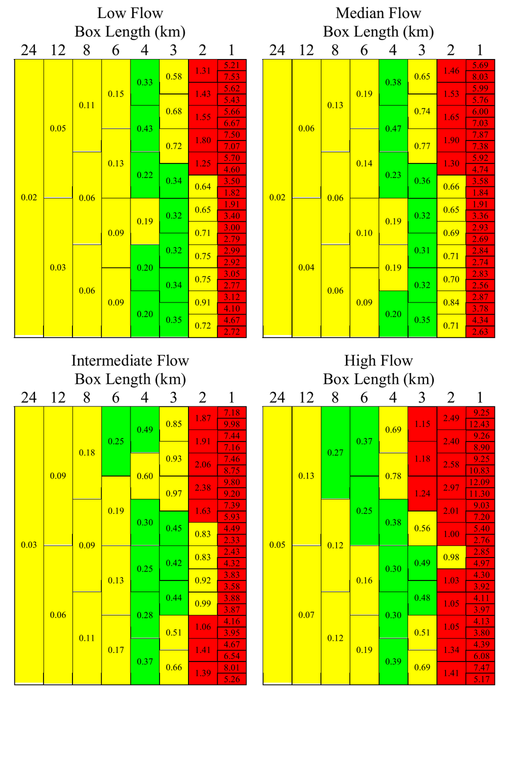
Small flow through a box relative to the box volume will require many time steps (inefficient, possible accumulation of round-off errors)

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.

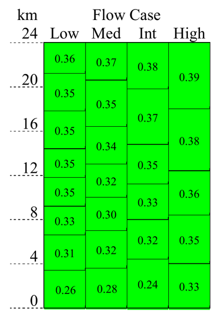
We explored the effects of different fixed box lengths on the use of a classic box model for residence time simulations. Spreadsheets are a convenient tool for this type of model.

(In)stability of flow:box volume ratios (R_i) for boxes of fixed arbitrary lengths

Upstream boxes are at the top



SqueezeBox varies box boundaries for optimum flow:box volume ratios (R_i)



“SqueezeBox” Model

A New Desktop Tool for Generating Optimum-Boundary Box Models

Miller and McPherson (1991) outlined a method for any chosen steady-state river flow, using continuous equations as smoothed representations of estuarine parameters:

Box boundaries can be drawn anywhere as necessary to maintain throughflow:volume ratios in the optimum range.

Equations describe cross-sectional area vs. distance along the estuary axis.

Salinities at the box centers must be calculated.

On a tidally-averaged basis, the flow of seawater up-estuary to any point should be relatively constant.

Simple mixing of up-estuary seawater flow with river flow could be used to predict salinity at any point in the estuary.

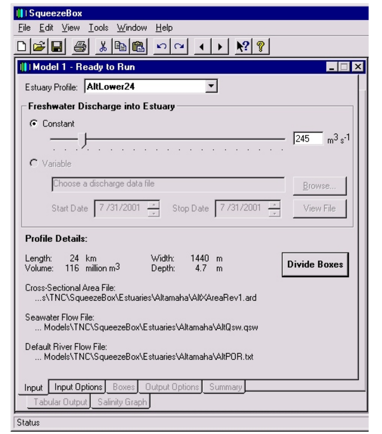
At several locations, salinity observations are paired with prior flow conditions.

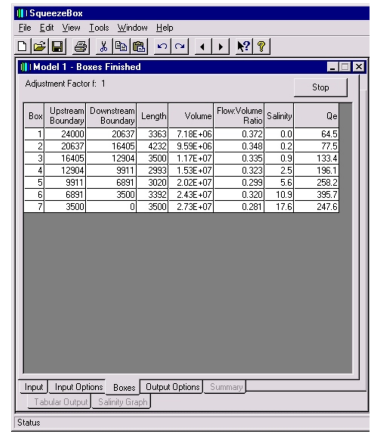
A conservative mixing equation is used to find the constant flow of seawater (Q_{sw}) that, when mixed with varying river inflow, predicts salinities that best fit the observations.

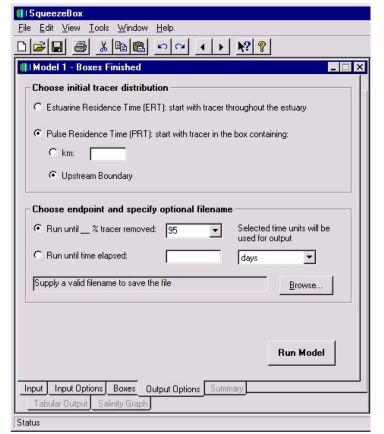
An equation is fit to Q_{sw} vs. distance along the estuary axis so that Q_{sw} (and therefore salinity) at the center of any box can be predicted.

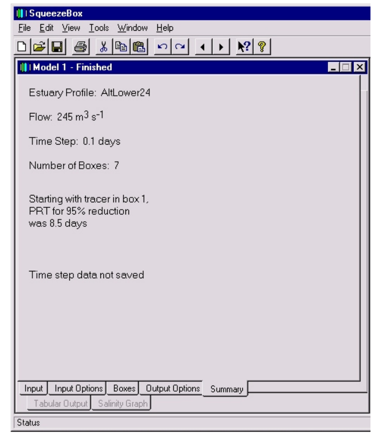
We have used Miller and McPherson’s method to create the desktop application “SqueezeBox”, written in Visual Basic, and applied it to the Altamaha River Estuary.

Preliminary results using a constant freshwater inflow are shown here, but we are in the process of developing it for variable freshwater inflow as well.

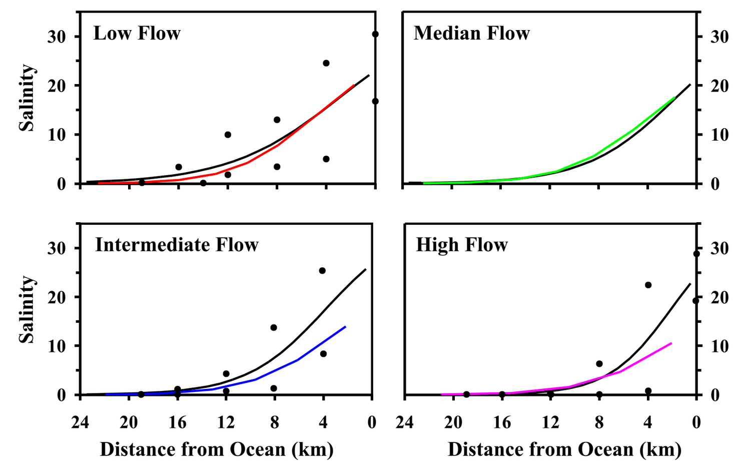








Salinity predicted by SqueezeBox (colors) reproduces field observations (black)



Residence Times PRT and ERT

PRT and ERT (days)
63% and 95% tracer removal
Altamaha River Estuary, lower 24 km

	SqueezeBox Simulation				4-km Box Simulation			
	PRT		ERT		PRT		ERT	
Flow Case	63	95	63	95	63	95	63	95
Low	5.5	10.6	3.2	8.4	5.9	12.4	3.6	10.1
Median	4.4	8.5	2.7	6.8	4.9	9.8	3.0	8.0
Intermediate	3.3	6.4	2.1	5.2	3.1	6.2	1.8	4.9
High	2.2	4.3	1.5	3.6	2.2	4.2	1.3	3.3

The classic box model and optimum-boundary SqueezeBox simulations calculate similar values for pulse and estuarine residence times, provided that classic boxes are chosen with regard to throughflow:volume ratios (e.g. 4 km fixed boundaries).

These residence times vary non-linearly with river flow, as do other mixing time scales (e.g. age) (Vallino and Hopkinson, 1998).

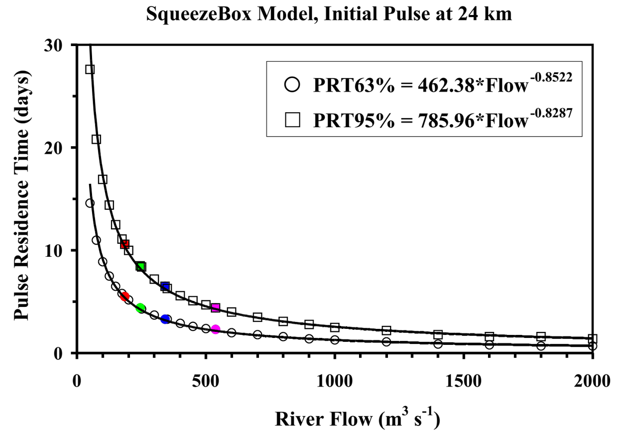
ERT is always shorter than PRT for a pulse introduced into the most upstream box, because for ERT particles originate throughout the estuary and some may exit immediately whereas for PRT the particles must all travel the length of the estuary. For the median flow case, the difference between these two values is 1.7 days regardless of the specified removal fraction.

If the entire estuary is treated as one box, then ERT and PRT are equivalent.

Classic box models may be used for residence time simulations if the box boundaries are chosen with care; however, SqueezeBox automates this tedious process and therefore is preferable if exploration of a variety of flow and salinity conditions is desired.

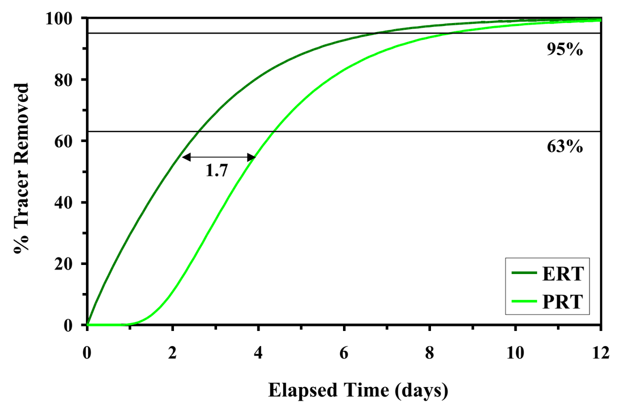
Residence time is a nonlinear function of flow

SqueezeBox Model, Initial Pulse at 24 km



ERT is shorter than PRT from upstream box

Median River Inflow



Transit Times

Average freshwater transit times (days)
Altamaha River Estuary, lower 24 km

		Box Model Simulations		
Flow Case	Flushing Time	SqueezeBox	4 km Boxes	1 km Boxes (unstable)
Low	5.7	5.2	5.6	1.9
Median	4.7	4.1	4.6	1.6
Intermediate	3.1	3.1	3.0	1.5
High	2.2	2.1	2.2	1.3

Average freshwater transit times calculated by the three models are very close, provided that boxes are chosen with regard to throughflow:volume ratios (e.g. 4 km fixed boundaries, SqueezeBox).

Boxes with unstable ratios (e.g. 1 km fixed boundaries) may yield over- or under-estimates of transit times and other time scales due to numerical instability.

Average freshwater transit times vary non-linearly with river flow. Alber and Sheldon (1999) found this to be a negative power function.

For this fast-flushing estuary, average transit times are very similar to PRT 63%. However, these are not equivalent concepts, and the values diverge for lower flows.

For calculation of average freshwater transit time all of these models perform well; the flushing time model may be preferred for its simplicity.

Conclusions

I) Any way you slice it, flushing and box models agree very well on various mixing time scales in the Altamaha River Estuary.
   A) Freshwater transit time is a useful scale for evaluating the potential for within-estuary processing of river-borne materials. For calculation of this single time scale, the simpler flushing time model is preferable.
   B) 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.
      1) Arbitrary box model boundaries can lead to unstable or inefficient simulations. Optimum-boundary models (Miller and McPherson, 1991) require more preliminary effort but provide stability and flexibility.
      2) SqueezeBox, a desktop tool for creating optimum-boundary models, increases model useability and will be enhanced to include variable river flow.
      3) Miller and McPherson’s tidally-averaged salinity prediction algorithm, used in SqueezeBox, appears to be a reasonable solution to the problem of predicting salinity at any point for any river flow rate.

II) Mixing time scales are non-linearly correlated with river flow.
   A) The time scales for the fast-flowing Altamaha River Estuary are all short and differences with flow are small on an absolute scale; however, much larger ranges would be expected for longer or more slowly flowing estuaries.
   B) Evaluating variability over the range of flow in an estuary is important for characterizing mixing time scales.

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