A Hydrodynamic Model Calibration Study of the Savannah River Estuary with an Examination of Factors Affecting Salinity Intrusion

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ABSTRACT

As part of a channel deepening feasibility study, a comprehensive field program and modeling study of the Lower Savannah River Estuary was conducted. The objective was to further our understanding of the estuary as an integrated system and to provide a tool for the evaluation of environmental impacts of the proposed 8-foot deepening of the shipping channel. Historic alterations to the estuary system, including the construction of a tide gate in one of the channels, earlier channel deepening projects and opening and closing various passages between the Front, Middle and Back Rivers, have shown that dramatic variations in the temporal and spatial distribution of salinity can result. Two areas of potential impact from the deepening were investigated using the predictive models. A potential for salinity increases in the brackish and fresh water tidal marshes in the upper portions of the estuary due to an upstream shift of the freshwater/saltwater interface and the potential impacts to the dissolved oxygen levels within the system due to increased stratification. The present discussion focuses on the factors affecting salinity intrusion in estuary.

To perform the analysis a 3-D hydrodynamic and water quality model system (WQMAP) was applied to the estuary and lower river. The process models within the system are based on the general curvilinear coordinate, boundary-conforming technique, which is ideally suited for application to the Savannah River, with its ability to replicate the complex geometry of the multiply interconnecting tidal, river system. The hydrodynamic model was run in its fully coupled, prognostic mode to predict the salinity intrusion in the lower river.

A detailed characterization and analysis of the estuary, based on historic and newly collected data, was used to quantify important mechanisms affecting circulation and salinity intrusion. Data gathered from July-September 1997 in a monitoring program, including current profiles, tidal elevations, salinity, temperature and dissolved oxygen at 14 stations throughout the lower river estuary, provided the basis for model calibration. Model-observation comparison methods were both qualitative and quantitative, where statistical measures and data reduction methods included RMS error, mean absolute error, error coefficient of variation, linear regression, spectral analysis and harmonic analysis. The data were also used to quantify the present temporal and spatial distribution of salinity and dissolved oxygen within the estuary. Data from a previous deepening were also utilized to evaluate the performance of the calibrated hydrodynamic/salinity model in projecting the impacts of future deepening projects.

Four primary factors were postulated to affect the longitudinal intrusion of salinity into the Savannah River Estuary: fresh water volume flow rate at the river head, tide range at the opening to the Atlantic, offshore mean sea surface elevation and river geometry. The hydrodynamic characterization of the estuary and preliminary model predictions determined that the controlling parameter in larger scale variations of the salinity intrusion were attributable to the stratification and de-stratification process caused by changes in the mean mixing energy associated with the spring-neap tidal cycle.

The calibration showed that model performed extremely well in the prediction of tidal amplitude and currents. The predicted salinity and salinity intrusion however did not fare so well with the traditional turbulence energy model. The predicted diffusivities were not sensitive enough to reproduce the development and collapse of stratification observed in the data, nor the large variation in the extent of the salinity intrusion up the Front River. The clear relationship observed between mixing and the range in current amplitude and therefor the tidal range were used to develop a direct Log Fit relationship between the range and the vertical eddy diffusivity.

The comprehensive comparison between model predictions and observations performed at each station throughout the estuary clearly indicate that in both a qualitative and quantitative comparisons the model is capturing most of the important physical and biogeochemical processes in the estuarine system. It is capable of reproducing complex, transient physical phenomena in this dynamic domain and is in very good agreement with observed values of surface elevation, currents, volume flows, salinity, and dissolved oxygen.

BACKGROUND

The Savannah River, which starts near Hartwell, Georgia at the confluence of the Tugaloo and Seneca Rivers flows along the South Carolina/Georgia border for approximately 320 km before discharging to the Atlantic Ocean. The river receives freshwater inflow from its drainage basin which covers a total area of 27,500 square km within southwestern North Carolina, western South Carolina and Georgia. The river discharges to the Atlantic Ocean at the Georgia/South Carolina border at Savannah.

Savannah Harbor constitutes the lower 34.3 km of the Savannah River from its mouth at Fort Pulaski up to Port Wentworth (Figure 1). This reach of the river, along with approximately 18 km offshore of Fort Pulaski has been maintained for navigation purposes since the early 1900s. Since that time the design depth of the channel has gone from 8 m MLW down to 12 m MLW with varying depths along specific reaches.

Presently the Georgia Ports Authority is examining the feasibility of deepening the harbor to 15 m MLW. Under this proposal the potential impacts of this action upon water quality conditions within the harbor will need to be evaluated. The following two specific areas of impact will need to be addressed through the application of predictive models:

- Potential salinity increases in the upstream portions of the Savannah River due to a shifting of the freshwater/saltwater interface upstream.
- Potential reduction in the dissolved oxygen conditions within the system.

Anthropogenic modifications of the Lower Savannah River Estuary, including the construction of a tide gate and the New Cut channel, between the Middle and Back Rivers, to control sedimentation in the harbor area and channel deepening have altered the temporal and spatial distribution of salinity. Past studies, (e.g. Pearlstine, 1990) have identified this shift in the salinity distribution as one of the more adverse environmental impacts to the various ecosystems within the estuary. This has lead to both the loss of

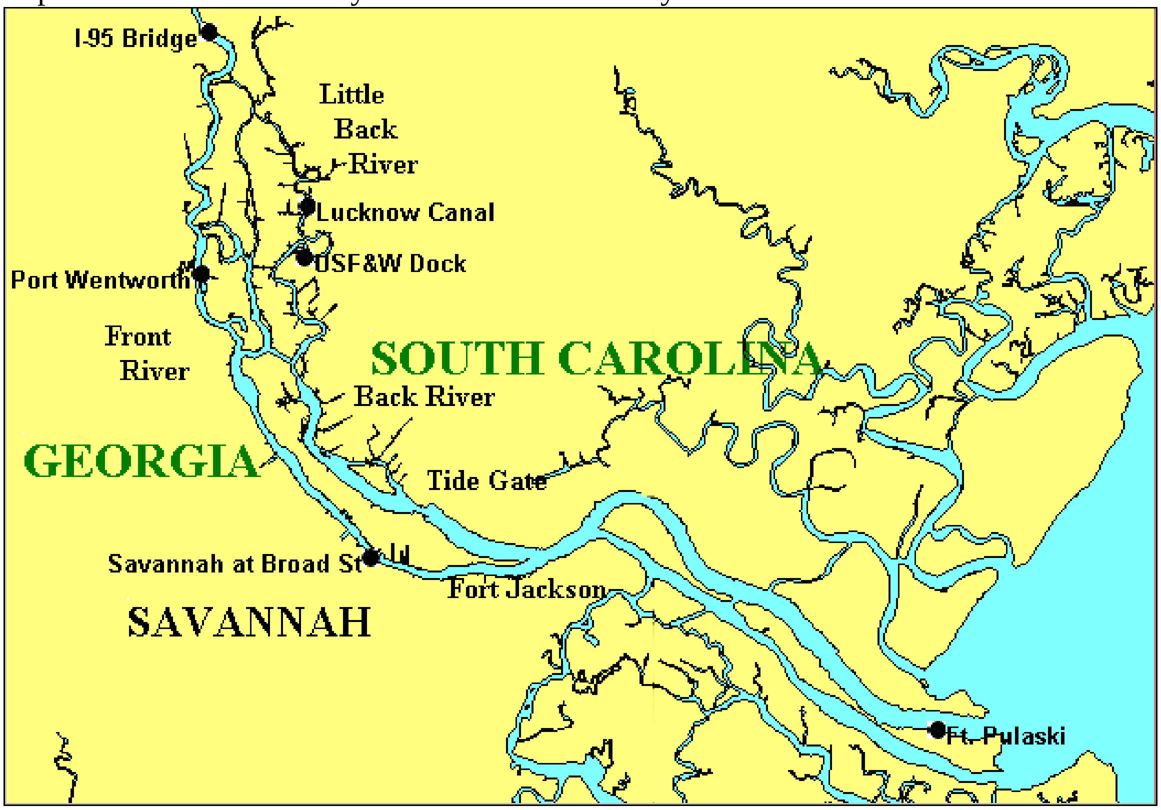


Figure 1 Map of the Savannah River Estuary. Historic water surface elevation and salinity monitoring stations are also shown.

freshwater wetlands within the Savannah National Wildlife Refuge and the reduction of the local striped bass population.

SAVANNAH RIVER DATA ANALYSIS

In 1987, under a *Feasibility Study* (ATM,1997), for a previous deepening, the USGS installed continuous monitoring instruments at various locations throughout the system (Figure 1). These stations monitored specific conductance and water level on 15-minute intervals. For all of the stations the specific conductance (and therefore the salinity upon conversion) were measured near the bottom. During this same time period, flow rates were measured at the Clyo gauging station located 100 km upstream. These stations have been maintained from 1987 to the present.

Statistical and multivariate correlation analyses of these historical data demonstrated that longitudinal intrusion of salinity into the Savannah River is a function of four primary factors:

- Freshwater inflow rate at the headwaters
- Tide range
- Offshore mean water level
- Physical geometry of the system (including structures and marsh systems)

The historical data were analyzed in order to understand the behavior and to quantify the relative influence of the various factors affecting the salinity intrusion. Figure 2a shows the salinity recorded at Port Wentworth versus the volume flow at recorded at Clyo for 1990, 1992, 1995 and 1996. Figure 2b shows the salinity at Port Wentworth versus the tidal elevation recorded at the NOAA station at Fort Pulaski at the mouth of the River. During the time period covered in the plots, three distinct conditions existed in the estuary:

1) Before March 1991 the tide gate was in operation and New Cut was open
2) after May 1992, New cut was closed, the tide gate was out of operation
3) after March 1994, the 4ft deepening had been completed, New cut was closed, and the tide gate was out of operation

The influence of the differing conditions can be seen quite clearly in both the salinity versus flow and the salinity versus tidal elevation data plots. In particular, the decommissioning of the tide gate between 1990 and 1992 is clearly visible in both data sets. After the tide gate was taken out of operation, (opened permanently), the mean salinity at Port Wentworth drops considerably.

Referring to Figure 2a it can be seen that through all four years of flow versus salinity data there is a clear inverse correlation between the river flow rate and salinity. The difference between the before and after channel deepening data sets (1992 and 1995) is not quite as dramatic but yielded an increase in the mean of about 0.5 ppt.

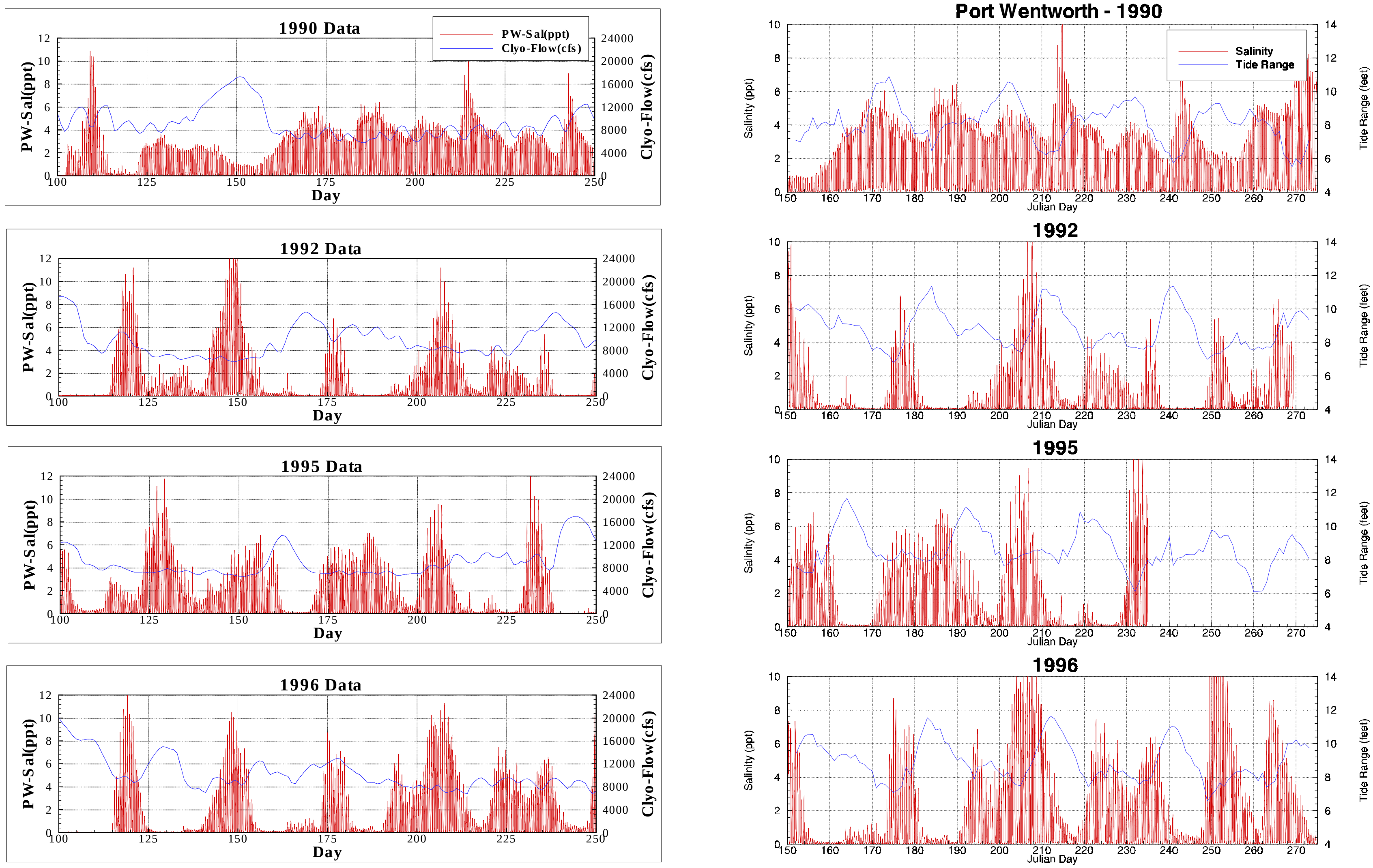
In the 1990 data set for salinity versus tidal elevation, (Figure 2b), there is a clear positive correlation between the spring/neap range variation and salinity. As the tidal range increases the salinity intrusion into the system also increases. After the decommissioning of the tide gate, however, the relationship is inverted, so that the maximum observed salinities now occur during the lower neap tide range, as can be seen in the 1992, 1995 and 1996 data sets. Similar analyses were performed on the data sets from the other continuous monitoring stations.

The following conclusions were reached from this data analysis:

- A clear impact of the tide gate decommissioning is seen in all of the data sets, with significant alterations in the means and maximums at the Little Back River Stations, and alteration in the means and maximums as well as the character of the salinity intrusion on the Front River.
- Salinity intrusion along the Front River is greater during the neap tide than spring tide range after the tide gate was permanently opened.
- Some impact of the deepening is evident on the Front River with changes in daily mean salinities on the order of 0.5 ppt.

- Negligible impacts upon the salinities measured at the Little Back River Stations are found due to the 1.2 m (4 ft) deepening.

A detailed description of the methodology and the results is presented in the Engineering Appendices of the *Feasibility Study*, (ATM, 1997) in the section entitled *Analysis of the Historic Data for the Lower Savannah River Estuary*.



(a) (b)

Figure 2 Historic observations at the Port Wentworth continuous monitoring station for (a) salinity versus flow rate and (b) salinity versus tidal elevation.

To better understand the complex dynamics of the system and for the purpose of model calibration, an intensive field-monitoring program to quantify the salinity and water quality conditions within the Lower Savannah River Estuary was conducted. During the summer months of 1997, 14 continuous monitoring stations, with permanently mounted instruments that recorded surface elevation, salinity, and dissolved oxygen (DO) at 15-minute intervals, were deployed. Figure 3 shows the locations of the stations throughout the system. The stations within the navigation channel generally recorded surface and bottom salinity and DO concentrations, while those outside of the channel recorded near-bottom concentrations. The instruments were placed near the bottom (1 m) in the reaches outside of the channel, in order to provide the worst case condition of salinity intrusion and DO concentration.

In order to quantify the vertical variation in the density-driven flow, as well as the tidal flow passing through the system, two bottom-mounted Acoustic Doppler Current Profilers (ADCP) at stations GPA-04 and GPA-08 and two electro-magnetic current meters (S-4) at GPA-10 and GPA-15 were deployed. The ADCPs recorded continuous currents at 1-meter intervals over the vertical water column, and the S-4 collected mid-depth current velocities, at 15-minute interval, during at least 30 days. In addition, boat-mounted ADCP transects measured cross-sections discharges across the width and depth of the river at critical locations. These data were used to quantify flux at these areas throughout the tidal cycle.

A detailed description of the methodologies utilized, the locations of stations, the data collected, and findings from the intensive field monitoring program is presented within the Engineering Appendices of the *Feasibility Study* (ATM, 1997). The section is entitled *Hydrodynamic and Water Quality Monitoring of the Lower Savannah River Estuary, July-September 1997*.

One of the major findings of the historic data analysis and the 1997 monitoring program was to confirm the importance of the stratification process and the density-driven currents as the primary mechanisms determining the upstream intrusion of salinity. The analysis of the historic data showed that following the decommissioning of the Tide Gate, the maximum salinity intrusion along the Front River, occurred primarily during neap-tide conditions, as opposed to maximums during spring tide when the Tide Gate was in operation. One potential cause for this alteration is the reduction in the velocities along the Front River above Fort Jackson, during ebbing tide following the decommissioning. Since the turbulence energy, which causes mixing, is directly proportional to the tidal velocities, a reduction in the flows causes an associated reduction in turbulent mixing. Therefore, during neap-tide conditions, there is not enough energy to break down the salinity gradient and water masses with higher salinity are able to intrude further into the system.

This system of stratification and collapse was again observed in the data from the monitoring program during the summer of 1997. As with the historical data, increased

Figure 3 Lower Savannah River Estuary map showing the 1997 long term monitoring stations GPA-01 through GPA-14. The WQMAP boundary-fitted model grid as applied to the estuary is also shown.

stratification and intrusion of the salinity wedge up the Front River was linked with neap tide conditions and destruction of stratification and decreased intrusion were related to the spring tide condition. Figure 4 shows the clear development and collapse of stratification at station GPA-04 near Fort Jackson just east of the confluence (or split) between the Front and Back Rivers. This is a critical juncture, and is indicative of, and in conjunction with the river flow rate controls, the salinity conditions farther upstream. Also plotted in Figure 4 is the tidal elevation at station GPA-01 just offshore of the Savannah River Entrance. It is clear that the state of stratification in the system is directly related to the tidal range, via the increasing and decreasing current velocity and therefor, turbulent energy in the system.

It is also clear from the observations that the relationship between the tidal range, turbulence and mixing places the system in a delicate balance between a mixed and a stratified system. In terms of the estuary number introduced by Thatcher and Harleman (1981), which is a ratio of the energy input by the tidal current to the energy needed for

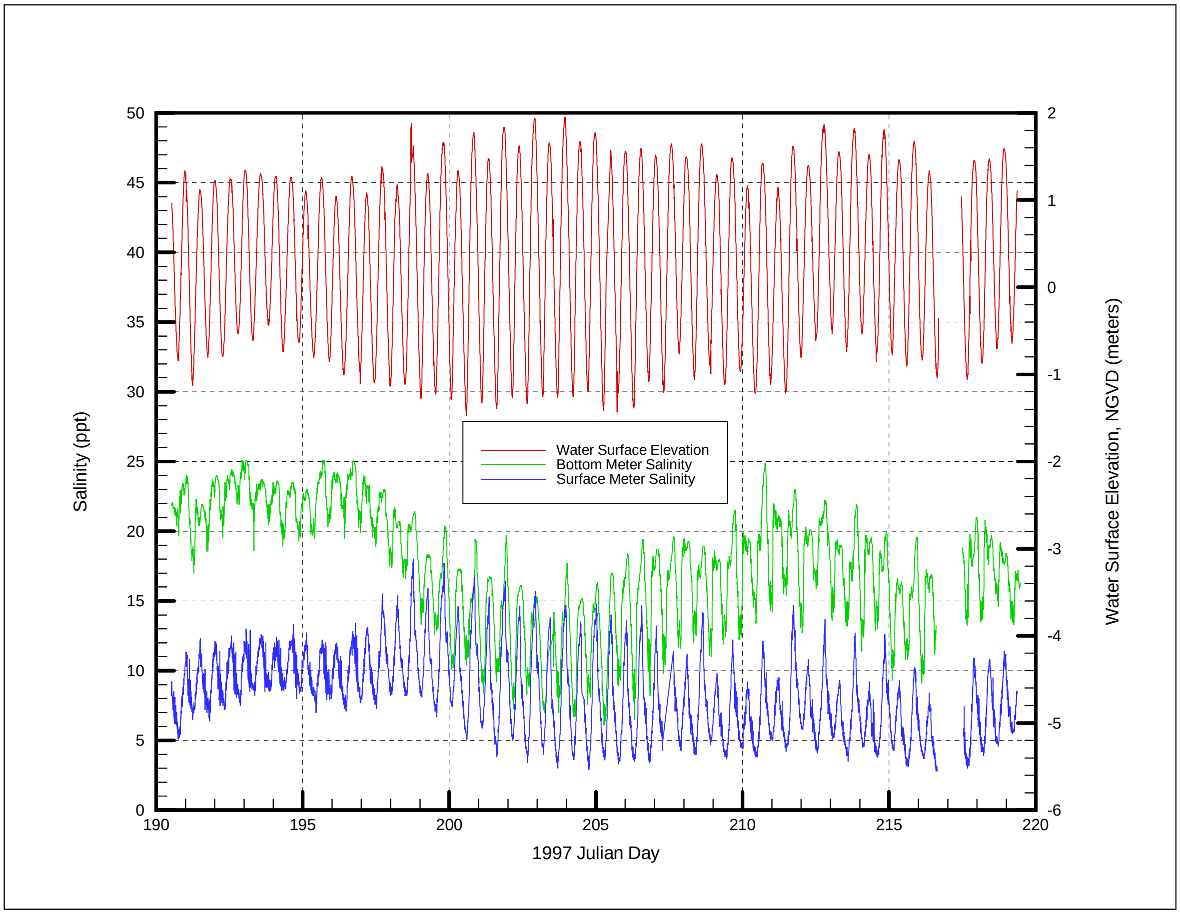


Figure 4 Observed tidal elevation and surface and bottom salinity for station GPA-04 at the Fort Jackson confluence of the Front and Back Rivers.

mixing, the Savannah River estuary can be classified, (Harleman and Ippen, 1967) at the low end of partly mixed conditions. Equation [1] gives the equation for evaluation of the estuary number as presented by Abraham (1988);

$$E_D = \frac{1}{\pi} \frac{u_t^3}{[\Delta\rho/\rho] g h_0 u_r} \qquad [1]$$

where

E_D = estuary number
u_t = amplitude of profile-averaged tidal velocity at estuary mouth (m/s)
u_r = river velocity, (flow rate over cross sectional area, m/s)
h_0 = depth at mouth of estuary (m)
$\Delta\rho$ = difference in density between river and sea water (kg/m^3)
ρ = density of fresh water (kg/m^3)
g = gravity (m/s^2)

and from Harleman and Ippen (1967), the ranges of estuary classifications can be determined as:

well mixed conditions, $E_D > 8$,
partly mixed conditions, $8 > E_D > 0.2$,
stratified conditions, $0.2 > E_D$

For the mean Savannah River flow of 328 m^3/s (11600 cfs) the river velocity may be determined to be in the range of 0.05 to 0.1 m/s. Using a mean, profile-averaged tidal velocity amplitude of 1 m/s derived from the ADCP stationed at GPA-04, fresh water and salt water densities of 996.8 and1024 (kg/m^3) respectively, an estuary depth of 14 m the estuary number is in the range of 1.8 to 0.8.

Abraham (1988) suggests that for sufficiently stratified estuaries, turbulence models used in salinity intrusion problems must be capable of reproducing the primarily internal mixing, which is developed from within the region where the mixing occurs, (eg. the interface), around the slack tides and the primarily external mixing, where energy for mixing is supplied by the solid boundaries, (e.g. the bottom), external to the region where the mixing occurs, when the tidal currents are large. The complexity and importance of this range of mixing regimes is compounded by the large variation in the tidal range between the spring and neap tidal cycle.

HYDRODYNAMIC MODEL DESCRIPTION

It is clear from the characterization of the Savannah River estuary that there are large variations in spatial scale within the study region. In general, the water body is long, thin, and full of turns and branches. For the level of prediction required for the present study, a full 3-dimensional, coupled, prognostic hydrodynamic, salinity, and water quality model is in order.

In answer to the problems posed above, a boundary-fitted coordinate, hydrodynamic, and transport model system was chosen. This system approach uses transformation functions such that all domain boundaries are coincident with coordinate lines. The transformation equations are applied to a user-defined grid of arbitrarily sized quadrilaterals, mapped to the coastal geometry of the water body in the study area (Figure 3). This approach is consistent with the variable geometry of coastal features of the Lower Savannah River Estuary. The hydrodynamic model (Muin and Spaulding, 1997; Huang and Spaulding, 1995; Swanson et al., 1989) and the mass transport model (Mendelsohn and Swanson, 1991) equations are written and solved on the boundary conforming, transformed grid using the well known finite difference solution technique (Spaulding, 1984; Thompson et al., 1977).

The boundary-fitted method uses a set of coupled quasi-linear elliptic transformation equations to map an arbitrary horizontal multi-connected region from physical space to a rectangular mesh structure in the transformed horizontal plane (Spaulding, 1984). The 3-dimensional conservation of mass and momentum equations, with approximations suitable for lakes, rivers, and estuaries (Swanson, 1986; Muin, 1993) that form the basis of the model, are then solved in this transformed space. In addition, an algebraic transformation is used in the vertical to map the free surface and bottom onto coordinate surfaces. The resulting equations are solved using an efficient semi-implicit finite difference algorithm for the exterior mode (2-dimensional vertically averaged) and by an explicit finite difference leveled algorithm for the vertical structure of the interior mode (3-dimensional) (Swanson, 1986).

The boundary conditions are as follows:

- At land, the normal component of velocity is zero
- At open boundaries, the free surface elevation must be specified and salinity specified on inflow. On outflow, salinity is advected out of the model domain
- A bottom stress or a no-slip condition can be applied at the bottom.
- No water or salt is assumed to transfer to or from the bottom
- A wind stress is applied at the surface

There are a number of options for specification of vertical eddy viscosity, A_v, (for momentum) and vertical eddy diffusivity, D_v, (for constituent mass [salinity]). The simplest formulation is that both are constant, A_{vo} and D_{vo}, throughout the water column. They can also be functions of the local Richardson number, which, in turn, is a function of the vertical density gradient and vertical gradient of horizontal velocity. More complex formulations include a mixing length model or a full 1 or 2-equation turbulence-closure model, adding the dependence on mixing length and turbulent energy.

A detailed description of the model with associated test cases can be found in Muin and Spaulding, 1997.

The boundary-fitted hydrodynamic and transport models are contained within the Water Quality Mapping and Analysis Program model system called WQMAP, (Mendelsohn et al ,1997). The hydrodynamic model was used to generate tidal elevations, velocities, and salinity distributions.

APPLICATION TO THE SAVANNAH RIVER

Figure 3 presents the computational grid used in the model simulations. The grid extends from the open boundary offshore Tybee Island to the USGS gauging station at Clyo approximately 100 km upstream. It includes the Front River, South Channel, Back River, Middle River, and the Little Back River. The extensive marsh areas of the system are represented by storage cells that are attached to secondary tributaries and feeder creeks. In addition, Union Creek, Knoxboro Creek, and Abercorn Creek were accurately represented in the grid. The model boundaries were determined from the NOAA digitized shoreline, and incorporated into WQMAP basemap.

The navigation channel depths utilized for the model calibration were taken from the USACOE 1997 Annual Survey. Depths outside of the maintained channel were taken from an intensive survey conducted by the USACOE in the following reaches: Front River from the Houlihan Bridge to the I-95 Bridge, Middle River, Little Back River and the South Channel.

The National Ocean Survey maintains a series of tide gauges along the coast including a station at Fort Pulaski. A time series of surface elevation recorded at this station were used to simulate the offshore water surface elevation variations.

The primary source of freshwater to the Lower Savannah River Estuary is from the Savannah River watershed. The upstream model boundary was placed at Clyo where the USGS maintains a stage height monitor. Detailed records, both past and present, are available for river flow past this site. Hourly volume flow records were obtained from the USGS for the summer 1997 period and used as input to the model.

CALIBRATION TO THE 1997 FIELD DATA

The primary objective of the model calibration was to be able to capture the dynamics of the system by satisfactorily reproducing the summer of 1997 data set. During this process, the grid configuration, time step, and model coefficients (e.g., bottom friction) were adjusted until the computed solution produced the best match to the observed data. The criteria for the desired level of accuracy are variable dependent, including (1) graphical comparison, (2) root-mean-square error (rms), (3) statistical comparison (mean, standard deviation), (4) coefficient of variation, and (5) linear regression.

Field data clearly show that the currents in Lower Savannah River Estuary are dominated by the tides, (barotropic circulation), where the semi-diurnal are the strongest (85 percent of the energy) components. The maximum tidal range is about 3 meters in the entrance and is amplified up to the area near station GPA09, (see Figure 2.2). At GPA10 the wave begins to be damped, most likely due to marsh inundation and super elevation of the mean water level (upstream riverbed elevation increases).

The model was run using 11 layers in the vertical with the 1-equation, turbulence model to obtain the vertical eddy viscosity. The barotropic time step was 10 minutes, although the model was still stable and accurate for 30-minute time step. The advective time step was 0.2 minutes due to the extremely large currents in the main channel of the river. For the initial simulations, the only physical parameter tuned was the bottom friction. The parameter g, which controls the mixing length, has been shown by Muin (1993) to be 0.3. After several simulations it was found that the quadratic law bottom friction coefficient, C_b equal to 0.0015 produce a best fit to current measurements at GPA-04 and GPA08. The surface elevation predictions were relatively insensitive to mixing and bottom friction.

In order to assess the accuracy of the model predicted circulation, surface elevation and currents, the following comparative analysis were performed:

1. Time series comparison between the measured and simulated of water surface elevation and currents.
2. Comparison of the spectral signal of the measured and simulated tidal wave and currents.
3. Comparison of the eight major tidal constituent components in the region (Z0, M2, N2, S2, O1, K1, M4, M6) for the simulated and observed tidal wave and currents.

The use of multiple analysis to quantify the errors between the simulated and measured tides and currents isolates individual weakness in the model simulations allowing further tuning of model input parameters. The graphical comparisons identify the overall quality of the simulations. The spectral comparisons isolate the ability of the model to simulate the energy in the various major frequencies, the sub-tidal, and the diurnal and higher order harmonics generated within the estuary. The harmonic analysis isolates the model's ability to replicate the primary astronomical forcing constituents and the shifting in those components due to the passage of the tidal wave through the system. The final calibrated model predictions compared very well with the observed trends and statistics. The details of the model calibration to 1997 field data have been covered elsewhere and will not be presented here. The interested reader is referred to ATM, 1998.

As an example of an integrated measure of the calibrated model's predictions, Figure 5 shows the comparison between measured and simulated discharge at Fort Jackson and the split between Front River and Back River. Accurate prediction of the volume flux is extremely important in determining the salinity intrusion into the estuary. The cross-sectional discharge, measured on September 10, 1997 (Julian Day 253), is presented in cubic meters per second. During September 10, maximum flood-tide discharge at Fort Jackson was around 2,700 m^3/s, which was then divided in about 35 percent to the Back River and 65 percent to the Front River. On the ebb tide, the maximum discharge at Fort Jackson was around 3,700 m^3/s, with the same percent-distribution between the Front River and the Back River.

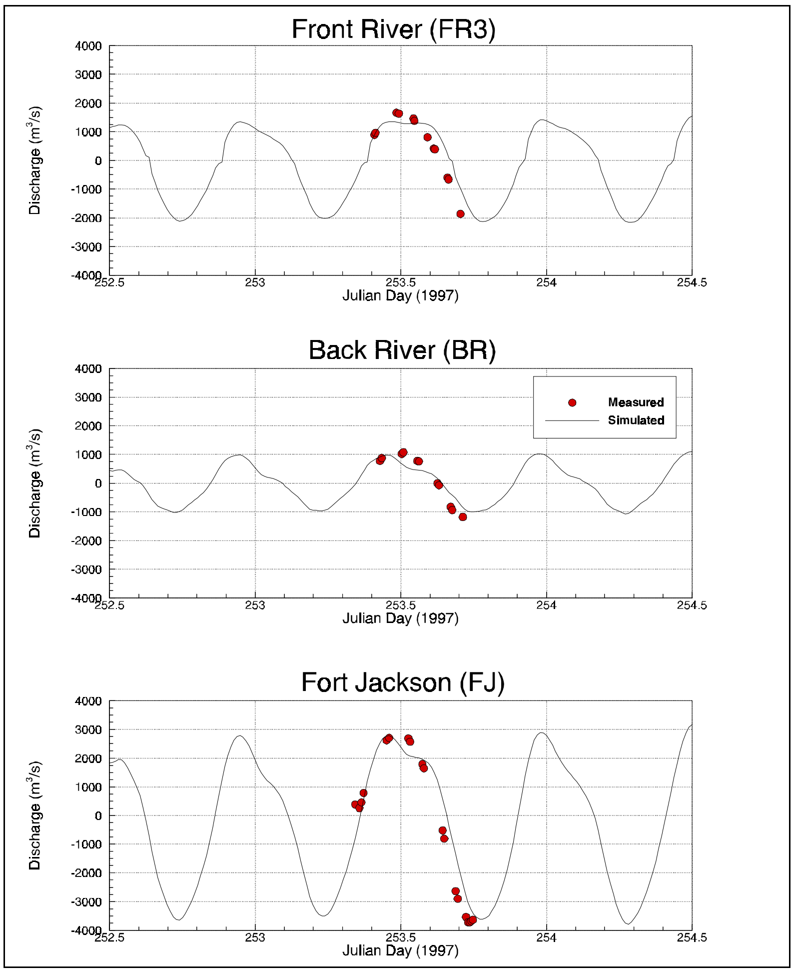


Figure 5 Model predicted versus observed volume flow at the three river branches at the Fort Jackson Confluence.

In summary, the model predicted circulation accurately reproduces the more important dynamics in the system, which are contained in the semi-diurnal components. Both the tidal prism, which dictates how much water moves in and out of the system (seen in the surface elevation variation), and the transport (based on currents, speed, direction and volume flux calculation) are accurately reflected in the model predictions.

VERTICAL MIXING IN THE MODEL

It is clear from the discussion above that a constant value for the vertical mixing would not be capable of capturing the dynamic range of salinity regimes seen in the data. Preliminary simulations using various constant vertical mixing coefficients quickly proved this assumption to be true although tidal velocity profiles and ranges were quite representative of the data for lower values of the vertical eddy viscosity, (for momentum). The constant values for the vertical eddy diffusivity, (for salt) produced either too stratified an estuary for lower coefficient values or a too mixed condition with larger coefficient values, which proved to severely restrict salinity intrusion, keeping the entire estuary far fresher than is seen in the data. For the lower constant diffusivity test simulations salinity values in the estuary were predicted to be in the observed range but produced almost none of the observed dynamics.

Test simulations using the turbulence energy model, (Muin and Spaulding, 1997), to predict the vertical eddy viscosity and diffusivity were then run. As expected, the turbulent energy in the system varied dramatically with both the major semi-diurnal tidal oscillations as well as the spring/neap range variation. An example of the model predicted vertical eddy diffusivity at station GPA-04 over time is plotted in Figure 6. In the figure, the calculated eddy diffusivities have been vertically averaged for clarity. The model actually predicts an eddy viscosity and diffusivity at every layer in every water cell. The large semi-diurnal variation as well as the variation in range is clearly visible. The turbulence model and the predicted vertical eddy viscosities performed extremely well in the prediction of tidal currents. The application and coefficients were calibrated to both the ADCP measurements at stations GPA-04 and GPA-08 where a number of levels were compared, and to the point current meters at stations GPA-10 and GPA-15.

The predicted vertical eddy diffusivities, salinity and salinity intrusion however did not fare so well. The predicted diffusivities were not sensitive enough to reproduce the development and collapse of stratification observed in the data. Nor was the model capable therefor of reproducing the large variation in the extent of the salinity intrusion up the Front River. A number of formulations were tested along with a large range of coefficients but the model was ultimately unable to improve the stratification simulation beyond a certain point. The model either produced too much mixing during the critical low flow periods or not enough mixing during the high flow. This may be due in part to the formulation of the turbulence model and the relative importance of the internally and externally derived mixing during low flow and slack tides. Abraham (1988) suggests that for certain types of sufficiently stratified flows turbulence models using standard damping functions such as those employed in the present model, may not be capable of reproducing the low water slack conditions which may influence the predictions in the present application. For a detailed analysis of the behavior of turbulence and mixing in stratified tidal flows the interested reader is referred to Abraham (1988).

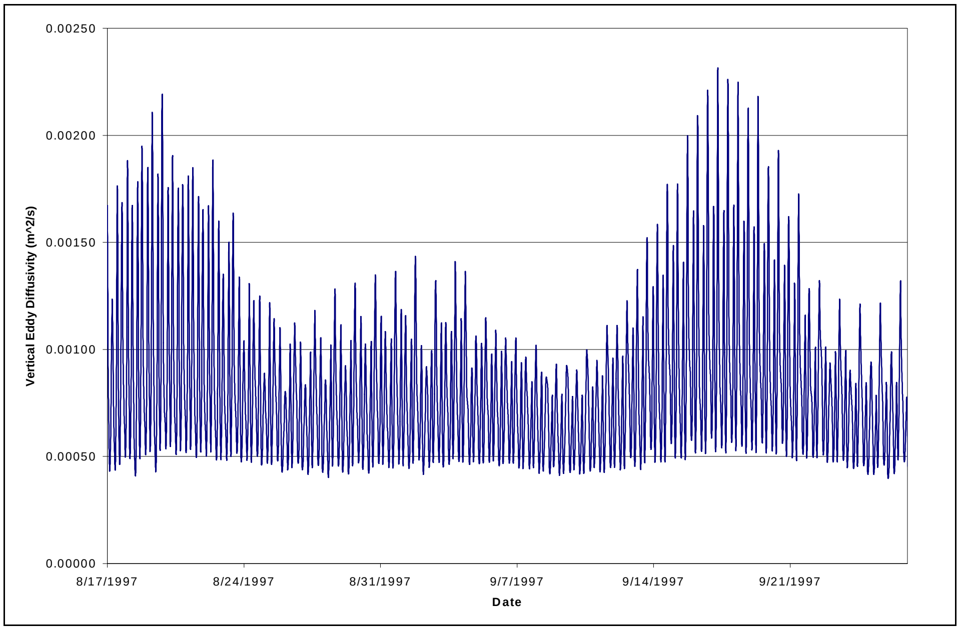


Figure 6 **Example model predicted vertical eddy diffusivity at station GPA-04. The eddy diffusivities have been vertically averaged for clarity.**

With the inability of the present formulation of the turbulence energy model to adequately determine the vertical eddy diffusivity and subsequent salinity regimes in the estuary an alternate method was sought. As the primary driving mechanisms for the development and collapse of salinity stratification and intrusion in the estuary and its relationship with the tidal regime is well understood in the present context of the Savannah River it seems possible that a simple, quantifiable relationship between the two could be developed. Although a simplified solution is not as elegant as a fully developed, energy based model, it allows for a level of prediction of vertical mixing without detracting from the solution of the prognostic salinity model. In that the prediction of the salinity intrusion into the estuary, and not the vertical mixing per se, was the intent of the present engineering project, it was determined that this approach was justifiable. It helped to develop our understanding of the relationship between the tidal range and mixing and allowed the incorporation of that knowledge into a model capable of predicting the salinity intrusion. The ultimate test of such a formulation is whether it works. Will it be able to predict the many and varied salinity regimes observed in the estuary, including the neap/spring cycle of stratification and mixing as well as the variation between high and low river flow periods.

From analysis of the data it is apparent that the behavior of salinity upstream in the estuary is dependent on the conditions observed at GPA-04, (Figure 4). GPA-04 was therefor selected as the indicator of stratification, (or mixing) in the lower estuary. The clear relationship between the range in turbulence energy, (and subsequent mixing) and the range in current amplitude and therefor the tidal range, keeping in mind the principal of parsimony, were used to develop a direct relationship between the range and the vertical eddy diffusivity. The relationship between the tide range and eddy diffusivity was assumed to be non-linear based on the earlier mixing studies as shown in Figure 6.

NEW VERTICAL MIXING MODEL DEVELOPMENT

A preliminary analysis using the surface and bottom salinities and current profile data at both GPA-04 and GPA-08 was performed to best determine the form that the mixing relationship should take and the range of expected mixing values. Many semi-empirical relationships for the eddy coefficients have been proposed in terms of the gradient Richardson number, (Ri) which relates the local gravity force to the inertial force, where,

$$A_v = A_0\, f(Ri)\ , \qquad \text{eddy viscosity} \qquad [2]$$
$$D_v = D_0\, g(Ri)\ , \qquad \text{eddy diffusivity}$$

and as suggested by Munk and Anderson, (1948) :

$$f(Ri) = (1 + \alpha\, Ri)^{-n} \qquad [3]$$
$$g(Ri) = (1 + \beta\, Ri)^{-m}$$

and the values of A_0 and D_0 are potentially determined from mixing length theory, (Blumberg, 1986) or arbitrarily calibrated to available data. The gradient Richardson number is given by:

$$Ri = -\frac{2g}{\rho h} \frac{\frac{\partial \rho}{\partial \sigma}}{\left(\frac{\partial u}{\partial \sigma}\right)^2 + \left(\frac{\partial v}{\partial \sigma}\right)^2} \qquad [4]$$

where

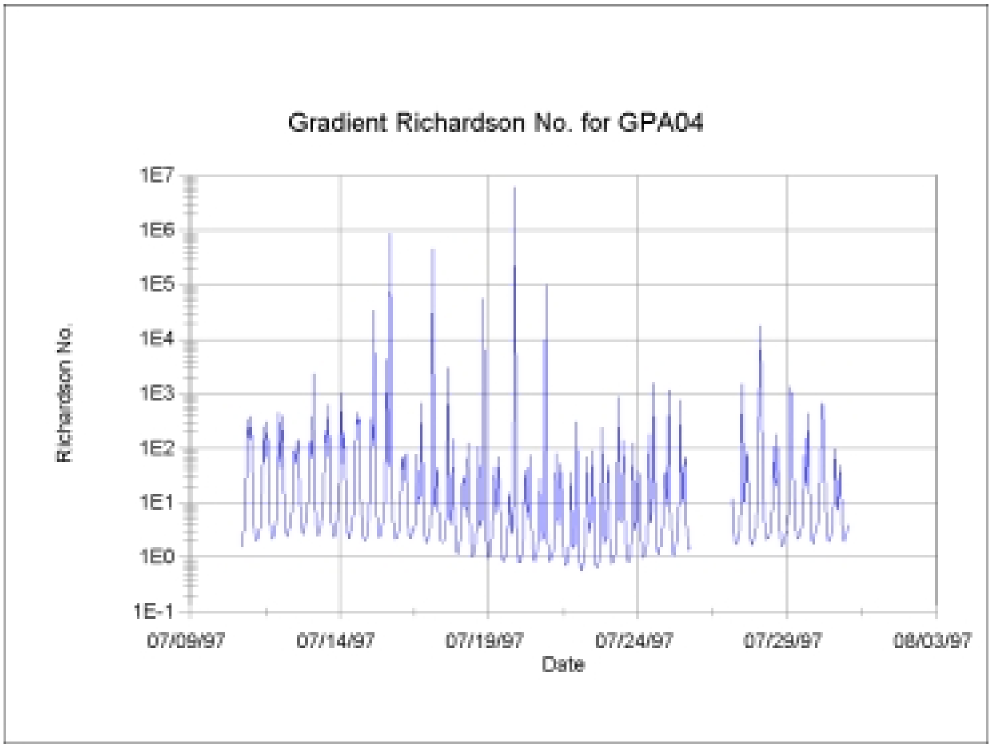
σ = vertical coordinate
u,v = velocity vector components

A number of authors have suggested values for the coefficients α, β, n and m, in Equation [3], the most well known being those of the original authors and those of Officer (1976) as given below in Table [1]:

Table 1. Values cited for α, β, n and m in the literature, (Blumberg, 1986).

Reference	α	n	β	m
Munk-Anderson (1948)	10	1/2	3.33	3/2
Officer (1976)	1	1	1	2
Bowden-Hamilton (1975)	1	7/4	7	1/4

Figure 7 shows the observed gradient Richardson number, calculated by Equation [4], as a function of time for (a) GPA-04 and (b) GPA08. Figure 8 is the filtered observations



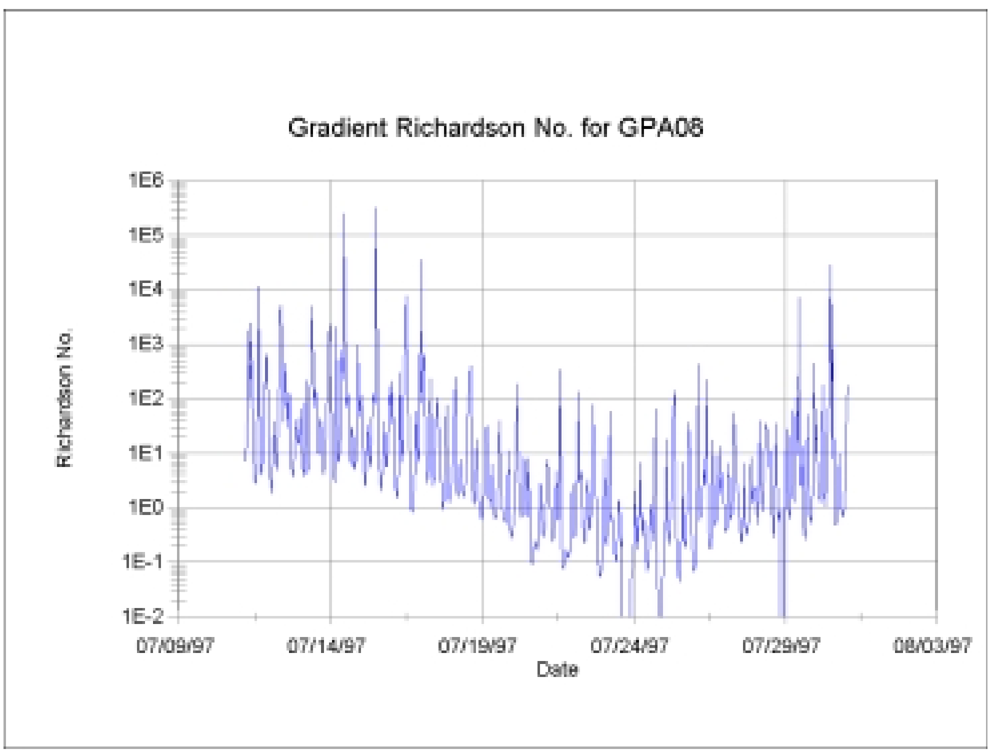


Figure 7 Observed gradient Richardson number calculated from the 1997 summer field data for station GPA-04 (top) and GPA-08(bottom).

plotted against the filtered tide range (m). Also shown in Figure 8 are two lines representing linear regressions of the Log (Richardson number) vs. range. The vertical mixing determined from the observed gradient Richardson number and the functional relationships given in Equations [2] and [3] is shown in Figure 9. Finally, a curve was fit to the D_v vs Tide Range data plotted in Figure 9 using a logarithmic relationship with the form given in Equation [5]. This will be called the Log Fit model.

$$\text{Log}_{10}(D_v) = \varphi \text{Rng} + \delta \qquad [5]$$

where

Rng = running mean tide range, (m)

φ,δ = curve fit coefficients

Figure 10 shows the data same data and Log Fit curve as plotted in Figure 9 except that the observed mixing values have been time averaged to better highlight the trend in the relationship between the mixing and tide range. It can now be seen that the Log Fit model curve closely follows the observed trend at station GPA-04.

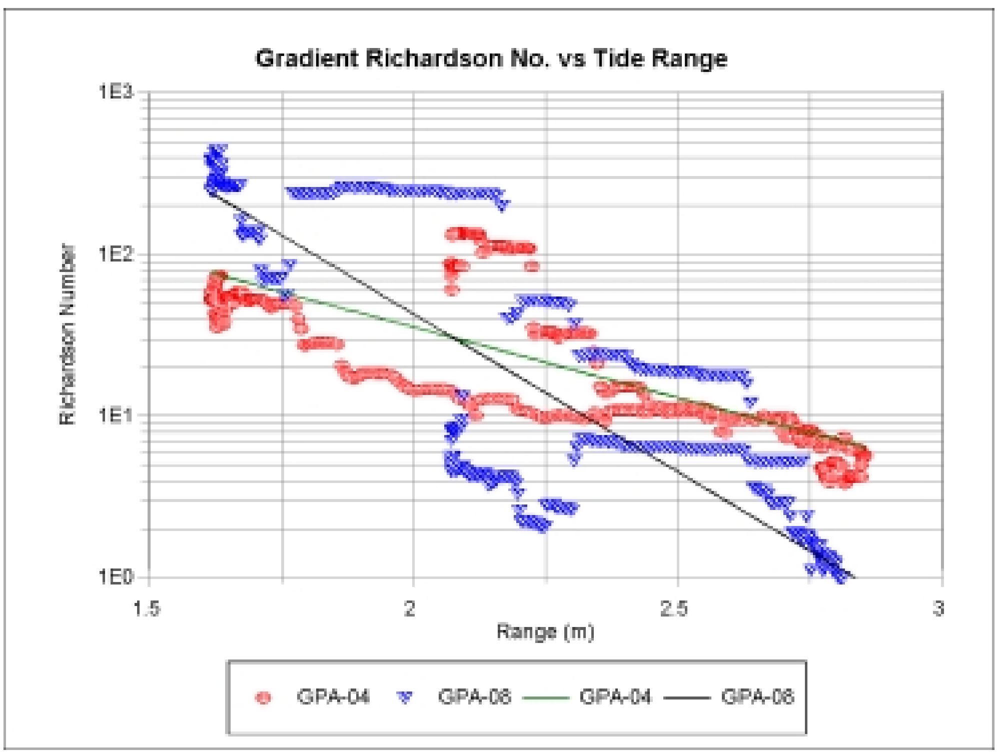


Figure 8 Gradient Richardson number versus tide range for stations GPA-04 and GPA-08.

The Log Fit vertical eddy diffusivity calculated using Equation [5], is plotted in Figure 9, labeled 'Curve Fit'. The diffusivity plotted as a function of time during the summer of 1997, is shown in Figure 11. Comparing the latter section of Figure 11 to the turbulence model predicted diffusivity plotted in Figure 6 it is clear that trends in the curves are similar. Because the Log Fit is a function of the tidal range and not the elevation, the semi-diurnal response seen in Figure 6 is absent from the curve in Figure 11. This

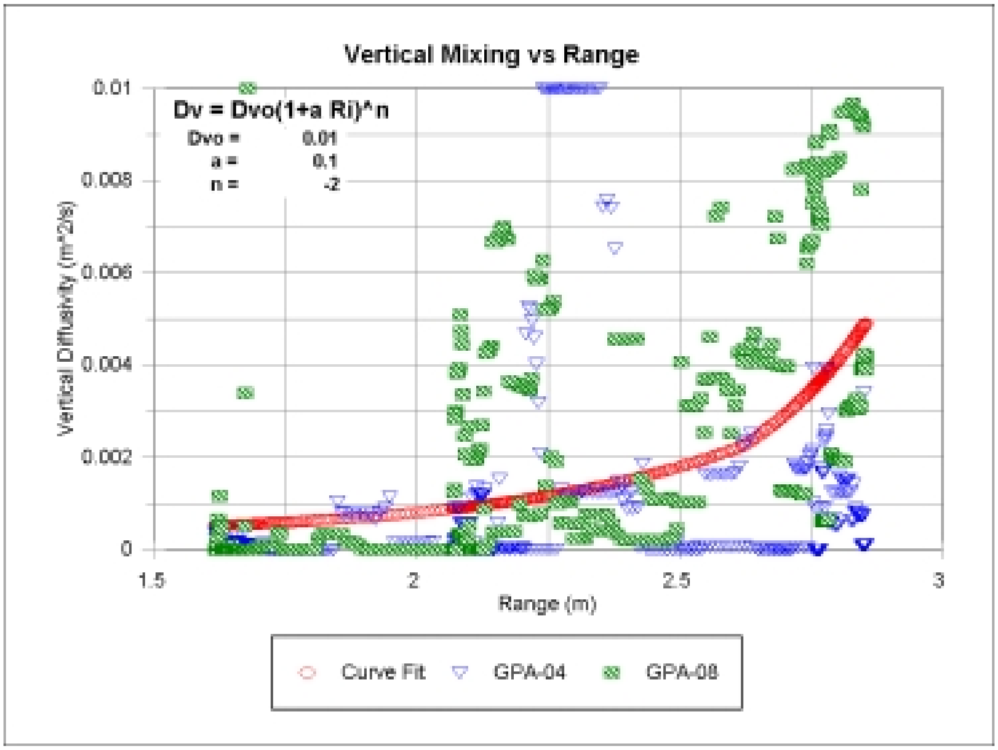


Figure 9 Observer vertical eddy diffusivity plotted as a function of tide range for stations GPA-04 and GPA-08 and compared to "Log Law" curve fit diffusivity.

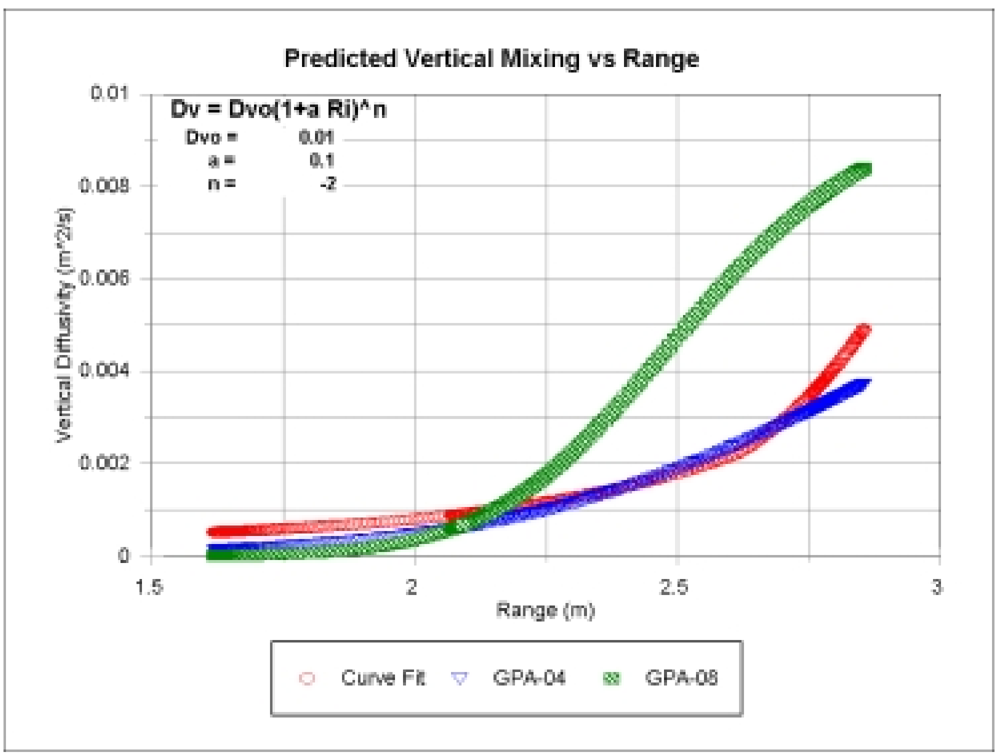


Figure 10 Same as Figure 9 but the observed eddy diffusivities have been smoothed to display the trend at station GPA-04.

smoother, parameterized version of the vertical mixing has lost some of the dynamic variability one might expect to observe but has retained a clear and positive link to energy input to the system via the tides.

A comparison of the model predicted salinities versus the observed salinities for the summer of 1997 is shown in Figure 12. The model predicted salinities clearly display the both the magnitude and the variation in the range of the values observed. This is true for both the surface and the bottom, which show distinctly different signals based on the mixing regime. The controlling stratification / de-stratification process is also extremely well reproduced.

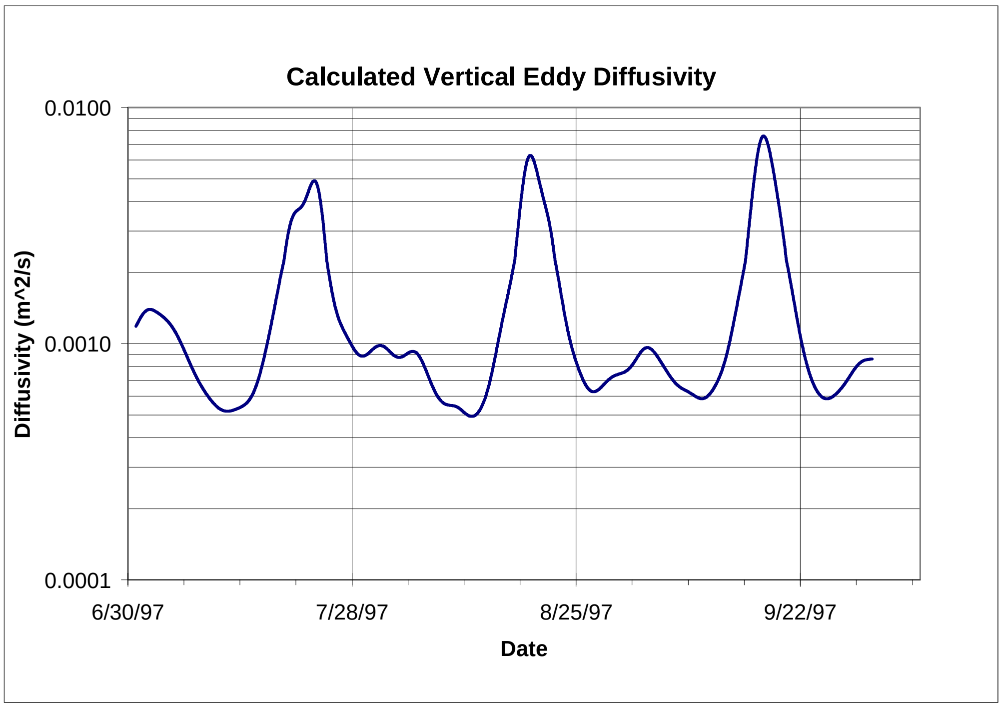


Figure 11 **Log Law model predicted vertical eddy diffusivity as a function of time for the 1997 summer simulation period.**

DISCUSSION AND CONCLUSIONS

There are several parameters in the foregoing argument that are essentially arbitrary. They are the vertical mixing coefficients in Equations [2], A_0 and D_0, and the constants and exponents used in Equations [3], α, β, n and m. Although some guidance is given in the literature, the values vary enormously, (e.g. Table [1]) and the final values must be determined empirically. The pathway to development of the final relationship between D_v and the tide range for the Savannah River application was iterative, where initial values for each of the coefficients were posited, values calculated, the curve fit coefficients φ and δ in Equation [5] calculated, and the model run using the new relationship. Predicted values of surface elevation, currents and salinity were compared to observations at each of the 15 GPA stations and statistically evaluated following the process, described in Section 3, for each of the parameter estimations. A minimization of the system wide errors, (differences between the model predicted and observed values), produced the final coefficients for the Log Fit model.

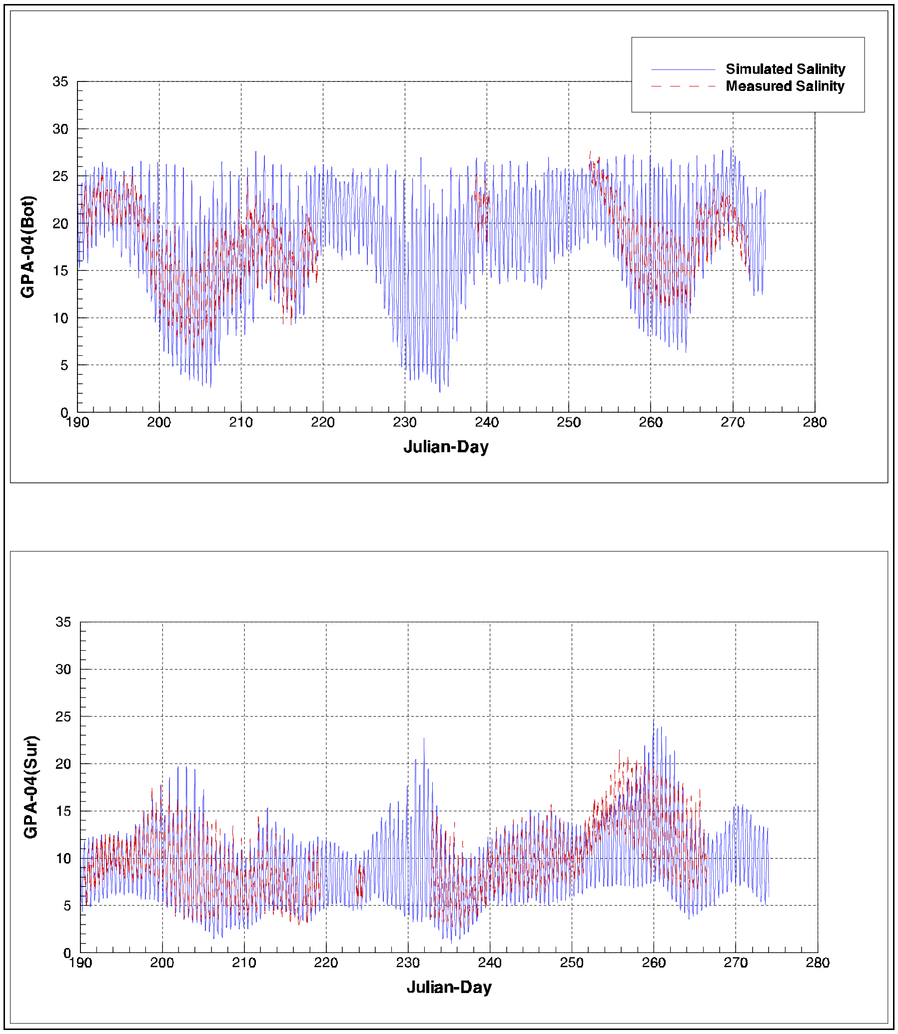


Figure 12 Predicted versus observed salinities for the bottom (upper figure) and surface (lower figure) at station GPA-04.

Preliminary calibration efforts also indicated that the substantial, inter-tidal marsh system plays a significant role in the hydrodynamics of the lower river estuary. In order to properly account for the marsh/river interaction a unique marsh boundary condition was developed and implemented. The boundary condition accounts for the storage of water, (and salinity), associated with marsh areas on the flood tide and release of water and salinity on the ebb tide. Marsh boundary conditions are specified through areal coverage, vegetation coverage porosity and front and back elevations. A reduced momentum equation is solved at the water/marsh boundary. Addition of the marsh boundary condition was shown to greatly improve surface elevation and flow predictions in the upper estuary and to a lesser extent, salinity intrusion.

Reviewing the calibration results, both qualitatively (visual inspection of the plotted time series) and quantitatively (statistical evaluation), it is clear that the selected approach performs extremely well. The model is quite capable of reproducing the trends as well as the magnitudes of salinity and its variation over a long period covering highly variable conditions in terms of both river flow rate and tidal amplitude.

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