Modelling residence-time response to freshwater input in Apalachicola Bay, Florida, USA

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Abstract:
Residence time of an estuary can be used to estimate the rate of removal of freshwater and pollutants from river inflow. In this study, a calibrated three-dimensional hydrodynamic model was used to determine residence time in response to the change of freshwater input in Apalachicola Bay. The bay is about 40 km long and 7 km wide, with an average 3 m water depth. Through hydrodynamic model simulations, the spatial and temporal salinity and the total freshwater volume in the bay were calculated. Then the freshwater fraction method was used to estimate the residence time. Results indicate that the residence time in Apalachicola Bay typically ranges between 3 and 10 days for the daily freshwater input ranging from 177 m$^3$/s to 4561 m$^3$/s. Regression analysis of model results shows that an exponential regression equation can be used to correlate the estuarine residence time to changes of freshwater input. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS residence time; hydrodynamic modelling; estuary

INTRODUCTION
Apalachicola Bay is located in the panhandle of Florida, and receives freshwater input from the Apalachicola River (Figure 1). It is connected to the Gulf of Mexico through five openings. The bay generally is shallow and flat. Water depth gently varies from approximately 4 m near ocean openings to about 2 m near the river mouth. Apalachicola River provides approximately 90% of freshwater discharge to the bay. The river flow rate is relatively strong. Daily average flow is 752 m$^3$/s based on historic data from 1939 to 1993. River flow generally is low during the summer and autumn seasons, and high in the spring season. Based on the observations between 1939 and 1993, the minimum daily flow is about 170 m$^3$/s in 1981, and the maximum is 5043 m$^3$/s in 1990. The strong freshwater input discharged from the river inflow into the saline estuarine receiving water causes the mixing of fresh and saline waters. Even though water depths are generally shallow, ranging from 2 m to 5 m in most areas of the bay, field observations show that the bay is strongly stratified, and this varies in the bay (Jin and Raney, 1991; Jones and Mozo, 1994).

The bay is a highly productive estuarine system, which in general produces 90% of the Florida’s commercial oyster harvest, and the third largest shrimp catch (Whitfield and Beaumariage, 1977). For these reasons, the bay has been designated as a National Estuarine Research Reserve, Outstanding Florida Water, State Aquatic Preserve and International Biosphere Reserve. The high seafood production in estuarine systems is often associated with sufficient freshwater input. The importance of freshwater inflow to the estuarine productivity and the aquatic ecosystem has been recognized by researchers and coastal managers for decades (e.g. Snedaker et al., 1977; Wilber, 1992; Livingston et al., 1997). Studies by Livingston et al. (2000) indicate that the oyster mortality is related directly to the salinity in the bay, which is dependent on the freshwater discharge. Oyster

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mortality owing to stenohaline predators (saltwater fishes) is a major determinant of oyster productivity in the bay. Low salinity as a result of sufficient river inflow limits the number of predators visiting the oyster beds, and so maintains the oyster productivity. Adequate freshwater inflow provides necessary nutrients and maintains appropriate flushing to assure the biological productivity of the system. Owing to the importance of freshwater input to the aquatic ecosystem in Apalachicola Bay, comprehensive water resource studies have been conducted by federal and state agencies of Florida, Georgia and Alabama to find solutions of balancing the needs of the fresh water in the upstream watersheds to avoid the adverse impact on the estuary (U.S. Army Corps of Engineers, 1998). As part of the comprehensive water resource study, a hydrodynamic mode of Apalachicola Bay was developed to examine the effects of changing freshwater inflow on the estuarine salinity (Huang and Jones, 1998, 2001).

Analysis and management of the water quality in Apalachicola Bay is of significant importance because water pollution and shellfish contamination are harmful to commercial fishery, the aquatic system, and public health. Faecal coliform carried by freshwater from Apalachicola River is the major pollutant source for Apalachicola Bay. It was used by Florida Department of Environmental Protection (FLDEP) as a major indicator bacteria group to classify the level of water pollution in the shellfish harvesting areas (Shields and Pierce, 1996). As consumption of contaminated oyster could cause illness or death, FLDEP conducts coliform studies (indicator of pathogen) in the bay, and has classified oyster harvesting areas into Approved, Conditional Approved Conditionally Approved and Prohibited zones.

Residence time is an important index for assessment of estuary water quality (Thomann, 1987). It shows the rate at which river freshwater is flushed out of an estuary, and therefore can be used to estimate the rate of removal of a pollutant carried by the freshwater. Long residence time means that it would take a long time to flush pollutant out of the bay. Mills et al.’s (1985) report U.S. to the Environmental Protection Agency (EPA) suggested that residence time should be examined for surface water quality analysis. Residence time can be studied by either field experiments or numerical modelling. For example, Asselin and Spaulding (1993) conducted field tracer experiments to study residence time in Providence River. Huang and Spaulding (1995) applied a hydrodynamic and pollutant transport model to study the residence time in Mount Hope Bay.
Swanson and Mendelsohn (1996) developed a commercial model and software to simulate residence time in estuaries and bays.

The primary objective of this study is to investigate the relationship between freshwater input and estuarine residence time under a baseline condition with the assumption of zero wind speed. A calibrated hydrodynamic model was used to determine the residence time in the estuary for the freshwater input range from a drought season to a wet season. As described in the following section, an exponential relationship obtained in this study provide a quick approach for water resource engineers and managers to estimate the estuarine residence time in response to the changes of freshwater input. Owing to the non-availability of long-term wind data and our primary interest in the relationship of residence time and river inflow, model simulations were conducted under zero wind speed condition.

RESIDENCE TIME DETERMINED BY THE FRESHWATER FRACTION METHOD

The freshwater fraction approach (Lauff, 1967; Swanson and Mendelsohn, 1996) is used in this study to determine the estuarine response to freshwater input. This technique provides an estimation of the time-scale over which contaminants or other material released in the estuary are removed from the system. Residence time in an estuary using the freshwater fraction method can be expressed by

\[ T = \frac{F}{Q} = \frac{\int f d(V)}{Q} \]  

(1)

where \( F \) is the accumulated freshwater volume in the estuary, which can be calculated by integrating the freshwater volume \( d(V) \) in all the subdivided areas over a period of time. In estuaries, \( F \) is the average freshwater volume over several tidal cycles. Variable \( Q \) is the average freshwater input for the study period and the term \( f \) is the freshwater content or the freshwater fraction, which is described by

\[ f = \frac{S_0 - S}{S_0} \]  

(2)

where \( S_0 \) is the salinity in the ocean, and \( S \) is the salinity at the study location.

In this study, we applied a previously calibrated hydrodynamic model for Apalachicola Bay (Huang and Jones, 2001) to determine the accumulated freshwater volume in the bay. In the hydrodynamic model, the bay was divided into many small areas called ‘grids’. Salinity in each grid was determined through hydrodynamic model simulations. The freshwater volume in each grid was calculated by multiplying the volume of the grid with the freshwater fraction using Equation (2). The accumulated freshwater volume was calculated by summing all the freshwater volume in the bay. Then, the residence time in the bay was calculated by using Equation (1).

For gradually varied flow, a long study period can be divided into several shorter periods. For example, a one-year study period can be divided into monthly periods. The residence time can be calculated for each subperiod by using the above formulae. Then, the residence time for the long-term period will be a time-dependent variable in terms of river inflow.

There is another method to determine the residence time, which tracks the change of concentration of an instant dye release in the bay. Huang and Spaulding (1995) used dye-release experiments and constituent transport modelling to study flushing time in Mount Hope Bay, Rhode Island. We used the freshwater fraction method instead of the dye tracking method in this study for two reasons:

1. it does not require the coupling of a constituent transport model and the expensive dye release experiments;
2. river inflow is the major pollutant source in Apalachicola Bay.
APALACHICOLA BAY HYDRODYNAMIC MODEL

Model theory

The Princeton ocean model (POM; Blumberg and Mellor, 1987) was applied to investigate the circulation in the Apalachicola Bay. It is a semi-implicit, finite-difference model that can be used to determine the temporal and spatial changes of surface elevation, salinity, temperature and velocity in response to wind, tide, buoyancy and Coriolis forces. The model solves a coupled system of differential, prognostic equations describing conservation of mass, momentum, heat and salinity at each horizontal and vertical location determined by the computational grid. This model incorporates a second-order turbulence closure submodel that provides eddy viscosity and diffusivity for the vertical mixing (Mellor and Yamada, 1982). This model has a history of successful applications in other estuaries; for example, Blumberg and Goodrich (1990) for Chesapeake Bay; Galperin and Mellor (1990a, b) for Delaware Bay, river and adjacent continental shelf; and Blumberg and Galperin (1990) for New York Bight. In all of these studies the model performance was assessed via comparisons with data, and a confidence level has been established that the model realistically reproduces the predominant physics. The model is capable of simulating time-dependent wind and multiple river inputs, and a variety of other forcing conditions. An important feature of the present model is the use of a horizontal orthogonal, curvilinear coordinate system that allows one to better represent coastline irregularities in systems such as the Apalachicola Bay. A detailed description of the model is presented by Blumberg and Mellor (1987), and the enhanced version of the curvilinear coordinate formulation is given by Blumberg and Galperin (1990). Major governing equations are given as follows:

continuity equation

\[ \frac{\partial}{\partial \xi_1} (h_2 U_1) + \frac{\partial}{\partial \xi_2} (h_1 U_2) + h_1 h_2 \frac{\partial W}{\partial z} = 0 \]  

(3)

momentum equations

\[ \begin{align*}
\frac{\partial}{\partial t} (h_2 U_1) &+ \frac{1}{h_1} \frac{\partial}{\partial \xi_1} [(h_2 U_1) U_1] + \frac{1}{h_2} \frac{\partial}{\partial \xi_2} [(h_2 U_1) U_2] + \frac{\partial}{\partial \xi_2} [(h_2 U_1) W] \\
&+ U_2 \left( \frac{2 U_1}{h_1} \frac{\partial h_1}{\partial \xi_1} - \frac{U_1 \partial h_2}{h_2} - \frac{U_2}{h_1} \frac{\partial h_1}{\partial \xi_1} \right) - U_2 f h_2 \\
&= - \frac{1}{\rho_0 h_1} \frac{\partial P_{\text{atm}}}{\partial \phi_1} + \frac{\partial}{\partial \xi_2} \left( - (h_2 U_1') \nu' \right) + F_1 h_2 \\
\frac{\partial}{\partial t} (h_1 U_2) &+ \frac{1}{h_1} \frac{\partial}{\partial \xi_1} [(h_1 U_2) U_1] + \frac{1}{h_2} \frac{\partial}{\partial \xi_2} [(h_1 U_2) U_2] + \frac{\partial}{\partial \xi_2} [(h_1 U_2) W] \\
&+ U_1 \left( \frac{2 U_2}{h_2} \frac{\partial h_2}{\partial \xi_1} - \frac{U_2 \partial h_1}{h_1} - \frac{U_1}{h_2} \frac{\partial h_2}{\partial \xi_1} \right) + U_1 f h_1 \\
&= - \frac{1}{\rho_0 h_2} \frac{\partial P_{\text{atm}}}{\partial \phi_2} + \frac{\partial}{\partial \xi_2} \left( - (h_1 U_2') \nu' \right) + F_2 h_1 \\
\end{align*} \]

(4)  

(5)

where \( U_1 \) and \( U_2 \) are the horizontal velocities and \( W \) is the vertical velocity calculated from continuity, \( \xi_1 \) and \( \xi_2 \) are horizontal curvilinear orthogonal coordinates, \( z \) is the vertical coordinate, \( h_1 \) and \( h_2 \) are metric coefficients, \( P_{\text{atm}} \) is the atmospheric pressure, and \( f \) is the Coriolis parameter. The term \( F_1 \) is related to the horizontal mixing processes and is parameterized as horizontal diffusion terms. The Reynolds stresses \((\partial U_1')\nu'\) and \((\partial U_2')\nu'\) are evaluated using the level 2 turbulence closure model of Mellor and Yamada (1982) modified by Galperin et al. (1988).
The salinity and temperature equation is

$$\begin{align*}
\frac{\partial (S, T)}{\partial t} &+ \frac{\partial U_1 (S, T)}{\partial \xi_1} + \frac{\partial U_2 (S, T)}{\partial \xi_2} + \frac{\partial W (S, T)}{\partial z} \\
&= A_H \left[ \frac{\partial^2 (S, T)}{\partial \xi_1^2} + \frac{\partial^2 (S, T)}{\partial \xi_2^2} \right] + \frac{\partial}{\partial \xi} \left[ K_v \frac{\partial (S, T)}{\partial \xi} \right]
\end{align*}$$

where $S$ is the salinity and $T$ is the temperature. Variable $K_v$ is the eddy diffusivity for salt and temperature, which is calculated from a second-order turbulent model (Mellor and Yamada, 1982). Density is a function of temperature and salinity calculated from the equation of state given by Fofnoff (1962). The horizontal diffusivity coefficient $A_H$ is calculated according to the Smagorinsky (1963) formulation where the coefficient $c$ is set to 0.05 for both parameters (Equations 5 and 6).

$$A_H = c \Delta x \Delta y \left[ \left( \frac{\partial U_1}{\partial \xi_1} \right)^2 + \left( \frac{\partial U_2}{\partial \xi_2} \right)^2 + \frac{1}{2} \left( \frac{\partial U_1}{\partial \xi_1} + \frac{\partial U_2}{\partial \xi_2} \right)^2 \right]^{1/2}$$

**Model calibration and verification**

The hydrodynamic model was previously calibrated and verified by Huang and Jones (1998). The model was applied to the bay using the horizontal orthogonal grid system given Figure 2. Five sigma layers were used to divide the vertical water column. Hourly observations of salinity, surface elevation, freshwater input and wind speed and directions were specified on the model boundaries. Model coefficients (bottom drag coefficient, bottom roughness, horizontal diffusion and viscosity, surface wind drag coefficient, time-step, vertical and horizontal grid) were selected to minimize the difference between model predictions and observations. Model simulations of hourly surface elevations and salinity reasonably match with observations obtained at stations within the bay. Details of the model calibration and verification were given in Huang and Jones (1998). Summary of the model coefficients is given in Table I.

In order to improve the model capability for those situations when observations of salinity at ocean boundaries are not available, the model ocean boundaries in this study were extended 10 km into the saline waters of the Gulf. Salinity at ocean boundaries was set as constant 34‰, which is independent of the variations of freshwater inflow from the river. Good agreement between model predictions and observations of surface elevation (Figure 3) and salinity (Figure 4) indicate that the calibrated hydrodynamic model is capable of predicting salinity in the estuaries under the modified ocean boundary conditions. In other words, the freshwater fraction can be reasonably calculated by the hydrodynamic model to estimate the residence time in the Apalachicola Estuary. Summary of the statistics of mean, standard deviation and correlation between model simulations and observations at stations S394 and S414 was given in Table II. Model to data comparisons of the monthly means were extremely close, with the largest difference being 1-4‰. The standard deviation of the model results was close to the standard deviation of the observations.

**AVERAGE SALINITY DISTRIBUTION IN APALACHICOLA BAY**

The freshwater fraction approach for residence time (Equation 1) uses the average salinity to calculate freshwater volume, it is helpful for us to investigate the average salinity distributions. Under annual averaged river flow condition at 752 m$^3$/s, model predicted subtidal salinity and currents are given in Figure 5. The subtidal salinity currents were obtained by averaging model results over a 24-h period to remove the tidal effects. Results show that salinity varied in both horizontal and vertical directions. Surface salinity varied from about 5‰ near the river mouth to about 30‰ near East Pass. Bottom salinity generally is larger than the surface salinity, which indicates the vertical stratification in the bay. For a given period of time, the freshwater
Figure 2. Apalachicola Bay hydrodynamic model grid system

Table I. Calibrated parameters used in the model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Stress Drag Coefficient( C_d )</td>
<td>0.0012</td>
</tr>
<tr>
<td>Bottom friction Coefficient( C_f )</td>
<td>0.003</td>
</tr>
<tr>
<td>Coefficient for calculating horizontal diffusivity( C_m )</td>
<td>0.05</td>
</tr>
<tr>
<td>Vertical sigma layers</td>
<td>5</td>
</tr>
<tr>
<td>Time-step</td>
<td>2 min</td>
</tr>
</tbody>
</table>

Figure 3. Comparison of model predictions of surface elevation with field observations at mid-bay
fraction in each model grid can be calculated from salinity by using Equation (2). The total freshwater volume in the bay can be obtained by integrating the freshwater volume in each model grid of the bay.

MODELLING RESIDENCE TIME IN APALACHICOLA BAY

Two-year-long flow records based on historic flow data in 1960 and 1980 in Apalachicola River were used to examine the residence time in response to changes of freshwater input. Model simulations were averaged every 30 days (or 30 diurnal tidal cycles) so that the tidal effects can be approximately eliminated, which will allow us to examine the temporal variation of residence time under gradually varied freshwater input conditions.

In order to study the typical ranges of residence time in Apalachicola Bay, we chose a dry year flow in 1986 and a wet year flow in 1960 in the study. The year of 1986 (Figure 6a) represents a drought year. Daily river flows in 1986 range from a minimum 177 m$^3$/s to a maximum 1634 m$^3$/s, with the annual average flow of 556 m$^3$/s. The river flow (Figure 7a) in 1960 represents a wet year. The daily flow in 1986 varied from a minimum 386 m$^3$/s, to average 782 m$^3$/s, and a maximum 4561 m$^3$/s.

Tidal boundaries were specified through harmonic analysis of tidal data for the 1993 period (Sun, 1998), which indicates that the diurnal tides are the dominant components in the area. Therefore, the diurnal tidal component from tidal harmonic analysis was used to specify the tidal boundaries. Tidal range is 0-54 m at

<table>
<thead>
<tr>
<th>Station</th>
<th>Mean Observation</th>
<th>Mean Model</th>
<th>Mean Error</th>
<th>Standard Variation Observation</th>
<th>Standard Variation Model</th>
<th>Standard Variation Error</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>S414</td>
<td>22.4</td>
<td>21.7</td>
<td>0.7</td>
<td>5.7</td>
<td>5.6</td>
<td>0.1</td>
<td>0.95</td>
</tr>
<tr>
<td>S394</td>
<td>24.1</td>
<td>24.9</td>
<td>0.8</td>
<td>5.4</td>
<td>5.1</td>
<td>0.3</td>
<td>0.94</td>
</tr>
</tbody>
</table>

Table II. Comparison of hourly model-predicted salinity with observations (June–July 1993)
Indian Pass, 0.54 m at West Pass, 0.56 m at Sikes Cut, 0.60 m at East Pass and 0.60 m at Landard Reef. Salinity at extended ocean boundaries in the Gulf is equal to 34‰. Zero wind speed was specified for the surface boundary as a baseline condition to examine the estuarine residence time responding to the freshwater input.

The hydrodynamic model simulations were used to calculate the residence time using the freshwater fraction approach as described in Equation (1). For the flow condition in the drought year of 1986, the model predictions of residence time are given in Figure 6b. The residence time increases as river flow decreases. The minimum residence time is 3-8 days, and the maximum residence time corresponding to the maximum river flow is 9.2 days in 1986. For the 1960 flow condition, the residence time ranged from a minimum 3-6 days, to a maximum 8-6 days (Figure 7b). As the river flow used in this study covers a drought season in 1986 and a flood season in 1960, results obtained from this study represent typical ranges of residence time for Apalachicola Bay.

CORRELATION OF RESIDENCE TIME TO FRESHWATER INPUT

Model results above show that the residence time decreases as freshwater input increases. Finding a general regression relationship between the residence time and the freshwater input would be helpful to understand the physical and hydrological processes in the river and estuarine system. Asselin and Spaulding’s (1993)
Figure 6. Time-series of freshwater input and residence time for the year of 1986: (a) freshwater input; (b) residence time.

Figure 7. Time-series of freshwater input and residence time for the year of 1960: (a) Freshwater input; (b) residence time.
study in Seekonk River and Providence River of Rhode Island suggested that an exponential function can be used to correlate the residence time with constant freshwater input. In the study of Apalachicola Bay, we consider that the river flow is gradually varied flow, and we may use an exponential empirical equation in the following form to correlate the flushing time and freshwater input

\[ T = \exp(C1 \times Q + C2) \]  

(6)

where \( T \) is residence time (days) and \( Q \) is freshwater input from the river (m\(^3\)/s).

Estimating coefficients \( C1 \) and \( C2 \) using 1986 data

A regression of the residence time \( T \) (days) versus river flow \( Q \) (m\(^3\)/s) (Figure 8) shows an excellent correlation \((r = 0.97)\)

\[ T = \exp(-0.0007 \times Q + 2.35) \]  

(7)

where \( T \) is the residence time (days) and \( Q \) is the freshwater input from the river (m\(^3\)/s).

The exponential response function indicates that the increase of residence time is larger at low flow season than at high flow seasons for a given reduction of freshwater input.

Verification of the regression coefficients \( C1 \) and \( C2 \) with 1960 data

In order to verify the generality of the residence time response function obtained from simulations under 1986 flow conditions, model simulations of residence time for 1960 flow conditions was used to examine the regression equation (Equation 7). As shown in Figure 9, excellent correlation \((r = 0.94)\) was found between the residence time obtained from 1960 simulations and those from the regression equation (Equation 7) based on the 1986 simulations. In other words, the residence time equation obtained from 1986 flow conditions also works well for other flow conditions such as the flow conditions of 1960.

Figure 8. Residence time \((T)\) and freshwater input \((Q)\) relationship for the year of 1986
The empirical regression equation (Equation 7) fits well with two independent data sets in Apalachicola Bay under gradually varied flow conditions ranging from a drought season to a flood season. Therefore, the equations can be used in future studies by researchers and water resource managers to enable a quick estimation of the estuarine residence time response to the changes of freshwater input as a result of either natural seasonal variations or freshwater diversion from upstream water management activities (e.g. increasing water demand for industrial usage or changing the reservoir operation schedule). In addition, Equation (7) may be used as a reference by researchers in applications to other estuaries to study the relationship between residence time and the freshwater input.

Comparison of regressions using exponential equation and linear equation

It would be helpful for us to better understand the relationship between river flow and residence time by comparing the regressions using exponential and linear equations. In order to cover a wider range of river flow and residence time, the data for years 1960 and 1986 were combined into one data set for the regression analysis. As shown in Figure 10, the exponential equation fits better with non-linear distributed data, especially for the low and high flow period.

DISCUSSION

Owing to the complexity of the estuarine dynamics and the expense of research costs, one research project usually is not able to cover many issues of the estuarine dynamics. Generally, the scope of a study project is limited by the data available and research funding. Given the limited data and funding support, researchers at times may focus on investigating the response of one estuarine parameter with particular interest to a specific boundary forcing. The contributions of a series of limited studies will gradually improve our understanding of the estuarine dynamics.

In field experimental studies, observed data often consist of mixed signals affected by winds and tides as well as freshwater inputs. In order to study the effects of a particular forcing function, researchers often use filtering and other methods of time-series analysis to remove the effects of other boundary forcing.
functions. For examples, Wong and Wilson (1984) conducted a field observation study to examine the effect of atmospheric forcing effects on the water levels in an estuary using the time-series observations of wind, tide and water levels. The empirical orthogonal function (EOF) method was used to separate the time-series signals into several orthogonal EOF modal series to correlate the low frequency wind and water-level variations after low-pass filtering. Goodrich (1988) used low-pass filtering to remove tidal signals and local winds in his field observations to find the correlation between estuarine volume variation and remote wind forcing. Asselin and Spaulding (1993) conducted field tracer studies of residence time in Seekonk River and Providence River of Rhode Island, where wind effects on salinity were not very significant owing to the narrow wind fetch. Using the field observations of salinity that includes wind and tide effects, Asselin and Spaulding (1993) showed good correlation between residence time and constant freshwater using an exponential function.

In numerical modelling studies, researchers can effectively investigate the estuarine response to a particular forcing function by designing specific boundary conditions in computer model simulations. Once the model has been calibrated using complete field observations that consist of all the boundary forcing (winds, river flow and water level variations), the model can then be used to examine the estuarine response to any boundary forcing functions. Therefore, we can use the numerical model to examine the response of a particular estuarine parameter (e.g. residence time) to a specific dynamic forcing function (e.g. river flow) while keeping other forcing constant (e.g. winds and tides). In this way, without the need to separate the effects of other boundary forcing, as is the case in an experimental approach, we can directly obtain the model predictions responding to a particular boundary function. In this study, our primary interest is to investigate how freshwater input affects the residence time in the estuary, which would be helpful for water resource management. In our model simulations, we used constant wind speed (zero in this case) as the boundary condition and averaged the residence time from model predictions over 30 days to remove the harmonic tidal signals. This approach is quite similar to that used by Wong and Wilson (1984) in the experimental investigation of estuarine response to a particular forcing function. As the effect of river flow was effectively separated from those influenced by wind and tides, we successfully
obtained a good regression equation that describes the relationship of residence time and freshwater inflow.

In this study, limited by the data available and the research budget, our primary objective was to investigate the residence time of estuarine systems responding to the variations of freshwater input under harmonic tides and zero wind speed conditions. The model calibration for Apalachicola Bay (Huang and Jones, 1998, 2001) was done using a complete data set that includes hourly observations of wind, tides and freshwater input for the period of June and July 1993. Therefore, the model is capable of predicting salinity variations in the bay under any wind speed conditions (such as the zero wind conditions). Owing to the lack of wind data for the years of 1960 and 1986 and our primary interest in the relationship between the dynamic river flow and the residence time, we used constant zero wind speeds and harmonic tides in the model boundaries. After removing the tidal effects by averaging the model predictions over 30 days, the results revealed the response of estuarine residence time to the remaining variable of river flow. The results of an exponential regression equation obtained from this study can be used as a baseline condition for water resource engineers to examine the residence time in Apalachicola Bay. It also can be used for the approximate estimations of residence time under weak wind conditions. Stochastic features of wind make it difficult to specify a general wind boundary condition. Detailed studies of wind effects on the estuary require long-term wind data and considerable efforts to characterize the stochastic wind patterns, which are beyond the scope and available data and budget for this study.

CONCLUSION

A calibrated hydrodynamic modelling was used in this study to examine the residence time responding to the time-dependent river inflow in Apalachicola Bay. The model was previously calibrated and verified with field observations for Apalachicola Bay (Huang and Jones, 2001), which indicated that the model was capable of reasonably calculating salinity and freshwater fraction in the bay in response to the variations of freshwater inputs. The freshwater fraction method was used to estimate the residence time response to the freshwater input. The daily river inflow used in this study ranges from 177 m^3/s in a drought season to 4561 m^3/s in a flood season based on the historic flow data. Model simulations indicate that the residence time in Apalachicola Bay typically ranges between 3 and 9 days.

Regression analysis of model results indicates that residence time is correlated to freshwater input in an exponential function in the Apalachicola Bay system. As a result, for the same reduction of freshwater input, residence time increases more in low flow conditions than in high flow conditions. In other words, modification of river flow during low-flow conditions will cause more changes to the estuarine residence time.

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