Hydrodynamic modeling and ecohydrological analysis of river inflow effects on Apalachicola Bay, Florida, USA

Wenrui Huang

Department of Civil Engineering, Florida A&M University-Florida State University College of Engineering, Tallahassee, Florida, 32310, USA

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ABSTRACT

This paper presents an integrated hydrodynamic modeling and probability analysis approach to assess the long-term effects of changing river inflows on the estuarine ecosystem. The probability analysis method, which is popularly used in advanced hydrological frequency analysis of river flows and rainfalls, has been applied to analyze the effects of changing inflow on salinity and thus on oyster ecology in Apalachicola Bay. Long-term salinity data were predicted through the application of a calibrated 3D hydrodynamic model under two river inflow conditions over a 10-year period. The first flow represents the historic flow. The 2nd flow condition, called Scenario-1, represents a regulated flow scenario to account for the potential increasing upstream water demands. Two stations, Mid Bay and Dry Bar, in the bay were selected to examine the estuarine responses. Under the historic flow condition, the maximum probability salinity at Dry Bar in the rich oyster reef is near 24 ppt, within the optimal salinity range for oyster growth of 16–26 ppt (Harned et al., 1996); the maximum probability salinity at Mid Bay station is 27 ppt, beyond the optimal salinity for oyster growth in mid-bay area where there is no oyster reef around. While it is difficult to examine the difference between two scenarios by conventional time series analysis of river flows and salinity, probability analysis reasonably characterizes and quantifies the changes of river flow and salinity patterns over the 10-year period. The Scenario-1 has caused the increase of the probability in low flows. Higher probability of low flows for the regulated flow scenario shortens the period of optimal salinity in the oyster reef, and cause substantial increase of exceedance probability of higher salinity in the oyster reef to the level beyond the optimal salinity range for oyster growth. The probability analysis approach has demonstrated its advantage for the risk assessments of the long-term estuarine ecohydrological effects under various regulated inflow scenarios to support estuarine water resources managements.

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1. Introduction

Apalachicola Bay is located in the panhandle of Florida, and receives freshwater input from the Apalachicola River in the south end of the Apalachicola–Chattahoochee–Flint (ACF) Basin (Fig. 1) in USA. The ACF Basin originates in North Georgia and Alabama, and terminates in Apalachicola Bay in Florida. The ACF Basin extends to a distance of approximately 385 miles and encompasses an area of 19,600 square miles. Apalachicola Bay is connected to the Gulf of Mexico through five openings. The bay is generally shallow and flat. Water depth gently varies from approximately 6 m near ocean openings to about 3 m near the river mouth. Apalachicola River provides approximately 90% of freshwater discharge to the bay. The river flow rate is relatively strong. Monthly average flow ranges from

450 to 1350 m³/s based on historic data from 1976 to 1996. The river inflow acts like a strong freshwater buoyant jet discharged into a saline receiving water. Even though water is shallow, field observations show that the bay is strongly stratified in both vertical and horizontal directions.

Apalachicola Bay is a highly productive barrier island estuary, which in general produces 90 percent of the state's commercial oyster harvest, and the third largest shrimp catch (Whitfield and Beaumariage, 1977). Preservation of the ecology in Apalachicola Bay has been recognized as of state, federal, and international importance. The bay has been designated as a National Estuarine Research Reserve, Outstanding Florida Water, State Aquatic Preserve, and International Biosphere Reserve. 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; Livingston et al., 2000). The high seafood production in estuary systems is often associated with sufficient
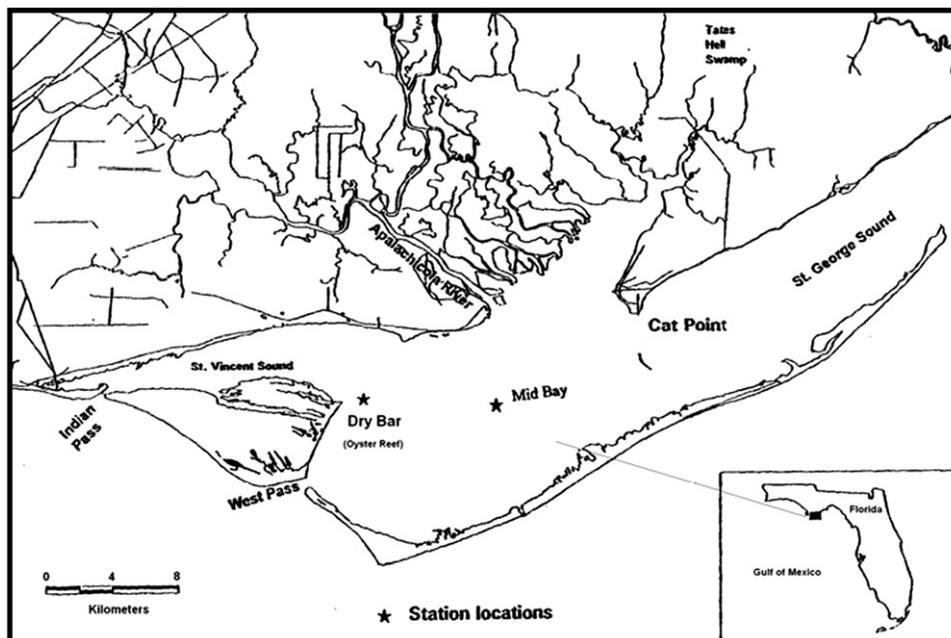
Fig. 1. Apalachicola Bay estuary study area, Florida, USA.

freshwater input. Currently, the bay is in relatively unaltered state with freshwater inflow as a major controlling factor to the ecosystem (Livingston, 1984; Livingston et al., 2000). Oyster mortality due to stenohaline predators (salt-water fish) is a major determinant of oyster productivity in the bay. Low salinity resulting from sufficient freshwater input limits the predators from the oyster beds and maintains the oyster productivity (Livingston et al., 2000). Freshwater carrying nutrients is also a key factor to support the growth of oysters, shrimps, and other species in the aquatic ecosystem. Modification of river flow patterns and reduction of flow rates will affect the circulation and salinity in the bay. As a result, it will affect predator-induced oyster mortality and growth (Livingston et al., 2000).

Balancing the increasing water demands for upstream users and downstream estuarine ecological system is a challenging task for water resources management in ACF Basin. During the past 160 years, the freshwater resources in the ACF Basin have been developed to meet various demands for municipal and industrial water supply, flood control, hydropower, navigation, agriculture water supply, and fish and wild life conservation. There are hundreds of reservoirs in the basin, which are used to regulate freshwater to meet certain water demands, which would modify the natural freshwater flow in Apalachicola Bay. Since 1950, considerable growth has occurred in the Atlanta–metropolitan area (upper ACF Basin). The population in this area increased from less than 0.5 million in 1950 to almost 3 million in 1993. This has resulted in a considerable increase of demands for freshwater resources from ACF Basin. Now, it has become an important issue how to appropriately allocate the river freshwater to balance the increasing needs of upstream freshwater demands and sufficient freshwater to maintain the downstream estuarine ecosystem. If upstream water supply demands increases, freshwater inflow from downstream of ACF Basin to Apalachicola Bay would be altered and reduced. In recent year, a basin-wide hydrological model (HEC-5 model) has been developed by US Army Corps of Engineers USACE to predict river flow scenarios under various proposals of upstream water usage and future water demand conditions. Because different flow scenario represents different reservoir operations and water withdrawals, there is no simple increasing or reduction relationship between different flow scenarios, which make it difficult to assess the long-term ecohydrological effects.

In this study, hydrodynamic modeling was conducted to quantify long-term effects of changing river flow on estuarine salinity in Apalachicola Bay. Model simulations were conducted for two flow conditions to predict time series of hourly salinity over the 10-year study period. Considering its advantages and popular applications in long-term hydrological data analysis, probability method was applied to the analysis of salinity data. While salinity probability can be used to describe how frequently salinity occurs in a given range that may be optimal for oyster growth, exceedance salinity can be used to show how often salinity may exceed a specified level that may cause adverse impact on oyster population. Salinity probability and exceedance probability under historic flow condition, or observed flow condition, were used as baseline condition to evaluate the effects of changing rivers on the estuarine oyster ecological system.

2. Review of oyster ecological studies in Apalachicola estuary

Environmental conditions in Apalachicola Bay, Florida, are highly advantageous for oyster propagation and growth (Livingston et al., 2000). Apalachicola Bay oysters are economically important, comprising more than 90% of Florida's annual oyster landings and 10% of the catch nationwide (Livingston et al., 2000). These features make the oyster an important resource both ecologically and economically in the Apalachicola Bay system and to the surrounding communities of the Florida Panhandle. The propagation, growth, reproduction, and survival of oysters as well as the distribution and production of oyster reefs are influenced by multiple factors, including water circulation, salinity, temperature, food, sedimentation, bottom type, predation, disease pollution, commercial harvesting, tropical storms, and hurricanes. One of the characteristics of the relationships between oyster dynamics and physical factors is that oysters are sensitive to changes in the salinity regime (e.g., Christensen et al., 1998; Livingston et al., 1999, 2000; Livingston, 2006; White and Wilson, 1996). Variations in freshwater inflow can alter bay salinity, and as a consequence, affect oyster dynamics. It is found that the observed changes in Apalachicola oyster population

dynamics are closely related to the changing salinity, which is responded to the variations of Apalachicola River flow. For example, oyster landings from 1959 to 1977 were correlated negatively with river flows (Meeter et al., 1979). More importantly, it was found that one possible explanation for the 2-year time lag between low flows and subsequent poor oyster production is predation by species such as stone crabs and oyster drills on newly settled spat during periods of high salinity (Wilber, 1992; Livingston et al., 2000). These facts indicate that variations in freshwater inflow tend to affect oyster productivity significantly through changing salinity regime in the bay. Moreover, as the human population grows, freshwater inflow to Apalachicola Bay tends to be reduced as a result of increased demands from urban and agriculture ecosystems.

In examining the relationship between estuarine salinity regime to oyster population dynamics, including growth and mortality, Christensen et al. (1998) and later Livingston et al. (2000) found that oyster growth in Apalachicola Bay was positively correlated with variation (i.e., standard deviation) in salinity, whereas oyster mortality was negatively related to maximum salinity. Livingston et al.'s analysis was based on a linear regression statistical model that linked experimental biological data with physical factors by coupling a hydrodynamic model with field oyster observations. However, the applicability of the regressive model was limited by the simple linear regression between oyster dynamics and physical factors, which is limited by the ranges and variability of the salinity data used to develop the statistical models. Furthermore, changes in the salinity regime were found to impact not only oyster mortality as a result of changes in predation and diseases, but also oyster processes such as filtration rate and respiratory rate (e.g., Powell et al., 1995). Wang et al. (2008) developed an oyster population model for Apalachicola Bay to describe oyster population processes (e.g., ingestion, assimilation, respiration, reproduction, spawning, recruitment, mortality) in relation to changing environmental factors (e.g., freshwater inflows, temperature, food concentration, and water velocity) through coupling to an Apalachicola Bay-specific hydrodynamic model. Coupling oyster population models with hydrodynamic models (Wang et al., 2008) improve understanding of the mechanisms that control the spatial and temporal variability in oyster population dynamics. Most previous researches regarding salinity and flow effects on oysters were investigated based on case studies for one- or two- year period.

Despite the progress in oyster ecological research, no literature can be found regarding the optimal salinity for growth in Apalachicola Bay. Literature data for other estuaries in United States may be helpful as references. For Southeastern North Carolina estuaries, an optimal range of salinity for oyster growth is about 16–26 ppt (Harned et al., 1996). The optimum salinity for the development of eggs of oysters from Long Island Sound, Peconic Bay, and Hodges Bar, Maryland was about 22.5 ppt when these oysters developed gonads at a salinity of 26.0–27.0 ppt (Davis, 1958). Quast et al. (1988) and Shumway (1996) described that the optimum range of salinities for oyster growth is 14–28 ppt. A minimum salinity of 10 ppt is required for growth with little growth occurring at salinities less than 5 ppt (Shumway, 1996).

3. Description of the hydrodynamic model of Apalachicola Bay

3.1. Model descriptions

In order to investigate the circulation in the Apalachicola Bay, the Princeton Ocean Model (POM, Blumberg and Mellor, 1987; Blumberg and Herring, 1987) was applied to 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 sub-model that provides eddy viscosity and diffusivity for the vertical mixing. This model has a history of successful applications in other estuaries; for example, Blumberg and Galperin (1990) for New York Bight, Blumberg and Goodrich (1990) for Chesapeake Bay, Huang and Jones (2001) and Huang et al. (2002a,b) for Apalachicola Bay. In all of these studies, the model performance was assessed via comparisons with data and a confidence 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 Apalachicola Bay system. Details of model descriptions were discussed by Blumberg and Mellor (1987), and the enhanced version of the curvilinear coordinate formulation is given by Blumberg and Galperin (1990). Major governing equations in the model are given below.

Continuity equation

$$\frac{\partial}{\partial \zeta_1}(h_2 U_1) + \frac{\partial}{\partial \zeta_2}(h_1 U_2) + h_1 h_2 \frac{\partial W}{\partial z} = 0, \tag{1}$$

Momentum equation (U_1 direction)

$$\begin{aligned}
&\frac{\partial}{\partial t}(h_2 U_1) + \frac{1}{h_1}\frac{\partial}{\partial \zeta_1}[(h_2 U_1)U_1] + \frac{1}{h_2}\frac{\partial}{\partial \zeta_2} \\
&[(h_2 U_1)U_2] + \frac{\partial}{\partial z}[(h_2 U_1)W] \\
&+ U_2\left(\frac{2U_1}{h_1}\frac{\partial h_1}{\partial \zeta_2} - \frac{U_1}{h_2}\frac{\partial h_2}{\partial \zeta_2} - \frac{U_2}{h_1}\frac{\partial h_2}{\partial \zeta_1}\right) - U_2 f h_2 \\
&= -\frac{1}{\rho_0}\frac{h_2}{h_1}\frac{\partial P}{\partial \zeta_1} + \frac{\partial}{\partial z}[\overline{-(h_2 u_1)w}] + F_1 h_2
\end{aligned} \tag{2}$$

U_1 and U_2 are the horizontal velocities and W is the vertical velocity calculated from continuity. ζ_1 and ζ_2 are horizontal curvilinear orthogonal coordinates, z is the vertical coordinate, h_1 and h_2 are metric coefficients, P_{atm} is the atmospheric pressure, and f is the Coriolis parameter. The terms F_1 is related to the horizontal mixing processes and is parameterized as horizontal diffusion terms. The Reynolds stresses $\overline{u_1'w'}$ and $\overline{u_2'w'}$ are evaluated using the level 2½ turbulence closure model of Mellor and Yamada (1982).

The salinity and temperature equations:

$$\frac{\partial(S,T)}{\partial t} + \frac{\partial U_1(S,T)}{\partial \zeta_1} + \frac{\partial U_2(S,T)}{\partial \zeta_2} + \frac{\partial W(S,T)}{\partial z}$$

$$= A_H\left[\frac{\partial^2(S,T)}{\partial \zeta_1^2} + \frac{\partial^2(S,T)}{\partial \zeta_2^2}\right] + \frac{\partial}{\partial z}\left[K_v\frac{\partial(S,T)}{\partial z}\right] \tag{3}$$

where S is the salinity and T is the temperature. 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. The horizontal viscosity and diffusivity coefficients A_H are calculated according to the Smagoringsky (1963) formulation where the coefficient c is set to 0.05 for both parameters (Equation (4)).

$$A_m, A_H = c\Delta x \Delta y \left[\left(\frac{\partial U_1}{\partial \zeta_1}\right)^2 + \left(\frac{\partial U_2}{\partial \zeta_2}\right)^2 + \frac{1}{2}\left(\frac{\partial U_1}{\partial \zeta_2} + \frac{\partial U_2}{\partial \zeta_1}\right)^2\right]^{\frac{1}{2}} \tag{4}$$

3.2. Descriptions of hydrodynamic model calibration and verification in previous studies

The three-dimensional hydrodynamic model of Apalachicola Bay was previously calibrated and verified by Huang and Jones (2001) and further improved by Huang and Spaulding (2002) and Liu and Huang (2009). Observed salinity, tides, winds and river flow during May were used as a 30-day spin-up period to provide initial salinity, temperature and water elevation conditions on June 1st. The model was calibrated for the period of June, and verified for the period of July–November using field observations. 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 predictions of surface elevation at Cat Point match well with field observations, with a correlation value of 0.99. Salinity results also reasonably followed the general trend of field observations. Model to field data comparisons of the monthly average salinity were extremely close with the largest difference being 1.7 ppt in upper East Bay. Salinity comparisons in St. George Sound were 1.3 ppt different while the remaining of the stations was less than 1 ppt. Examples of model verification and model predicted salinity field are given in Figs. 2 and 3, respectively. Details of descriptions of the Apalachicola Bay hydrodynamic model are given in Huang and Jones (2001) and Huang et al. (2002a,b).

4. Time series of river inflow scenarios for 1980–1989 period

Two river inflow conditions were provided by Northwest Florida Water Management District (NWFWMD), an agency of the State of Florida responding to water management, to support this study. The first flow data set is the "historic flow", or the observed flow rates. The 2nd flow, named "Scenraio-1", represents a flow scenario to account for increasing upstream water demands and changing reservoir operations resulting from various water management planning alternatives. A basin-wide hydrological model (HEC-5) for ACF Basin developed by US Army Corps of Engineers is able to simulate river flows from ACF Basin to Apalachicola Bay under various water management scenarios. Based on the long-term flow scenarios, the objective of this study is to investigate the effects of changing river inflows on salinity in Apalachicola Bay, and so as to the oyster ecology.

Time series of daily flow rates during 1980–1989 were presented in Fig. 4a. The differences of flow rates, as shown Fig. 4-b, were obtained by subtracting the historic flow rates from the flow rates the Scenario-1 flow. Based on the time series plot, it is very difficult to find out the pattern to describe the changes of river inflows. The flow difference is a simple constant. It is actually varies
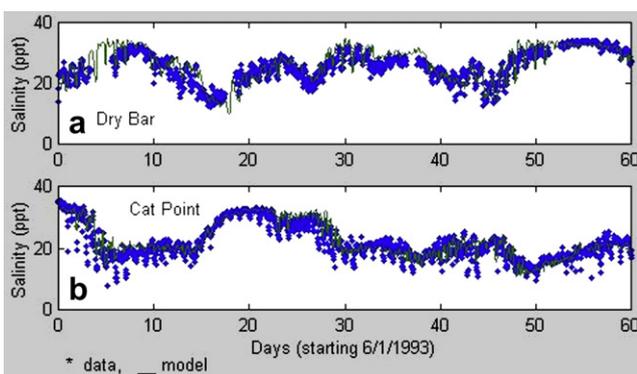

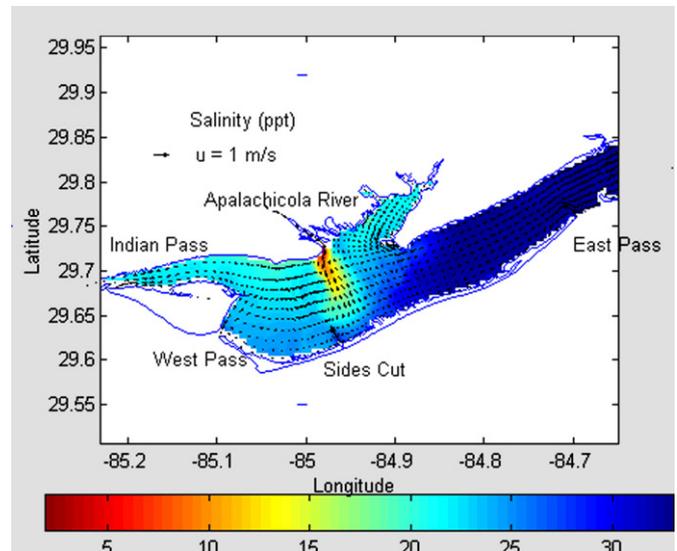**Fig. 2.** Example of model verification by Huang et al. (2002a).

Fig. 3. An example of model predicted salinity distribution in Apalachicola Bay.

from time to time. The maximum flow difference reaches above 2000 m^3/s in early 1980. Statistics of inflows are given in Table 1. Under historic flow condition, the mean and standard deviation are 700 m^3/s and 476 m^3/s, respectively. The scenario flow reduces the mean flow from 700 m^3/s to 683 m^3/s, and minimum flow from 164 m^3/s to 106 m^3/s. However, the scenario flow increases the standard deviation from 476 to 560 m^3/s, and the maximum flow from 3598 m^3/s to3737 m^3/s. While the mean flow is only reduced 2.4%, the standard deviation increases 17%.

5. Hydrodynamic model simulations of salinity for 1980–1989 period

The previously calibrated and verified hydrodynamic model (Huang and Jones, 2001; Huang et al., 2002a) was applied to simulate salinity variations in responses to two river flow conditions as described above. Tides at ocean boundaries were specified through the harmonic analysis of the data as described by Huang et al. (2002b). Previous study by Huang and Jones (2001) indicates that the average wind speed is close to zero during the six-month period between June and November of 1993. Therefore, in order to compare the effects of changing river inflows on the estuary, wind speeds were set to zero as the baseline condition for the evaluation of river flow effects on estuarine salinity. In model simulations, the first 31-days were used as the spin-up period to set up appropriate initial conditions for model simulations.

Model outputs were recorded for surface and bottom salinity at two stations in Apalachicola Bay. As shown in Fig. 1, Mid Bay station is located near the middle of the bay and directly faces to the Apalachicola River discharge. The Dry Bar station is located in the rich oyster reef in the western area of the bay. While the Mid Bay station near the middle of the bay can be used to represent the average estuarine environment, the Dry Bar station located in the oyster reef can be used to examine the effects of river inflows on oyster ecology, which is the important indicator of estuarine ecosystem in Apalachicola Bay.

Time series of hourly surface and bottom salinity for the two flow conditions during 1980–1989 were obtained from hydrodynamic model simulations, and are presented in Fig. 5.

The bottom mean salinity is about 22 ppt at Mid Bay and approximately 20 ppt at Dry Bar. These mean salinity values are near the optimum salinity of 22.5 ppt for the development of eggs
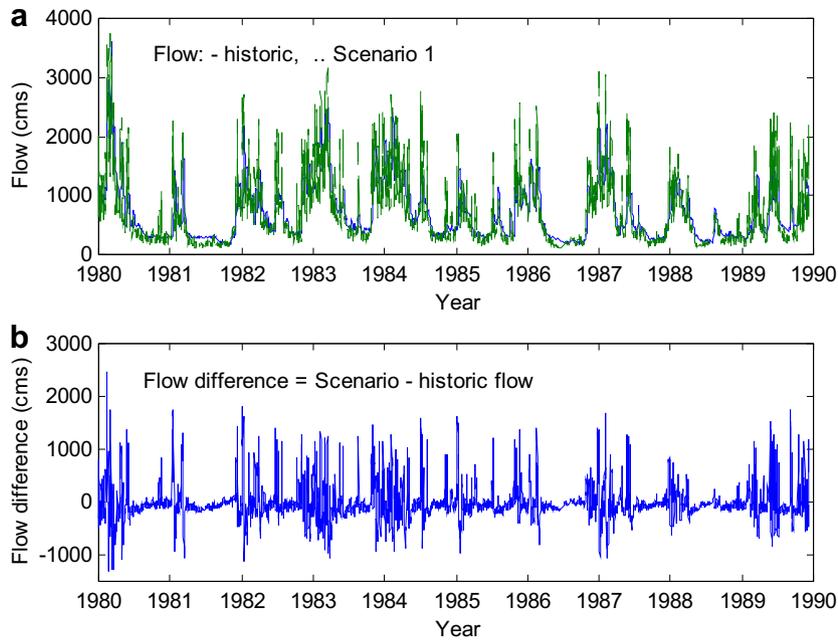
Fig. 4. River inflows (m^3/s, or cms) during 1980–1989.

of oysters from Long Island Sound (Davis, 1958), and within the optimal range of salinity for oyster growth (16–26 ppt) from Southeastern North Carolina estuaries (Harned et al., 1996). The mean bottom salinity may be considered as an important factor for the existence of the oyster reef around Dry Bar. However, it is unable to explain why there is no oyster reef around mid-bay area, although the mean bottom salinity is close to the optimal salinity for oyster growth. Maximum salinity in Mid Bay is higher than that in Dry Bar.

Salinity differences between Scenario flow and historic flow are presented in Fig. 6. Salinity statistics are given in Table 2 for Mid Bay station and Table 3 for Dry Bar station. In both Mid Bay and Dry Bar, the increase of mean salinity and standard deviation by the Scenrio-1 flow are very small, less than 0.5 ppt near bottom and less than 0.8 ppt near surface, respectively. The increase of maximum surface and bottom salinity from flow scenario is 3.2 ppt and 1.4 ppt, respectively, at Mid Bay, and 2.4 ppt and 1.7 ppt, respectively, at Dry Bar. However, the maximum value of instant salinity difference as shown in Fig. 6 at times reaches above 10 ppt. The minimum salinity for the flow scenario slightly decreases from that for the historic flow condition. Therefore, the conventional statistical analysis seems unable to characterize the modifications of salinity in the bay from Scenrio-1 flow condition.

6. Probability analysis of long-term ecohydrological effects on estuarine by changing river inflow scenarios

6.1. Probability analysis method

Probability analysis method has been popularly used in advanced hydrological frequency studies of rainfalls and river flows. However,

Table 1
Statistics of river inflows (m^3/s) for the 1980–1989 period.

	Mean	Standard deviation	Max.	Min.
Historic flow	700	476	3598	164
Scenario-1	683	560	3737	106
Difference	−17	84	139	−58
Difference (%)	−2.4%	17%	3.9%	−3.5%

its applications to analysis of long-term salinity variations for estuarine ecohydrological studies are limited mainly due to the lack of long-term salinity data. Several hydrology textbooks (Chow et al., 1988; Viessman and Lewis, 1996) provide details of descriptions of the probability method, or frequency analysis method. Brief descriptions given below are based on Chow et al. (1988). For a random variable X, a set of observations $x_1, x_2, ..., x_n$ are sampled. The feasible range of the random variable X is divided into equal discrete interval Δx. If the number of observations n_i in interval i, covering the range $[x_i–\Delta x, x_i]$, is divided by the total number of observations n, the result is called the *relative frequency function* $f_s(x_i)$. It is also an estimation of $P(x_i–\Delta x \leq X < x_i)$, the *probability* that the random variable X will lie in the interval $[x_i–\Delta x, x_i]$.

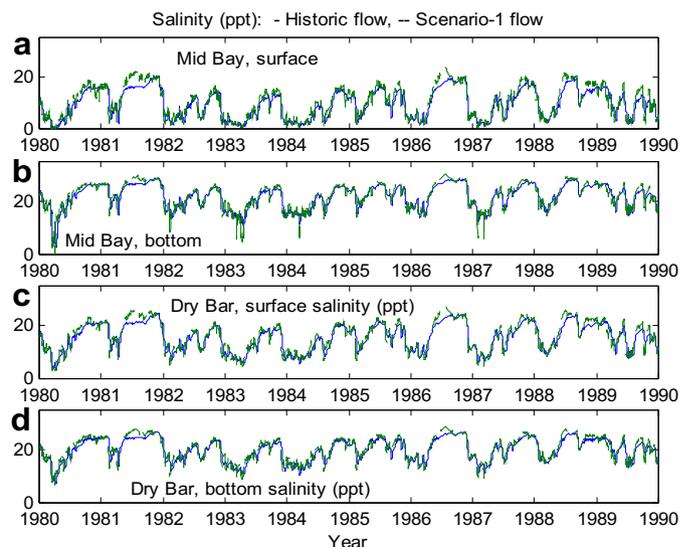$$P(x_i - \Delta x \leq X < x_i) = f_s(x_i) = \frac{n_i}{n} \tag{5}$$

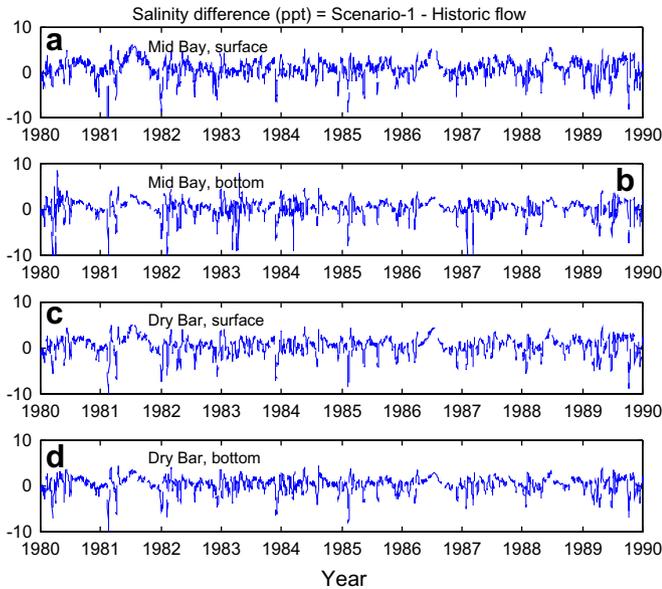**Fig. 5.** Time series of salinity at Mid Bay and Dry Bar stations.

Fig. 6. Time series of salinity differences between Scenrio-1 flow and historic flow conditions.

The subscript s indicates that the function is calculated from sample data.

The sum of the values of relative frequencies up to a given point is called the *cumulative frequency function* $F_s(x)$, or the *cumulative probability* $P(X \leq x_i)$ for the random variable X will lie for $X \leq x_i$:

$$P(X \leq x_i) = F_s(x_i) = \sum_{j=1}^{i} f_s(x_i) \qquad (6)$$

In hydrological frequency analysis, the *exceedance probability* is more commonly used than the cumulative probability. While $P(X < x_i)$ describes the *cumulative probability* of the random variable X for the range of $X \leq x_i$, $P(x_i \leq X)$ represents the *exceedance probability* of the random variable X for the range of $X \geq x_i$. *Exceedance probability* can be calculated by the following procedures: The samples are sorted from high to low by the descending order. If n is the total number of samples, and m is the rank of descending values, the *exceedance probability* of the mth largest value, x_m, for the random variable X is given by Weibull formula:

$$P(X \geq x_m) = \frac{m}{n+1} \qquad (7)$$

6.2. Probability analysis of river inflows during 1980–1989

Probability analysis was conducted for the time series of daily river flows during 1980–1989 as shown in Fig. 7. The probability distributions of the historic flow are used as the baseline to examine

Table 2
Salinity (ppt) statistics at Mid Bay station.

	Mean	Standard deviation	Maximum	Minimum
	Surface (bottom)	Surface (bottom)	Surface (bottom)	Surface (bottom)
Historic flow	9.8 (21.9)	5.5 (4.5)	20.2 (28.8)	0.2 (2.6)
Scenraio-1	10.5 (22.2)	6.1 (4.9)	23.4 (30.2)	0 (0)
Difference	0.7 (0.3)	0.6 (0.4)	3.2 (1.4)	−0.2 (−2.6)

Table 3
Salinity (ppt) statistics at Dry Bar station in the oyster reef.

	Mean	Standard deviation	Maximum	Minimum
	Surface (bottom)	Surface (bottom)	Surface (bottom)	Surface (bottom)
Historic flow	15.7 (20.2)	5.1 (4.2)	24.8 (26.9)	3.3 (7.2)
Scenraio-1	16.3 (20.6)	5.6 (4.6)	27.2 (28.6)	3.0 (6.8)
Difference	0.6 (0.4)	0.4 (0.4)	2.4 (1.7)	−0.3 (−0.4)

the magnitude of flow modifications under the Scenario-1 flow condition. As shown in Fig. 7a, the maximum relative frequencies for both flow conditions occur near $Q = 400$ m^3/s, which are lower than the mean river flows of approximately 700 m^3/s as shown in Table 1. However, the maximum frequency of the Scenario-1 flow is approximately 16%, which is less than the 18% value for the historic flow condition. In low end flow area, flow rates under Scenario-1 condition are lower than those under historic flow condition. In high-end flow conditions, flows under Scenario-1 are slightly higher than those under historic flow condition. Fig. 7b characterizes the changes of exceedance probability distributions in the Scenario-1 flow condition. For flow rate less than 1400 m^3/s, the exceedance probability under Scenario-1 flow condition is lower than that under historic flow condition. For flow rate above 1400 m^3/s, the exceedance probability under Scenario-1 flow condition is higher than that under historic flow condition. Probability analysis of daily river flows over a 10-year period has shown its capability of characterizing and summarizing the modifications of the historic flow pattern by a river flow scenario resulted from the changes of upstream reservoir operations and water demands.

6.3. Probability analysis of salinity in responses to river inflows during 1980–1989

Common statistical analysis as shown in Tables 2 and 3 indicate that there are no significant differences in mean salinity and standard deviations between historical flow condition and Scenario-1
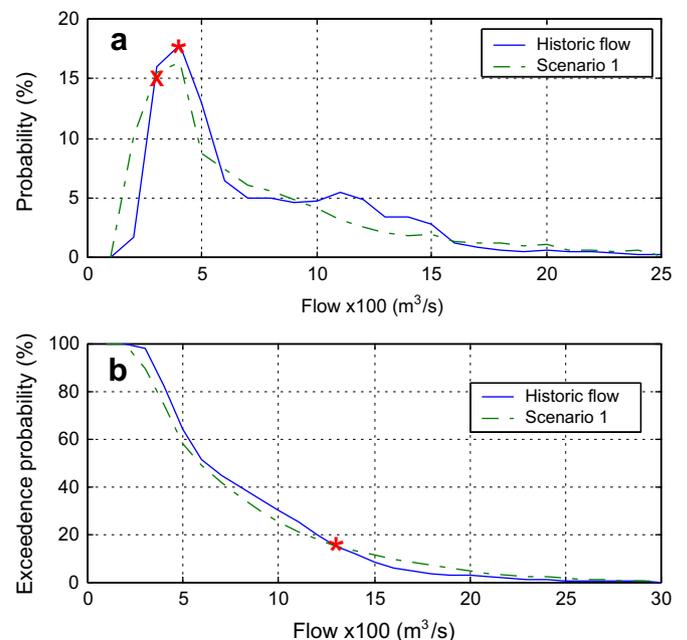

Fig. 7. (a) Probability density and (b) exceedance probability of river inflows.

flow condition over the 10-year period. This shows that averaging over the long-term period makes it difficult to examine the changes of probability distributions of river flows.

Probability analysis was conducted for hourly salinity at two critical stations in Apalachicola Bay to characterize the salinity responses to the changes of river inflows. One is selected at Mid Bay to characterize the general response of the estuarine salinity. Another station is located at Dry Bar, a major oyster reef, to show the long-term impact on oysters. Hourly salinity outputs hydrodynamic model simulations were ranked from high to low in descending order, m is the rank of descending values. The values of salinity were then divided into groups in every 1 ppt interval, or $S_i = S_{i-1} + 1$. n_i represents the number of salinity samples within $S_{i-1} \leq S < S_i$, or $S_{i-1} \leq S < S_{i-1} + 1$. For the total n number of salinity values, the *exceedance probability* for salinity $S > S_m$ can be estimated by:

$$P(S \geq S_m) = \frac{m}{n+1}. \tag{8}$$

Salinity ranging from 0 ppt to 34 ppt was divided in every 1 ppt interval, *relative frequency function* $f_s(x_i)$, or the *probability* that salinity lies between interval $S_{i-1} \leq S < S_{i-1} + 1$ is calculated by:

$$p(S_{i-1} \leq S < S_i) = \frac{n_i}{n}. \tag{9}$$

Salinity probability can be used to investigate how often salinity occurs at every 1-ppt interval. For example, $p(5 \text{ ppt} \leq S < 6 \text{ ppt}) = 10\%$ indicates salinity within the value ($5 \text{ ppt} \leq S < 6 \text{ ppt}$) occurs with 10% probability value, or 10% of total hours considering hourly interval of the time series salinity data. The probability density distribution can also be used to identify the salinity that has mostly occurred in the estuary, or the *maximum probability salinity.*

Probability distributions of salinity at Mid Bay are given in Fig. 8a and b. In comparison to those under historic flow condition, the peak value of probability density distribution under Scenraio-1 condition is lower, and skews toward higher salinity. At Mid Bay station, surface

salinity under historic flow reaches maximum 9% probability near $S = 4$ ppt and $S = 16$ ppt condition; but under Scenario-1 it changes to a 7% peak probability near $S = 3$ ppt and another peak probability of 6% near $S = 14$ ppt. Maximum probability for bottom salinity at Mid Bay is near $S = 27$ ppt for both historic and Scenario-1 conditions. However, the peak probability of bottom salinity under historic flow condition is 14% in comparison to the 8% peak probability under Scenario-1 condition. In both Fig. 8a and b, Scenrio-1 has shown to increase the possibility in high salinity area.

Probability distributions of salinity at Dry Bar, the site of rich oyster reef, are given in Fig. 8c and d. There are two peaks in surface salinity distributions. Under historic flow condition, the first peak probability of 7% occurs at surface salinity $S = 10$ ppt, and the second peak probability of 9% at $S = 22$ ppt. Under flow Scenario-1, the first peak probability of 5% occurs at surface salinity $S = 10$ ppt, and the 2nd peak probability of 6.5% at $S = 22$ ppt. For surface salinity larger than 23 ppt, the corresponding probability under flow Scenario-1 is generally higher than that under historic flow condition. For bottom salinity, there is one distinguished peak of probability at $S = 24$ ppt for both flow conditions. The peak probability for bottom salinity at $S = 24$ ppt is 14% under historic flow condition, and 8% under historic flow. For bottom salinity above the value of 26 ppt, the probability under Scenario-1 flow condition is higher than that under the historic flow condition. In general, the Scenrio-1 flow has shown to increase the probability density of high-end salinity.

Because the salinity of maximum probability under historic flow condition represents the *most frequent salinity* that occurred in the natural environment in the past, it may significantly affect oyster growth and mortality, and can be used as an indicator to evaluate the oyster ecology in Apalachicola Bay. Referring to the optimal range 16–26 ppt of salinity for oyster growth (Harned et al., 1996) for Southeastern North Carolina estuaries, the peak probability of bottom salinity of 27 ppt at Mid Bay station explains the fact of no major oyster reefs near mid-bay areas in Apalachicola Bay. At Dry Bar
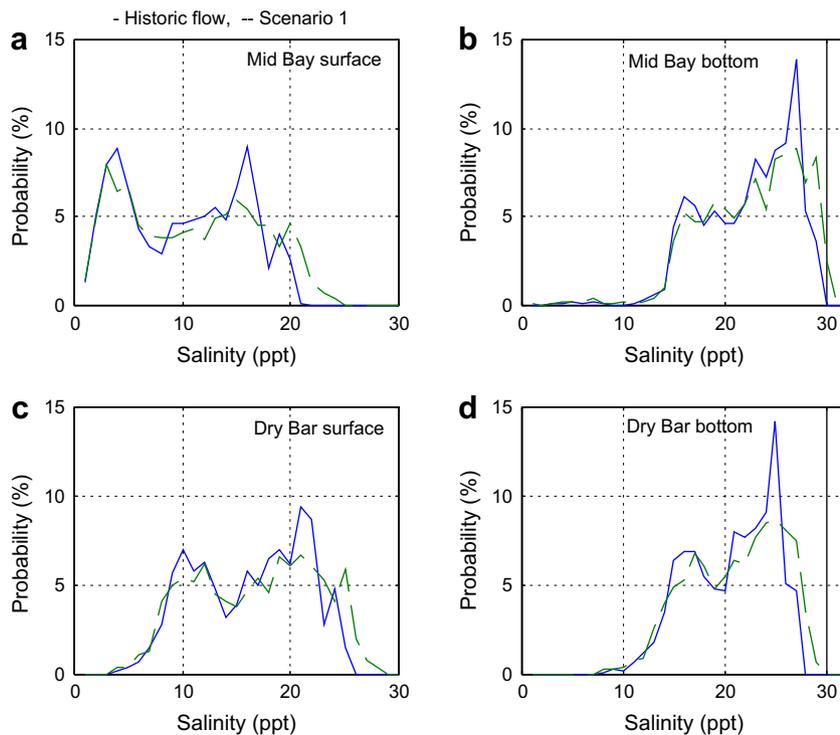

Fig. 8. Probability density of salinity at Mid Bay and Dry Bar during 1980–1989. Optimal salinity for oyster growth (Harned et al., 1996) ranges from 16 to 26 ppt.
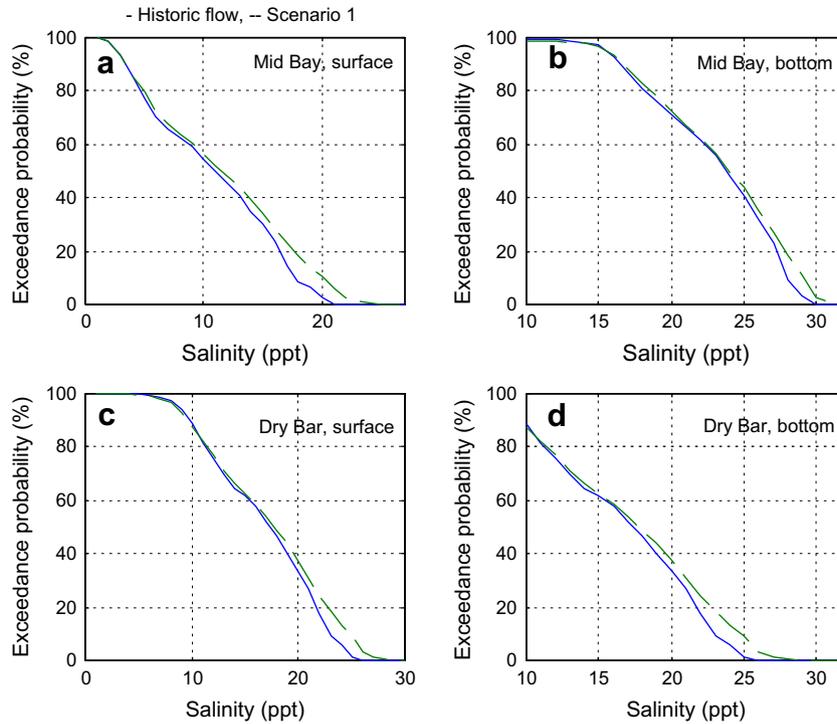
- Historic flow, -- Scenario 1

Fig. 9. Exceedance probability of salinity at Mid Bay and Dry Bar during 1980–1989. Optimal salinity for oyster growth (Harned et al., 1996) ranges from 16 to 26 ppt.

station, the peak probability of bottom salinity of 24 ppt falls within the range of optimal salinity for oyster growth, which is a good explanation for the historical oyster reef in Dry Bar. Therefore, $S = 24$ ppt can be considered as the *optimal salinity* for oyster growth in Apalachicola Bay. Although the flow Scenario-1 does not change the peak bottom salinity at Dry Bar, it reduces the peak probability from 14% to 8% at $S = 24$ ppt, or shortens the time of optimal salinity for oyster growth.

The *exceedance probability* for salinity at Mid Bay and Dry Bar are given in Fig. 9. In general, for salinity above 15 ppt, exceedance probabilities under Scenario-1 flow condition are higher than those under historic flow conditions at both Mid Bay and Dry Bar stations. This indicates Scenraio-1 will lead to longer period of higher salinity in the bay that may cause adverse impact to oyster growth. For the peak probability bottom salinity of 24 ppt at Dry Bay, the exceedance probability substantially increases from 5% under historic flow condition to 15% under Scenrio-1 flow condition. The significant increase of the exceedance probability above most frequently occurred salinity ($S = 24$ ppt) near the oyster reef in Apalachicola Bay is the indication of adverse impact from Scenario-1 flow. As described by Wilber (1992) and Livingston et al. (2000), high salinity in the bay can cause poor oyster production by predation from

invasive species such as stone crabs and oyster drills on newly settled spat. Summaries of salinity probability at Dry Bar are given in Table 4.

6.4. Discussion

Modifications of river inflows to estuaries are affected by many different factors (e.g., by increasing water demands for domestic, industrial, and agriculture usages; or by changing reservoir operations for the navigation or hydropower purposes). Probability density can be used to characterize hydrological patterns of flow scenarios and salinity over a long-term period. The integrated hydrodynamic modeling and probability analysis approach presented in this study has demonstrated its advantage for risk assessments of long-term estuarine ecohydrological effects by changing river inflows. With the hydrodynamic model capable of predicting long-term salinity variations in response to various water management inflow scenarios, probability analysis can be used to characterize the river inflows and salinity probability distributions from the long-term irregular time series data. The salinity at peak probability density shows the most frequently occurring salinity that is an important ecological indicator for risk assessments of the environmental impacts on oysters from changing upstream river inflow patterns.

7. Conclusion

In this study, ecohydrological analysis for Apalachicola Bay has been conducted by integrated long-term hydrodynamic model simulations and probability analysis. Two river inflow scenarios covering a 10-year period from 1980 to 1989, historical flow condition and Scenario-1 condition, were selected for this study. Scenrio-1 represents the modifications of historical flow by changing upstream reservoir operations and water demands. It is difficult to show the different pattern between the two flow scenarios by traditional statistical analysis methods. However, probability analysis clearly shows that Scenrio-1 flow tends to occur more frequently in low-flow end but less frequently in high-flow end. The calibrated

Table 4
Surface and bottom salinity probability at Dry Bar in the oyster reef.

	Maximum probability Salinity (ppt)	Maximum probability (%)	Exceedance probability (%) at MP salinity
	Surface (Bottom)	Surface (Bottom)	Surface (Bottom)
Historic flow	27 ppt (24 ppt)	14% (14%)	5% (5%)
Scenario-1	27 ppt (24 ppt)	8% (8%)	16% (15%)
Difference	0 ppt (0 ppt)	−6% (−6%)	11% (10%)

Note: (1). MP = maximum probability. (2) Optimal salinity for oyster growth (Harned et al., 1996) ranges from 16 to 26 ppt.

hydrodynamic model was used to simulate salinity responses to river inflows during 1980–1989. Time series of salinity difference between two river inflow conditions were presented for estuarine ecohydrological analysis.

To investigate ecohydrological characteristics in Bay under the historic flow conditions, probability analysis of the time series of salinity was conducted. Salinity at Mid Bay station was selected to characterize the general condition in the bay, while salinity at Dry Bar was selected to examine how river flow affects salinity and oysters in a rich oyster reef. Bottom salinity of maximum probability represents the most-influencing salinity to the oyster ecology because it occurs most frequently over a long-term period. Referring to the optimal range 16–26 ppt of salinity for oyster growth (Harned et al., 1996) for Southeastern North Carolina estuaries, environment for oyster growth was assessed by examining the bottom salinity of maximum probability. At Mid Bay where there is no oyster reef, maximum probability of bottom salinity occurs at $S = 27$ ppt, which is above the optimal range of salinity (16 ppt–26 ppt) for oyster growth. In addition, the sum of mean salinity and standard deviation yield a value of 27 ppt, the upper end of salinity variation above 26 ppt. This indicates that high salinity is the main reason for lack of oyster reefs around mid-bay area. At Dry Bar, the maximum probability of bottom salinity occurs at $S = 24$ ppt within the range of optimal salinity for oyster growth as described by Harned et al. (1996). In addition, the sum of the mean salinity (20.2 ppt) and standard deviation (4.2 ppt) is also below 26 ppt. This shows that both most frequently occurred salinity and mean salinity at Dry Bar provide optimal salinity environment to support oyster growth. Therefore, the salinity of maximum probability is a major factor for the existence of the rich oyster reef near Dry Bar in the past several decades.

Effects of the flow scenario resulting from the changing upstream water demands and reservoir operations can be examined by comparing salinity probability distributions and exceedance probability. For the flow scenario selected in this study, results indicate that the flow scenario does not change the salinity value at the maximum probability in the oyster reef. However, the maximum probability of the optimal salinity ($S = 24$ ppt) decreases from 14% to 8% which indicates the shortened time of optimal salinity in the oyster reef. In addition, the increase of exceedance probability for $S = 24$ ppt from 5% to 15% shows longer period of high salinity above the optimal salinity that will cause adverse impact on oyster growth.

Acknowledgement

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