Georgia Water Resources Institute
Annual Technical Report
FY 2012

Introduction

The Georgia Water Resources Institute (GWRI) engages in interdisciplinary research, education, technology transfer, and information dissemination, in collaboration with various local, state, and federal agencies, and other water stakeholders. At the state and local levels, GWRI collaborates with and supports the Georgia Environmental Protection Division/Georgia Department of Natural Resources, water and power utilities, environmental organizations and citizen groups, and lake associations. At the regional level, GWRI has strong involvement with the ACF Stakeholders, a grass roots umbrella organization with membership from 56 river basin stakeholder groups in Georgia, Alabama, and Florida that is in the process of a comprehensive consensus building process to try and reconcile various socioeconomic and environmental interests and develop a shared vision river basin plan for the Apalachicola Chattahoochee Flint (ACF) river basin. At the national level, GWRI has collaborative efforts with the California Energy Commission, California Department of Water Resources, National Oceanic and Atmospheric Administration, U.S. Army Corps of Engineers, U.S. Bureau of Reclamation, U.S. Geological Survey, and the U.S. Environmental Protection Agency. Finally, GWRI has significant international involvement in China, Africa, and Europe with support from the U.S. Agency for International Development, World Bank, Food and Agriculture Organization of the United Nations, and other international organizations. In all initiatives, the Institute strives to bring to bear expertise from a variety of disciplines, including civil and environmental engineering, atmospheric sciences, agriculture, oceanography, forestry, ecology, economics, and public policy. This year's funded activities include:

RESEARCH PROJECTS

(1) Impact of Upstream Water Use on Salinity and Ecology of Apalachicola Bay, Beatriz Villegas and Philip J. W. Roberts, sponsored by USGS under grant #1266663 (Fund R7113).

(2) Monitoring Diurnal and Seasonal Cycle of Evapotranspiration over Georgia using Remote Sensing Observations, Jinfeng Wang, sponsored by USGS under grant #1266663 (Fund R7113).

(3) Integrated Forecast and Reservoir Management (INFORM) for Northern California, Phase II: Operational Implementation, Aris Georgakakos co-PI, Georgia Institute of Technology, joint project with the Hydrologic Research Center, San Diego, California, sponsored by the California Energy Commission under grant #2006Q15.

(4) Upstream Regulation Forecast Adjustment for U.S. River Basins, , Aris Georgakakos co-PI, Georgia Institute of Technology, joint project with the Hydrologic Research Center, San Diego, California, sponsored through Contract Agreement with the NOAA Office of Hydrologic Development (OHD)

(5) Technical Support for the Development of a Sustainable Water Management Plan for the Apalachicola-Chattahoochee-Flint (ACF) River Basin, Aris Georgakakos PI, Georgia Institute of Technology, sponsored by the ACF Stakeholders

PROFESSIONAL AND POLICY IMPACT Regional: GWRI has provided technical support to the ACF Stakeholders to aid in the development of a sustainable water management plan for the ACF river basin. GWRI performed a comprehensive review of the unimpaired flow dataset that forms the basis for the technical modeling of water management alternatives. The strengths and weakness of the existing dataset were determined and communicated to the ACF Stakeholders to establish confidence in the validity of modeling results. Several areas for improvement were identified, some of which are being addressed by GWRI in a 2013 USGS 104(b) grant. GWRI is also involved in the evaluation of water management alternatives. The first phase of this process involved creating baseline scenarios to establish the current baseline conditions in the ACF basin. Subsequent phases will explore a variety of water management alternatives aimed at improving some of the conditions and developing a sustainable water management plan that satisfies the need of all the various entities that form the ACF Stakeholders.

California: GWRI continued its collaborative efforts with the Hydrologic Research Center in San Diego, by operationalizing an integrated forecast-management system for the Northern California water resources system (including the Sacramento and San Joaquin River basins). With funding from the California Energy Commission and the Department of Water Resources, GWRI and HRC have completed the second project phase aiming to finalize and transfer the forecast-decision tools to the responsible agencies and evaluating alternative climate and demand change mitigation measures. GWRI expanded its modeling capabilities by adding models for flood control and in-stream water temperature forecasting and management.

U.S.: GWRI is involved in the on-going National Climate Assessment (NCA), and the Institute Director is the Convening Lead Author the NCA Water Resources Chapter. The first draft of the chapter can be obtained from the following website:
http://ncadac.globalchange.gov/download/NCAJan11-2013-publicreviewdraft-chap3-water.pdf. The chapter is currently undergoing revisions in response to public comments and is expected to be released as part of the complete NCA report in early 2014.

JOURNAL PUBLICATIONS (CURRENT AND PRIOR YEARS)

1. Villegas, B., P. Roberts, and A.P. Georgakakos, “A Mathematical Model of the Apalachicola Bay Salinity and its Effects on Oyster Harvesting,” Journal of Estuarine, Coastal, and Shelf Science, in review.

2. Lu, C., Du, P., Chen, Y., Luo, J. (2011), Recovery efficiency of aquifer storage and recovery (ASR) with mass transfer limitation, Water Resour. Res.,47, W08529, doi:10.1029/2011WR010605.

3. Lu, C., Luo, J. (2012), Boundary condition effects on estimating maximum groundwater withdrawal in coastal aquifers, Ground Water, 50(3), pp.386-393.

4. Chen, Y., Lu, C., Luo, J. (2012), Solute transport in transient divergent flow, Water Resour. Res., 48, W02510, doi:10.1029/2011WR010692.

5. Atreya, A., S. Ferreira and W. Kriesel (2012) “Forgetting the Flood? Changes in Flood risk Perceptions over Time”,University of Georgia, Athens, GA. Presented at UGA Department of Agricultural and Applied Economics Seminar Series, Athens, August 17, 2011.

6. Atreya, A., S. Ferreira and W. Kriesel (2012) “Forgetting the Flood? Changes in Flood risk Perceptions over Time”,University of Georgia, Athens, GA. Presented at UNICT- EAERE- FEEM Belpasso International Summer School on Environmental and Resource Economics, Belpasso, Sicily, Italy, Sept 4-10, 2011.

7. Atreya, A. and S. Ferreira (2012) “Analysis of Spatial Variation in Flood Risk Perception” Presented at UGA Department of Agricultural and Applied Economics Seminar Series, Athens, January 18, 2012.

8. Atreya, A. and S. Ferreira (2011) “Flood Risk and Risk Perception: Evidence from Property Prices in Fulton County, Georgia” Presented at CIMR- Climate Information for Managing Risk, Local to Regional Adaptation and Mitigation Strategies, An International Symposium, Orlando Florida, May 24-27, 2011.

9. Atreya, A. and S. Ferreira (2012) “Variation in Flood Risk Perception: Does Scale Matter?” Presented at ICARUS- Initiative on Climate Adaptation Research and Understanding through the Social Sciences, Columbia University, New York, May 18-20, 2012.

10. Atreya, A. and S. Ferreira (2012) “Spatial Variation in Flood Risk Perception: A Spatial Econometric Approach” To be presented Agricultural and Applied Economics Association 2012 Annual Meeting, Seattle, Washington, August 12-14, 2012.

11. Atreya, A., S. Ferreira and W. Kriesel (2012) “Forgetting the Flood? Changes in Flood risk Perceptions over Time” Submitted to Land Economics.Kellock, K., B. Trushel, P. Ely, C. Jennings and R.B. Bringolf.

12. Kellock, K. and R.B. Bringolf. 2011. Assessment of endocrine disruption in fish and estrogenic potency of waters in Georgia. Proceedings of the 2011 Georgia Water Resources Conference, Athens, GA, April 11–13, 2011.

13. Intersex fish in small impoundments: why won’t the boys be boys? Iowa State University, Department of Natural Resource Ecology and Management. Ames, IA. May 4, 2012.

14. Intersex fish in Georgia. University of Georgia Fisheries Society. Athens, GA. February 16, 2012. 15. A survey of intersex bass in Georgia: Serendipity strikes again? University of Georgia, Warnell School of Forestry & Natural Resources. Athens, GA. September 22, 2011.

16. Intersex fish: not just in Wastewater anymore. Auburn University, Department of Fisheries and Allied Aquaculture. Auburn, AL. September 16, 2011.

17. K. Kellock, C. Jennings, P. Ely, B. Trushel, and R.B. Bringolf. Intersex fish: Not just in wastewater anymore. Presented at the 2012 Southeast Regional Chapter of the Society of Environmental Toxicology and Chemistry. Pensacoala, FL. Mar. 16-17, 2012.

18. Kellock, K.A., C.A. Jennings, P. Ely, B. Trushel, and R.B. Bringolf. Intersex fish influenced by factors other than municipal wastewater effluent. Presented at the 2012 annual meeting of the Georgia Chapter of the American Fisheries Society. Macon, GA. Feb. 7-9, 2012.

19. Bringolf, R.B., K. Kellock, B. Trushel, P. Ely, and C. Jennings. Intersex fish: Not just in wastewater anymore. Presented at the 2012 annual meeting of the Southern Division of American Fisheries Society. Biloxi, MS. Jan. 26-29, 2012.

20. Kellock, K. and R.B. Bringolf. Intersex fish influenced by factors other than municipal wastewater effluent. Presented at the 2011 Society of Environmental Toxicology and Chemistry North America Meeting. Boston, MA. Nov. 7-12, 2011.

21. Kellock, K. and R.B. Bringolf. Assessment of endocrine disruption in fish and estrogenic potency of waters in Georgia. Presented at the 2011 Georgia Water Resources Conference, Athens, GA, April 11–13, 2011. Awarded Best Student Presentation.

22. Bringolf, R.B., K. Kellock, B. Trushel, P. Ely and C. Jennings. Survey of intersex bass and estrogens in GA waters. Presented at the 2011 Meeting of the Georgia Chapter of the American Fisheries Society. Perry, GA. Feb. 2-3, 2011.

23. Georgakakos, K.P., Graham, N.H., Cheng, F.-Y., Spencer, C., Shamir, E., Georgakakos, A.P, Yao, H., and Kistenmacher, M., “Value of Adaptive Water Resources Management in Northern California under Climatic Variability and Change: Dynamic Hydroclimatology,” J. Hydrology, in press, on line reference doi:10.1016/j.jhydrol.2011.04.032, 2011.

24. Georgakakos, A.P, Yao, H., Kistenmacher, M., Georgakakos, K.P., Graham, N.H., Cheng, F.-Y., Spencer, C., Shamir, E., “Value of Adaptive Water Resources Management in Northern California under Climatic Variability and Change: Reservoir Management,” J. Hydrology, in press, on line reference doi:10.1016/j.jhydrol.2011.04.038, 2011.

25. Zhang, F. and A. P. Georgakakos, “Joint Variable Spatial Downscaling,” Climatic Change, in press, on line reference doi.org/10.1007/s10584-011-0167-9, 2011.

26. Chen, C-J., and A.P. Georgakakos, “Hydro-Climatic Forecasting Using Sea Surface Temperatures—Methodology and Application for the Southeast U.S.,” Journal of Climate Dynamics, in press.

Research Program Introduction

None.

Impact of Upstream Water Use on Salinity and Ecology of Apalachicola Bay

Basic Information

Title:	Impact of Upstream Water Use on Salinity and Ecology of Apalachicola Bay
Project Number:	2011GA289B
Start Date:	3/1/2012
End Date:	2/29/2013
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Congressional District:	5th
Research Category:	Water Quality
Focus Category:	Surface Water, Water Quality, Hydrology
Descriptors:	None
Principal Investigators:	Philip Roberts, Philip Roberts

Publication

1. Villegas, B., P. Roberts, and A.P. Georgakakos, “A Mathematical Model of the Apalachicola Bay Salinity and its Effects on Oyster Harvesting,” Journal of Estuarine, Coastal, and Shelf Science, in review.

Impact of Upstream Water Use on Salinity and Ecology of Apalachicola Bay

Phase 2 - Final Report

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CONTENTS

EXECUTIVE SUMMARY

Biological productivity in estuaries is strongly influenced by freshwater inflows that provide nutrients and determine salinity variations; in particular, oyster growth and mortality are directly related to salinity. The salinity in Apalachicola Bay, Florida, is heavily influenced by flows in the Apalachicola River, the lower part of the Apalachicola-Chattahoochee-Flint (ACF) river basin. The ACF is shared by Alabama, Florida, and Georgia, and is subject to on-going negotiations on competing water demands that may result in significant operational and flow regime changes. Apalachicola Bay is the most important ACF basin ecosystem.

The bay is hydrodynamically complex. The river flow enters perpendicular to the main estuary axis as a surface buoyant jet. Its subsequent mixing in the bay is influenced by periodic tidal currents that are primarily diurnal and semidiurnal. Winds, particularly those blowing along the long estuary axis, can significantly affect circulation and volume fluxes and therefore salinity and water quality. Although the bay is very shallow it can have strong vertical density stratification. The relative magnitudes of the various driving forces, wind, tide, and freshwater inflow, vary, resulting in significant temporal and spatial (i.e., horizontal and vertical) salinity variations.

A three-dimensional hydrodynamic model of the bay was set up, calibrated and validated using Delft3D and existing data. The purpose of the model is to assess the impacts of upstream regulation and climatic changes on salinity.

The modeling effort resulted in realistic simulations of the major estuary hydrodynamic characteristics. The modeled water levels are in very good agreement in phase and magnitude with measured values at all available recording stations. Salinity results also follow reasonably well the general observational trends.

Long term salinity variations were assessed through a 29-year simulation experiment, clearly showing the significant influence of river discharge on salinity. Salinity in oyster bar regions exhibits considerable variability over intra-annual time scales, but its interannual and long term statistical distribution is consistent with previously identified ranges favorable to oysters. Salinity-based indicators for environmental change and oyster sustainability are proposed and used to identify the existence of possible trends. Such trends are indeed detected, with salinity conditions gradually shifting away from those favorable to oysters.

A preliminary assessment of the effect of sea level rise was performed by running the model for the period 2008-2010, which covered 3 different hydrologic periods, using the measured wind and river discharges but adding 0.30 m to the measured water levels. The modeling results predicted a significant increase of salinity in the bay with daily average salinity incerases up to 10 ppt at Cat Point and 13 ppt at Dry Bar.

LIST OF FIGURES

1. Introduction

Recent decades have seen rapid population growth with accompanying increases in water demand, agricultural expansion, severe droughts, urbanization, river pollution, endangered ecosystems, and litigious transboundary water disputes. In estuarine environments the decisions of water flow management in the watershed could have large impacts in terms of flushing, water quality, and particularly salinity.

The Apalachicola Bay, a barrier island estuarine system located in the Florida Panhandle (Figure 1), supports 131 freshwater and estuarine fish species and serves as a nursery for many significant Gulf of Mexico species (the Gulf sturgeon, oysters, etc.). The river and estuary ecology depend on the historical hydrological conditions under which they have evolved. These include magnitude, variability, frequency, and persistence of floods, droughts, and normal periods. Biological productivity of the bay is strongly influenced by the amount, timing, and duration of the freshwater inflow. It provides essential nutrients that form the base of the food web in the Bay and any alteration of flow in the watershed can disrupt the nutrient inputs of the ecosystem.

Figure 1. Apalachicola Bay

Salinity and temperature have dominant effects on oyster population; Livingston et al. (2000) showed that oyster mortality is directly related to salinity in the Bay. Developing a comprehensive understanding of the linkages between river hydrology, estuarine salinity, and fish ecology is critical for the development of a sound instream flow policy for ecosystem protection and sustainability.

The primary purpose of this study is to set up and validate a mathematical model for Apalachicola Bay and use it to assess (i) historical salinity ranges for optimal oyster growth, (ii) the impact of upstream water use change and river regulation on the bay, and (iii) the impact of climate change on the bay.

2. Oysters in Apalachicola Bay

Oysters are suspension feeders and tend to occur in dense beds where environmental conditions are favorable. These beds grow horizontally by larvae attaching themselves to hard substrates and vertically by larvae attaching themselves to other oysters. The vertical growth of oyster beds is advantageous because it allows the living oysters to remain above accumulating fine-grained sediment where nutrient supply is optimal (Lenihan, 1999; Schulte et al., 2009). Aggregations of live oysters and empty shells are called oyster bottoms, beds, banks, reefs, or bars although these expressions are not well-defined biologically and are used interchangeably.

Environmental conditions in Apalachicola Bay are highly advantageous for oyster propagation and growth (Livingston et al., 2000). The bay, a shallow lagoon set off from the West Florida continental shelf by barrier islands, lies at the mouth of a large river that serves as a source of food, fresh water, and salinity variation that protects against predators and disease (Sun and Koch, 2001; Edmiston, 2008). Additionally, its location at the eastern end of the Florida panhandle keeps the water relatively warm throughout the year (annual range, 5° – 35°C).

American oyster, Crassostrea Virginica, is the dominant species on the Apalachicola bars. Apalachicola Bay provides about 90% of the oysters harvested in Florida and about 10% of the total U.S. oyster landings. In addition to being an important economic booster for the region, oysters play an important role in sustaining the marine community as filter feeders. They consume phytoplankton and filter organic matter from water, improving water quality and benefiting all organisms in the community.

The spawning season in Apalachicola Bay (April–October) is one of the longest in the country. The growth of oysters is continuous throughout the year and considerably more rapid and more extensive than that observed in northern waters, usually achieving a harvest marketable size of 76 mm in approximately 18 months.

Surface sediment samples show that the oyster beds consist of shelly sand, while much of the remainder of the bay floor is covered by mud delivered by the Apalachicola River. The present oyster reefs rest on sandy delta systems that advanced southward across the region between 6400 and 4400 before the present time (BP) when sea level was 4 to 6 m lower than present. Oysters started to colonize the region around 5100 yr BP and became extensive by 1200 and 2400 yr BP. Since 1200 yr BP, their aerial extent has decreased due to burial of the edges of the reefs by the prodelta mud that continues to be supplied by the Apalachicola River. Oyster reefs that are still active (Figures 2 and 3) are narrower than the original beds, have grown vertically, and have become asymmetrical in cross-section. Their internal bedding indicates they have migrated westward, suggesting a net westerly transport of sediment in the bay (Twichell, 2010).

The relationship between sedimentation rates and sea-level rise has been explored extensively (Bryant, 2001). Sea level rise results in increased inundation and coastal erosion, and the balance between sea level rise and sedimentation rates is critical to the trophic status of estuaries as well as the long-term geomorphology. If sedimentation rates are greater than the sea level rise, then over centuries to millennia, estuaries can be filled in, while if the reverse is true, the coastal zone can ultimately be submerged (Surratt, 2008).

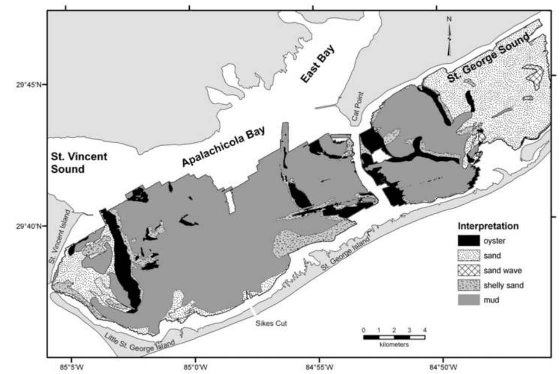

Figure 2. Surficial geology, from Twichell 2010

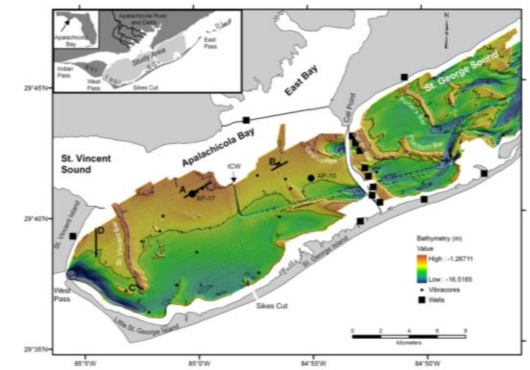

Figure 3. Apalachicola bay largest oyster reefs (labeled in white), from Twichell, 2010

Generally, this process waxes and wanes over millions of years for all estuarine systems, and presently the Apalachicola Bay is subject to rising sea levels, which began less than 20,000 years ago (Livingston, 1984) (Figure 4). Within the last century, the rate of sea level rise has doubled to the present rate of about 1.5 mm per year in the northeastern Gulf of Mexico and is expected to double again by the year 2100. Nevertheless, the present sea level rise rate is an order of magnitude lower than sedimentation rates for the estuary and an annual average of 1.5 million metric tons (Kofoed and Gorsline, 1963), nearly the entire river's sediment load, is currently being deposited in the bay and delta.

The modern Apalachicola Delta formed after the last major rise in sea level. The barrier system enclosing the modern bay was constructed by intermittent growth caused by longshore drift and from offshore material transported directly to the beach (Stapor, 1973). The Florida panhandle coast is composed of many longshore drift cells rather than one well-integrated system. In the case of the Apalachicola region these cells experience little, if any, net exchange of sand (Stapor, 1973). Because the river is the only major source of sediment in the region the most likely source for the sediment that composes the surrounding barrier islands is reworked river sediment. The period of time during which these major coastal sand features were formed apparently correlates to a point in geologic history when sea level was either rising or at a standstill (Banister, 2008).

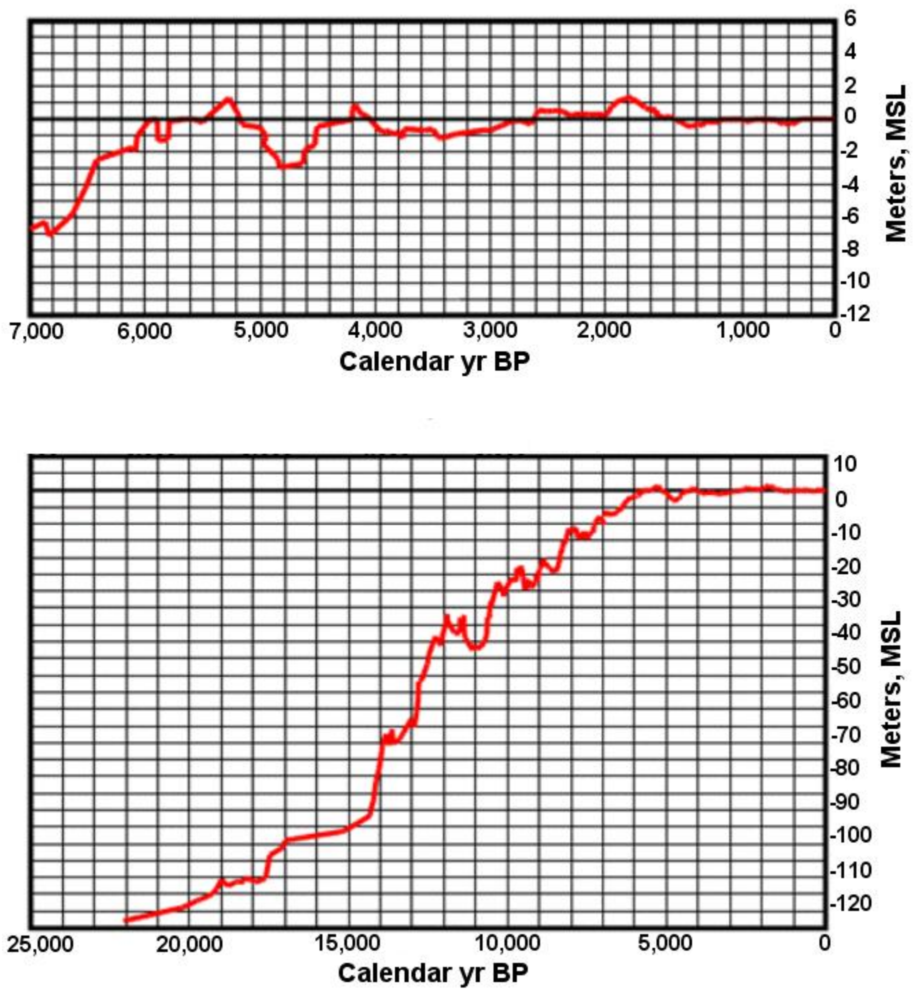

Figure 4: Late quaternary sea-level curves for the Gulf of Mexico, from Banister, 2008

Studies of environmental conditions indicate that salinity, temperature, and nutrient availability influence the oyster population of Apalachicola Bay (Livingston et al., 2000). Yet the distribution of oyster reefs in the bay is not exclusively controlled by oceanographic conditions. Otherwise the reefs would be found in a more symmetrical and uniform pattern around the river mouth. Instead the reefs occur in isolated patches at a scale that is finer than measured variations in oceanographic and nutrient conditions (Livingston et al., 2000). While substrate type contributes to oyster reef distribution, it is not the sole control. The absence of oyster reefs east of Porter's Bar and west of St. Vincent Bar (Figure 2), both areas where the bay floor is sandy, is likely controlled by changes in salinity and nutrient availability with increasing distance from the river mouth. The higher suspended sediment concentrations immediately off the river mouth may limit the growth of oysters there and may also contribute to more rapid burial of the reef margins.

The abundance of crevices and food on the oyster bars provide optimal habitat conditions for a variety of organisms. The oyster-associated community varies somewhat with the salinity regime, which is the most important limiting factor on the bar itself (Menzel et al., 1966). Prolonged high salinity (during droughts) allows certain predators to infiltrate the bars and decreased river flow reduces food supplies. By contrast, prolonged low salinities (during floods) eliminate many of the predators but can also stress the oysters and increase mortality.

While predators and environmental changes can alter the productivity of the oysters and the composition of the associated community, these effects are often slow and variable. Swift (1897) listed three natural conditions that can significantly harm Apalachicola Bay oyster bars: severe freezes, prolonged freshets (floods), and hurricanes.

Salinity is a physiological constraint on the oysters, their space competitors, and their predators. Salinity also represents an indirect measure of the food supply that is filtered with various efficiencies dependent upon the suspended matter concentration and the dilution of land-based pollutants (Turner, 2006). Thus, to characterize the optimal salinity conditions for oysters requires a good understanding of the many interlinked biological, geological, physical, and social factors which support sustainable and healthy ecosystems.

Wang et al. (2008) developed an oyster population model of Apalachicola Bay that simulates a diversity of processes (including ingestion, assimilation, respiration, reproduction, spawning, recruitment, and mortality) and coupled it with a hydrodynamic model. They used the model to examine the effects of changes in freshwater flow and salinity on oyster growth rates. They simulated oyster populations at two sites, Cat Point and Dry Bar. Statistical analyses suggested that oyster growth rates are significantly related to salinity. Lowest oyster growth rates tend to occur in mid-spring due to low salinity caused by the highest Apalachicola River freshwater inflows, whereas the growth peaks tend to occur in mid-summer because of the warm temperature and high food supply. Changes in freshwater inflows affect oyster growth rates through salinity variations as well as other environmental factors such as food availability. Changes in oyster growth rates depend on whether actual salinity levels are within the salinity range conducive to optimal growth.

The salinity range for optimal growth is estimated to lie between 20 to 25 ppt at Cat Point and 17 to 26 ppt at Dry Bar (Wang et al., 2008). Oysters grow better with a fluctuating salinity within the normal range than with a relatively constant salinity (Stanley and Sellers, 1986). Moreover, oysters may have different salinity optima (Shumway, 1996). The optima appear to vary not only for oyster populations in different geographic regions, but also for oysters within the same bay but different freshwater influence, such as at Cat Point and Dry Bar. On the other hand, the values of the coefficient of determination (r2) of the “growth rates–salinity” regression models were less than 0.60 (0.46 at Cat Point and 0.57 at Dry Bar, respectively), indicating that one single factor such as salinity, though a major determinant, could not explain all the variations in oyster growth patterns. This result demonstrates that multiple environmental factors and their interaction should be considered to understand more fully oyster population dynamics in a variable environment.

Petes et al. (2012) applied a combination of laboratory experiments and field observations to investigate the effects of reduced freshwater input on Apalachicola oysters. Monthly surveys of oyster condition and disease were performed at Cat Point and Dry Bar, the major oyster reefs in Apalachicola Bay, from November 2007 to December 2008. The results showed that oyster mortality was strongly linked to both salinity and seasonal temperature. In the winter, when Dermo (P. marinus) typically remains dormant due to cold water temperatures, mortality was low at all salinities. The synergistic effects of low temperature and low salinity have been shown to reduce Dermocell viability (La Peyre et al., 2010). In the summer experiment, in temperature conditions favoring parasite proliferation, mortality was highest at 33 ppt (high salinity), intermediate at 25 ppt, and lowest at 17 to 9 ppt (low salinity). This evidence indicates that oysters in Apalachicola Bay experience chronic exposure to high-salinity water during drought, placing them at high risk of disease-related mortality. It is also likely that these high-salinity conditions led to slow growth, given that salinity exceeded optimal ranges for oyster growth (estimated at 20–25 ppt for Cat Point and 17–26 ppt for Dry Bar; Wang et al., 2008). This finding has important implications for the Apalachicola Bay oysters as upstream water demands intensify, climate change is expected to exacerbate droughts (Georgakakos et al., 2013), and sea level continues to rise (National Climate Assessment, 2013).

The purpose of this study was to develop a mathematical model of the bay as a tool to assess salinity variations and their potential effect on the ecosystem as a result of changing hydrological conditions and water resources management strategies in the ACF, and also potential effects of climate change on salinity in the bay.

3. Apalachicola Bay Mathematical Model

3.1 Study Area

The Apalachicola Bay estuarine system (Figure 1) is approximately 65 km long and 5.5 to 12 km wide, except at its western end, where it narrows to less than 2 km. It is a shallow water system; the depth gently varies from approximately 6 m near the ocean openings to about 3 m near the river mouth. The long axis of the bay is approximately in the east - west direction. It is connected to the Gulf of Mexico through five inlets: Indian Pass, West Pass, East Pass, Sikes Cut and Lanark Reef, and receives freshwater input from three river systems (the Apalachicola, the Whiskey George and Cash Creek, and the Carrabelle), with most flow (about 90%) occurring through the main stem of the Apalachicola River. The river flow rate is relatively high, with monthly average flows ranging from 450 to 1350 m^3/s based on historic data from 1976 to 1996. The river inflow acts like a strong freshwater surface buoyant jet discharged into a saline receiving water. Previous studies show the predominant importance of the river discharges on the salinity fluctuations at the bay.

The hydrodynamics of the bay are complex. It is subject to periodic tides that are primarily diurnal and semidiurnal. Due to the East-West estuary axis and the long wind fetch along this axis with major inlets at each end, winds can play a significant role in volume exchanges between the Bay and the Gulf and can significantly affect salinity and water quality in the bay. The main river flow enters perpendicular to this axis as a surface buoyant jet. Even though the water is shallow, field observations show that the bay is strongly stratified in both vertical and horizontal directions. The relative magnitudes of the various driving functions, wind, tide, and freshwater inflow, vary, resulting in significant horizontal and vertical variations in salinity in the bay. Flows and circulation result from baroclinic forcing (density currents) and barotropic forcing (due to tides and winds). Vertical mixing is significantly affected (reduced) by the vertical density stratification, dictating a three-dimensional (3D) model. These factors make prediction of salinity variations particularly challenging.

3.2 Previous Modeling Studies

Huang and Jones (1997) set up, calibrated, and verified a hydrodynamic model of Apalachicola Bay using daily freshwater inflows from the Apalachicola River measured by the USGS and an extensive field data observation program conducted by NW Florida Water Management District (NWFWMD) during May to November 1993. Within the bay, hourly data were obtained from two tidal stations, six salinity stations, and several current stations. Hourly wind speed and direction were observed at mid-bay. Data were also collected at five boundary openings connected to the Gulf (Indian Pass, West Pass, Sikes Cut, East Pass, and Lanark Reef) that included hourly salinity and temperature (surface and bottom), and surface elevation. Huang and Jones (2001) used their model to investigate the long-term transport of fresh water in the bay and subsequently (2010) developed an integrated hydrodynamic modeling and probability analysis approach to assess the long-term effects of changing river inflows on the estuarine ecosystem. Their analysis of spatial distributions of seasonal average salinity and currents shows that the long-term freshwater transport was strongly affected by the forcing functions of wind and density gradient in the bay. The water column was strongly stratified near the river mouth, gradually changing to well mixed near the ocean boundaries. Vertical stratification in the bay changed due to wind-induced mixing and mass transport. Due to the density gradients, surface residual currents carrying fresher water were directed away from the river toward the Gulf, while the bottom residual currents with more saline water entered the bay from the Gulf of Mexico. To assess the long-term effects of changing river inflows on the estuarine ecosystem, Huang and Jones predicted long-term salinity data with a 3D hydrodynamic model under two river inflow conditions over a 10-year period and used probability analysis to characterize and quantify the changes of river flow and salinity patterns over the 10-year period.

Sun and Koch (2001) analyzed water elevations, wind speed, current velocity, and salinity collected at multiple stations by the Northwest Florida Water Management District NWFWMD at half hour intervals from April 1993 to August 1994. The authors employed cross-correlation techniques, autoregressive integrated moving average (ARIMA), and dynamic regression transfer models using the Box-Jenkins methodology to analyze the time series data. Among their main conclusions is that tidal water level fluctuations result only in short-term periodic variations in salinity, with a linear transfer function that has a lag-two (in hours) as the highest coefficient. The cross-correlation analysis shows that the Apalachicola River, being the major freshwater source of the bay, strongly affects the currents and salinity in the bay area over the long term. Though regional precipitation controls the amount of freshwater inflow, either through river discharge or groundwater seepage, its effect on the daily salinity variation is statistically insignificant. In contrast, the effect of daily wind stress is significant. Salinity is positively correlated with western currents in the bay because most of the oceanic flow enters the bay from the east. A lag between the daily discharge and salinity indicates that up to a week is required for the peak of the inflow fresh water to flush through the bay exit.

A hydrographic survey was conducted on April 5-6, 2003 by Faure and Dottori (2003) in the western part of Apalachicola Bay. They measured temperature and salinity and found that the density profiles are dominated by salinity variations with temperature playing an insignificant role. Although the bay is very shallow, there can be very strong vertical density gradients.

3.3 The Hydrodynamic Model

The hydrodynamic model used is Delft3D, a widely-used two and three-dimensional modeling system to investigate hydrodynamics, sediment transport, morphology, and water quality. While applicable to a wide variety of situations, the package is mostly used for the modeling of lakes, rivers, coastal waters, and estuaries. The FLOW module of Delft3D is a multi-dimensional (2D or 3D) hydrodynamic (and sediment transport) simulation program which calculates unsteady flow and transport phenomena resulting from tidal and meteorological forcing on a curvilinear, boundary-fitted grid. The hydrodynamic module Delft3D-FLOW solves the unsteady non-linear shallow water equations in three dimensions with a hydrostatic assumption. The equations are formulated in orthogonal curvilinear coordinates or in spherical global coordinates. The model includes tidal forcing, Coriolis forces, baroclinic motions (density-driven flows as pressure gradient terms in the momentum equations), an advection-diffusion solver to compute density gradients with an optional facility to treat very sharp gradients in the vertical, space and time varying wind and atmospheric pressure, advanced turbulence models to account for the vertical turbulent viscosity, and diffusivity based on the eddy viscosity concept. The driving forces are open boundary conditions (water levels), inflows from adjacent rivers, and meteorology (winds). The standard drying and flooding algorithm in Delft3D-FLOW is efficient and accurate for coastal regions, tidal inlets, estuaries, and rivers. Delft3D allows for terrain-following, the so called sigma coordinate system. The utilization of sigma grids tolerates much smaller levels of horizontal viscosity and diffusivity. The main advantage of sigma coordinates is that, when cast in a finite difference form, a smooth representation of the bottom topography is obtained.

3.4 Data

Physical, hydrological, and meteorological data were obtained from the NOAA National Geophysical Data Center, U.S. Geological Survey (USGS), Apalachicola National Estuarine Research Reserve (ANERR), Northwest Florida Water Management District, and the National Data Buoy Center (NDBC_NOAA), and used to set up the grid, define boundary and initial conditions, and perform model calibration and validation.

The bathymetric data was downloaded from the NOAA National Geophysical Data Center U.S. Coastal Relief Model (www.ngdc.noaa.gov/mgg/coastal/crm.html). The water depth gently varies from approximately 6 m near the ocean openings to about 3 m near the river mouth (Figure 5).

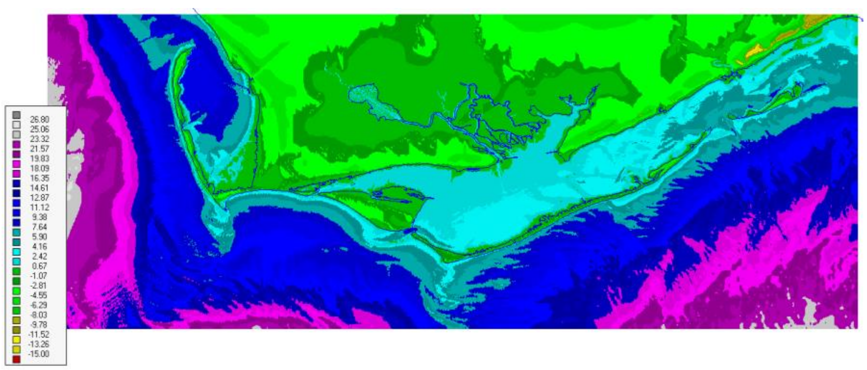

Figure 5. Bathymetry (NOAA National Geophysical Data Center U.S. Coastal Relief Model)

The stations used for model set up are shown on Figure 6. Water levels and winds recorded every 6 minutes at the NOAA station APXF1 were used at the model open boundaries and to represent the wind field over the bay. Daily average river discharges measured by the USGS at the Sumatra hydrological station were used to represent the Apalachicola river freshwater contribution to the estuary. ANERR salinity and sensor depth data recorded at three points inside the bay: CatPoint (CP), DryBar (DB) and EastBay (EB), were used to perform model calibration and validation.

Figure 6. Locations of Recording Stations

3.5 Model Set-up

A three-dimensional model for the Apalachicola Bay was set up, calibrated and validated. The driving forces were divided into open boundary conditions (water levels), hydrology of the adjacent watershed (river tributaries), and meteorological conditions on the Bay (winds). The simulations were made using time series data over the simulated period. The horizontal grid was implemented using Delft3D_RFGGrid (Figure 7) and the vertical numerical grid (i.e., cell depths) was implemented using Deltft3D_QUICKIN. Model grid sizes were defined based on analyses of the local bathymetry and numerical stability issues. The grid sizes ranged from 200 m near the Apalachicola river mouth to 600 m near the barrier islands. The vertical grid consists of five uniform sigma layers.

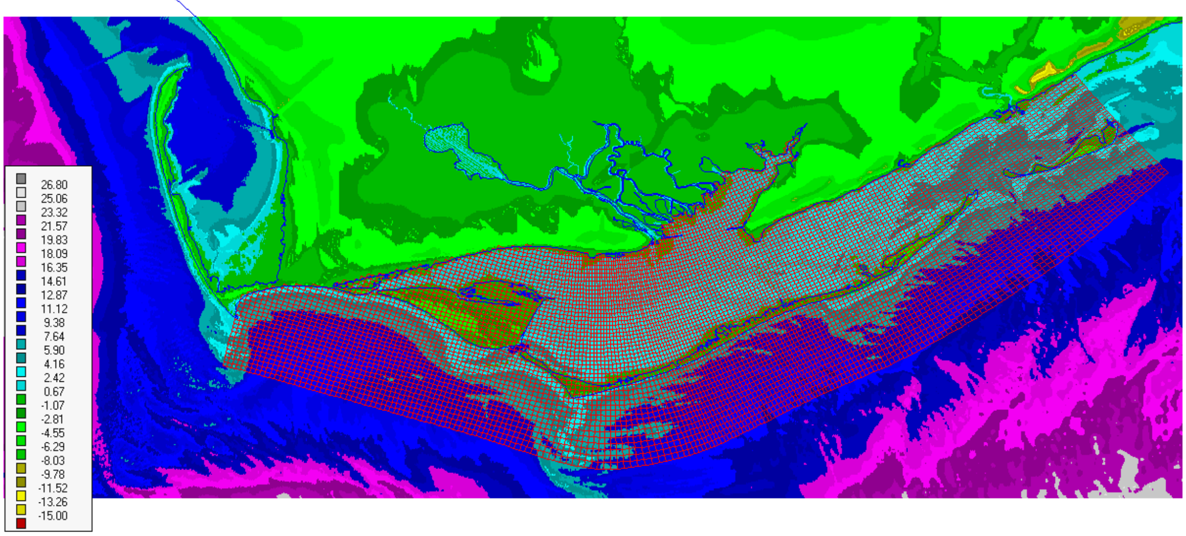

Figure 7. Model domain and grid

For calibration and validation the model was run for three consecutive years: 2008, 2009, and 2010, which covered three different hydrologic periods: dry, wet, and normal. The Apalachicola river daily average discharges recorded at the Sumatra hydrological station are shown in Figure 8. The years are classified as "dry," "wet," and "normal" as indicated.

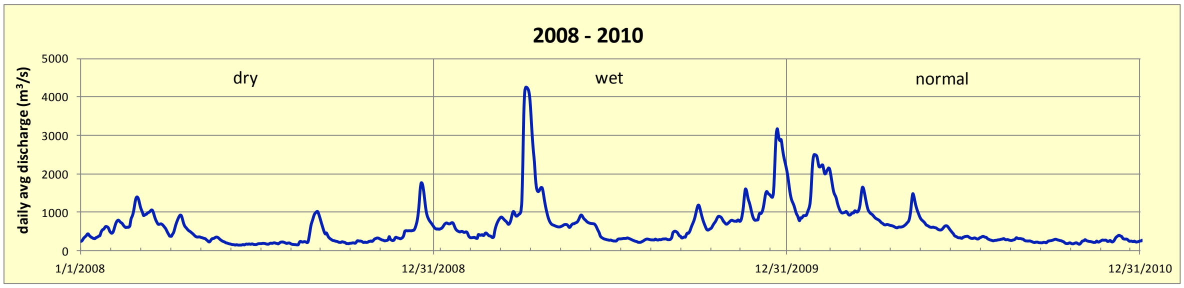

Figure 8. Apalachicola river daily average discharges at Sumatra.

Frequency distributions of the wind speeds and directions are shown in Figure 9. For the January 2008 to December 2010 period, the average wind speed was 3 m/s and the highest speed was 14.3 m/s recorded on October 24, 2008. The winds are predominantly from the northeast with speeds ranging mostly from 2 to 3 m/s.

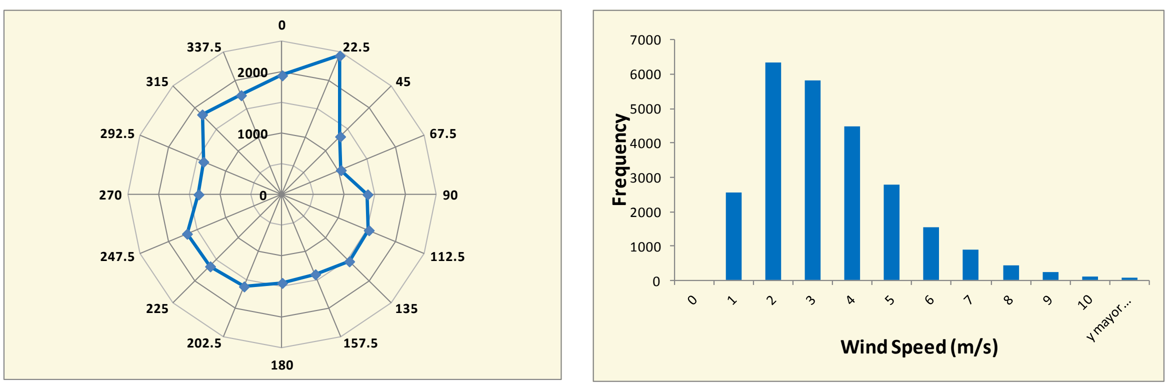

Figure 9. Wind speed and direction frequency distributions at APXF1.

The initial hydrodynamic condition for the entire domain corresponds to a stationary condition (zero velocity, or cold start). Uniform values for all dependent variables were assumed at the start of the simulation. The initial water level and salinity conditions were set according to measured values, and the time step was set according to accuracy considerations (Courant Number) and sensitivity analyses. Initial values for physical parameters such as bottom roughness, wind drag coefficients, and viscosities where estimated according to former studies in the literature.

3.6 Model Calibration

For calibration purposes the model was run from October 2007 to December 2008. The first three months corresponds to a warm up period. Time series of simulated and measured salinities and water levels were compared at three different locations inside the bay (CP, DB, and EB). The model parameters were adjusted to achieve acceptable agreement. The normalized Fourier norm (*Fn*) as defined by Schwab (1983),

$$Fn = \frac{\|V_0, V_c\|}{\|V_o, 0\|}$$

where,

$$\|Vo, Vc\| = \sqrt{\frac{1}{M}\sum_{t=\Delta}^{M\Delta t}|V_0 - V_c|^2} \quad \text{and} \quad \|Vo, 0\| = \sqrt{\frac{1}{M}\sum_{t=\Delta}^{M\Delta t}|V_0 - 0|^2} \ ,$$

was used as a metric of statistical comparisons of observed and simulated parameters.

The *Fn* can be thought of as the relative percentage of variance in the observed parameter (Vo) that is unexplained by the calculated parameter (Vc). Specifically, for perfect prediction, $Fn = 0$, while when *Fn* is in the range $0 < Fn < 1$, the model exhibits useful prediction skill.

Figure 10 shows water level comparisons at EB for a 2 month period (from April 1 to June 1, 2008); for this period an *Fn* value of 0.06 was achieved, indicating 94% correct model predictions.

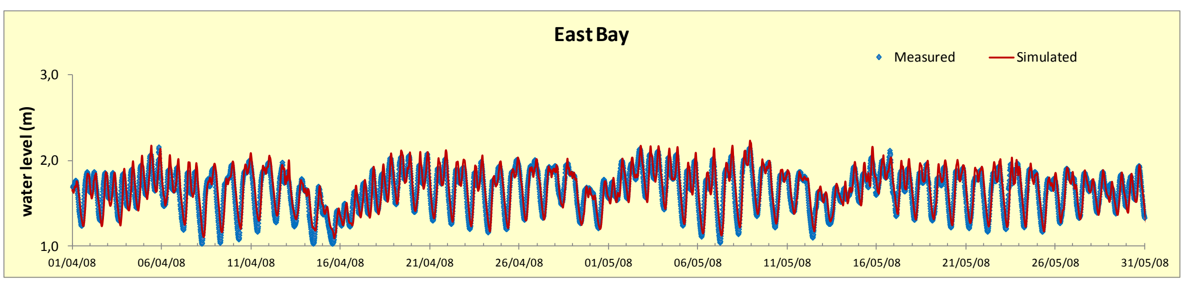

Figure 10. Simulated and observed water levels from April 1 to June 1, 2008

Salinity and water level comparisons at CP and DB for a two month period (from April 1st to June 1st, 2008) are presented in Figures 11 and 12. The modeled water levels were in very good agreement in phase and magnitude with measured values. Daily average salinity results also reasonably followed the general trend of field observations, but high frequency fluctuations (sub-daily) were not so well simulated.

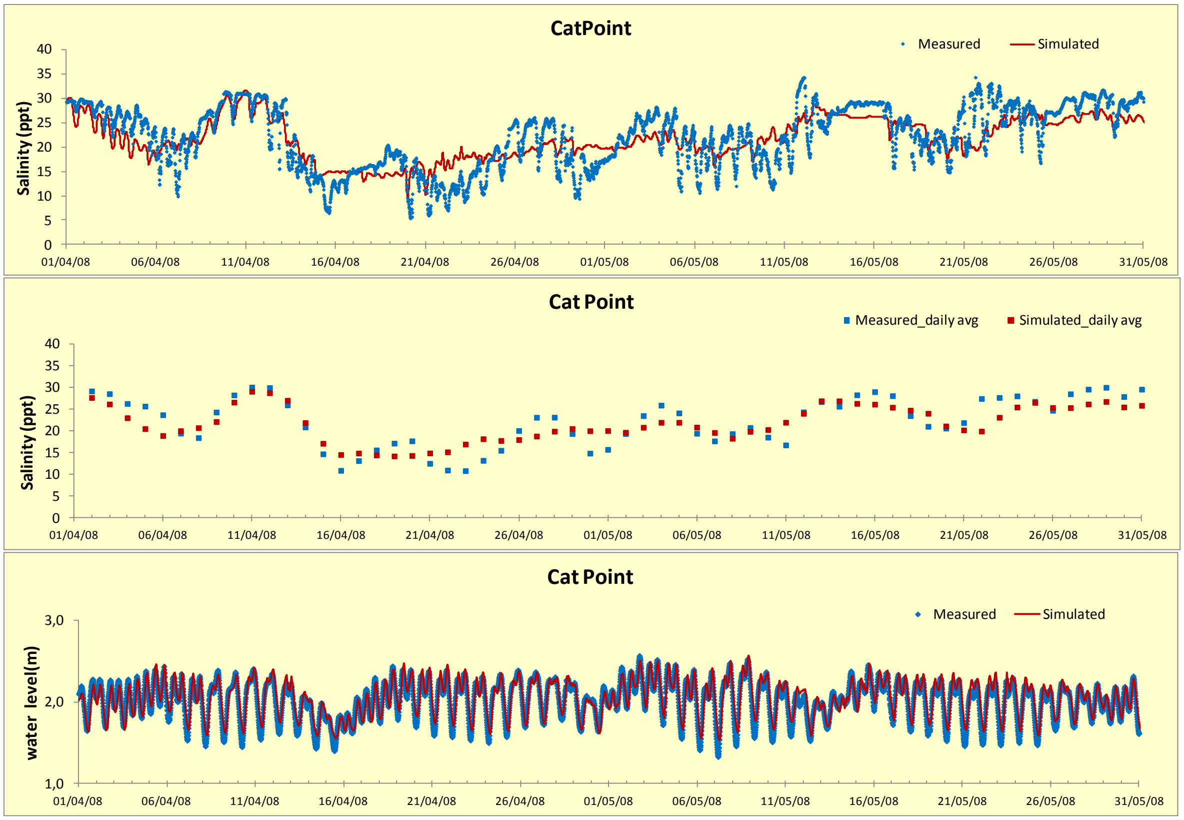

Figure 11. Simulated and observed salinity and water levels at Cat Point from April 1 to June 1, 2008

Figure 12. Simulated and observed salinity and water levels at Dry Bar from April 1 to June 1, 2008

During this period there is an evident disagreement between depth sensor measurements and simulated values from May 8th to May 23rd at station DB. Given that the differences between the two values are constant and that this temporary behavior is seen several times during the simulated period it is clear that the difference is due to instrumental malfunction. There was also a clear discrepancy between the measured and simulated salinities for those same days, indicating that the salinity sensor may have been malfunctioning too. At the end of the calibration process the following values were adopted for the physical parameters: 0.015 Manning roughness; 10 m^2/s horizontal eddy viscosity and diffusivity; and 0.0012 wind drag coefficient.

3.7 Model Validation

For validation, the model was run for another 2 years, 2009 and 2010. Figures 13 and 14 show typical depth-averaged velocity vectors and salinity contours over the model domain.

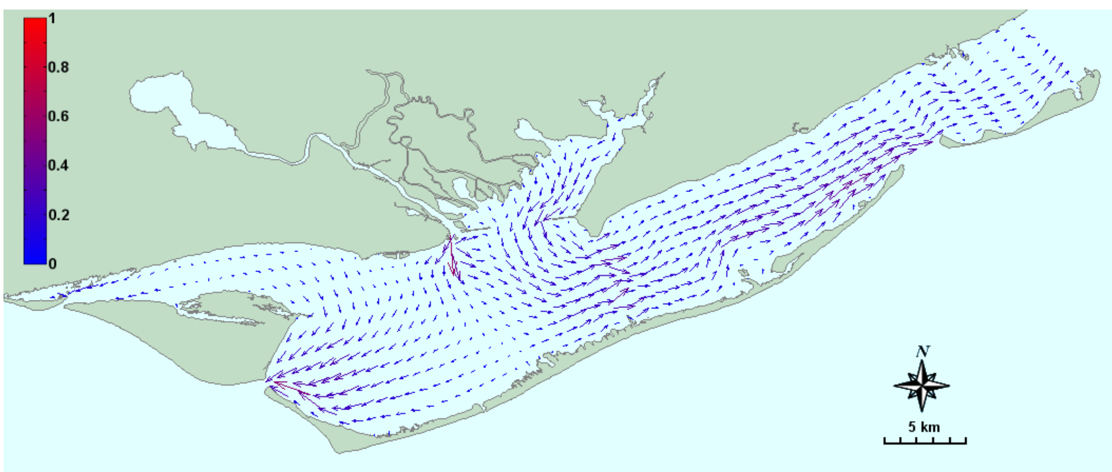

Figure 13. Depth averaged velocity

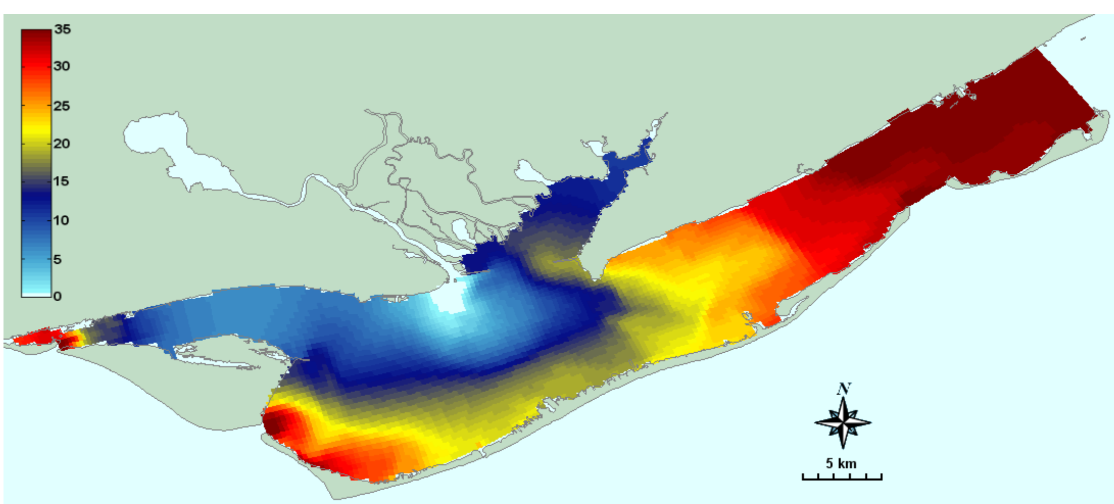

Figure 14. Surface salinity

The current velocities in the bay vary from zero to more than 1 m/s, and the flow directions change from predominantly southwest at high tides to northeast at low tides. The central part of the bay has relatively weak currents. The currents are stronger at the river entrance and the eastward ocean entrance. Tidal water level fluctuations result only in short-term periodic variations in salinity.

Because the mouth of the Apalachicola River is in the northwest segment of the bay, the west and north sides of the bay are less saline than the east and south sides. The west and north sides of the bay also have larger seasonal fluctuations in precipitation and therefore river discharge.

Salinity and water level comparisons at CP and DB for a two month period (from September 1st to November 1st, 2009) are presented in Figures 15 and 16. The modeled water levels were again in very good agreement in phase and magnitude with measured values. Salinity results also reasonably followed the general trend of field observations. Sensor depth miscalibration episodes can also be observed during this time period.

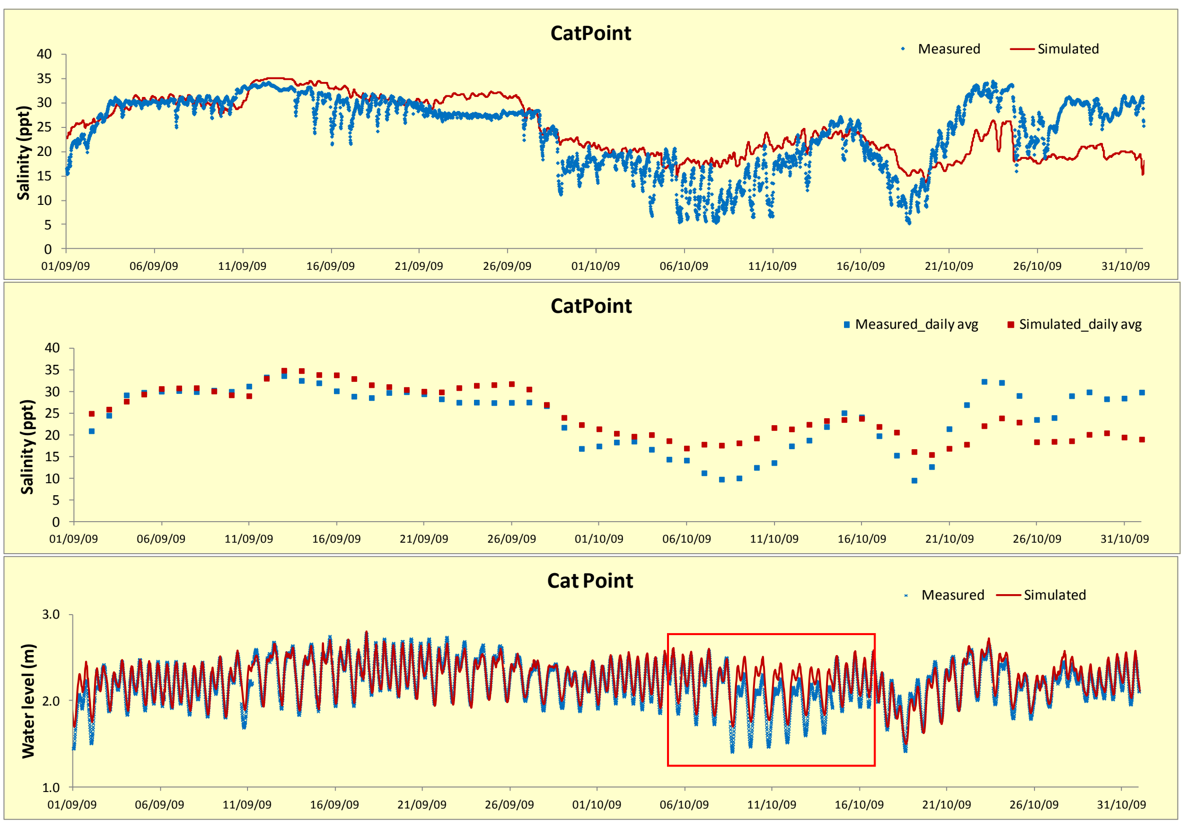

Figure 15. Simulated and observed salinity and water levels at Cat Point from Sep 1st to Nov 1st 2009; An instrument malfunctioning period is noted.

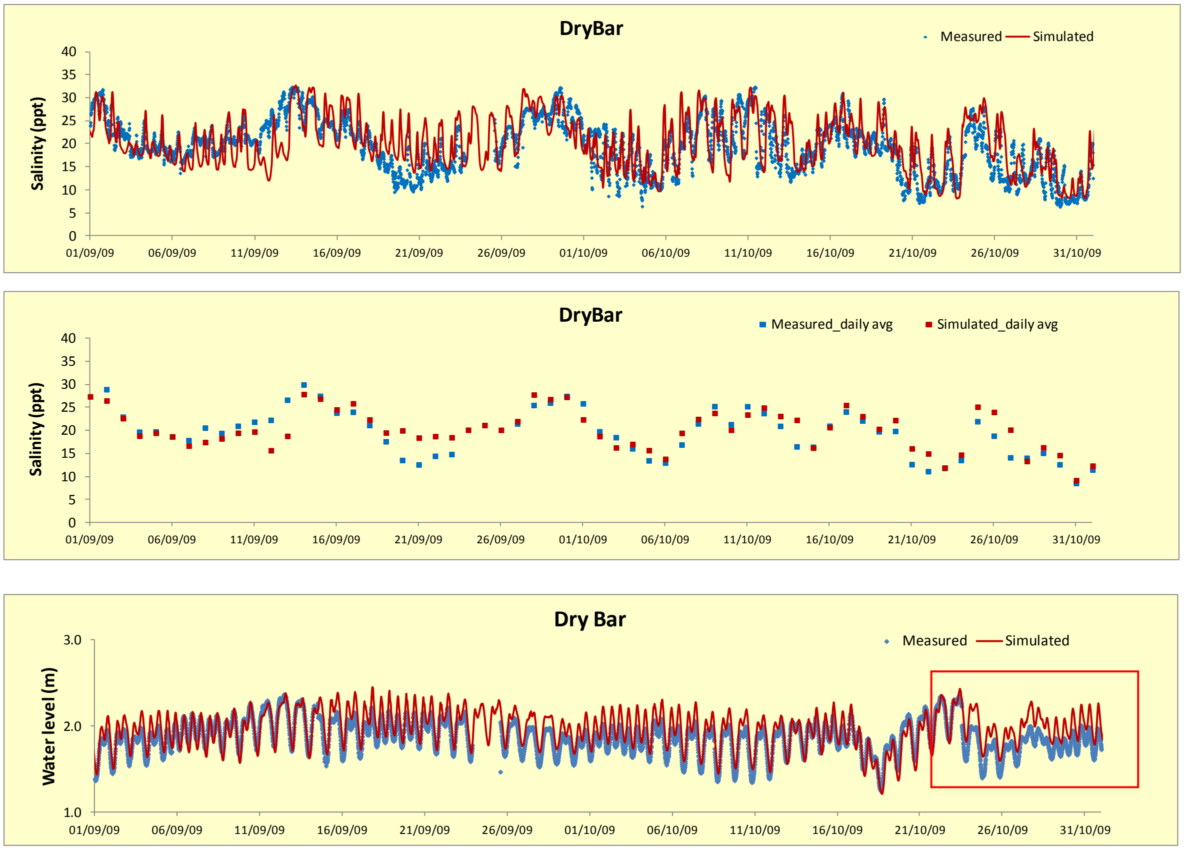

Figure 16. Simulated and observed salinity and water levels at Dry Bar from Sep 1st to Nov 1st 2009; Instrument malfunctioning is noted at the end of the period.

Figure 17 shows the simulated vertical salinity profiles at DB and CP on 31 December 2008 and 27 July 2008 respectively. The bottom water is more saline than the surface water because of the density difference between salty and fresh water. The stratification can be very strong, up to 8 ppt over a few meters depth.

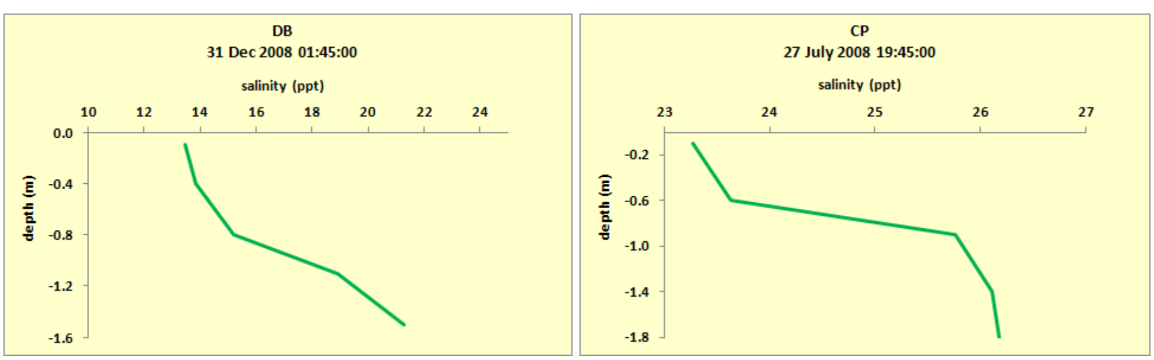

Figure 17. Typical simulated salinity profiles for two monitoring points: CP and DB

Although no direct validation against currents or stratification can be done for the present results, due to lack of measured data for the simulated time frame, the present model setup resulted in plausible simulations of the estuary's major hydrodynamic characteristics. The modeled water levels were in very good agreement in phase and magnitude with measured values for all available recording stations for the entire simulation with *Fn* values exceeding 90%. Daily salinity results also reasonably followed the general field observation trends. Comparisons of model to field data of monthly average salinity values were very close resulting in *Fn* values higher than 80%.

4. Long Term Salinity Assessments

Subsequent to the calibration and validation phase, the model was run for 29 consecutive years to generate a long term data base suitable for assessing trends. Salinity data was extracted from the simulated time series at 186 observation points defined inside the model domain covering the bay major oyster bars, Dry Bar and Cat Point (Figure 18). These data were first averaged spatially over the cells at Dry Bar and Cat Point, and subsequently aggregated over a range of time scales (monthly, seasonally, semi-annually, annually, and bi-annually).

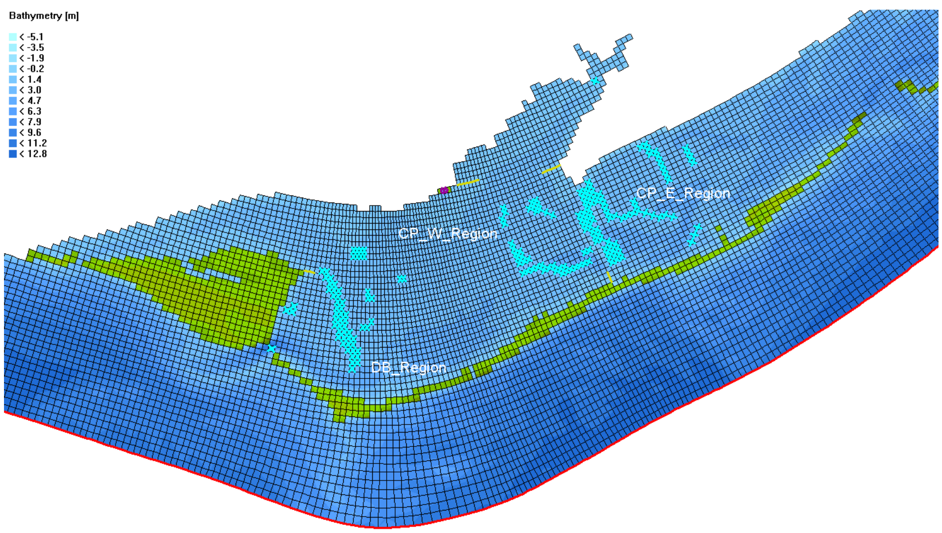

Figure 18. Apalachicola Bay Oyster Bar Regions (cyan color)

The purpose of this analysis is to (a) characterize the salinity conditions at these two sites in relation to the optimal Salinity Range for Oyster Growth (SROG), (b) assess the existence of trends, if any, and (c) develop ecologically relevant salinity indicators that can be used (as part of a more complete indicator set) to measure the impacts of climatic and upstream regulation changes on the ecology of the Apalachicola Bay.

Figure 19 and 20 depict various statistics of the simulated salinity data from 1984 to 2012 for the lowest model layer. The statistics are presented in the form of box plots showing the median, 25^{th} and 75^{th} percentiles (bracketing the inter-quartile range), and the minimum and maximum values. The last box plot on each graph includes all data values. For comparison, the figures also include the SROG ranges (Wang et al., 2008).

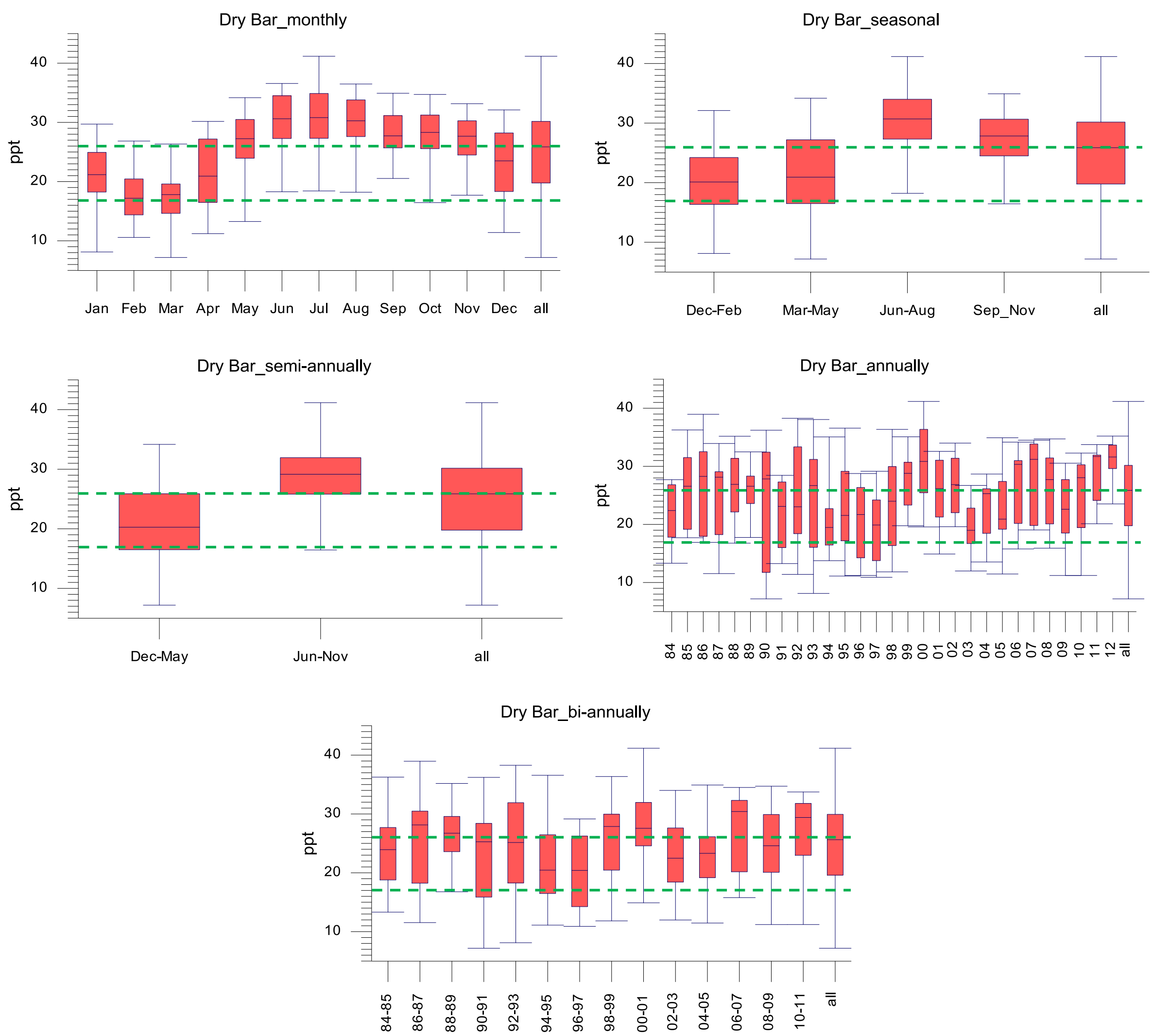

Figure 19. Simulated Salinity Statistics (box-plots) at Dry Bar and associated SROGs (green lines)

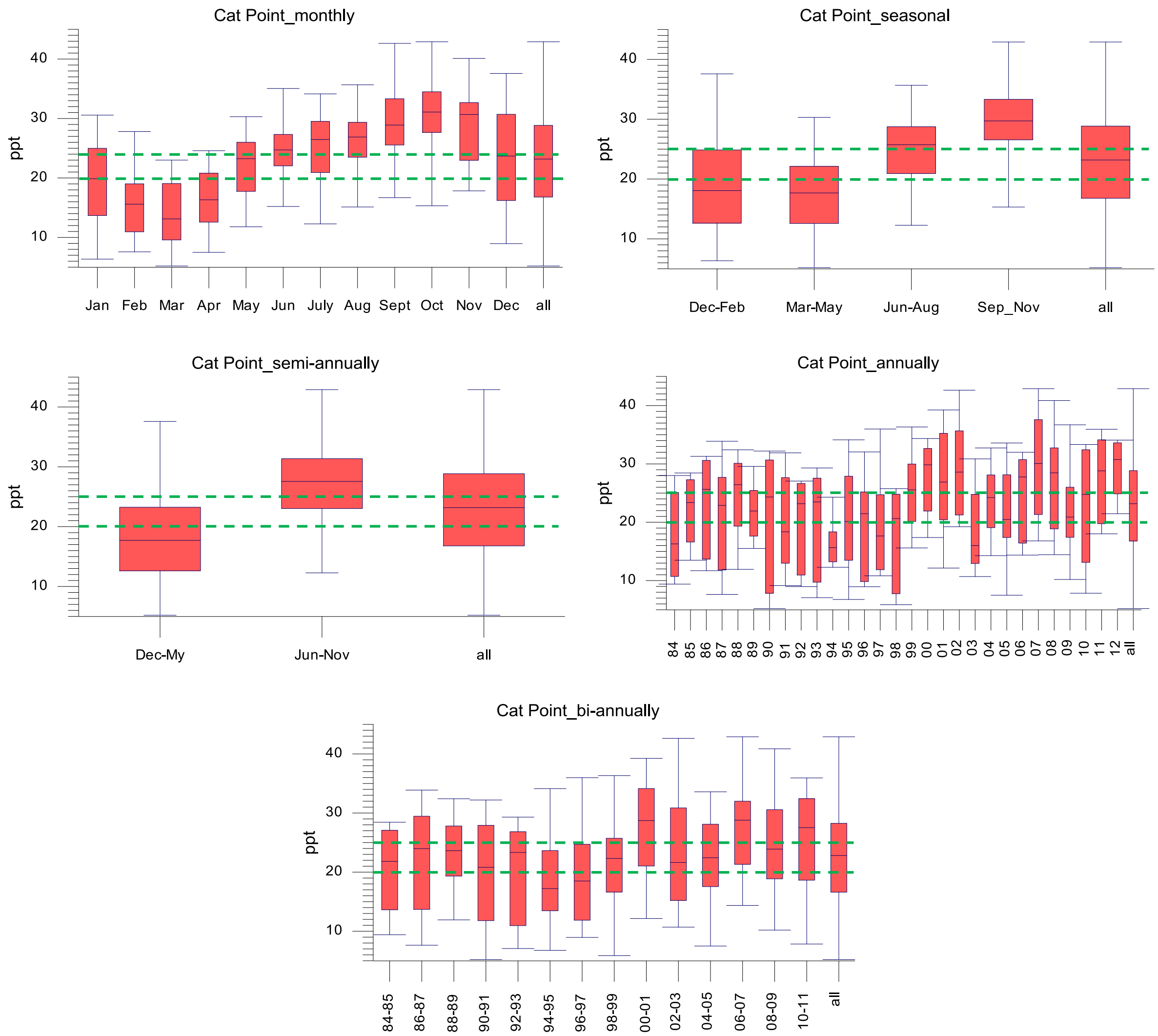

Figure 20. Simulated Salinity Statistics (box-plots) at Cat Point and associated SROGs (green lines)

The results support the following observations:

- The salinity distribution varies considerably relative to the SROGs over monthly and seasonal time scales. For some months and seasons, the salinity inter-quartile range lies entirely outside the SROGs. This occurs in June, July, August, September and October at Dry Bar, and in February, March, April, September, October, and November at Cat Point.
- The semi-annual, annual, and especially bi-annual salinity distributions are less variable and tend to contain the SROGs within their inter-quartile range.
- The long term (29-year) salinity median is within the corresponding SROG at both sites, at Dry Bar very near its upper limit and at Cat Point near its center point. At Dry Bar, the SROG range brackets a larger percentage of the salinity data (38%) than at Cat Point (17%).

Thus, the optimal oyster growth ranges (SROGs) identified by Wang et al. (2008) are consistent with the inter-annual and long-term salinity assessment results in this study. This finding (a) independently confirms the validity of the SROGs defined by Wang et al. (2008), and (b) points toward salinity indicator time scales that could be used to assess environmental change impacting the Apalachicola Bay oysters. More specifically, oysters at Dry Bar and Cat Point experience and have adapted to considerable intra-annual salinity variation. Thus, *inter-annual* salinity statistics are expected to be more effective oyster sustainability indicators than *intra-annual* salinity statistics.

Toward developing such indicators, Tables 1 and 2 provide the annual and bi-annual salinity frequency being above, within, and below the SROG range at Dry Bar and Cat Point. They also include the mean value, standard deviation, and coefficient of variation (CV=StDev/Mean) in each case.

Table 1. Annual Salinity Variation Frequencies Relative to SROG

	Dry Bar			Cat Point		
	Prob	Prob	Prob	Prob	Prob	Prob
Years	[S > 26 ppt]	[17 ≤ S ≤ 26 ppt]	[17 ppt < S]	[S > 25 ppt]	[20 ≤ S ≤ 25 ppt]	[20 ppt < S]
1984	0.266	0.521	0.213	0.234	0.189	0.577
1985	0.539	0.461	0.000	0.425	0.256	0.319
1986	0.628	0.284	0.088	0.535	0.053	0.412
1987	0.580	0.204	0.216	0.345	0.233	0.422
1988	0.688	0.161	0.151	0.615	0.071	0.314
1989	0.554	0.446	0.000	0.259	0.442	0.299
1990	0.624	0.061	0.315	0.488	0.119	0.393
1991	0.323	0.357	0.320	0.341	0.103	0.556
1992	0.379	0.424	0.197	0.380	0.232	0.388
1993	0.562	0.174	0.264	0.429	0.188	0.383
1994	0.176	0.484	0.340	0.000	0.207	0.793
1995	0.321	0.458	0.221	0.332	0.174	0.494
1996	0.342	0.292	0.366	0.251	0.296	0.453
1997	0.178	0.463	0.359	0.226	0.090	0.684
1998	0.376	0.355	0.269	0.156	0.393	0.451
1999	0.721	0.279	0.000	0.552	0.220	0.228
2000	0.745	0.255	0.000	0.678	0.133	0.189
2001	0.505	0.321	0.174	0.562	0.211	0.227
2002	0.541	0.459	0.000	0.580	0.247	0.173
2003	0.164	0.590	0.246	0.226	0.069	0.705
2004	0.271	0.596	0.133	0.479	0.227	0.294
2005	0.254	0.611	0.135	0.281	0.232	0.487
2006	0.702	0.198	0.100	0.605	0.128	0.267
2007	0.674	0.326	0.000	0.664	0.137	0.199
2008	0.535	0.367	0.098	0.628	0.115	0.257
2009	0.340	0.449	0.211	0.322	0.372	0.306
2010	0.575	0.238	0.187	0.497	0.087	0.416
2011	0.692	0.308	0.000	0.684	0.081	0.235
2012	0.817	0.183	0.000	0.766	0.234	0.000
Avg.	0.489	0.368	0.143	0.425	0.206	0.369
std	0.189	0.140	0.123	0.184	0.097	0.172
CV	0.386	0.380	0.858	0.432	0.473	0.466

Table 2. Bi-Annual Salinity Variation Frequencies Relative to SROG

	Dry Bar			Cat Point		
	Prob	Prob	Prob	Prob	Prob	Prob
Years	[S > 26 ppt]	[17 ≤ S ≤ 26 ppt]	[17 ppt < S]	[S > 25 ppt]	[20 ≤ S ≤ 25 ppt]	[20 ppt < S]
84-85	0.400	0.488	0.112	0.322	0.232	0.446
86-87	0.618	0.256	0.126	0.436	0.145	0.419
88-89	0.638	0.283	0.079	0.439	0.257	0.304
90-91	0.488	0.186	0.326	0.414	0.101	0.485
92-93	0.462	0.321	0.217	0.398	0.227	0.375
94-95	0.247	0.484	0.269	0.189	0.154	0.657
96-97	0.356	0.582	0.062	0.216	0.228	0.556
98-99	0.554	0.306	0.140	0.361	0.321	0.318
00-01	0.627	0.278	0.095	0.624	0.184	0.192
02-03	0.361	0.511	0.128	0.397	0.153	0.450
04-05	0.261	0.630	0.109	0.371	0.236	0.393
06-07	0.702	0.243	0.055	0.635	0.142	0.223
08-09	0.435	0.428	0.137	0.487	0.235	0.278
10-11	0.640	0.263	0.097	0.596	0.080	0.324
Avg.	0.476	0.376	0.148	0.414	0.204	0.382
std	0.150	0.144	0.030	0.141	0.069	0.113
CV	0.315	0.383	0.204	0.339	0.338	0.295

A question of practical importance (to the Apalachicola Bay environment and ecology stakeholders) is whether significant environmental trends are occurring in the Bay. To explore this question, the frequency with which the average bi-annual salinity falls above, within, and below the corresponding SROG ranges at Dry Bar and Cat Point (in Table 2) is plotted in Figures 21 and 22. The graphs in this figure show clear and consistent salinity trends. In both sites, the frequency of the average salinity being within the corresponding SROG range is declining, the frequency that salinity is above the SROG is increasing, and the frequency that salinity is below the SROG is declining. Altogether, these trends indicate that, on inter-annual time scales, Bay conditions are gradually becoming more saline, shifting away from the conditions favorable to oysters. The reasons underlying these trends are directly related to changes in the Apalachicola River flow (Georgakakos et al., 2010). Such changes are the combined effect of declining basin runoff and increasing upstream water use. Anecdotal evidence provided by oyster fishermen to the Apalachicola-Chattahoochee-Flint Basin Stakeholders confirms that oyster harvesting is under increasing stress in recent decades.

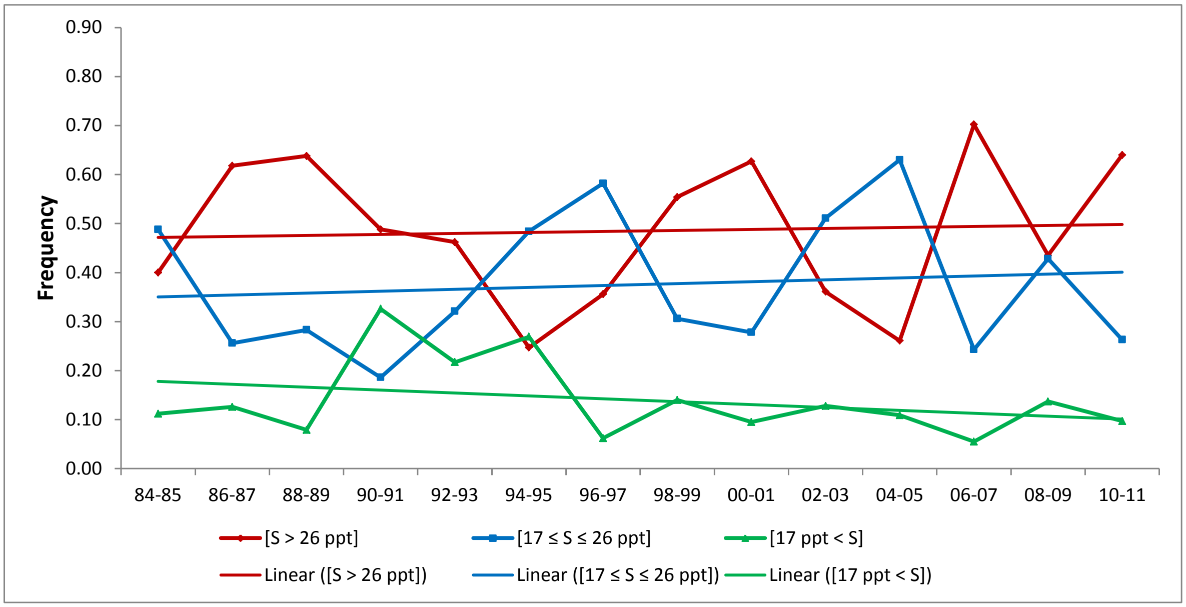

Figure 21. Frequency of Average Bi-Annual Salinity being above, within, and below the SROG Range at Dry Bar

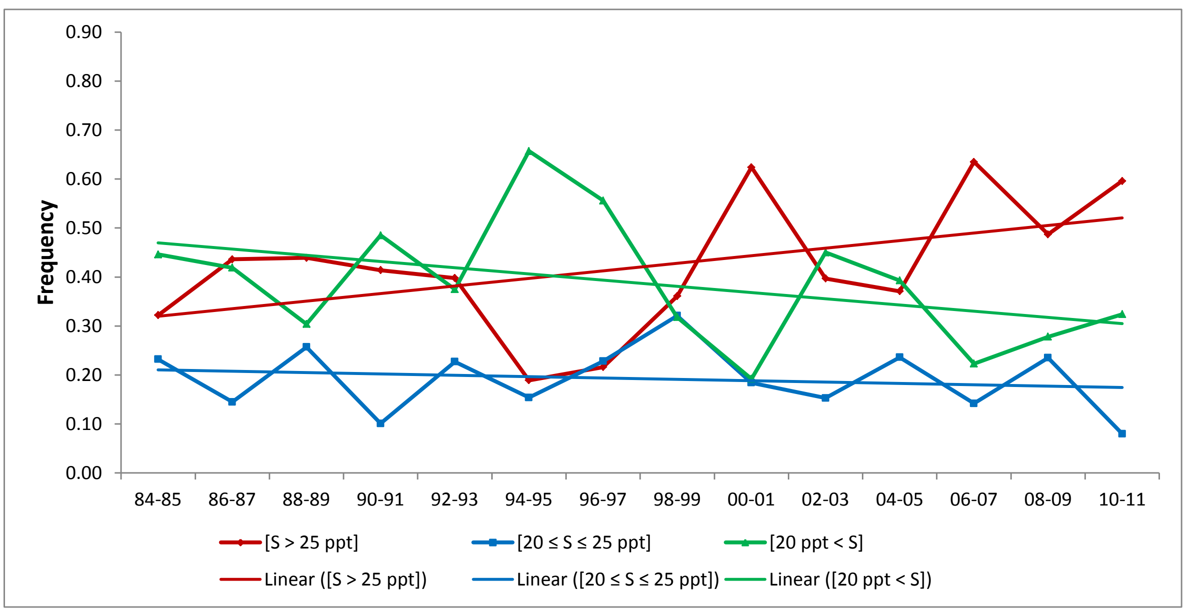

Figure 22. Frequency of Average Bi-Annual Salinity being above, within, or below the SROG Range at Cat Point

5. Preliminary Assessment of Sea Level Rise

According to the National Climate Assessment (NCA) for 2013 the projected sea level rise over the next 100 years varies between 0.66 ft (0.2 m) and 6.6 ft (2.01 m) (Figure 23). For our assessment we consider a conservative increment of 0.3 m.

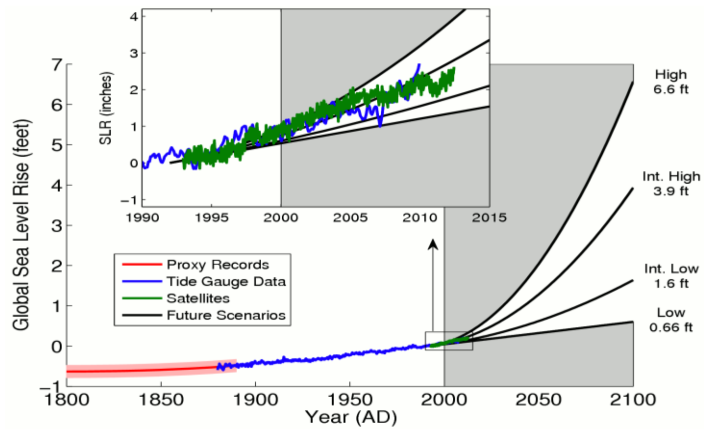

Figure 23. Projected Sea Level Rise in the coming 100 years (NCA, 2013)

Figure 24 shows the predicted Apalachicola Bay coastline (blue line) assuming a sudden 0.30 m sea level increase using the existing bathymetry and topographic data. The red line is the present coastline.

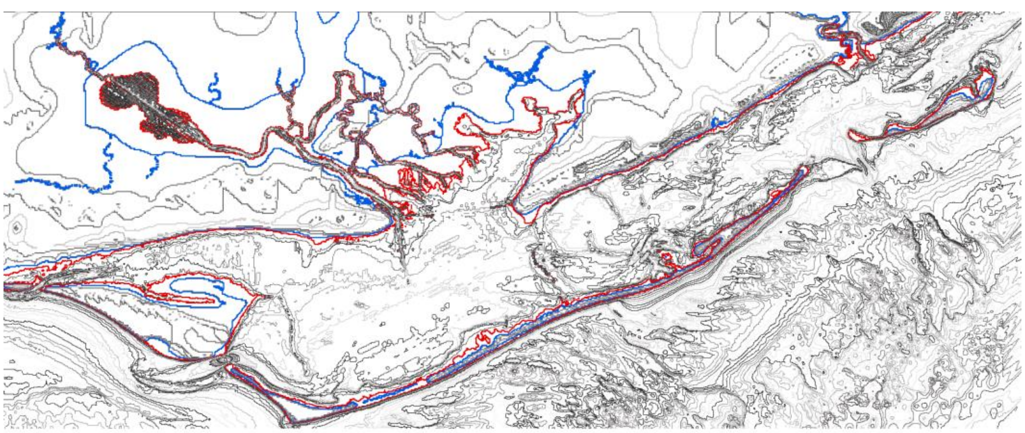

Figure 24. Actual (red) and predicted (blue) Apalachicola Bay coastline

However, the predicted coastline may be unrealistic. As the sea level rises the river continuously adjusts its margins according to its energy, depositing sediments (Surratt, 2008). Sedimentologic and geomorphologic modeling of the area could give insights into better estimates of the changing River Delta.

Based on the above statement, our preliminary modeling assessment will preserve the Apalachicola River Delta as it is now. Then, for insight on how sea level rise could modify the bay hydrodynamics we run the model for the period 2008-2010, which covered 3 different hydrologic periods, using the measured wind and river discharges but adding 0.30 m to the measured water levels.

Time series of simulated daily average salinities for both actual and hypothesized 0.3 m sea level increase scenarios and for two main monitoring stations; Cat Point and Dry Bar are shown on Figure 25. The results predicted a significant increase in bay salinity with daily average increases up to 10 ppt at Cat Point and 13 ppt at Dry Bar.

Apalachicola River discharges and daily average differences for both actual and hypothesized 0.3 m sea level increase scenarios for the entire simulation period at CP and DB are shown on Figure 26. Average differences are more scattered at Dry Bar, a monitoring station highly influenced by ocean water coming through West Pass. Less variability and minimum differences are shown at Cat Point, a monitoring station located at the center of the bay and more directly influenced by the Apalachicola river discharge, particularly during low Apalachicola River discharges.

6. Conclusions

The relationships between oyster dynamics and physical factors are multivariable and nonlinear. Good understanding of the oyster population dynamics requires careful consideration of hydrodynamic, biological, and geomorphological factors and their interactions.

Salinity is a major factor impacting oysters. This report describes the set-up, calibration, and validation of a hydrodynamic mathematical model of the Apalachicola Bay. The model was shown to simulate with good accuracy the estuary hydrodynamic response to river flow, tide, and wind forcing. In particular, water levels were in very good agreement in phase and magnitude with measured values for all available recorded data. Daily average simulated salinity also agreed well with observed values, while at sub-daily time steps the correlation was lower.

Calculated monthly and seasonal salinity averages are lower during spring and higher during fall due to seasonal variations in the Apalachicola River. After validation with a three year data set, the model was run for 29 years to assess long term salinity conditions and trends. The results are consistent with the optimal salinity ranges for oyster growth identified by previous studies (Wang et al., 2008), and motivate the development of salinity metrics as indicators of environmental and ecological change. These indicators show that Bay salinity conditions are gradually changing in ways unfavorable to oyster growth. The main reason for these trends is the declining Apalachicola River flow, which, in turn, is the result of hydro-climatic and water use changes in the Apalachicola-Chattahoochee-Flint (ACF) River Basin.

Figure 25. Sea level rise assessment, daily average salinities period 2008-2010

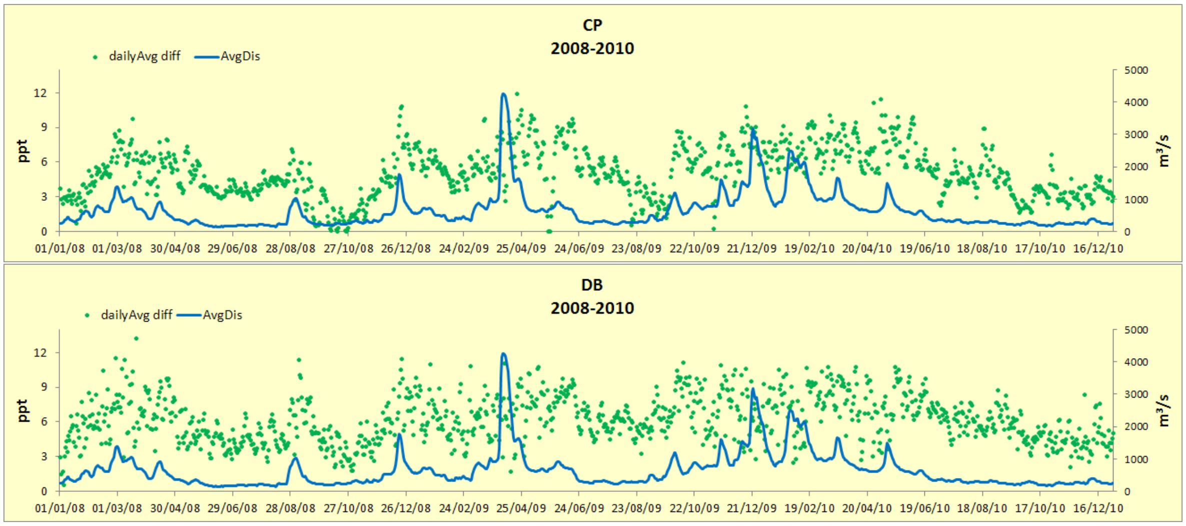

Figure 26. Sea level rise assessment, daily average differences and river discharges, 2008-2010

For insight on how Sea Level Rise could modify the bay hydrodynamics we run again the model for the period 2008-2010, which covered 3 different hydrologic periods, using the measured wind and river discharges but adding 0.30 m to the measured water levels. Modeling results predicted a significant increase in bay silinity with daily average salinities increases up to 10 ppt at Cat Point and 13 ppt at Dry Bar.

The study findings raise critical questions for the environmental and ecological future of Apalachicola Bay, especially in view of the projected climatic trends (Georgakakos et al., 2013; National Climate Assessment, Water Resources Chapter) and the continuing ACF discussions toward a sustainable water management plan. A follow-up study by the authors aims to explore these questions further.

7. References

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Monitoring Diurnal and Seasonal Cycle of Evapotranspiration over Georgia using Remote Sensing Observations

Basic Information

Title:	Monitoring Diurnal and Seasonal Cycle of Evapotranspiration over Georgia using Remote Sensing Observations
Project Number:	2012GA314B
Start Date:	3/1/2012
End Date:	2/28/2014
Funding Source:	104B
Congressional District:	GA
Research Category:	Climate and Hydrologic Processes
Focus Category:	Hydrology, Surface Water, Climatological Processes
Descriptors:	None
Principal Investigators:	Jingfeng Wang

Publications

There are no publications.

Progress Report of GWRI 104B

Monitoring Diurnal and Seasonal Cycle of Evapotranspiration over Georgia using Remote Sensing Observations

PI: Jingfeng Wang
with
Husayn A. El Sharif and Shawna McKnight

24 May 2013

1. Research Activities

The objective of this project was to test and develop a new method of monitoring diurnal and seasonal variations of evapotranspiration over Georgia using satellite-based remote sensing observations for agricultural and water resources management. An agricultural model, Decision Support System for Agrotechnology Transfer – Cropping Systems Model (DSSAT-CSM) was modified and expanded to allow the use of remote sensing soil moisture data for predicting yield various crops at field and regional scales. This effort has led to the Georgia Tech team (Wang, Georgakakos and Bras) to be selected one of the early adaptor teams of the NASA Soil Moisture Active Passive (SMAP) mission. As an SMAP early adaptor team, we participated in the SMAP Validation Experiment 2012 (SMAPVEX12) in Winnipeg, Canada 6 June – 19 July 2012. Two graduate students have participated in the research activities including model development and simulation and field experiment.

2. Model Development and Simulation

The goal of model development is to assess the value of incorporating remotely sensed soil moisture information from the NASA SMAP mission into the agricultural model for predicting crop yield, irrigation water-budget allocations, and preparedness for climate change induced extreme hydrological events at regional scales. Furthermore, once the agricultural model of focus in this project (DSSAT-CSM) is reformulated into state-stage space, a dynamic programming approach may be adopted to optimally allocate irrigation decisions to produce a desired regional crop yield.

DSSAT-CSM Crop-Systems Model The Decision Support System for Agrotechnology Transfer – Cropping Systems Model (DSSAT-CSM) is a widely used bio-physical model for simulating the phenology, growth, development, and yield of various crops and cultivars given inputs of soil, weather, and management conditions (Jones, et al., 2003). DSSAT-CSM version 4.5 includes 29 crops and fallow fields (Tsuji, et al., 1994; Hoogenboom, et al., 1999; Jones, et al., 2001; Jones, et al., 2003; Daroub, et al., 2003; Brumbelow and Georgakakos, 2007a, b; Liu, et al., 2011). DSSAT-CSM is composed of a main driver program, a land unit module, as well as modules for weather, soil, plant, soil-plant-atmosphere interface, and management. The main driver program controls each of the primary modules and allows each module to read its own inputs, initialize variables, compute rates, integrate its own variables, and write outputs independent of other modules (Jones, et al., 2003). This feature is especially important to this project as the soil-plant-atmosphere module has been modified in this project in order to incorporate remotely-sensed soil moisture data.

Regional Climate Model To forecast near-term and long-term regional soil moisture distribution under projected various climate change scenarios including extreme hydrological events (droughts and floods), the Weather Research and Forecasting (WRF) model developed by a "collaborative partnership, principally among the National Center for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration (NOAA), the National Centers for Environmental Prediction (NCEP), the Forecast Systems Laboratory (FSL), the Air Force Weather Agency (AFWA), the Naval Research Laboratory, the University of Oklahoma, and the Federal Aviation Administration (FAA). WRF affords researchers the ability to conduct simulations reflecting either real data or idealized configurations. WRF is an operational forecasting model that is flexible and efficient computationally, while offering the advances in physics, numerics, and data assimilation contributed by the research community" (WRF, 2013). Recently the WRF model has been coupled with one of the most sophisticated hydrologic models, Triangulated Irregular Network (TIN)-based Real-time Integrated Basin Simulator with VEGetation Generator for Interactive Evolution (tRIBS-VEGGIE) (Ivanov et al., 2008a,b). The coupled WRF-tRIBS-VEGGIE model is intended to downscale soil moisture data products to 1 km spatial and daily temporal resolution.

SMAP Early Adopter Simulation Data Set The National Snow and Ice Data Center (NSIDC) archives and distributes SMAP validation data (i.e. SMAP test bed) accessible only to SMAP Early Adopters. The SMAP test bed data available to SMAP Early Adopters are an SMAP-like product with one year of global coverage. Of particular interest to this project is the Level-2 Radar Soil Moisture (Active) data set featuring simulated soil moisture data at 3 km resolution. The simulation data will be used for testing the modified DSSAT-CSM model to allow the use of remote-sensing soil moisture data inputs from SMAP once the satellite observations become available in early 2015.

Sensitivity of Crop Yield and Irrigation Demand to Soil Moisture Data Resolution The impact of the spatial and temporal resolution of soil moisture records on crop yield and irrigation demand can be simulated by selecting random samples of SMAP soil moisture pixels and using interpolation methods such as the inverse distance weighting method to create regional soil moisture maps. The interpolated soil moisture map can then be used as model input of the DSSAT-CSM. Results from multiple model runs using an increasing number of randomly sampled SMAP pixels will allow for quantifying the change in uncertainty (standard deviation) in regional crop yield and irrigation demand in comparison to that using all available SMAP pixels. The statistical analysis will be performed with the following steps: (1) start from a soil moisture map provided by SMAP data products for a region at the beginning of the growing season. This map would contain a total of N pixels. Soil moisture at the center of a pixel, θ_i, is taken as the representative value for the pixel. (2) Randomly select J data points from the grid of θ_i points as control points. Each control point is referred to as θ_j and participates to create a new interpolated soil moisture map. (3) With J randomly selected control points, use the inverse distance weighting method (Shepard, 1968) to estimate soil moisture at each point of the original grid according to,

$$\hat{\theta}_i = \sum_{j=1}^{J} \frac{\theta_j {d_{i,j}}^{-\alpha}}{\sum_{m=0}^{J} {d_{i,m}}^{-\alpha}}$$

where $\hat{\theta}_i$ is a soil moisture estimated at location (point) i based on a summation of "real" soil moisture data at control points represented by θ_j which are weighted inversely by the distance, $d_{i,j}$, between points i and j. m is a dummy index. The exponent α is a power parameter that further increases the importance of nearby control points when α is greater than 1 and is recommended to be taken as 2 (Shepard, 1968). (4) Calculate the domain mean of estimated soil moisture, $\bar{\bar{\Theta}}$, for the experiment k:

$$\bar{\bar{\Theta}}_k = \frac{1}{N} \sum_{i=1}^{N} \hat{\theta}_i$$

(5) Initialize DSSAT-CSM using the $\hat{\theta}_i$ values and simulate the total yield and irrigation demand for the region at the end of the growing season. (6) Repeat steps 3-5 many times (depending on the spatial extent of the soil moisture grid) to create a histogram of $\bar{\bar{\Theta}}_k$ to fit selected probability distributions. Based on the Central Limit Theorem, a Gaussian distribution is the most probable distribution with mean μ_Θ and standard deviation σ_Θ estimated from the histogram. Follow the same procedure for total domain crop yield and irrigation demand. (7) Repeat steps 2-6 to test the sensitivity of the distribution by using different number of data points J.

Results from these experiments will be used to quantify the uncertainty in crop yield and growing season irrigation demand as a function of the uncertainty in the mean soil moisture of the domain. Such results can be used to characterize the utility of the finer resolution data provided by the SMAP mission. The experiments are also intended to derive the probability distribution of crop yield and irrigation demand for the entire season from that of domain mean soil moisture at the beginning of the growing season.

Findings At this stage of the project, the source programming code of the DSSAT-CSM software has been successfully modified to incorporate remotely-sensed soil moisture data products. Input files are in ASCII text file format with date and "observed" soil moisture reading. These input files are used to override the water balance calculations of the DSSAT-CSM water balance sub-module in the topmost (0 – 5cm) soil layer. Preliminary experiments have been carried out using synthetically generated daily soil moisture data sets along with default DSSAT-CSM soil, weather, and crop data sets. The DSSAT-CSM is primarily intended to operate at the field scale. As such, regional analysis of crop yields can be conducted by aggregating model results for multiple fields, each with their own required input data sets. This requires running multiple iterations of DSSAT-CSM as well as automating the management and processing the data outputs of each model run. To accomplish this, the modified DSSAT-CSM software suite was incorporated into a UNIX computer cluster environment provided by Georgia Institute of Technology consisting of 256 nodes (CPUs) each with 2.2 GHz and 252 GB RAM to allow multiple runs. To test the automation procedure an experiment was conducted using a default year 1981 DSSAT-CSM maize crop data set for Florence, South Carolina along with synthetically generated daily soil moisture data. The experiment involved developing a 4 x 4 spatial grid of individual fields, each with their own daily soil moisture sequence. Each field or "pixel" was assigned spatial coordinates such that the previously mentioned inverse distance weighting (IDW) interpolation procedure could be carried out. Using the IDW procedure, the quantity of control points, J, ranged from 1 to 16. For each possible J, 10 iterations were carried out in which fields were randomly selected to participate in the interpolation. For each iteration, final crop yield was modeled for the 16 pixels in the spatial domain. 2,560 runs of DSSAT-CSM were conducted, producing the following results:

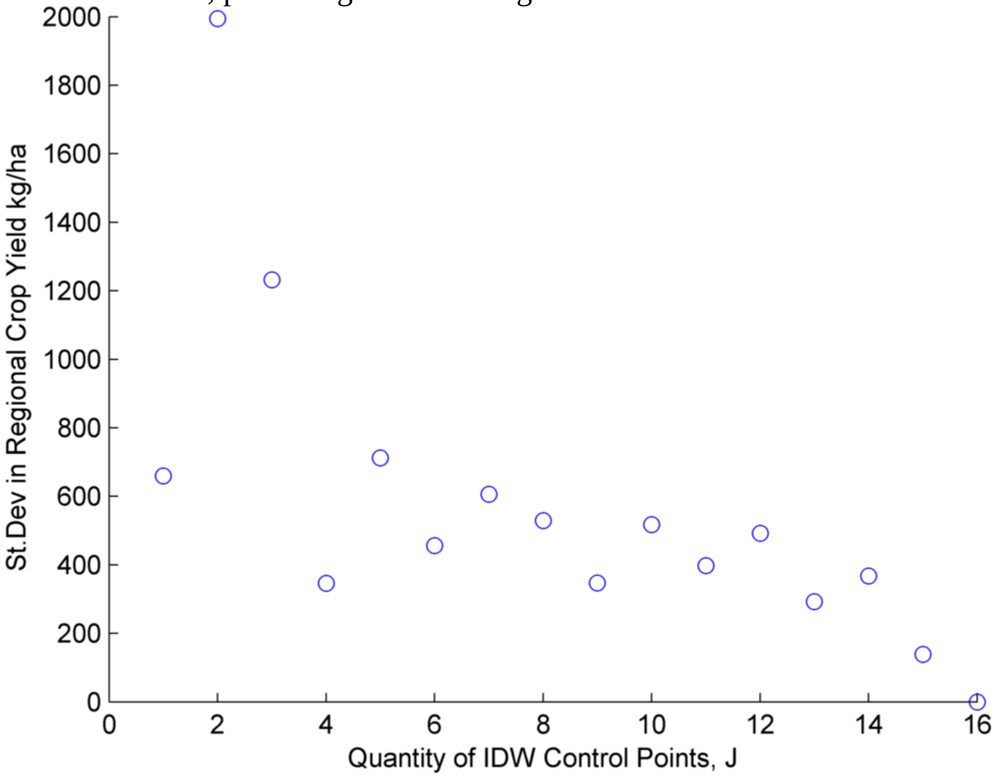

Figure 1: Uncertainty in regional crop yield for a given quantity of control points participating in inverse distance weighting interpolation of soil moisture. Note: soil moisture data at participating control points were synthetically generated.

As expected, using the synthetically generated soil moisture data sets, uncertainty in regional crop yield (represented by the standard deviation in regional crop yield) decreases as the resolution of the "observed" soil moisture data set (represented by J) increases. Interestingly, when J was in the range of 6 – 13, increases in J resulted in relatively minor decreases in uncertainty. This may suggest that thresholds exist beyond which increased spatial resolution of soil moisture data will not provide significant benefits to crop yield modeling. Determining the existence and magnitude of this threshold requires non-synthetic soil moisture data; however, this experiment provides a procedural template to carry out such an analysis.

This stage of the project was primarily focused on developing the environment for analysis of modeled regional crop yield and irrigation demand given input of remotely-sensed soil moisture products. The DSSAT-CSM software suite was successfully modified to accept daily resolution soil-moisture inputs derived from observations or interpolation. An automation procedure was developed to allow DSSAT-CSM to provide results at regional scales. The next stage of research will involve spatial and temporal downscaling of SMAP-Early Adopter and SMAP-similar remotely sensed soil moisture data sets using the coupled WRF-tRIBS-VEGGIE hydrologic model. With this information, the sensitivity of modeled regional crop yield to increased resolution soil moisture data products can be practically determined. Further research will also include the incorporation of dynamic programming to optimize regional irrigation allocations which would involve the reformulation of essential components of the DSSAT-CSM to state-stage space.

3. Field Experiment

The SMAP Validation Experiment 2012 (SMAPVEX12) was conducted in Winnipeg, Canada 6 June–19 July 2012 to collect ground data of soil moisture and other hydro-meteorological variables. The study domain is a 13x70 km^2 in Southwest of Winnipeg. 55 agriculture fields containing canola, cereals, corn, grasslands, pastures, and soybean were sampled throughout the duration of the campaign. Five additional forest sites were sampled to assist in the radar algorithm development for forest soil moisture retrieval. The relatively long sampling period allows for data collection for the bulk of the growing period to be documented as well as multiple soil dry-down periods. Each field contains 14 individual sampling sites arranged into two parallel transects approximately 200m apart. Each point within a transect is approximately 100 m apart. Three of the soil sampling sites in each field were also used for vegetation sampling. Measurements of plant height, stem diameter, LAI and biomass were taken to document growth, phase and structure of the vegetation as the growing season progressed. Ground radiometer measurements were also taken weekly on vegetation sampling days. Soil moisture were taken at the first and last points of each transect for calibration of the hydro-probes. With the exception of the pasture, grasses and cereals, the vegetation is planted in rows in troughs of soil. These troughs and rows cause heterogeneity in the soil moisture throughout the field. Soil moisture measurements were taken three times at each site so that an average could be obtained to allow for continuity throughout the field. Measurements were taken at the top, side and bottom of each trough. Soil temperature, skin temperature and shaded skin temperature were also recorded at the first and last point in each transect. Most sites also contain an in-situ soil moisture station to provide more frequent sampling. The Passive/Active L-band Sensor (PALS) was installed on a Twin Otter airplane that flew when weather permitted. Flights were concurrent with soil moisture sampling days. The experiment site condition and field experimental work are shown in the graphics below.

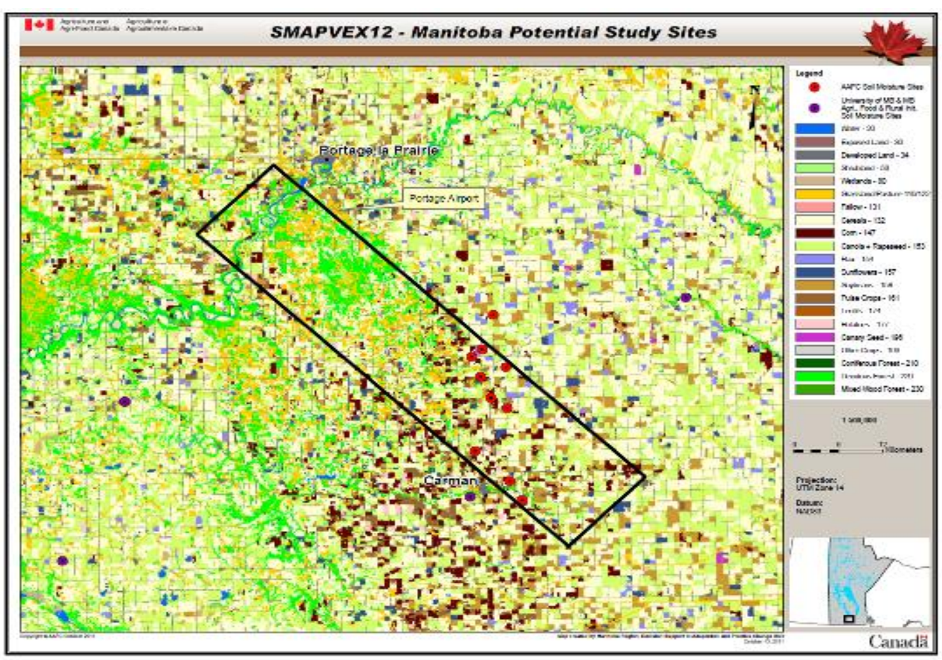

Figure 1 (above): Study site Southwest of Winnepeg in Manitoba, Canada. The black rectangle contains all 55 sampled agriculture fields. Image credit: University of Sherbrooke. http://pages.usherbrooke.ca/smapvex12/images/

Figure 2: LAI and NDVI measurements in a bean field. Image credit: Steven Chan, JPL http://smap.jpl.nasa.gov/blogs/20120713/

Figure 3: Trecking through a Winter Wheat _eld with site vegetation samples and equipment. Image credit: Steven Chan, JPL

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Information Transfer Program Introduction

None.

USGS Summer Intern Program

None.

Student Support					
Category	Section 104 Base Grant	Section 104 NCGP Award	NIWR-USGS Internship	Supplemental Awards	Total
Undergraduate	0	0	0	0	0
Masters	3	0	0	0	3
Ph.D.	4	0	0	0	4
Post-Doc.	2	0	0	0	2
Total	9	0	0	0	9

Notable Awards and Achievements

GWRI is providing technical support to the ACF Stakeholders (a grass-roots stakeholder organization encompassing 56 stakeholder groups in Georgia, Alabama, and Florida) toward the development of a sustainable water management plan. The GWRI support includes the development of comprehensive basin-wide modeling tools, formulation of alternative development and management scenarios, development of stakeholder interest metrics, performance of comprehensive assessments, and consensus building. This is an important and hopeful contribution for the southeast region because ACF water sharing negotiations have been unsuccessful for more than two decades. However, the current negotiations are led by an inclusive stakeholder organization (rather than state agencies and governor offices), and there is cautious optimism that they will lead to a consensus water management plan.

Publications from Prior Years