Technical Documentation to Support Development of Minimum Flows and Levels for the Caloosahatchee River and Estuary

Appendices

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Technical Documentation to Support Development of Minimum Flows and Levels for the Caloosahatchee River and Estuary

Appendix A

Caloosahatchee River MFL Research Program Progress Report

Contents

Florida Bay and Lower West Coast Division
Southern District Restoration Department

South Florida Water Management District

January 2003

Caloosahatchee River MFL Research Program -- Progress Report

Introduction

As part of the development of the Caloosahatchee MFL, a scientific peer review of the technical criteria was conducted and a report produced (Edwards et al 2000). Comments from the public and other State and Federal agencies also were solicited. The review committee approved the general scientific approach used in establishing the MFL. However, specific scientific deficiencies in the technical documentation of the rule were identified. A research program was initiated to address these concerns and included additional field observations, laboratory experiments and development of modeling tools. Major criticisms of the initial effort were:

1. Lack of a hydrodynamic/salinity model
2. Lack of a population model for *Vallisneria americana*
3. No quantification of the habitat value of *V. americana* beds
4. Effects of MFL flows on downstream estuarine biota

Research Program Components:

Component 1: CH3D Hydrodynamic salinity model of Caloosahatchee:

Background: A CH3D hydrodynamic model originally developed for the entire Charlotte Harbor system is being adapted for use in the Caloosahatchee. The model is three dimensional, time-dependant and employs a curvilinear grid. The purpose of the modeling effort is two-fold. The first is to simulate the distribution of salinity in the estuary under minimum flow conditions. The present MFL rule states that a discharge of 300 cfs at S-79 is necessary to maintain a salinity of 10 ppt at the Ft. Myers Yacht Basin. The model will be used to evaluate this proposition.

The second use of the model will be to reconstruct the 31-year salinity history in the protected area under different land use conditions in the watershed. Specifically, conditions with and without CERP projects will be contrasted. The CERP Projects are the recovery strategy for the MFL and this exercise will evaluate this strategy.

Status: The model has been calibrated using a 3-month data set, without ground water input. Validation using an additional 3 months is underway. Flow vs salinity distribution curves for constant discharges have been developed. A multiple regression model that relates daily salinity at Ft. Myers and at Bridge 31 to discharge at S-79 has been developed and calibrated using a10 year period of daily salinity data. It is now possible to predict daily average salinity for 31 years at Ft. Myers, Rte. 31 Bridge and through interpolation, two stations located between Ft. Myers and Bridge 31.

Future Improvements: The District is working to improve the CH3D model. The model has inadequate bathymetry and a survey of the Caloosahatchee is planned for FY03. Further calibration and validation are required with groundwater and tributary input from the tidal basin. The speed of the model will be improved by acquisition of a new parallel code and grid editor.

Component 2: Population model for *Vallisneria americana*

Background: A Stella based population level model of *V. americana* in the Caloosahatchee is currently under development. The purpose is to include more environmental factors than just salinity and arrive at a better estimate of the effects of freshwater inflow on performance of *V. americana*. In conjunction with 31 years of salinity data, the model will be used to evaluate present and future ability to meet MFL. The model will not be totally complete in time for the criteria review. Nevertheless, we will attempt to use the model as it is.

Status: The original model had one forcing function: salinity. The new model has salinity, light, and temperature. The model has been calibrated using four years of data (1998-2001). At present, the model can simulate growth of *V. americana* at two stations in the protected area of the estuary.

Future Improvements: Additional input data and information concerning the growth and survival of *V. americana* in the Caloosahatchee Estuary will be required to make the model more robust. Specific needs are to:

1. Develop a method to predict variation in water transparency for long-term or other simulations.

2. Develop relationships to relate mass to blade and shoot densities, and blade length with existing data.
3. Develop improved algorithms for light and salinity.
4. Incorporate blade length as a state variable to more accurately represent light availability for mature plants.
5. Add population and demographic characteristics to describe seed production and dispersal.

Component 3: Additional Experimental Studies

Background: Two experiments at the Gumbo Limbo Mesocosm Facility will provide addition data for the *V. americana* modeling effort. An experiment quantifying the response of *V. americana* to high salinity has already been conducted. We now have data on growth and mortality of *V. americana* at salinities ranging from 0 to 30 ppt. An experiment evaluating the interaction of light and salinity was conducted in April and May, 2002.

Status: Both experiments have been conducted. Results of the first have been incorporated into the model. Results of the second will not be available for this review.

Component 4: Quantify the habitat value of *Vallisneria americana* beds

Background: This is being accomplished through a contract (C-12836) with Mote Marine Lab (3 years). The overall objective is to identify which organisms use *V. americana* habitat in the Caloosahatchee River and how season, salinity and plant /bed morphometry affect habitat use.

Status: The study began in January of 2002. Results will not be available for this review.

Component 5: Effects of MFL flows on other biota, especially those located downstream

Flow Effects on Oysters

Background: Effects of low flows on downstream oysters, *Crassostrea virginica*, are being examined through a contract (C-12412) with Florida Gulf Coast University. The objectives of this study are several fold:

1. To examine seasonally the mortality and disease prevalence.
2. To investigate growth, mortality and reproductive potential of oysters under various salinity regimes.

3. To study oyster spat settlement as a function of salinity.
4. To investigate the role of oyster reefs as essential fish habitat and determine whether the condition of individual oysters affects overall habitat suitability.

Status: Dr. Volety, Principal Investigator, has submitted a progress report (July 2002) that addresses the freshwater inflow requirements of oysters in the Caloosahatchee.

Effects of Flows on Zooplankton and Ichthyoplankton

Background: The District has monitored zooplankton and larval planktonic fish at 7 stations in the Caloosahatchee Estuary, San Carlos Bay under a range of freshwater discharge conditions at S-79. Monitoring was not continuous but occurred on a monthly basis during the following periods 1986 – 1989, 1994-1995, and 1998. Data have been analyzed to investigate the effects of discharge on the abundance and distribution of these groups in the estuary.

Component 6: Monitoring of *Vallisneria americana* beds.

Background: A monthly monitoring program at four stations was initiated in 1998. The data are used to examine potential effects of salinity and other water quality parameters on Vallisneria.

Status: On-going

Component 7. *Vallisneria americana* Restoration and Seed Bank Studies

Background: These studies are being carried out through contract with the Conservancy of Southwest Florida and are intended to:

1. Determine the importance of the seed bank in reestablishing tape grass
2. Determine if planting seagrasses enhances their reestablishment
3. Establish the optimal conditions and methods for tape grass re-vegetation
4. Calculate an effort (time, expenditure) budget for a tape grass restoration program

Status: Started August 2003. On-going

Literature Cited

Edwards, R. E., W. Lung, P.A. Montagna, and H. L. Windom. 2000. Final review report. Caloosahatchee Minimum Flow Peer Review Panel, September 27-29, 2000. Report to the South Florida Water Management District, West Palm Beach, FL.

Technical Documentation to Support Development of Minimum Flows and Levels for the Caloosahatchee River and Estuary

Appendix B

Effects of seasonal and water quality parameters on oysters (*Crassostrea virginica*) and associated fish populations in the Caloosahatchee River.

Contents

Progress Report submitted
to
Dr. Peter Doering

July 2002.

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Effects of seasonal and water quality parameters on oysters (*Crassostrea virginica*) and associated fish populations in the Caloosahatchee River.

Progress Report submitted

to

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July 2002.

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Abstract

Disease prevalence (% infected oysters) and intensity of oyster pathogen, *Perkinsus marinus*, were investigated at five locations (Piney Point, Cattle Dock, Bird Island, Kitchel Key and Tarpon Bay) in the Caloosahatchee Estuary in relation to season and freshwater releases (i.e., salinity) from Lake Okeechobee. Ten oysters per month were analyzed from each sampling location during September 2000 - June 2002. Data were analyzed as year 1 (September 2000 - August 2001) and Year 2 (September 2001 - June 2002). Freshwater releases > 300 cubic feet per second (CFS) from Lake Okeechobee by the South Florida Water Management District (SFWMD) during dry months (Nov - May) in year 2 resulted in lower salinities at all locations compared to year 1. Freshwater releases during the dry months in Year 1 were less than 300 CFS. Salinities during sample collection were regressed against monthly average of 30-day moving average flow to predict salinity changes at the sampling locations. Results suggest that freshwater releases of 1000 CFS from Lake Okeechobee may decrease salinities at the sampling locations by 3.6 - 6 ppt (downstream - upstream locations) from respective prevailing salinities. Salinity, and temperature during the study period ranged from 3 - 40 ppt and from 16 - 32ºC respectively. Prevalence of *P. marinus* ranged from 0 - 90% while the intensity of infection ranged from 0 - 2.5 (on a scale of 0 - 5). Concomitant with higher freshwater releases and lower salinities at all sampling locations in year 2, intensity of *P. marinus* infection in oysters was significantly lower during year 2 compared to year 1. Infection intensity was also significantly different between sampling locations. It should be noted that while the prevalence of infection was high, overall infection intensities at various sampling locations were light (0.170 - 0.753) during both years suggesting that decreased freshwater releases less than 300 CFS (and higher salinities) did not result in lethal (heavy) infection intensities. Flows between 500 and 2000 CFS will result in optimum salinities for oysters and will result in sustaining and enhancing oyster populations in the Caloosahatchee Estuary. Data suggests that well-timed fresh water releases into Caloosahatchee River may prevent or lower *P. marinus* infections to non-lethal levels (light) in oysters and enable them to survive longer. Effects of high freshwater releases (and lowered salinities) on the condition index, recruitment, gonadal index, and growth of juvenile oysters are being examined in a series of field and laboratory experiments. The use of adaptive management approaches involving freshwater releases to sustain and enhance oyster populations is valuable to the ecology of the Caloosahatchee Estuary.

Introduction

A fundamental management goal of the Watershed Research and Planning Department is to "Protect, Enhance, and Rehabilitate Estuarine Ecosystems". Using a suite of responses from Valued Ecosystem Component (VEC) species - oysters - the effects of freshwater releases from Lake Okeechobee were assessed. VEC species are those that sustain the ecological structure and function of dominant estuarine communities. These species provide not only food, but also the physical habitat utilized by other organisms for living space, refuge, and foraging sites. Examples of dominant estuarine communities are oyster bars and grass beds, with prominent species being the American oyster, *Crassostrea virginica* and the submerged aquatic vegetation (SAVs), *Vallisneria americana*, *Halodule wrightii*, and *Thalassia testudinum*. Historically, grass beds and osyter reefs have been dominant components of the Caloosahatchee estuarine system. Both habitat types still exist in the system today.

Oysters not only represent an important fisheries species commonly found in estuaries of the Atlantic and Gulf coasts of the U.S., but they are important ecologically. Individual oysters filter 4-34 liters of water per hour, removing phytoplankton, particulate organic carbon, sediments, pollutants, and microorganisms from the water column. This filtration process results in greater light penetration immediately downstream, thus promoting the growth of submerged aquatic vegetation. Although oysters assimilate 70% of the organic matter filtered, the remainder is deposited on the bottom where it provides food for benthic organisms. This secondary production, combined with a complex, three-dimensional, reef structure serving as nesting habitat and/or refuge, attracts numerous species of invertebrates and fishes (e.g., blue crab, mud crabs, grass shrimps, penaeid shrimp, blennies, gobies, killifishes, skilletfish, toadfishes). Furthermore, many of these organisms serve as forage for important fisheries species, birds, and mammals. Oysters are not only an important fisheries species, but oyster reefs serve as essential fish habitat. Due to their sessile nature, oysters make excellent candidates to investigate cause and effects relationship in examining watershed alteration effects. Due to the ecological role of oysters, their protection and restoration should therefore be a focus of resource managers.

The protozoan parasite, *Perkinsus marinus* has devastated oyster populations in the Atlantic (Burreson and Ragone-Calvo 1996), where it is currently the primary pathogen of oysters, and in the Gulf of Mexico (Soniat 1996). Andrews (1988) estimated that *P. marinus* can kill ~80% of the oysters in a bed. The distribution and prevalence of *P. marinus* is influenced by temperature and salinity with higher values favoring the disease organism (Burreson and Ragone-Calvo 1996, Soniat 1996, Chu and Volety 1997).

While the South Florida Water Management District (SFWMD) has conducted considerable research on SAV (Chamberlain and Doering 1998a, Chamberlain and Doering 1998b, Kraemer et al. 1999), studies involving other valued ecosystem components, such as oyster reefs, that occur in the higher salinity waters of the lower Caloosahatchee Estuary are presently lacking, but clearly necessary. To our knowledge, this project represents the first study of oysters in the Caloosahatchee River and will provide critical information for use in applying the VEC approach. The ultimate goal of this project is examine the effect of minimum flows and levels of freshwater into the Caloosahatchee Estuary and to provide target conditions for watershed management in the Caloosahatchee River that will sustain and enhance oyster populations.

This report summarizes the results of *Perkinsus marinus* infection prevalence and intensities in oysters from Caloosahatchee River during September 2000 - June 2002, focusing on the dry months (November - May). The overall objectives of the project were to evaluate the effect of season and spatial variation on condition and health of oyster populations in the Caloosahatchee and to determine the suitability of oyster habitat to crustaceans and fishes in relation to oyster health and condition. Results related to spat recruitment potential, and habitat suitability of oyster reefs for crustaceans and fishes in the Caloosahatchee River will be addressed in the next report.

Materials and Methods

Sampling Locations: Monthly water quality measurements and oyster collections were made at Piney Point (PP, 4 km upstream from river mouth), Cattle Dock (CD, 2 km upstream from river mouth), Bird Island (BI, 4 km downstream from river mouth), Kitchel Key (KK, 6 km downstream of river mouth), and Tarpon Bay (TB, 12 km downstream of river mouth).

Freshwater Releases and water quality: Data on freshwater releases from Lake Okeechobee via S-79 locks were obtained through continuous water quality monitoring by SFWMD (courtesy of Dr. Peter Doering and Ms. Kathy Haunert). Monthly means of the 30-day moving average flow (in cubic feet per second; CFS) were obtained from September 2000 - May 2002. Salinities and temperatures at sampling locations were noted during monthly samplings. Relationship between flows from S-79 locks and salinities at various sampling locations were assessed by regression analyses. Since salinities observed at the sampling locations included freshwater dilution due to rainfall and sheetflow, influence of these two factors could not be separated in the analyses.

P. marinus prevalence and intensity: Ten oysters from each of the five sites were assayed monthly for the prevalence (% infected oysters) and intensity of infection of *P. marinus* using Ray's fluid thioglycollate medium technique (Ray 1954, Volety et al. 2000). The intensity of infections were recorded using a scale in which 0 = no infection, 1 = light, 2 = light - moderate, 3 = moderate, 4 = moderate - heavy, 5 = heavy. Three-way ANOVA was used to detect the differences in *P. marinus* infection intensities due to sampling year / flow (no flow (<300 CFS) vs. low flow (>300 CFS)), sampling month, and sampling location.

Statistical anayses: Relation between freshwater releases at S-79 and salinities at various sampling locations were analyzed using correlation and regression analyses. Effect of sampling year, sampling month (season), and sampling location on *P. marinus* intensity were examines using a three-way ANOVA. When significant differences in means were observed, a multiple comparison test (Dunnett's T-3) was used assuming unequal variance.

Results

Water quality parameters: Temperature, salinity and freshwater flow (releases from S-79 were investigated during the study period. Mean monthly 30-day moving average flow at S-79 ranged from a minimum of 0.7 CFS in March 2001 to a maximum of 3813 CFS in September of 2001 (Fig. 1). Freshwater releases from S-79 were also higher during the dry months of year 2 (> 300 CFS) compared to year 1 (< 300 CFS). In general, freshwater releases were high in the summer months (July - October) and low during the dry / winter months (November to June). There was a significant inverse correlation between flows at S-79 and salinities at all sampling locations (65 - 76% correlation; $P < 0.0001$). Salinity at all locations decreased with increasing freshwater flows. Regression analyses for each site indicated that there was a highly significant relation between freshwater flow and salinities at all stations (Table 1). These regressions explained 43 - 58% of the variation (Fig. 2). Shell Point was considered as the river mouth (Chamberlain and Doering 1998a, b). Results suggest that for every 1000 CFS released at S-79, salinities at PP, CD, BI, KK, and TB would decrease by 6, 5.7, 5.3, 4.3, and 3.6 ppt, respectively from their ambient salinities (Table 1). According to our model, at zero flow, salinities at PP, CD, BI, KK, and TB would be 28.5, 29.9, 32.7, 33.5, and 36.6 ppt respectively (Table 1). Since observed salinities at these locations would also be influenced by sheet flow resulted by rainfall, and tides, effect of rainfall / sheet flow and tides could not be separated from the model. However predicted salinity at these locations are in very close agreement (± 3 ppt) with those predicted by Bierman's model (1993). Temperature during the study period ranged from 18 - 31ºC (Fig. 3). With the exception of Jan - Feb 2002, temperatures in corresponding months during years 1 and 2 were similar (<4ºC difference; Fig. 3). Salinities at all sampling locations were higher during year 1, a period of no flow - low flow, compared to year 2 where flows were higher than 300 CFS (Figs. 4 - 8).

P. marinus prevalence: Similar to salinities, prevalence of *P. marinus* in oysters from all locations was lower during dry months of year 2 compared with those from year 1 (Fig. 9 - 14; Table 2, $P < 0.0001$). The differences in prevalence between years, as expected, was more pronounced at upstream locations compared to the downstream location (TB). Prevalence of *P. marinus* infection during the dry months in first and second years at the sampling locations were as follows: PP - year 1, 20 - 40%; year 2, 0 - 11%, CD -year 1, 20 - 90%; year 2, 11 - 90%, BI - year 1, 13 - 90%; year 2, 0 - 60%, KK - year 1, 0 - 80%; year 2, 0 - 40%, and, Tarpon Bay - year 1, 0 - 50%; year 2, 0 - 50%.

P. marinus intensity: Intensity of *P. marinus* infections in oysters were calculated as weighted prevalence. This procedure incorporates the prevalence of infection and intensity of infections in individual oysters in calculating a weighted prevalence. Concomitant with salinities and freshwater flows, and similar to prevalence of *P. marinus*, intensity of infections in oysters from all sampling locations except the downstream station Tarpon Bay, was lower during year 2 compared to those in year 1

(Figs. 15-20; Table 2, P < 0.0001). Infection intensities during the dry months in first and second years at the sampling locations are as follows: PP - year 1, 0.2 - 0.4; year 2, 0 - 0.11, CD -year 1, 0.2 - 2.4; year 2, 0.1 - 1.5, BI - year 1, 0.2 - 2.5; year 2, 0 - 0.6, KK - year 1, 0 - 0.8; year 2, 0 - 0.6, and, Tarpon Bay - year 1, 0 - 0.5; year 2, 0 - 1. These results suggest that with the exception of CD and BI locations, oysters from all locations, during both no flow - low flow (year 1; < 300 CFS), and low flow - intermediate flow (year 2; > 300 CFS) had light infections that are non-lethal. Typically, intermediate - heavy infections (intensity 3 - 5) are considered lethal.

Summary and conclusions

Past studies demonstrated that low salinities (<12 ppt) retarded *P. marinus* infections in oysters (Ray 1954, Andrews and Hewatt 1957, Chu et al. 1993, Ragone and Burreson 1993, Chu and Volety 1997). Our field study demonstrates the relation between varying salinities and disease prevalence and intensity in oysters in the field. Despite the high prevalence of infection in oysters (0 - 90%), disease intensity is low due to a combination of factors -- temperature and salinity acting antagonistically resulting in low intensities (light infections). Given the flow rates from S-79, based on our model and that of Bierman (1993), salinities at all locations would have encountered salinities of 6 - 12 ppt, values that would retard development of *P. marinus* infections. The upstream station, PP, had the lowest infection intensities in oysters and lowest salinities. Higher infection intensities in oysters from CD may be as a result of the water quality and high boat wakes. This site receives water output from the City of Cape Coral and nearby marinas. As mentioned earlier, higher temperatures and salinities favor *P. marinus*. In the Caloosahatchee estuary, when summer temperatures reach as high as 32ºC, *P. marinus* infection prevalence and intensity should be high. However, during summer months, the combination of freshwater releases by SFWMD and high rainfall decreases the salinities to 0 - 12 ppt, depending on the station, keeping infection levels low. Similarly, during winter, when freshwater releases are none - low, and rainfall is lacking, salinities are high (30 -40 ppt). These high salinities should result in heavy *P. marinus* infections in oysters. However, during the winter months, temperatures are lower (15 - 18ºC) resulting in low infection levels despite high salinity. Temperatures and salinities in Caloosahatchee estuary act antagonistically keeping *P. marinus* infections at low levels. Similar decreases in *P. marinus* intensities in oysters concomitant with decreased salinities were observed in other southwest Florida estuaries (Thurston et al. 2001, Volety et al. 2001a, b). However, it has to be cautioned that high flow (> 3000 CFS) freshwater releases during summer time may have negative impacts on oyster populations.

Although oysters tolerate salinities between 0 - 42 ppt, growth is best achieved at salinities of 14 - 28 ppt; slower growth, poor spat production, and excessive valve closure occur at salinities below 14 ppt (see Shumway 1996). Battaller et al. (1999) reported lower growth and condition index of oysters grown at a low salinity site compared to a high salinity site in Canada. Similar results are seen in our current study (results not shown). Since the metabolic energy remaining after reproduction and daily maintenance is converted to biomass, an oyster stressed either by its water quality or by disease has less energy for growth and reproduction. In addition, oyster larvae respond to water flow, salinity, temperature and a host of chemical cues from adult oysters, hard substrates, and old oyster shells colonized by bacteria. The net result is that oyster larvae typically settle more frequently in areas of low flushing, higher salinities, and a dense accumulation of adults. In contrast, low salinities result in poor spat settlement and lower growth rates (Shumway 1996). Sudden changes in water quality and resulting poor oyster health may cause a shift in patterns of recruitment and survival. Either of these responses have significant impacts on recruitment of spat into the populations.

Oysters in the Caloosahatchee estuary reproduce between May and October (see previous progress report), a period that coincides with heavy rainfall and freshwater releases in excess of 4000 CFS. According to our model, as well as Bierman's model, these flows and rainfall will depress the salinity at all sampling locations to 4 - 15 ppt for extended periods (2-3 months). Lower salinities not only impact the survival, but also high flow flushes out the oyster spat produced during this period from the estuary into the ocean where suitable substrates for attachment are lacking. In fact, our laboratory experiments indicate that salinities < 5 ppt for more than 2-4 weeks would result in 80% mortality of oysters (see previous report). Given that flows in the Caloosahatchee River exceeded 3000 CFS during August - October 2001, salinities in all the sampling locations would have been between 2 - 15 ppt, conditions that are stressful to oysters and oyster spat. In addition, as a result of these high flows, large amount of spat would have been flushed into the Gulf of Mexico resulting in poor settlement.

In conclusion, under the current freshwater release regime and seasonal patterns, antagonistic effects of temperature and salinities keep *P. marinus* infection in oysters at low levels in the Caloosahatchee River. Freshwater releases from Lake Okeechobee during the dry months in year 1 were none - low (< 300 CFS) compared to year 2 when water releases were higher than 300 CFS (Fig 1). Lower salinities at all stations corresponding with freshwater releases indicate that salinities were influenced by the water releases by SFWMD (Correlation 65 - 76%). While the infection levels in oysters are lower in the dry months of year 2, compared to year 1, overall infections are light (Figs 15 - 20). These results suggest that flows < 300 CFS, do not cause "significant harm" as measured by *P. marinus* infections in the Caloosahatchee oyster populations. It has to be cautioned that the current study did not examine the effects of marine predators (oyster drills, crown conchs, whelks etc.) that dominate high salinity waters. Given that optimum salinity for oysters ranges from 14 - 28 ppt, under the prevailing salinity regimes, high flows exceeding 3000 CFS may cause severe mortality and low spat recruitment into the system. Flows between 500 CFS and 2000 CFS would result in salinities of 16 - 28 ppt at all stations. Under the current water management practices, oysters in the Caloosahatchee River are not stressed by low flows (< 300 CFS), but are stressed due to high flows exceeding 3000 CFS for extended periods (2 - 4 weeks).

Given our laboratory and field studies, a single freshet event (< 3 ppt), lasting up to 2 weeks will not have any significant effect on the mortality of oysters. While flows above 300 CFS resulted in lower disease intensities in all sampling locations, intensities under low flows (< 300 CFS), resulted in overall low - moderate non-lethal infections. Flows between 500 and 2000 CFS will result in optimum salinities for oysters and will result in sustaining and enhancing oyster populations in Caloosahatchee Estuary. The use of adaptive management approach involving freshwater releases to sustain and enhance oyster populations is invaluable to the ecology of the Caloosahatchee Estuary.

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Table 1: Model to predict relation between S-79 flows and salinities at sampling locations in Caloosahatchee Estuary.

Sampling station	**Location in River (from the mouth)**	**Regression Equation**	**R-Sq %**	**P-value**	**Predicted salinity at zero flow**	**Predicted change in ambient salinity per 1000 CFS release at S-79**
Piney Point	4 km upstream	Salinity = -0.006*flow + 28.49	58.1	0.0000	28.49 ppt	6.0 ppt
Cattle Dock	2 km upstream	Salinity = -0.006*flow + 29.88	54.2	0.0000	29.88 ppt	5.7 ppt
Bird Island	4 km downstream	Salinity = -0.005*flow + 32.67	48.0	0.0000	32.67 ppt	5.3 ppt
Kitchel Key	6 km downstream	Salinity = -0.004*flow + 33.51	42.8	0.0000	33.51 ppt	4.3 ppt
Tarpon Bay	12 km downstream	salinity = -0.004*flow + 36.53	57.5	0.0000	36.53 ppt	3.7 ppt

Table 2: Analyses of variance of *P. marinus* disease intensity in oysters from Caloosahatchee Estuary.

Source	**Type III SS**	**df**	**Mean Square**	**F**	**Significance (P)**
Station	28.15	4	7.04	16.99	0.000
Month	22.99	6	3.83	9.26	0.000
Year	11.85	1	11.85	28.60	0.000
Month*Station	23.35	24	0.97	2.35	0.000
Year*Month	4.55	4	1.14	2.75	0.028
Station*Month	27.27	6	4.54	10.98	0.000
Station*Month*Year	50.3	24	2.10	5.06	0.000

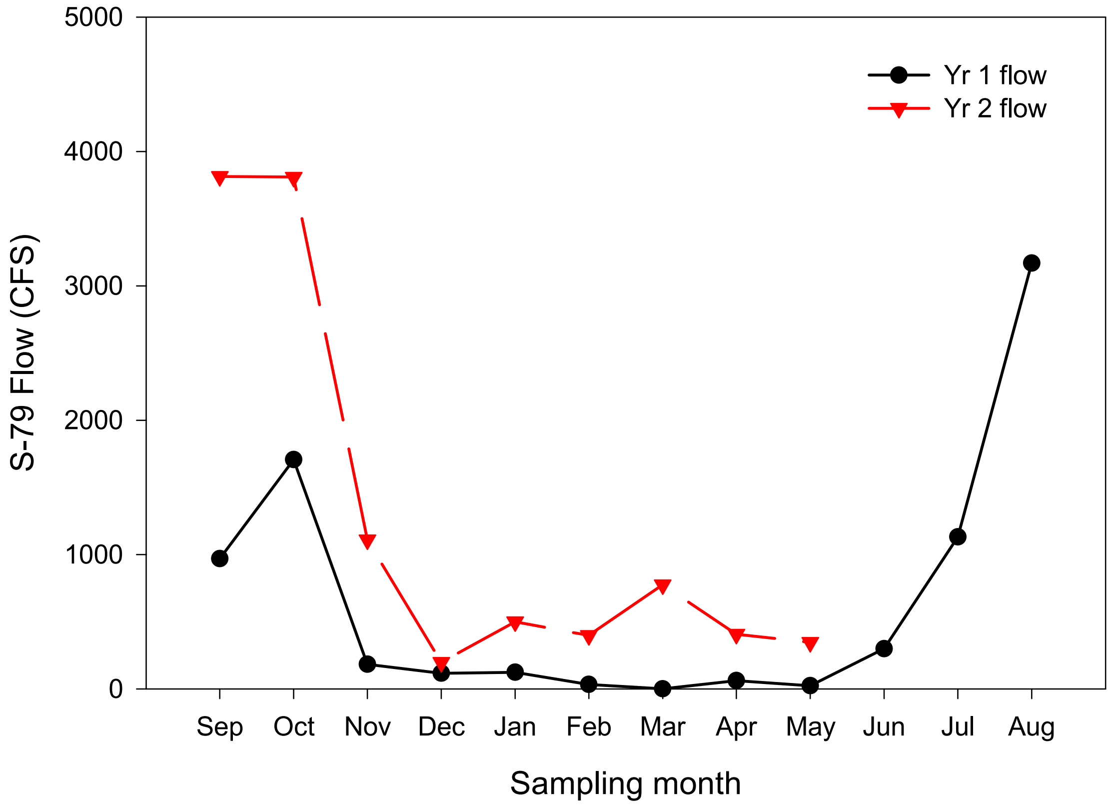

Fig. 1: Flow (in CFS) at S-79 in Caloosahatchee River during years 1 and 2. Years 1 and 2 are from September 2000 - August 2001, and from September 2001 - Present, respectively. Flow rates (< 300 CFS) were observed during winter / dry months (Nov - May) in Year 1 compared to Year 2.

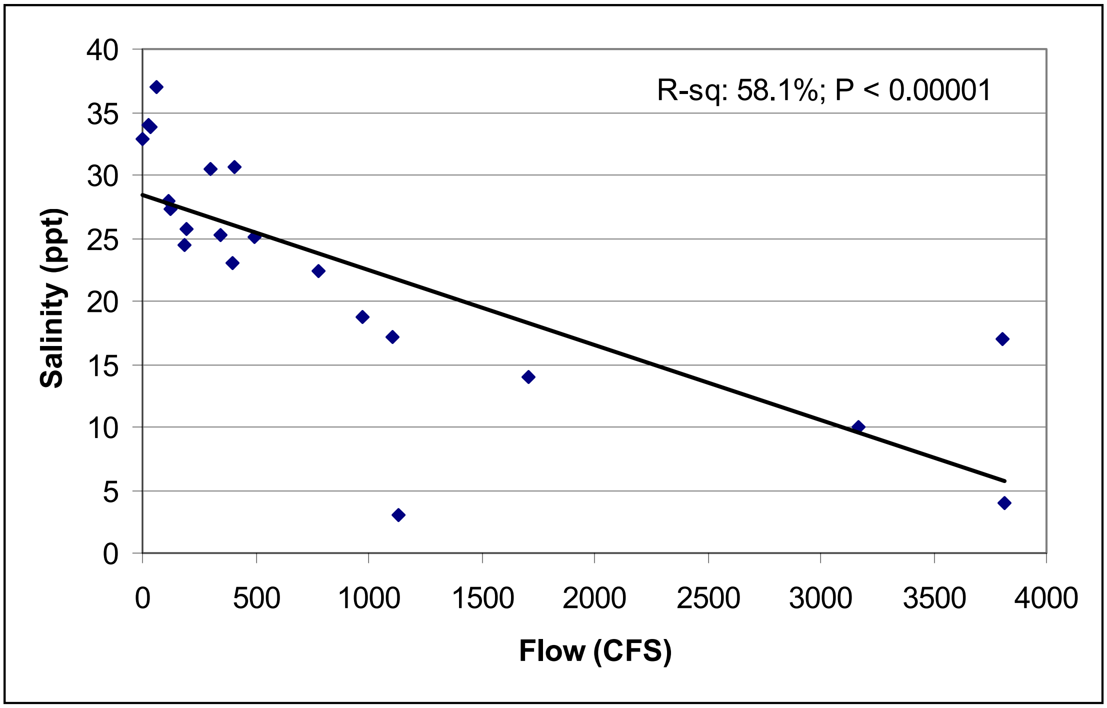

Fig. 2: Relation between S-79 flow (in CFS) and salinity at the upstream station, Piney Point, in Caloosahatchee River. Monthly average of 30 day moving average of flow at 79 was regressed against observed salinity (during sampling) at Piney Point. Effect of sheet flow and rainfall on the salinity in the sampling locations was not included in the regression model. Regression equation was as follows: Salinity = -0.006 x flow in CFS + 28.49. These results suggest that a flow of 1000 CFS at S-79 locks would result in a decrease of 6 ppt at Piney Point. Similar regression equations were constructed for Cattle Dock, Bird Island, Kitchel Key and Tarpon Bay.

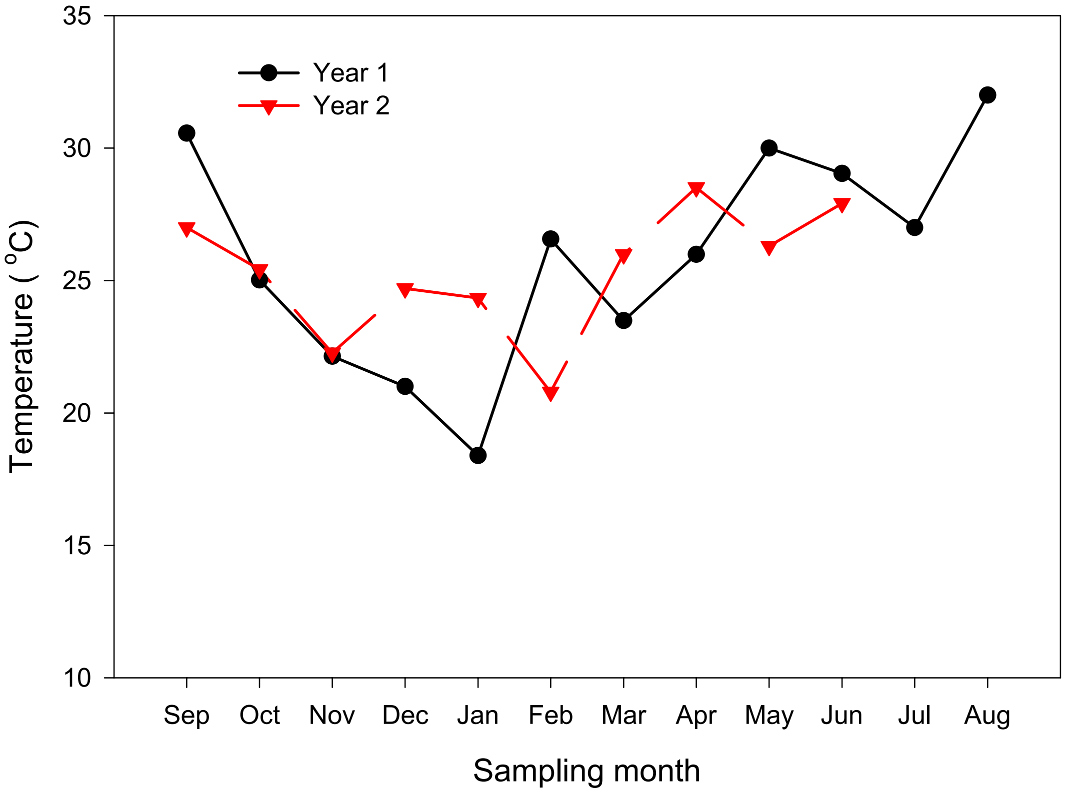

Fig. 3: Temperature (ºC) at Piney Point in Caloosahatchee River during years 1 and 2. Years 1 and 2 are from September 2000 - August 2001, and from September 2001 - Present, respectively. Temperatures were similar at all sampling locations (±1ºC). As expected, temperatures were lower in winter and spring months (Nov-Apr) compared to summer and Fall months.

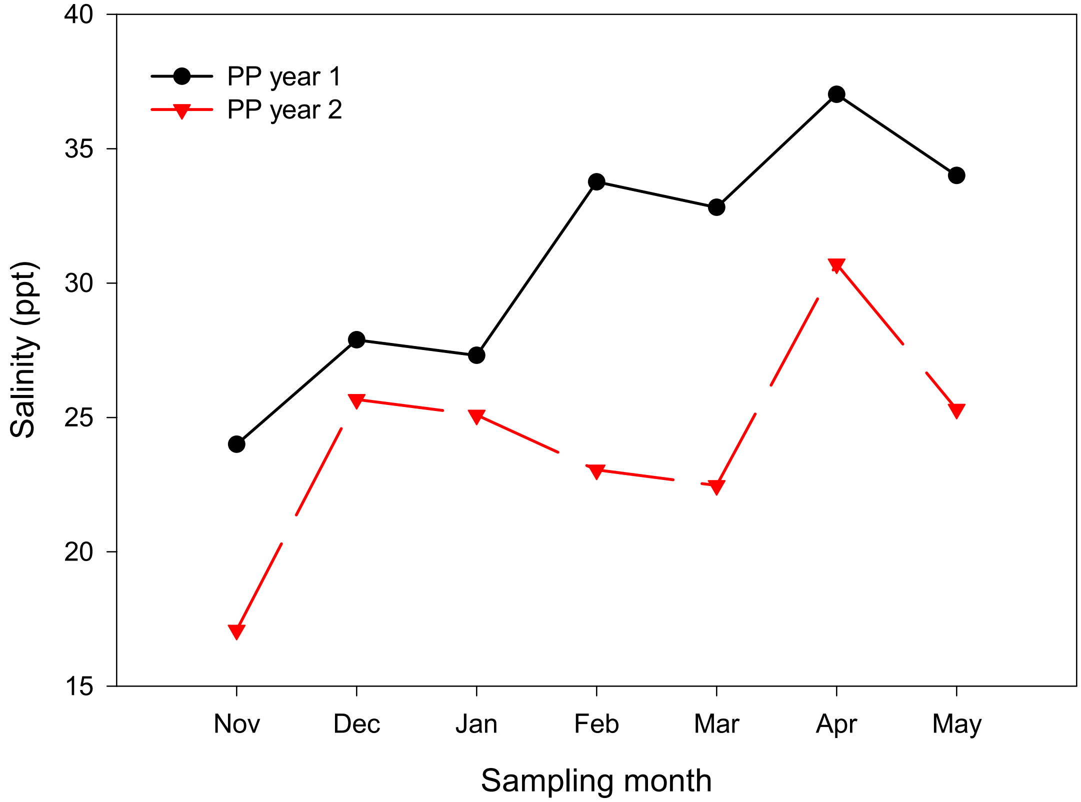

Fig. 4: Salinity (ppt) at Piney Point (PP) in Caloosahatchee River during dry months in years 1 and 2. Years 1 and 2 are from September 2000 - August 2001, and from September 2001 - Present, respectively. Salinities at all stations decreased with increased flow from S-79 locks. In addition, salinities in year 2 were lower than those in year 1 due to freshwater releases from Lake Okeechobee during year 2.

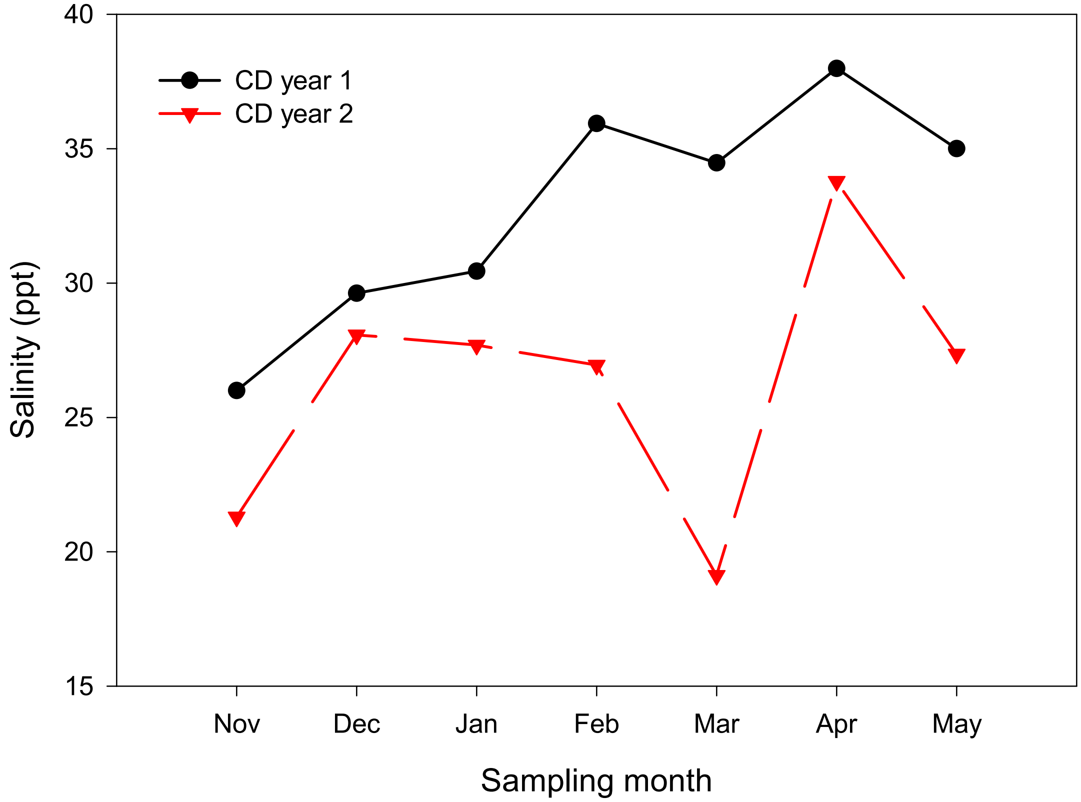

Fig. 5: Salinity (ppt) at Cattle Dock (CD) in Caloosahatchee River during dry months in years 1 and 2. Years 1 and 2 are from September 2000 - August 2001, and from September 2001 - Present, respectively. Salinities at all stations decreased with increased flow from S-79 locks. In addition, salinities in year 2 were lower than those in year 1 due to freshwater releases from Lake Okeechobee during year 2.

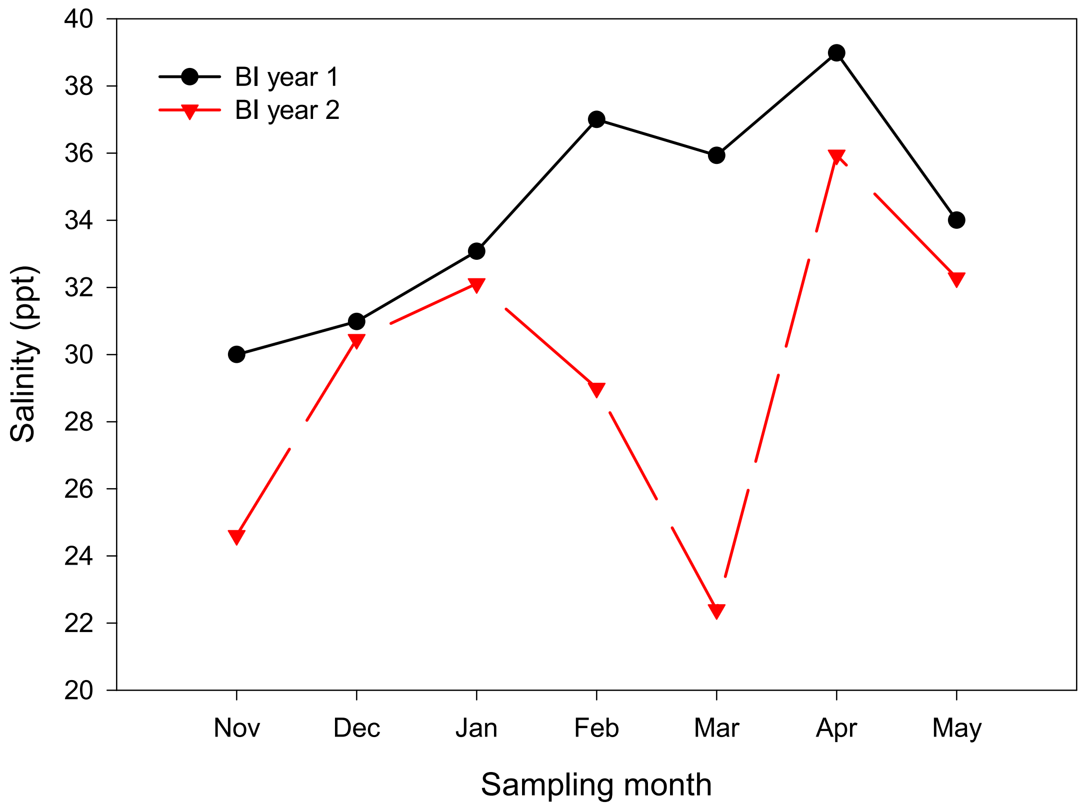

Fig. 6: Salinity (ppt) at Bird Island (BI) in Caloosahatchee River during dry months in years 1 and 2. Years 1 and 2 are from September 2000 - August 2001, and from September 2001 - Present, respectively. Salinities at all stations decreased with increased flow from S-79 locks. In addition, salinities in year 2 were lower than those in year 1 due to freshwater releases from Lake Okeechobee during year 2.

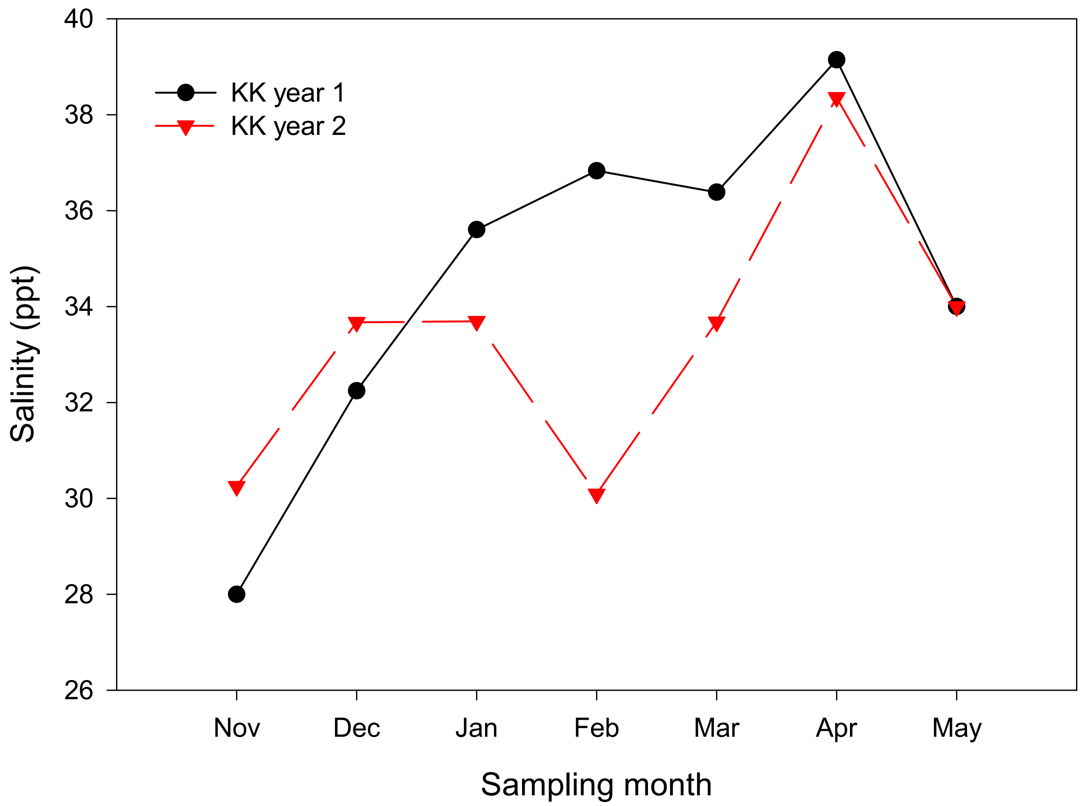

Fig. 7: Salinity (ppt) at Kitchel Key (KK) in Caloosahatchee River during dry months in years 1 and 2. Years 1 and 2 are from September 2000 - August 2001, and from September 2001 - Present, respectively. Salinities at all stations decreased with increased flow from S-79 locks. In addition, salinities in year 2, with the exception of Nov - Dec, were lower than those in year 1 due to freshwater releases from Lake Okeechobee during year 2.

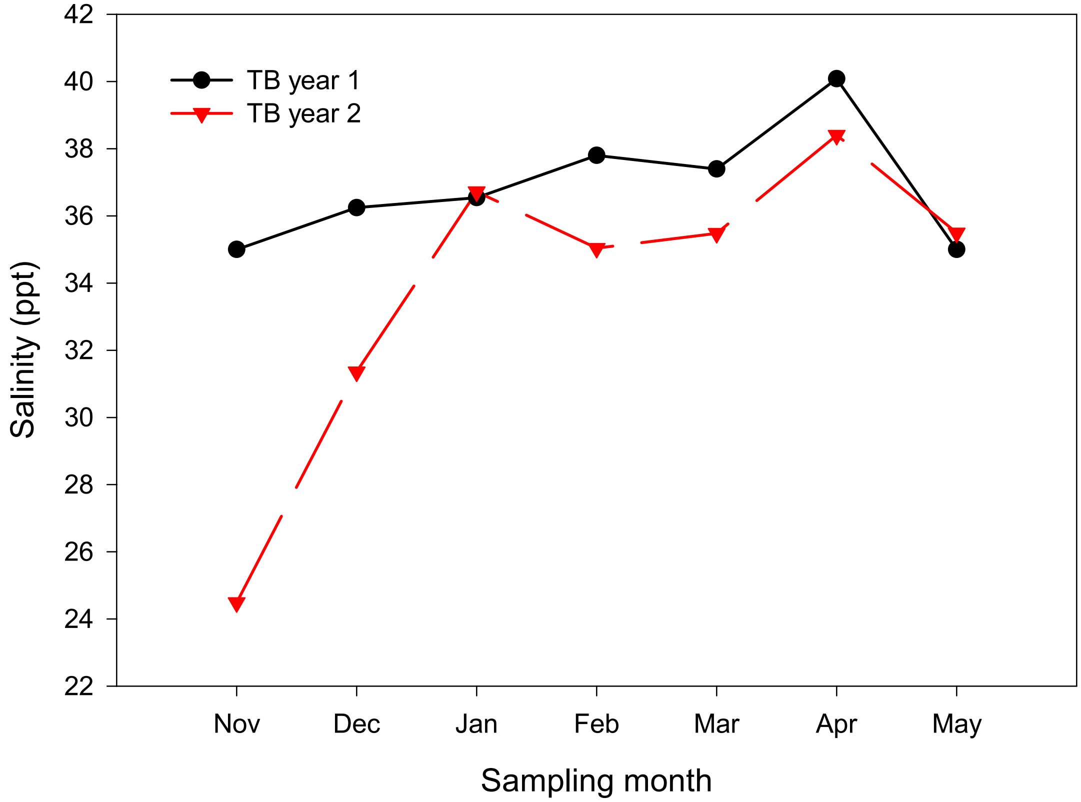

Fig. 8: Salinity (ppt) at Tarpon Bay (TB) in Caloosahatchee River during dry months in years 1 and 2. Years 1 and 2 are from September 2000 - August 2001, and from September 2001 - Present, respectively. Salinities at all stations decreased with increased flow from S-79 locks. In addition, salinities in year 2 were lower than those in year 1 due to freshwater releases from Lake Okeechobee during year 2.

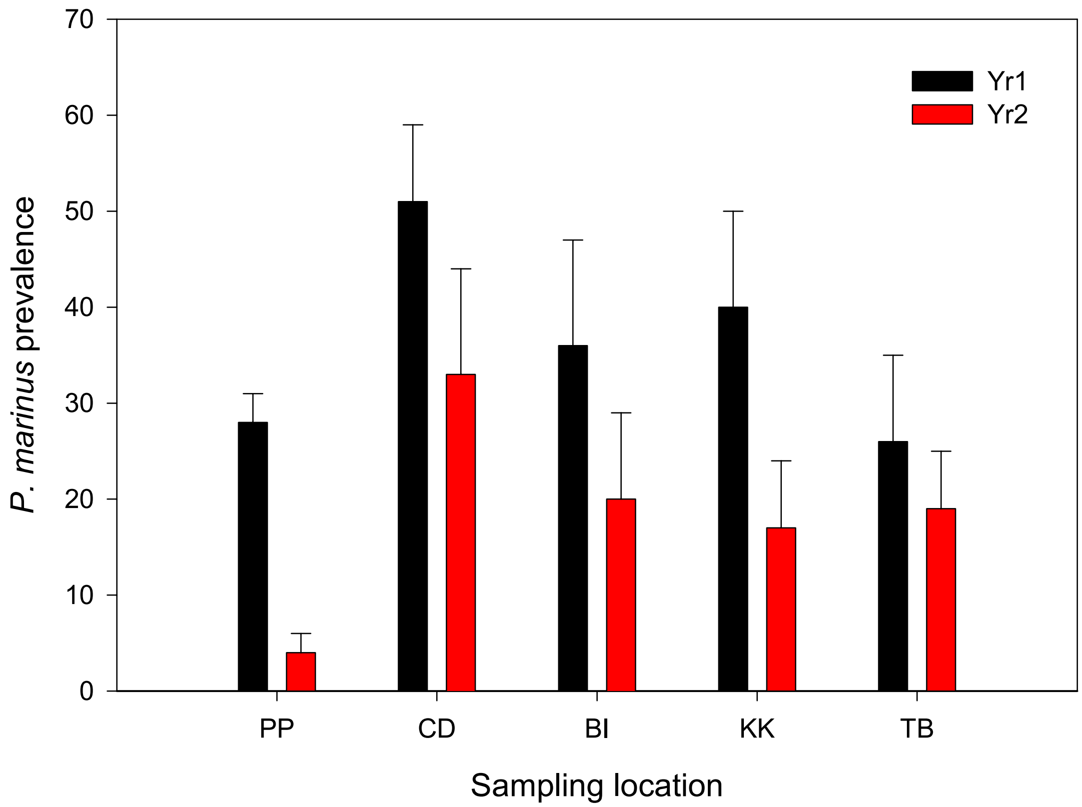

Fig. 9: Mean *P. marinus* prevalence (± SE) during winter months in oysters from Piney Point (PP), Cattle Dock (CD), Bird Island (BI), Kitchel Key (KK), and Tarpon Bay (TB) in Caloosahatchee River during years 1 and 2. November - May were considered as dry months due to the paucity of rainfall. Years 1 and 2 are from September 2000 - August 2001, and from September 2001 - Present, respectively. Ten oysters per month were randomly samples from the sampling locations per month and prevalence of *P. marinus* in oysters was analyzed according to Ray 1954. Increased freshwater releases from Lake Okeechobee and resulting decreased salinities resulted in lower infection intensities in oysters from all upstream locations.

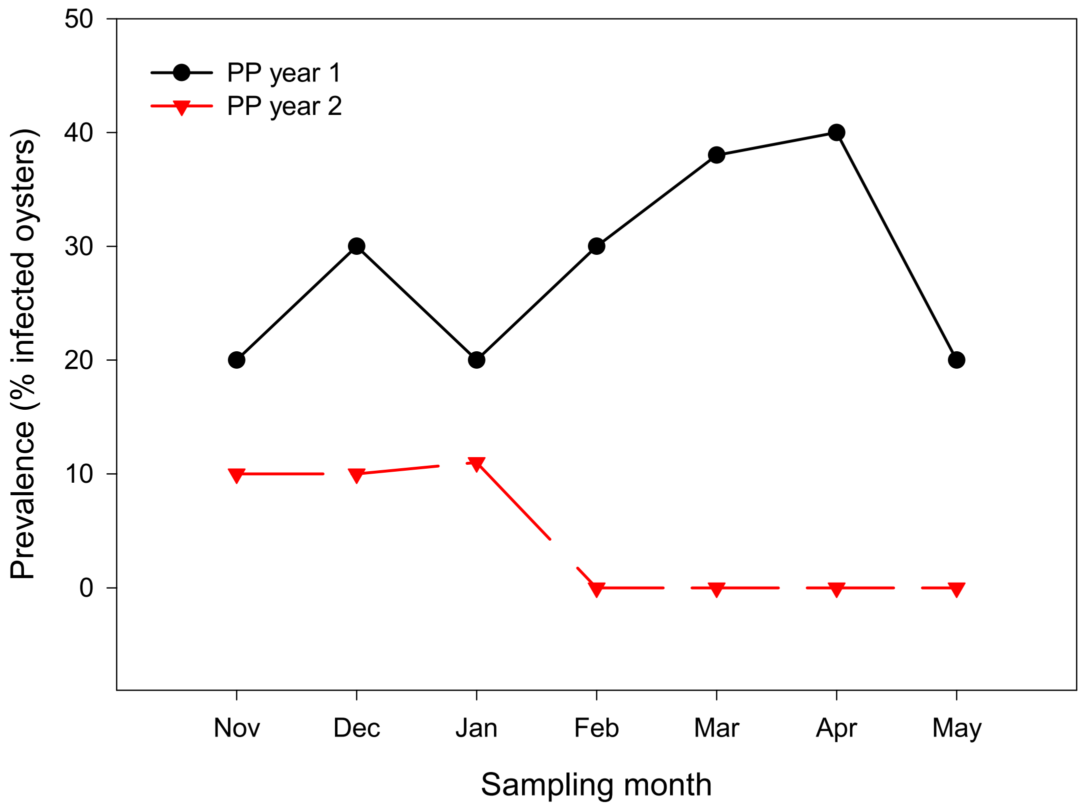

Fig. 10: Mean *P. marinus* prevalence (± SE) during winter months in oysters from Piney Point (PP) in Caloosahatchee River during years 1 and 2. November - May were considered as dry months due to the paucity of rainfall. Years 1 and 2 are from September 2000 - August 2001, and from September 2001 - Present, respectively. Increased freshwater releases from Lake Okeechobee and resulting decreased salinities during year 2 resulted in lower prevalence of *P. marinus* infections in oysters.

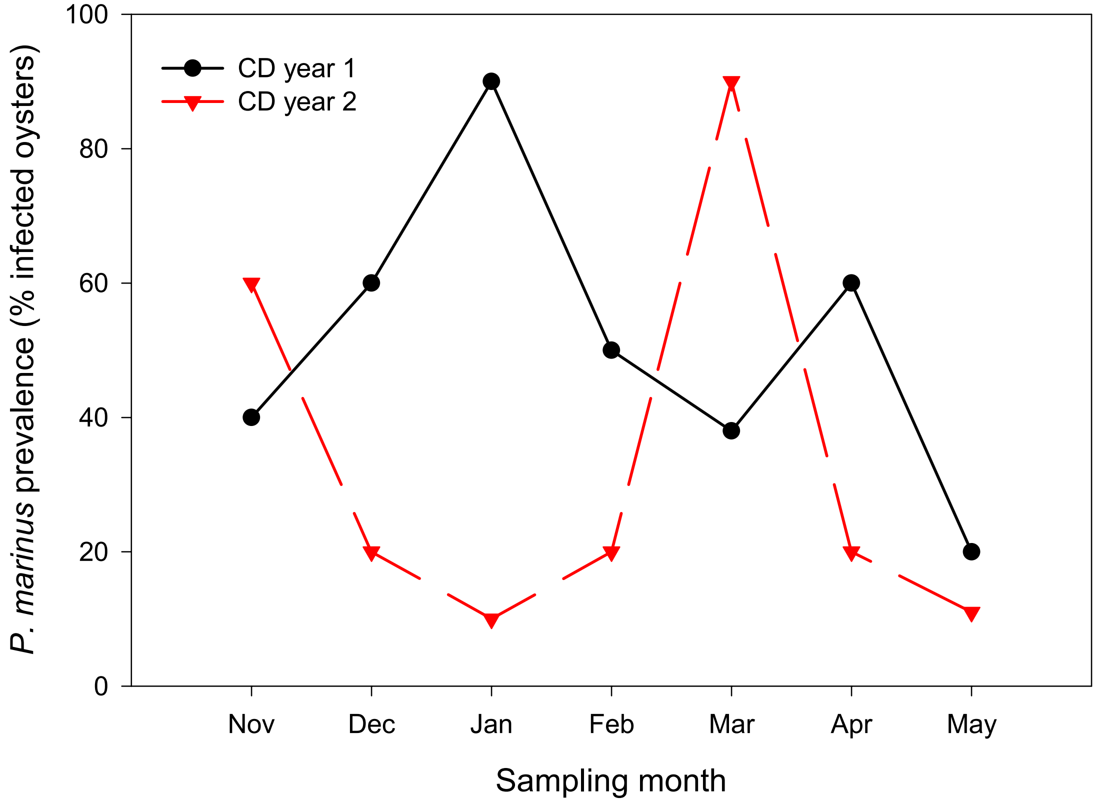

Fig. 11: Mean *P. marinus* prevalence (± SE) during winter months in oysters from Cattle Dock (CD) in Caloosahatchee River during years 1 and 2. November - May were considered as dry months due to the paucity of rainfall. Years 1 and 2 are from September 2000 - August 2001, and from September 2001 - Present, respectively. Increased freshwater releases from Lake Okeechobee and resulting decreased salinities during year 2 resulted in lower prevalence of *P. marinus* infections in oysters. Cattle Dock site also receives runoff water from the City of Cape Coral and nearby marinas.

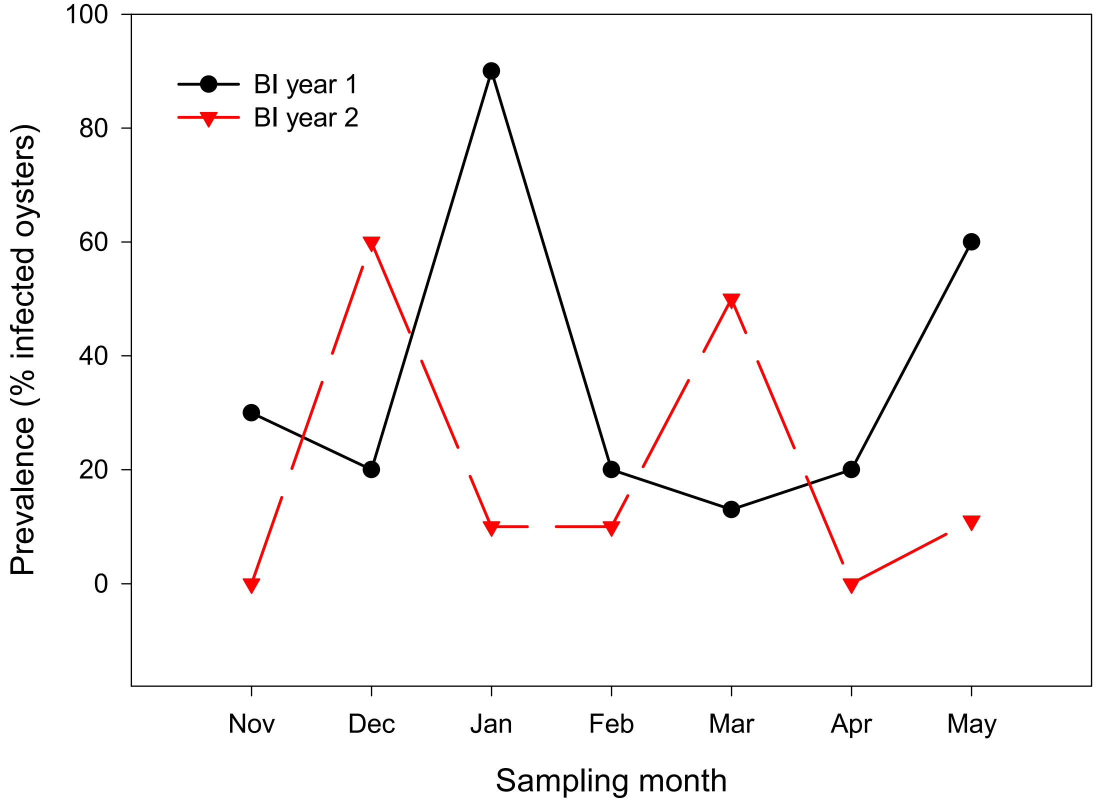

Fig. 12: Mean *P. marinus* prevalence (± SE) during winter months in oysters from Bird Island (BI) in Caloosahatchee River during years 1 and 2. November - May were considered as dry months due to the paucity of rainfall. Years 1 and 2 are from September 2000 - August 2001, and from September 2001 - Present, respectively. Increased freshwater releases from Lake Okeechobee and resulting decreased salinities during year 2 resulted in lower prevalence of *P. marinus* infections in oysters, however, due to the proximity of this station to marine environment and higher salinities, effects of freshwater releases are less pronounced.

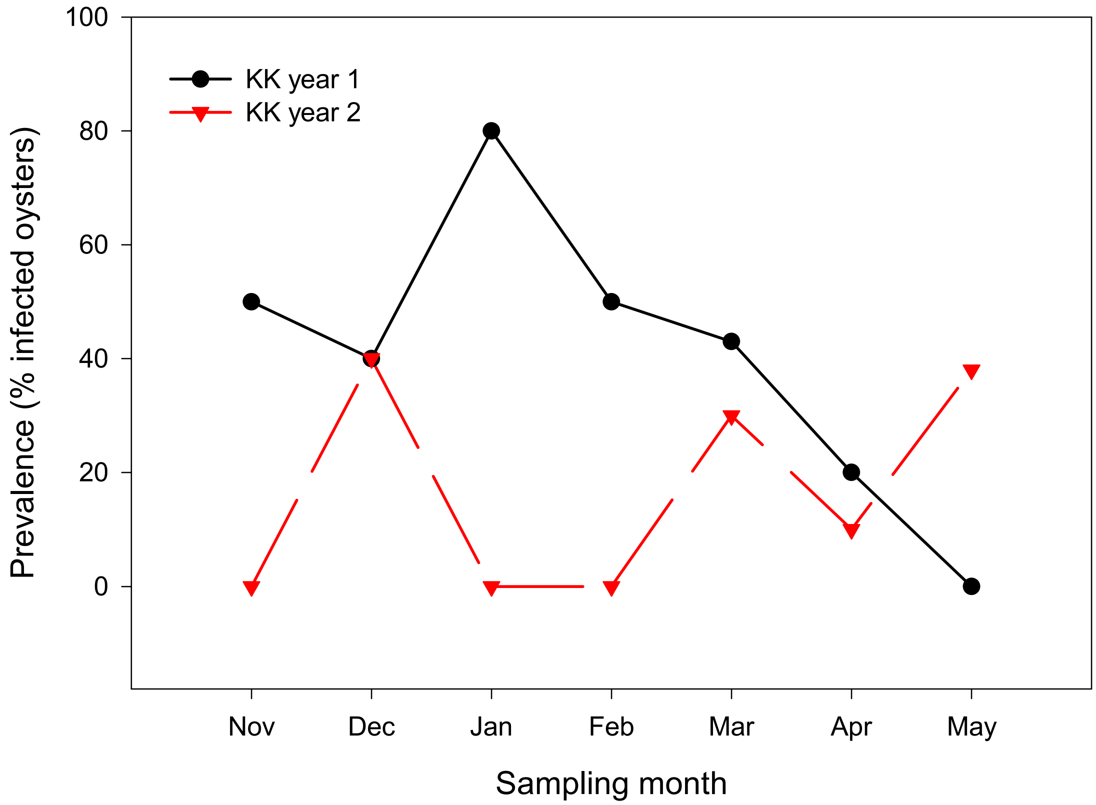

Fig. 13: Mean *P. marinus* prevalence (± SE) during winter months in oysters from Kitchel Key (KK) in Caloosahatchee River during years 1 and 2. November - May were considered as dry months due to the paucity of rainfall. Years 1 and 2 are from September 2000 - August 2001, and from September 2001 - Present, respectively. Increased freshwater releases from Lake Okeechobee and resulting decreased salinities during year 2 resulted in lower prevalence of *P. marinus* infections in oysters, however, due to the proximity of this station to marine environment and higher salinities, effects of freshwater releases are less pronounced.

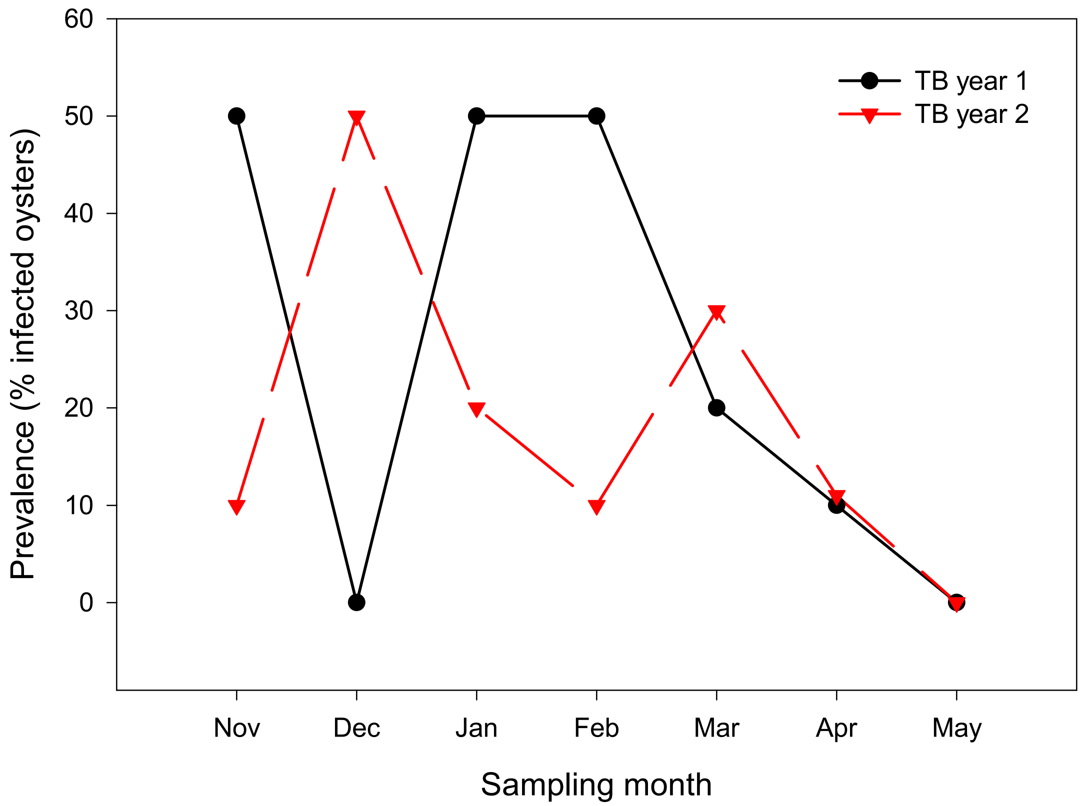

Fig. 14: Mean *P. marinus* prevalence (± SE) during winter months in oysters from Tarpon Bay (TB) in Caloosahatchee River during years 1 and 2. November - May were considered as dry months due to the paucity of rainfall. Years 1 and 2 are from September 2000 - August 2001, and from September 2001 - Present, respectively. Increased freshwater releases from Lake Okeechobee and resulting decreased salinities during year 2 resulted in lower prevalence of *P. marinus* infections in oysters, however, due to the proximity of this station to marine environment (downstream of river) and higher salinities, effects of freshwater releases are less pronounced.

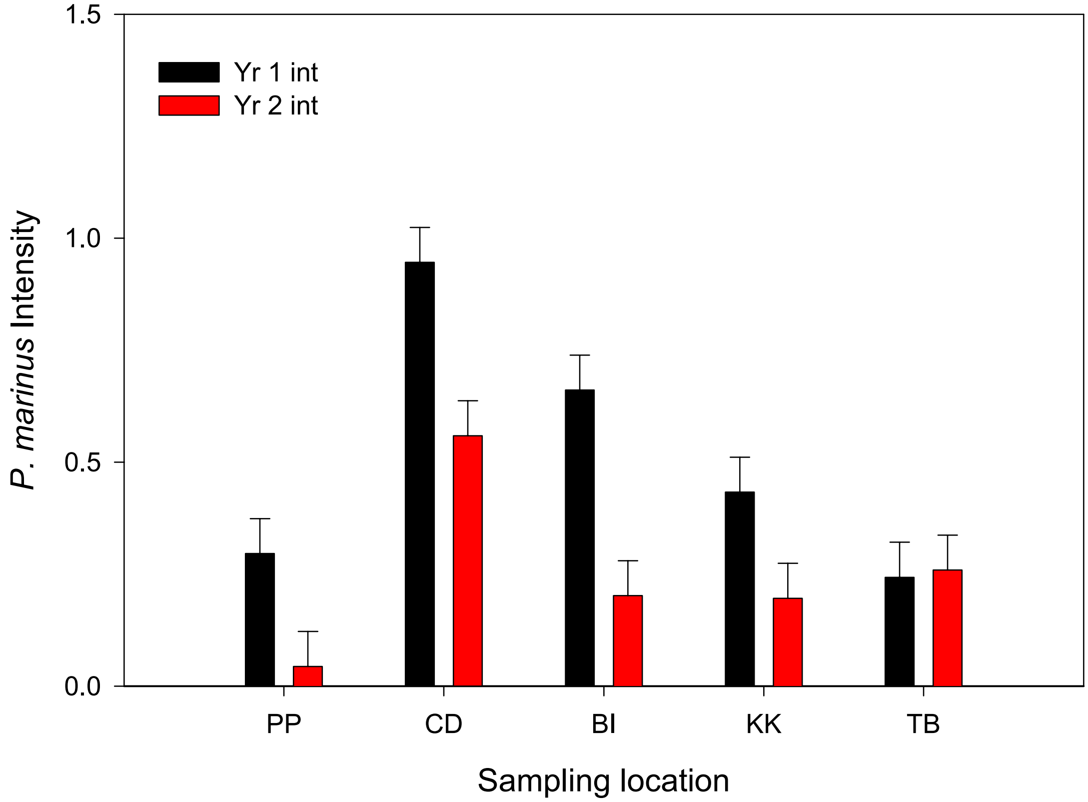

Fig. 15: Mean *P. marinus* intensity (± SE) during winter months in oysters from Piney Point (PP), Cattle Dock (CD), Bird Island (BI), Kitchel Key (KK), and Tarpon Bay (TB) in Caloosahatchee River during years 1 and 2. November - May were considered as dry months due to the paucity of rainfall. Years 1 and 2 are from September 2000 - August 2001, and from September 2001 - Present, respectively. Ten oysters per month were randomly samples from the sampling locations per month and intensity (Int) of *P. marinus* (weighted incidence) was analyzed according to Ray 1954. Increased freshwater releases from Lake Okeechobee and resulting decreased salinities resulted in lower infection intensities in oysters from all upstream locations.

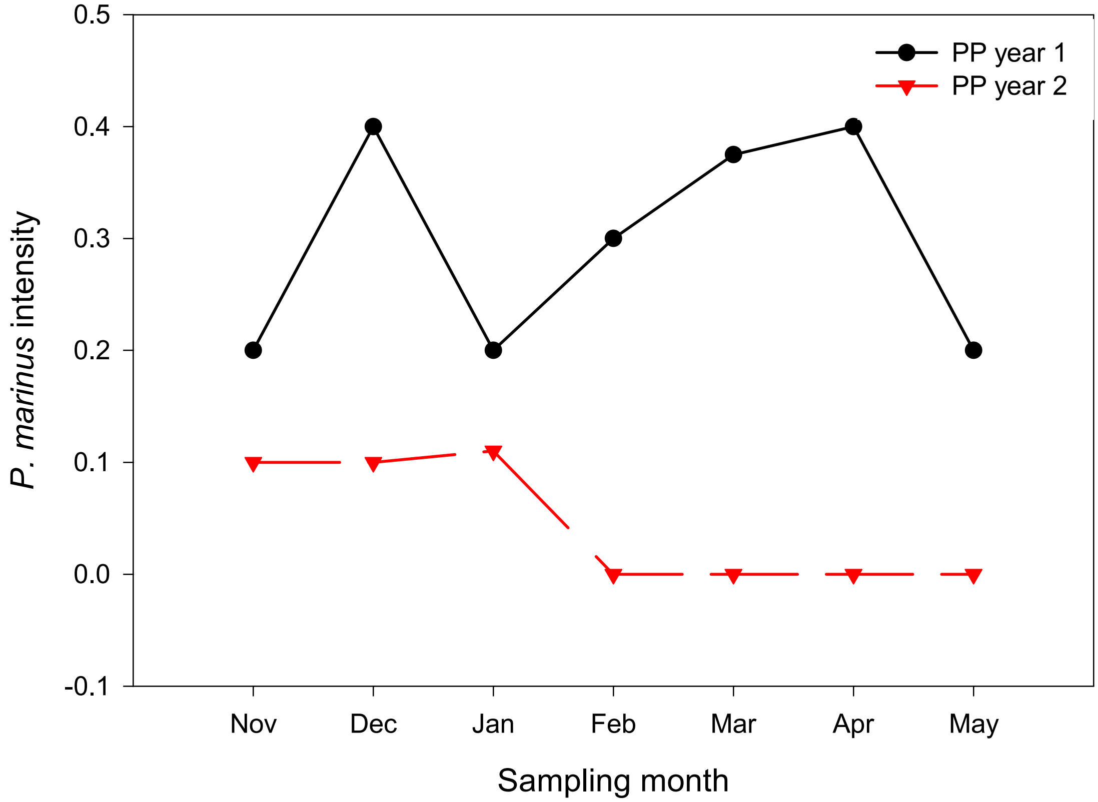

Fig. 16: Mean *P. marinus* intensity during winter months in oysters from Piney Point (PP) in Caloosahatchee River during years 1 and 2. November - May were considered as dry months due to the paucity of rainfall. Years 1 and 2 are from September 2000 - August 2001, and from September 2001 - Present, respectively. Increased freshwater releases from Lake Okeechobee and resulting decreased salinities during year 2 resulted in lower prevalence of *P. marinus* infections in oysters.

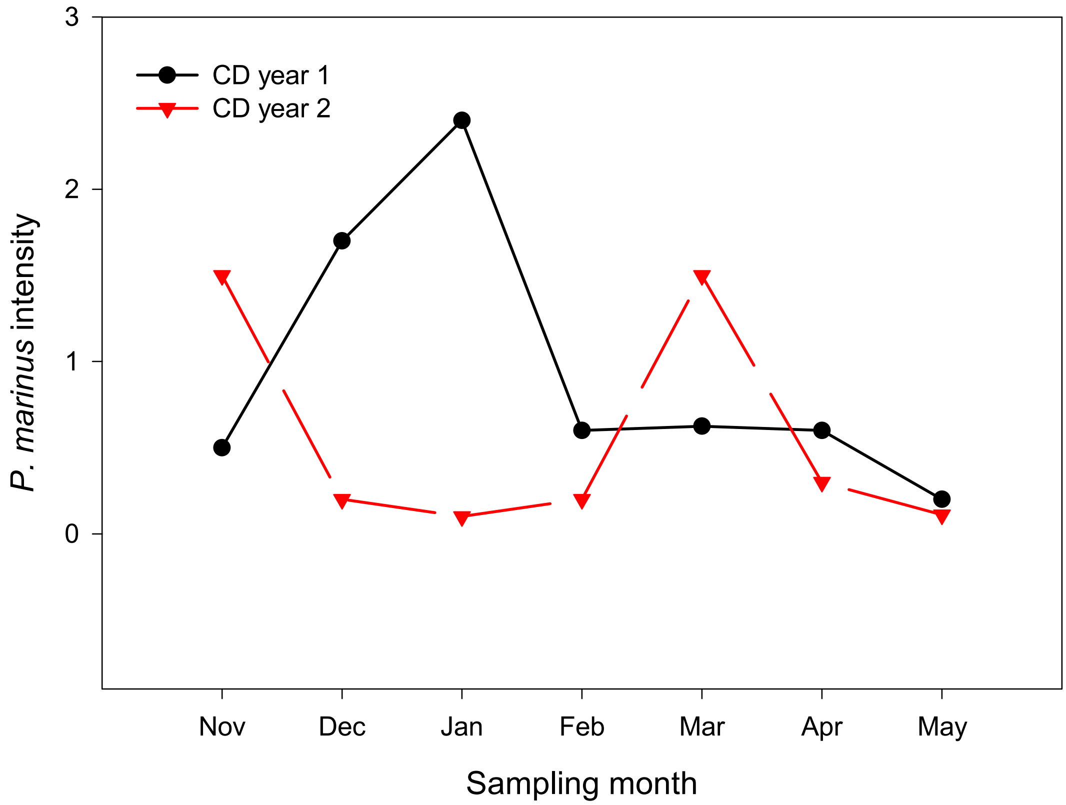

Fig. 17: Mean *P. marinus* intensity during winter months in oysters from Cattle Dock (CD) in Caloosahatchee River during years 1 and 2. November - May were considered as dry months due to the paucity of rainfall. Years 1 and 2 are from September 2000 - August 2001, and from September 2001 - Present, respectively. Increased freshwater releases from Lake Okeechobee and resulting decreased salinities during year 2 resulted in lower prevalence of *P. marinus* infections in oysters. Cattle Dock site also receives runoff water from the City of Cape Coral and nearby marinas.

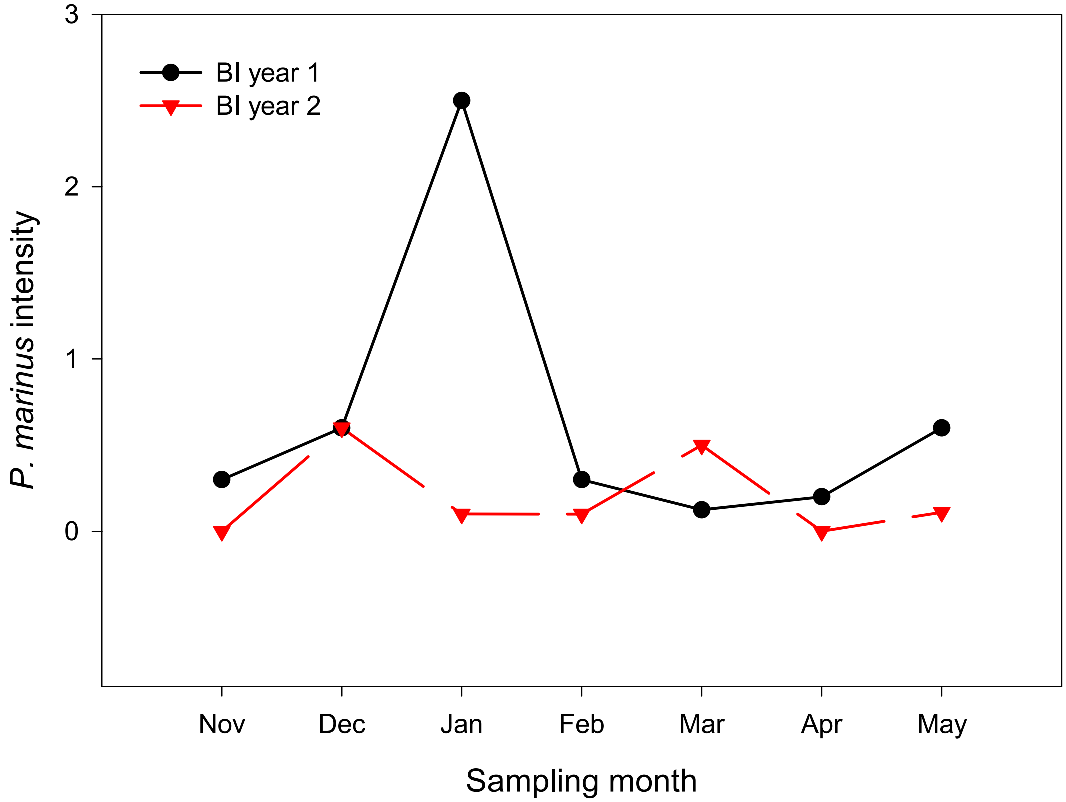

Fig. 18: Mean *P. marinus* intensity during winter months in oysters from Bird Island (BI) in Caloosahatchee River during years 1 and 2. November - May were considered as dry months due to the paucity of rainfall. Years 1 and 2 are from September 2000 - August 2001, and from September 2001 - Present, respectively. Increased freshwater releases from Lake Okeechobee and resulting decreased salinities during year 2 resulted in lower prevalence of *P. marinus* infections in oysters.

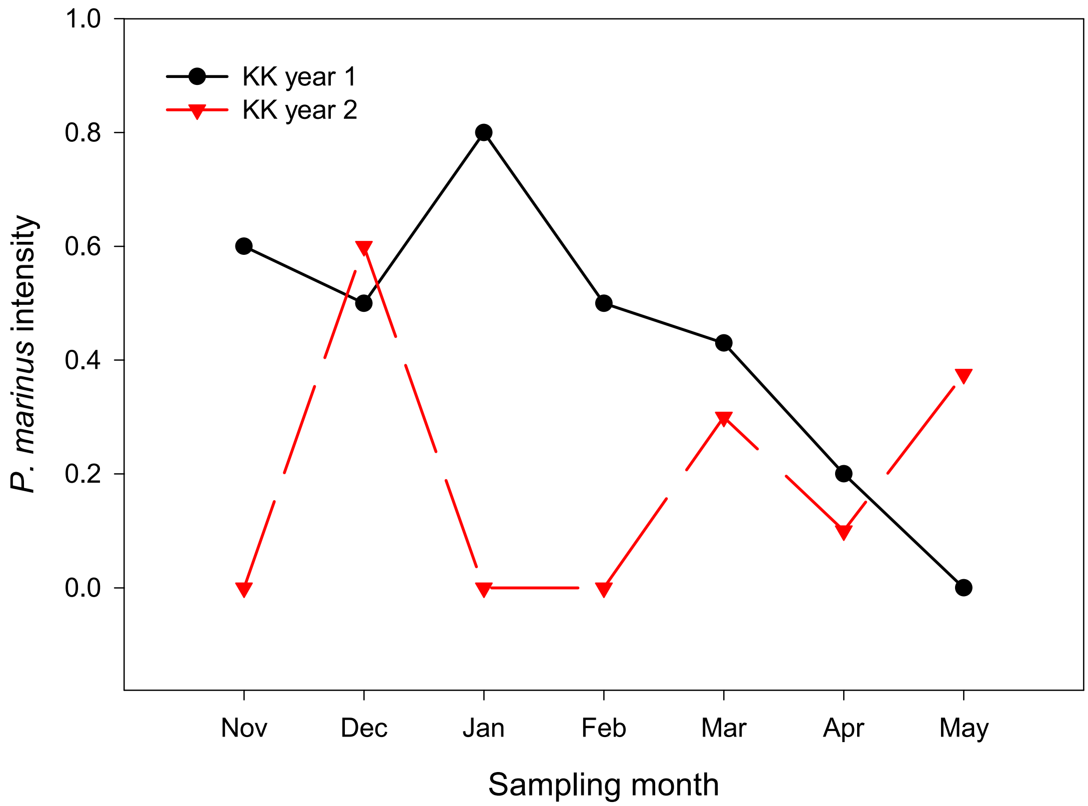

Fig. 19: Mean *P. marinus* intensity during winter months in oysters from Cattle Dock (CD) in Caloosahatchee River during years 1 and 2. November - May were considered as dry months due to the paucity of rainfall. Years 1 and 2 are from September 2000 - August 2001, and from September 2001 - Present, respectively. Increased freshwater releases from Lake Okeechobee and resulting decreased salinities during year 2 resulted in lower prevalence of *P. marinus* infections in oysters.

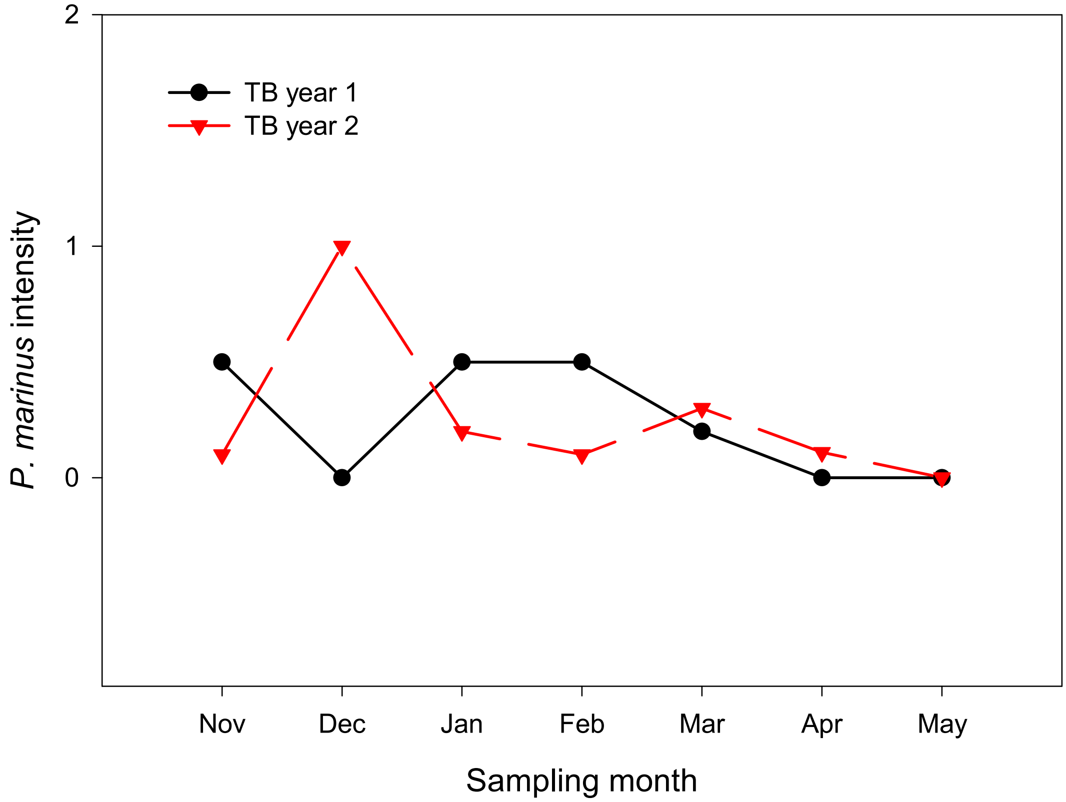

Fig. 20: Mean *P. marinus* intensity during winter months in oysters from Tarpon Bay (TB) in Caloosahatchee River during years 1 and 2. November - May were considered as dry months due to the paucity of rainfall. Years 1 and 2 are from September 2000 - August 2001, and from September 2001 - Present, respectively. Increased freshwater releases from Lake Okeechobee and resulting decreased salinities during year 2 resulted in lower prevalence of *P. marinus* infections in oysters, however, due to the proximity of this station to marine environment (downstream of river) and higher salinities, effects of freshwater releases are less pronounced.

Technical Documentation to Support Development of Minimum Flows and Levels for the Caloosahatchee River and Estuary

Appendix C

Impacts of Freshwater Inflows on the Distribution of Zooplankton and Ichthyoplankton in the Caloosahatchee Estuary, Florida

By Chamberlain, R.H., P.H. Doering, K.M. Haunert, and D. Crean

Contents

Florida Bay and Lower West Coast Division
Southern District Restoration Department

South Florida Water Management District

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by
Chamberlain, R.H., P.H. Doering, K.M. Haunert, and D. Crean

Introduction

An average monthly freshwater inflow of 300 cfs has been established as the minimum flow and level (MFL) to protect the upstream freshwater-brackish plant, Vallisneria americana (Figure 1), from high salinity exposure during the dry season (MFL Document – SFWMD 2000). A maximum discharge limit of 2,800 cfs has been recommended to protect downstream seagrass from being adversely impacted by low salinity conditions (Chamberlain and Doering 1998a, b; Doering et al. 2002). Expert reviewers of the MFL document suggested that further investigation was needed to understand how the above-recommended inflows influence other biota in the Caloosahatchee Estuary. This summary paper highlights the results of two data analysis efforts, previously presented as posters (Chamberlain et al. 1999, 2001), with the following goals: (1) characterize the spatial and seasonal abundance of zooplankton and ichthyoplankton as it relates to freshwater inflow; (2) specifically assess the potential influence of above-recommended discharges on these components of the plankton community; and (3) determine inflows that tend to maximize abundance.

Methods

Paired 0.5 mm conical zooplankton nets with a 243 micron mesh were obliquely towed from the stern of a 20’ boat. Another pair of nets with a 505-micron mesh was concurrently deployed from a side boom to collect ichthyoplanton. The ichthyoplankton nets also proved successful at collecting fish eggs, shrimp, and crab larvae. A flow meter was affixed in the mouth of one zooplankton and one ichthyoplankton net. Nocturnal samples were collected monthly at six (6) stations (Figure 1) and a seventh station in Pine Island Sound every other month during 1986-1989. Zooplankton only samples were again collected during abnormally high freshwater inflows in 1998. Net samples were identified to the lowest taxonomic level possible. Repetitive samples of zooplankton in the water column were also collected with a bilge pump in 1988-1989 at stations 1, 2, 4, 5 during low to moderate inflows, and again during high inflows in 1994 -1996 and 1998. A fixed volume was filtered through a 60-micron mesh and individual zooplankton were sorted into major groups and enumerated. Freshwater inflow volume through S-79 was measured daily throughout the year. Water quality, including salinity, was sampled during each trip.

Results

Zooplankton

There were 108 invertebrate taxa collected during the 1986-1989 zooplankton net sampling. The copepod, Acartia tonsa comprised 52% of the total density. In the pump samples, copepod nauplii and all other copepod stages constituted 67% of the zooplankton, contributing 45% and 22% respectively. Over 90% of the crab and shrimp larvae in the ichthyoplankton nets were Minippe mercenaria (stone crabs). Penaeus sp. comprised approximately 7% and Callinectes sp. accounted for approximately 2%.

In general, mean zooplankton density (net samples) increased with increasing distance from S-79. Statistical differences, as judged by a multiple range test, are shown in Figure 2 (bottom). The greatest zooplankton density occurred at higher salinity stations (> 20ppt) farthest from S-79. A similar trend appeared for the pump samples, however not as strongly, with station 5 supporting the least zooplankton density.

Stations 5 and 6 accounted for over 99% of the shrimp and crab larvae enumerated in the ichthyoplankton nets. The peak abundance occurred at station 6 where salinity was nearly the highest. Blue crab larvae (Callinectes sapidus) require salinity above 20 ppt, demonstrating the importance of establishing a maximum discharge limit for station 6.

There were apparent differences in density between seasons at each station during both pump and net sampling (Figure 3). This was most evident in the pump samples, with the period of April – July being the most productive, followed by December – March. Zooplankton density was lowest during the rainiest portion of wet season, August – November. A similar, but less evident seasonal influence can be seen in the net samples. The same order of seasonal ranking appears (April – July and December – March > the August – November), but only at stations 3, 4, and 5. Seasonal influences become less clear at the estuarine boundaries.

Inflow volume appears to be more of an influence than salinity. Density decreases as inflows increase at most stations for both pump and net samples, as shown in Figure 4. In zooplankton net samples, inflows that exceed 1,500 cfs and approach 3,000 cfs or greater are associated with the lowest zooplankton density, except at the farthest downstream stations (6 and 7).

In zooplankton net samples, the average density for all stations combined were further separated into 6 inflow categories and tested for significant differences (Figure 5). Optimal inflows associated with the highest zooplankton densities occurred in the 150-600 cfs range. Flows higher or lower than this were associated with lower densities. Inflows that approach and exceed 1,200 cfs supported the least zooplankton density.

Again in the zooplankton net samples, the same 6 flow categories were used to examine the influence of freshwater input at each station (Figure 6). Except at station 6, the same general trend appears for most stations as was seen when flow was examined for all stations combined. Inflows that approach and exceed 2,500 cfs were associated with the least zooplankton; and inflows in the 2nd and usually 3rd categories (151 - 600 cfs) always supported the greatest density of zooplankton.

Ichthyoplankton

Average monthly discharges from S-79 ranged from 69 to 4,510 cfs during 1986-1989 (Figure 7). These inflows were highly variable between months and years. Average discharge was < 1,000 cfs during January through June, but approached 2,000 cfs during the remaining six months. High variability in discharge resulted in wide fluctuations in salinity, with a range >20 ppt (Figure 8) at Stations 3, 4, and 5.

Five fish families contributed > 1% to the total fish abundance. Engraulidae, Gobiidae, Sciaenidae, Clupeidae and Blennidae accounted for approximately 96% of the total abundance. Anchoa mitchelli was the dominant single species comprising 54% of the number of fish collected. Fish egg composition was dominated by Engraulids, with Sciaenids also making a significant contribution.

As with inflow and salinity, the average ichthyoplankton density was highly variable between stations (Figure 9). The distribution pattern generally followed that of Anchoa. The median density followed the longitudinal salinity distribution as did average density to a lesser extent. Significant differences between stations also followed the median values. Station 6 was associated with the greatest density, station 5 ranked 2nd, and Station 2 was associated with the lowest density. The density of fish eggs generally followed the same patterns of distribution and significance as the ichthyoplankton.

The average ichthyoplankton density was greater for most of the estuary during the spring months, March through June (Figure10). This is when inflow is usually lower (Figure7). The high density at Station 3 during November through February was primarily due to a high abundance of Anchoa mitchelli that occurred late in February 1986. High ichthyoplankton density occurred during July through October only at Station 6. During this time period, discharges are usually greater (Figure 7). It is likely that Station 6 offers better salinity conditions for most species than upstream when discharges are high.

Average egg density is also greatest during spring, for both Engraulids and Sciaenids (Figure 11). November through February produced the 2nd highest abundance. Anchovies prefer spawning upstream of Shell Point at Stations 4 and 5 during the dry season, November –June. As with ichthyoplankton, Engraulid egg density (Figure 11a) increases downstream at station 5 and 6 during the wet season, July – October. Average Sciaenid egg density (Figure 11b) also was greatest during spring, but remained high at Station 6 during this season, compared to declining trend of Engraulid eggs. Sciaenids generally seem to prefer spawning farther down stream in higher salinity water, which is especially evident as seasonal freshwater inflows increased during the wet season.

Analysis of data at each station determined that when inflows were < 600 cfs, ichthyoplankton density was significantly greater at Stations 3, 4, and 5. The same was true for eggs, except at Station 2, where inflows < 600 cfs also were associated with greater density. No significant differences in densities associated with inflows were found at the remaining stations.

During the dry season (November – June) is when the estuary is most likely to suffer a lack of minimum flows to support upstream submerged plants, but also most threatened by large Lake Okeechobee regulatory releases. When the dry season was examined separately during this analysis, inflows that exceeded 2,500 cfs were associated with the lowest ichthyoplankton and egg density and inflows < 600 cfs had greater densities.

Inflows were consistently lower during the spring months of 1989 than during 1987 and 1988. Since spring is the most productive time in the estuary, extra sampling was conducted in March and April during each of these three years. During 1987 and 1988 freshwater inflows averaged 1,836 and 1,854 cfs, while in 1989 the mean inflow was 433 cfs. In 1989, ichthyoplankton density was greater in the estuary, especially upstream of Shell Point (Figure 12). More of the estuary also was used for spawning during 1989 (Figure 13). This suggest that lower flows favor increased utilization of the estuary.

Conclusion

Zooplankton

Mean zooplankton density increased along with salinity and distance from S-79. The late spring to early summer season is generally when zooplankton density is greatest, just prior to the wet season's heaviest rainfall runoff during August to November when density is lowest. High freshwater inflows and lower salinity drive zooplankton down regardless of the season. Zooplankton were weakly related to salinity, but correlated well with freshwater inflow volume, possibly due to a "wash out" effect.

Some freshwater inflow is important to the estuary in order for zooplankton to achieve maximum density. At most stations, except those farthest downstream (6 and 7) the greatest densities were measured when inflows range was150-600 cfs. Except at station 6, inflows that exceed 1,200-1,500 cfs were associated with reduced zooplankton density. Inflows that were greater than 2,500-3,000 cfs supported the lowest density.

Ninety percent of the shrimp and crab larvae were collected at station 5 and 6, with the peak abundance occurring at station 6, when salinity exceeded 20-25 ppt. Therefore inflows that normally do not exceed 2,500 -3,000 cfs will protect the San Carlos Bay spawning and rearing area. Inflows that remain below 1,200-1,500 cfs will also provide habitat upstream of Shell Point.

Ichthyoplankton

Freshwater inflows < 600 cfs were associated with the highest ichthyoplankton and egg density. The maximum ichthyoplankton utilization of the estuary and spawning occurred in more areas during low flows. Ichthyoplankton and eggs were greatest during the dry season, especially in spring. Dry season and spring minimum inflows necessary to protect upstream SAV will not adversely impact ichthyoplankton and egg abundance. Inflow < 600-800 cfs, associated with higher seagrass production near Station 5 (Doering et al. 2002), should also maximize ichthyoplankton and egg abundance in this region and downstream.

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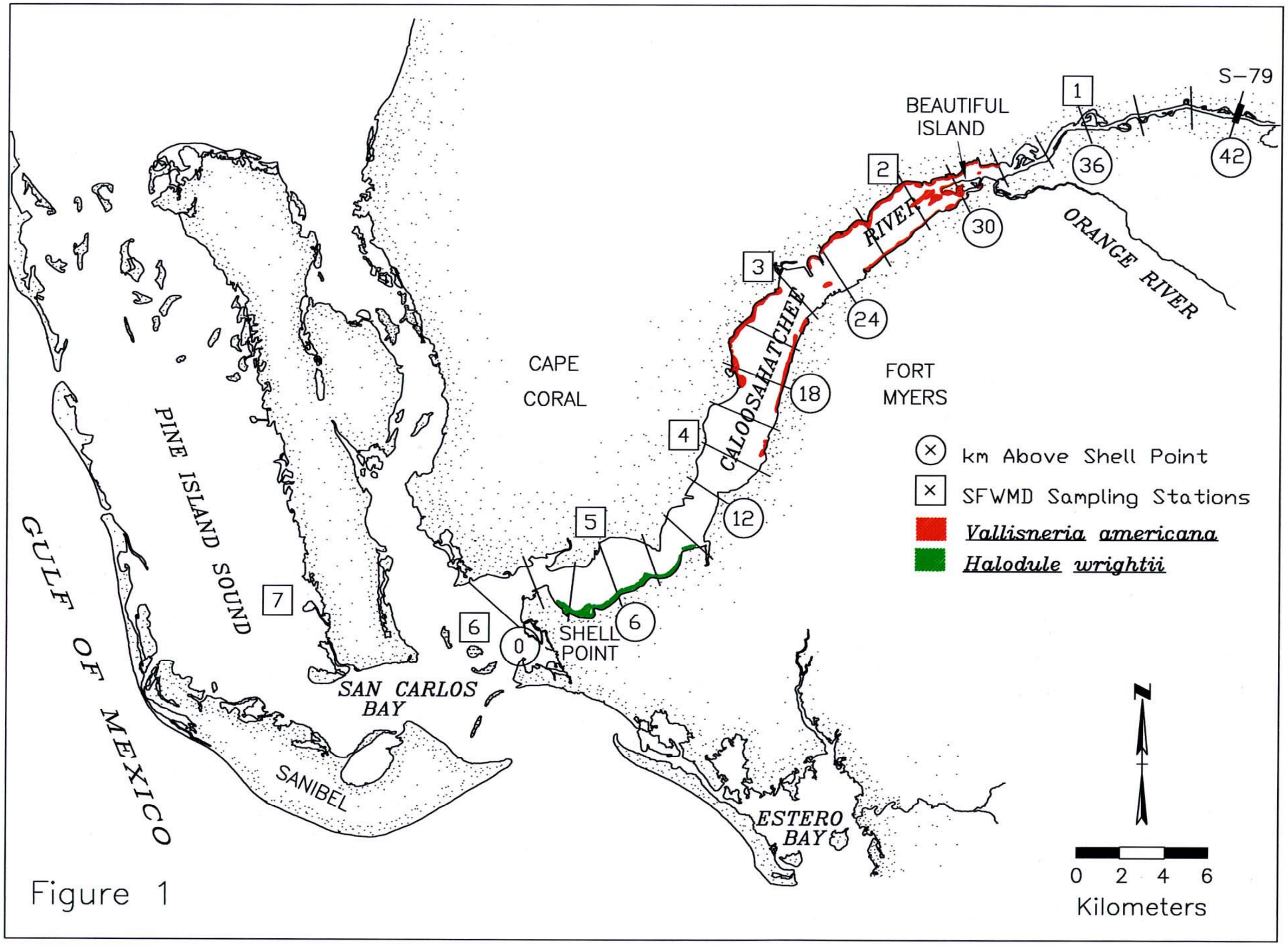
FIGURES


S-79
BEAUTIFUL ISLAND
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18
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30
36
42
RIVER
ORANGE RIVER
CALOOSAHATCHEE
CAPE CORAL
FORT MYERS
SHELL POINT
PINE ISLAND SOUND
GULF OF MEXICO
SAN CARLOS BAY
SANIBEL
ESTERO BAY
km Above Shell Point
SFWMD Sampling Stations
Vallisneria americana
Halodule wrightii
N
0 2 4 6
Kilometers

Figure 1

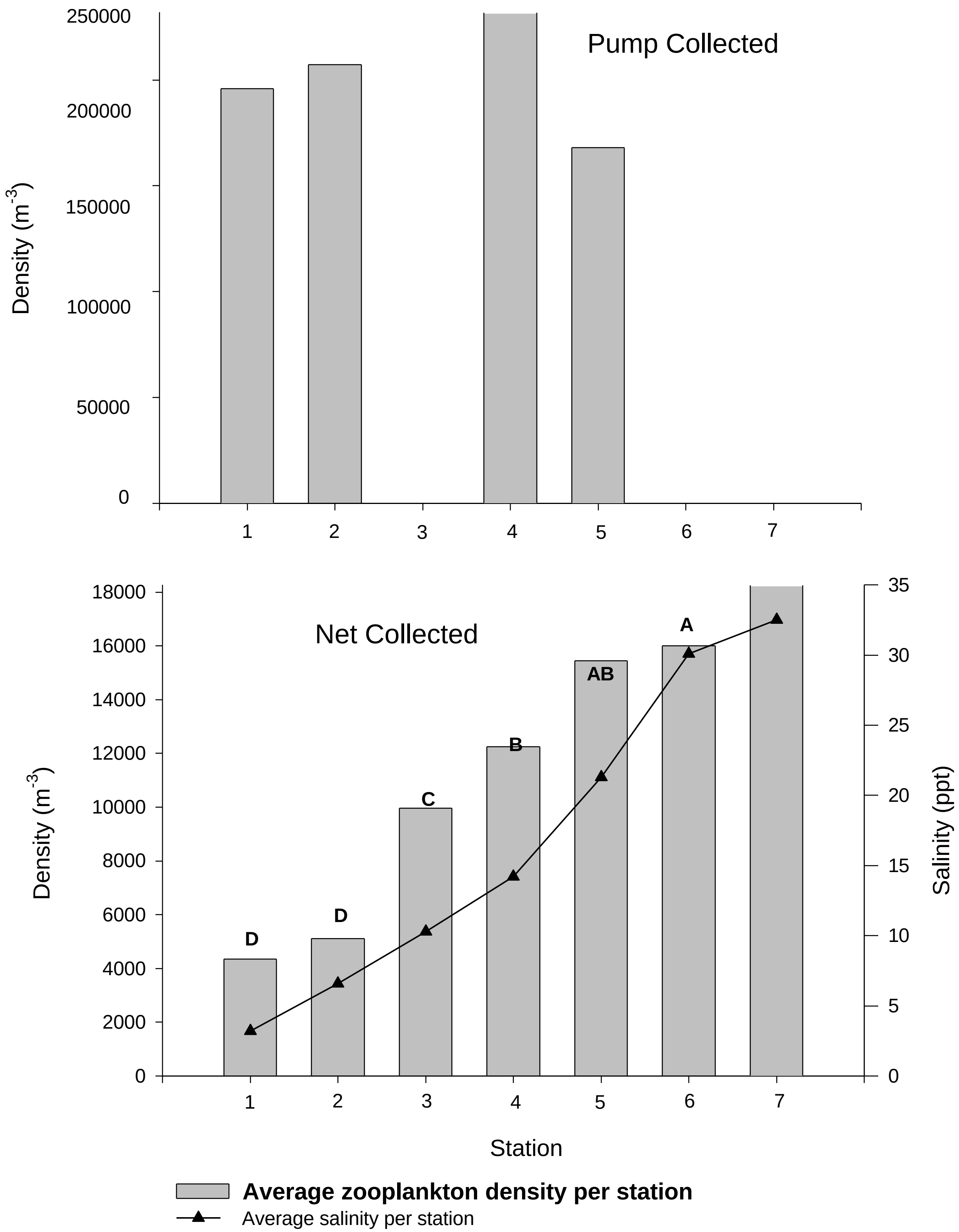

Pump Collected
Density (m-3)
250000
200000
150000
100000
50000
0
1
2
3
4
5
6
7
Net Collected
Density (m-3)
Salinity (ppt)
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
35
30
25
20
15
10
5
0
D
D
C
B
AB
A
Station
Average zooplankton density per station
Average salinity per station

Figure 2

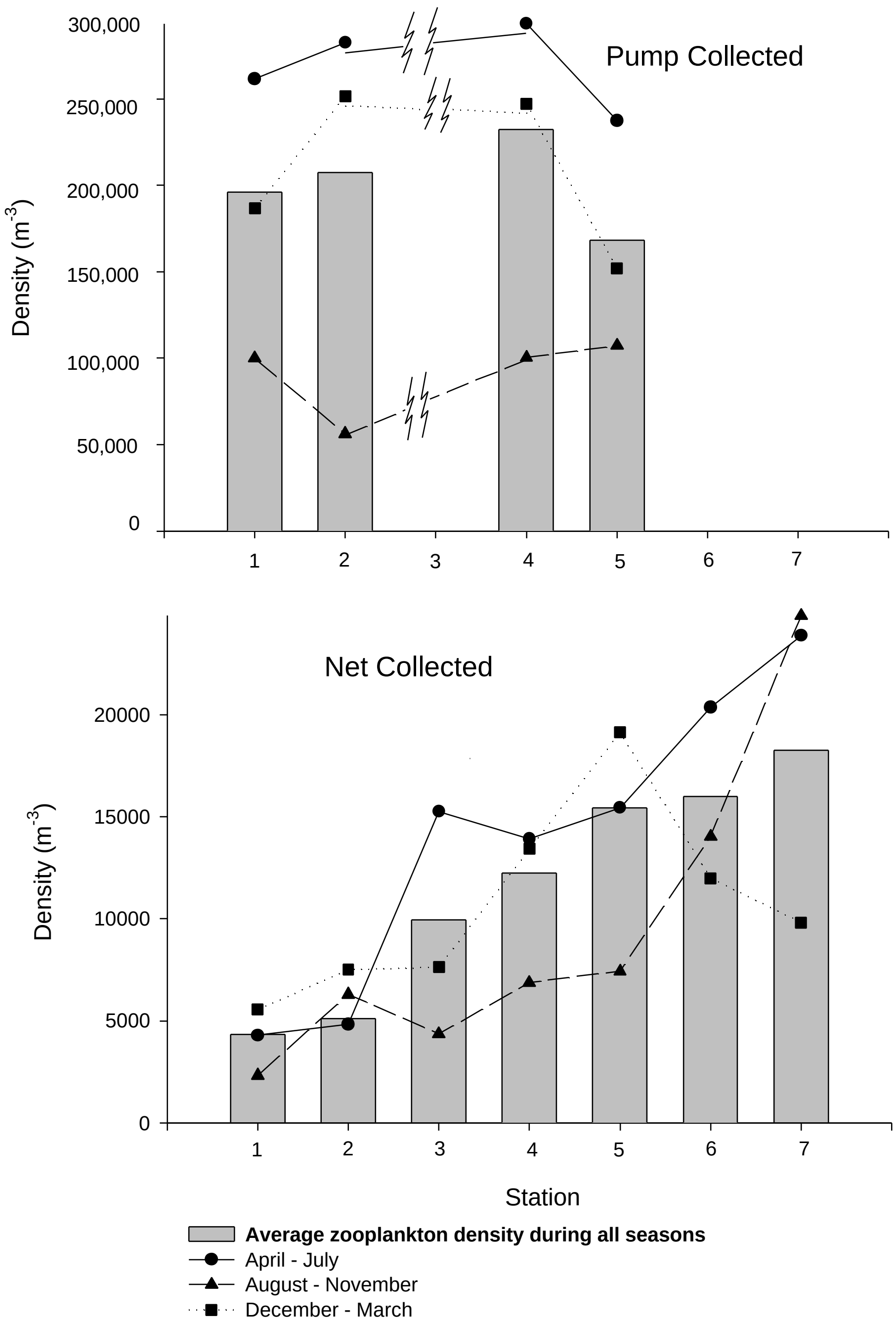
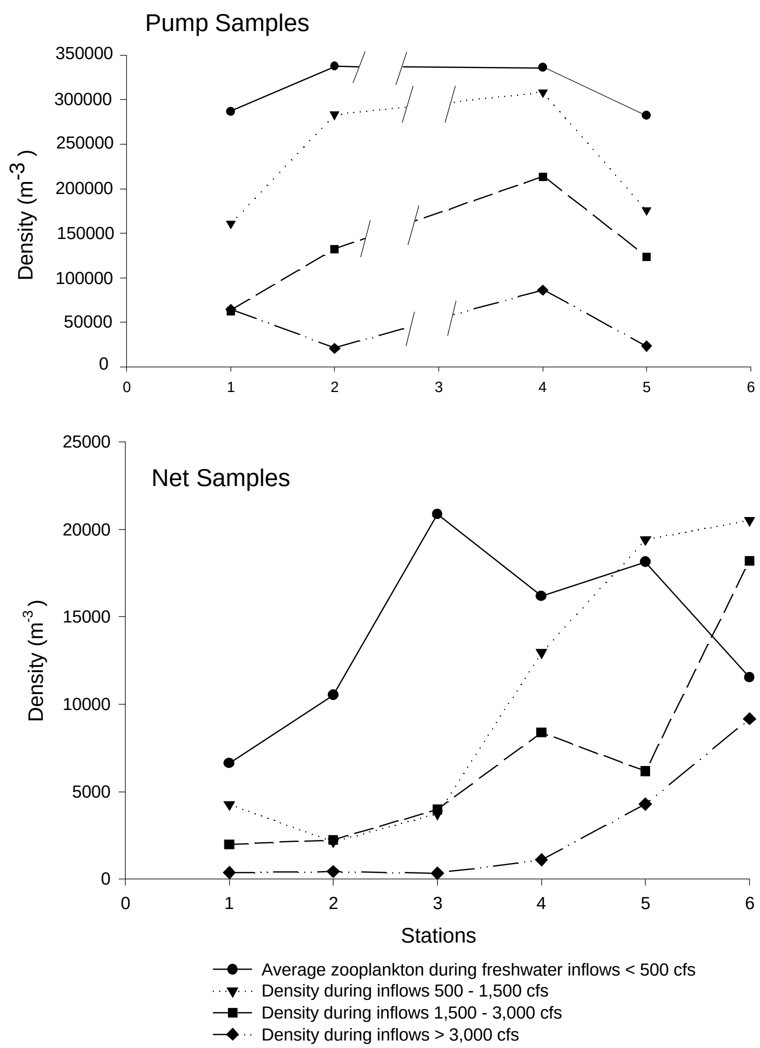

Pump Collected
Density (m-3)
300,000
250,000
200,000
150,000
100,000
50,000
0
1
2
3
4
5
6
7
Net Collected
Density (m-3)
20000
15000
10000
5000
0
Station
Average zooplankton density during all seasons
April - July
August - November
December - March

Figure 3



Pump Samples
Density (m^{-3})
350000
300000
250000
200000
150000
100000
50000
0
0
1
2
3
4
5
6
Net Samples
Density (m^{-3})
25000
20000
15000
10000
5000
0
Stations
Average zooplankton during freshwater inflows < 500 cfs
Density during inflows 500 - 1,500 cfs
Density during inflows 1,500 - 3,000 cfs
Density during inflows > 3,000 cfs

Figure 4

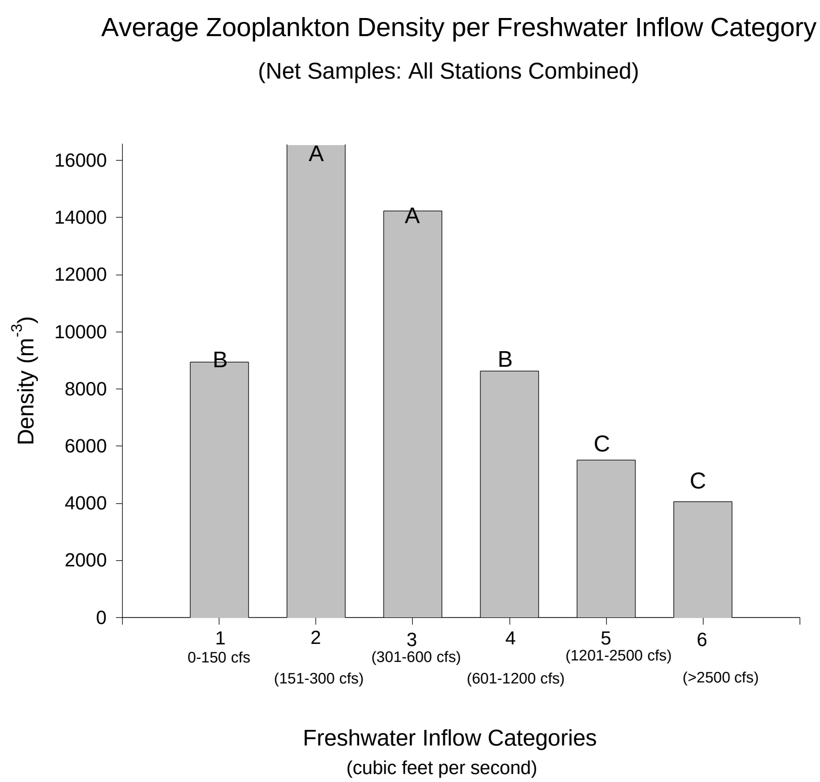

Average Zooplankton Density per Freshwater Inflow Category
(Net Samples: All Stations Combined)
Density (m^{-3})
16000
14000
12000
10000
8000
6000
4000
2000
0
B
A
A
B
C
C
1
0-150 cfs
2
(151-300 cfs)
3
(301-600 cfs)
4
(601-1200 cfs)
5
(1201-2500 cfs)
6
(>2500 cfs)
Freshwater Inflow Categories
(cubic feet per second)

Figure 5

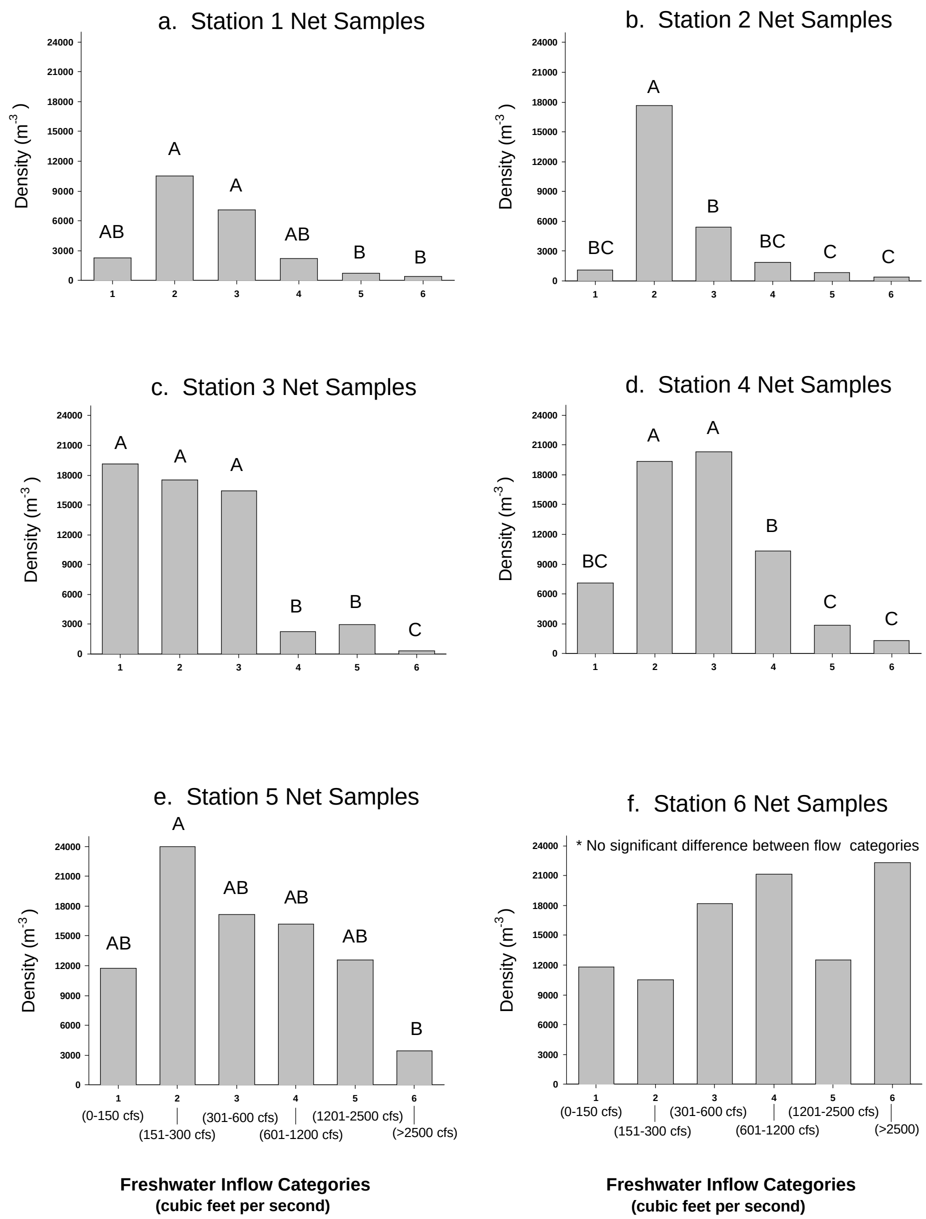

a. Station 1 Net Samples
b. Station 2 Net Samples
c. Station 3 Net Samples
d. Station 4 Net Samples
e. Station 5 Net Samples
f. Station 6 Net Samples
* No significant difference between flow categories
Density (m-3)
(0-150 cfs)
(151-300 cfs)
(301-600 cfs)
(601-1200 cfs)
(1201-2500 cfs)
(>2500 cfs)
Freshwater Inflow Categories
(cubic feet per second)

Figure 6

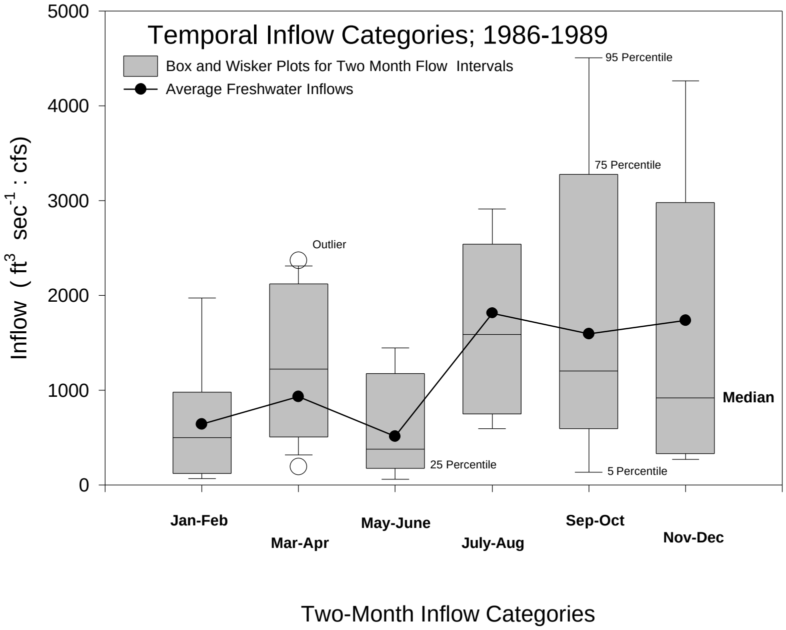

Temporal Inflow Categories; 1986-1989
Box and Wisker Plots for Two Month Flow Intervals
Average Freshwater Inflows
95 Percentile
75 Percentile
Outlier
Median
25 Percentile
5 Percentile
Inflow (ft3 sec-1 : cfs)
5000
4000
3000
2000
1000
0
Jan-Feb
Mar-Apr
May-June
July-Aug
Sep-Oct
Nov-Dec
Two-Month Inflow Categories

Figure 7

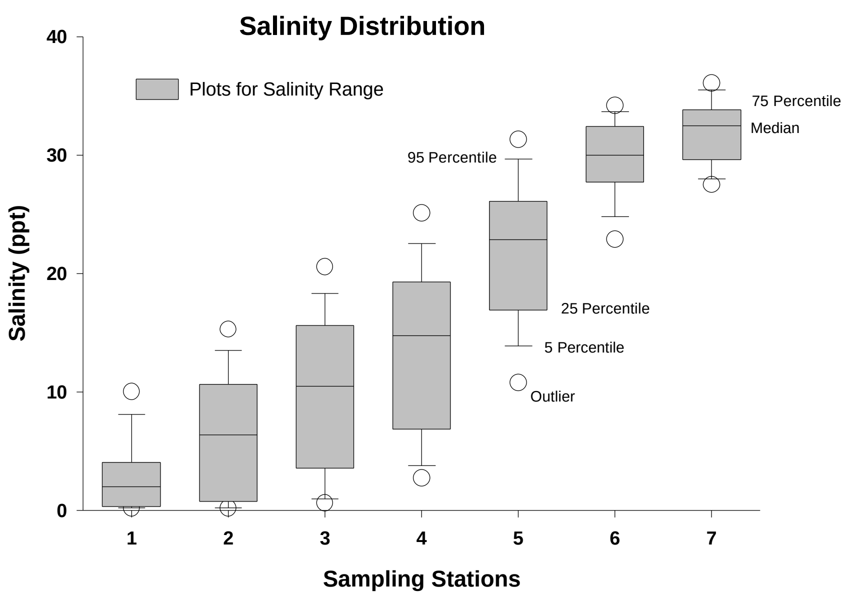

Salinity Distribution
Plots for Salinity Range
Salinity (ppt)
0
10
20
30
40
1
2
3
4
5
6
7
Sampling Stations
95 Percentile
75 Percentile
Median
25 Percentile
5 Percentile
Outlier

Figure 8

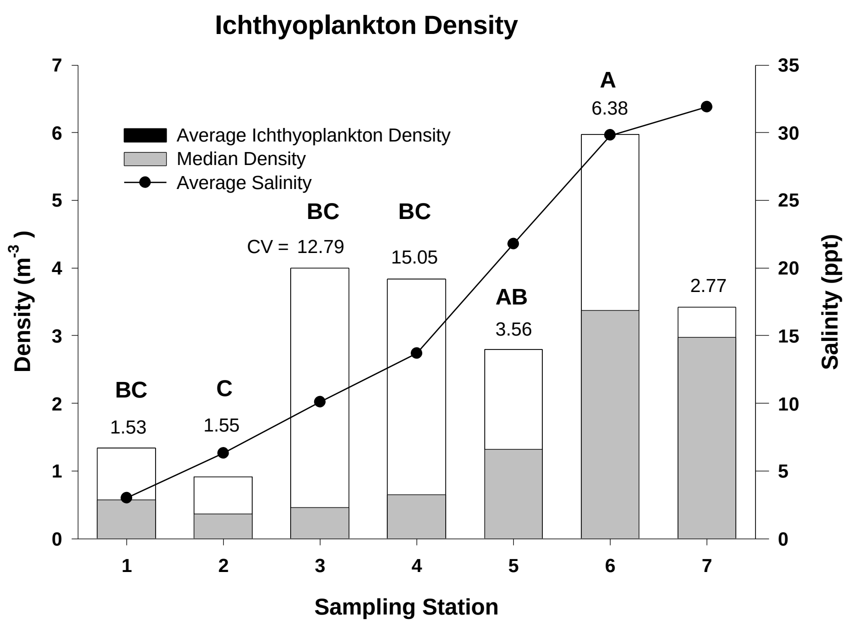

Ichthyoplankton Density
Average Ichthyoplankton Density
Median Density
Average Salinity
Density (m-3)
Salinity (ppt)
Sampling Station
0
1
2
3
4
5
6
7
0
5
10
15
20
25
30
35
BC
1.53
C
1.55
BC
CV = 12.79
BC
15.05
AB
3.56
A
6.38
2.77

Figure 9

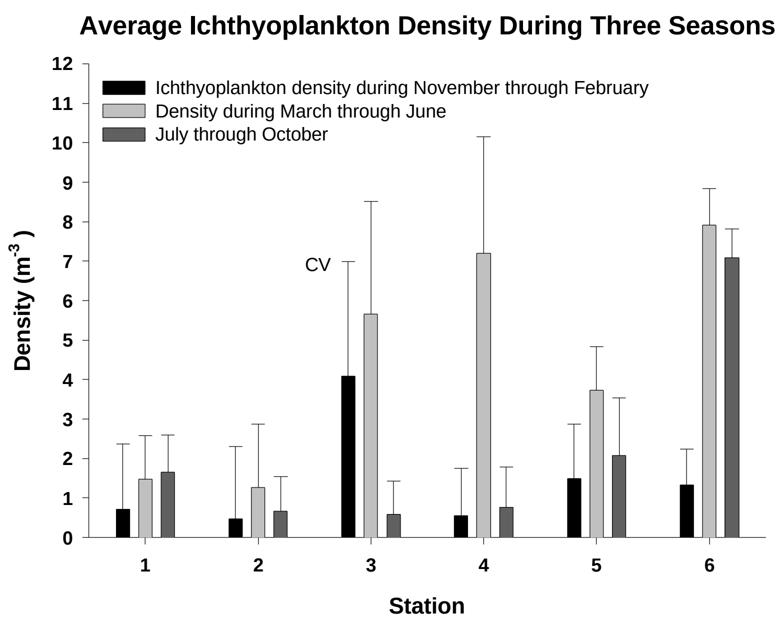

Average Ichthyoplankton Density During Three Seasons
Ichthyoplankton density during November through February
Density during March through June
July through October
CV
Density (m-3)
Station
0
1
2
3
4
5
6
7
8
9
10
11
12
1
2
3
4
5
6

Figure 10

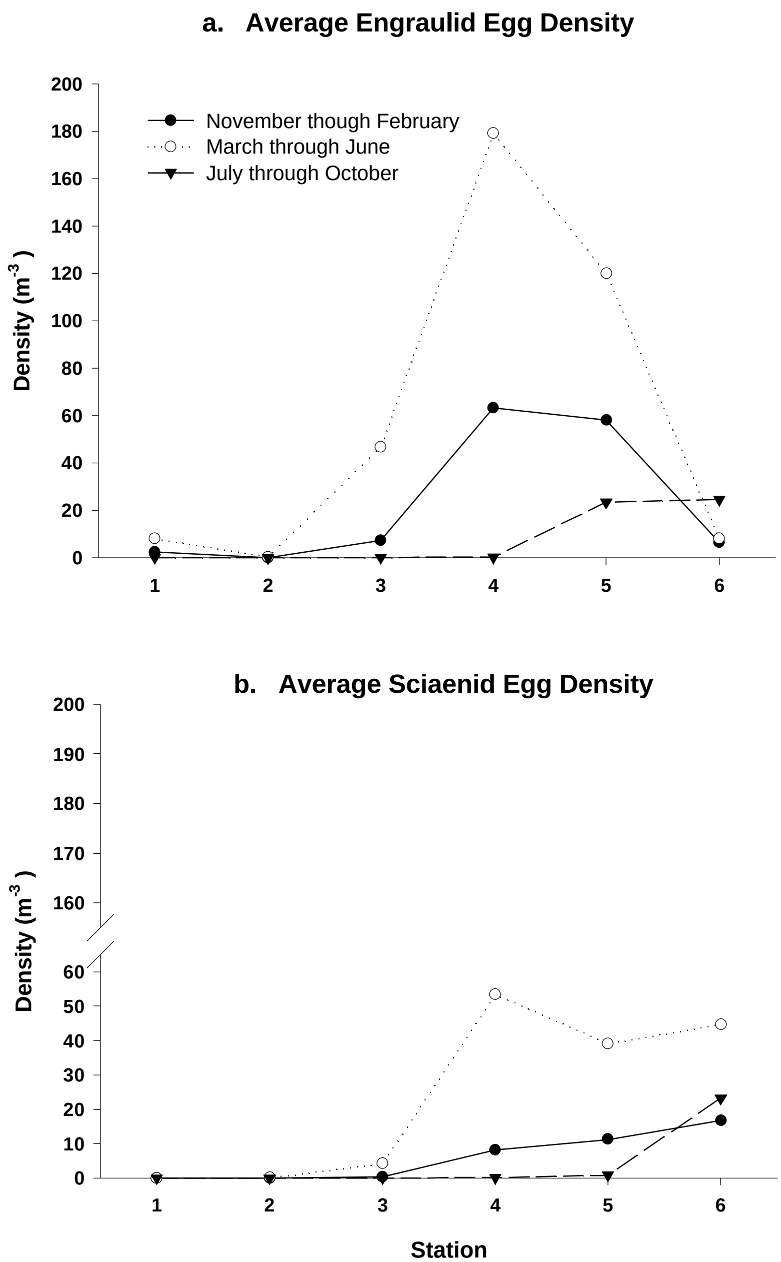

a. Average Engraulid Egg Density
200
180
160
140
120
100
80
60
40
20
0
Density (m-3)
November though February
March through June
July through October
1
2
3
4
5
6
b. Average Sciaenid Egg Density
200
190
180
170
160
60
50
40
30
20
10
0
Density (m-3)
1
2
3
4
5
6
Station

Figure 11

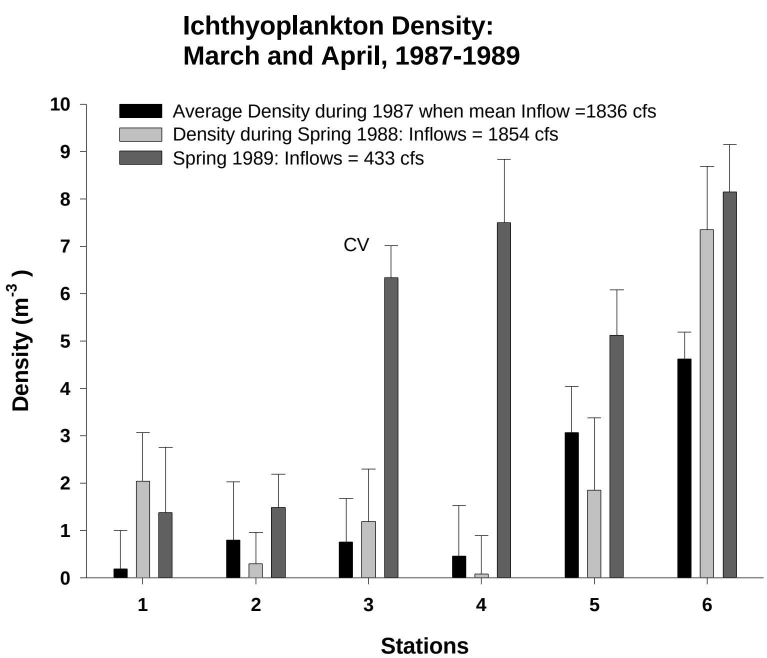

Ichthyoplankton Density:
March and April, 1987-1989
Average Density during 1987 when mean Inflow =1836 cfs
Density during Spring 1988: Inflows = 1854 cfs
Spring 1989: Inflows = 433 cfs
CV
Density (m-3)
Stations
0
1
2
3
4
5
6
7
8
9
10

Figure 12

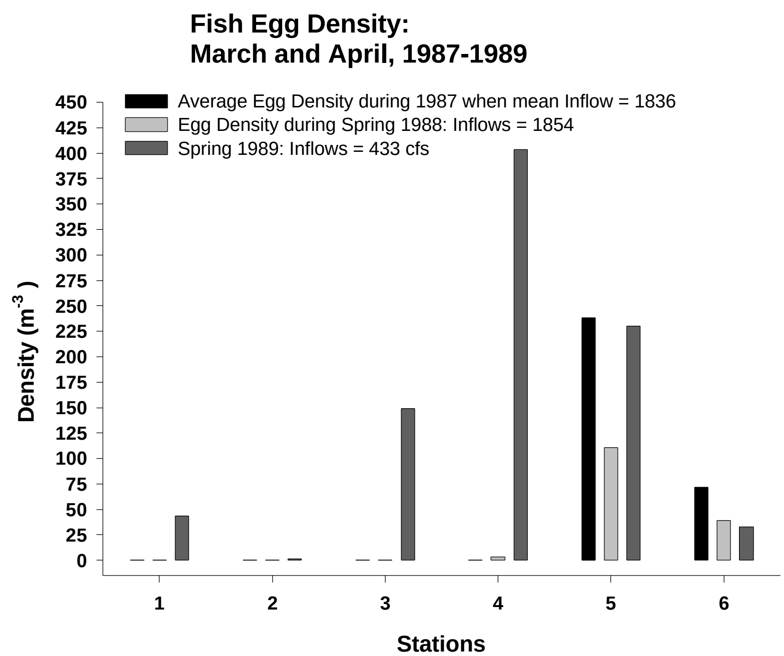

Fish Egg Density:
March and April, 1987-1989
Average Egg Density during 1987 when mean Inflow = 1836
Egg Density during Spring 1988: Inflows = 1854
Spring 1989: Inflows = 433 cfs
Density (m-3)
450
425
400
375
350
325
300
275
250
225
200
175
150
125
100
75
50
25
0
1
2
3
4
5
6
Stations

Figure 13

Technical Documentation to Support Development of Minimum Flows and Levels for the Caloosahatchee River and Estuary

Appendix D

Salinity Tolerance of Vallisneria and Salinity Criteria

P.H. Doering

Contents

Florida Bay and Lower West Coast Division
Southern District Restoration Department
South Florida Water Management District

January 2003

Salinity Tolerance of *Vallisneria* and Salinity Criteria

Introduction

The Caloosahatchee MFL rule includes two salinity criteria. An exceedance occurs (1) if the 30-day moving average salinity at Ft Myers exceeds 10 ppt and (2) if a single daily average salinity exceeds 20 ppt. The research program initiated in response to the scientific peer review has generated new laboratory and field data on the salinity tolerance of *V. americana.* In this report data are analyzed to determine if these threshold salinities are still supported. The technical criteria also state that a flow of 300 cfs is necessary to maintain Vallisneria in the upper estuary. Data from our field monitoring program are analyzed to determine if this flow is supported.

Methods

Salinity Tolerance of Vallisneria

Salinity tolerance was determined both from an analysis of monitoring of field populations and from laboratory mesocosm experiments designed to measure the effects of salinity on growth and mortality. Detailed descriptions of laboratory methods may be found in Doering et al. 1999, Doering and Chamberlain 2000, and Doering et al. 2001. A brief description appears below.

V. americana collected from the Caloosahatchee, was planted in rectangular tubs (14 cm H x 24 cm L x 15 cm W) containing sediment from the site of collection. Initially, tubs contained 4 to 8 shoots. Tubs and plants were distributed among ten cylindrical mesocosm tanks (1.3 m in diameter x 1 m deep, n=4 to 6 tubs/tank depending on the experiment) filled with water to a depth of 60 cm (volume=800 l). The tanks were located indoors at an aquarium facility at the Gumbo Limbo Nature Center in Boca Raton, FL. A 1000 Watt metal halide lamp, kept on a L:D photoperiod of 12:12 h, supplied light to each tank.

A given salinity was maintained by mixing appropriate volumes of fresh and salt water (total volume=114 l) from each of two head tanks located above each mesocosm. Head tanks were alternately filled and emptied into the mesocosms using solenoid valves controlled by timers. Thus, water was delivered to the mesocosms in a series of 114-liter pulses. Water in the mesocosms was replaced 3 times daily. Salt water was pumped from the Atlantic Ocean. Tap water, passed through a series of activated charcoal towers and filters (20 micron pore size) to remove chlorine, was used as a source of fresh water.

The net growth data summarized in this report was collected during 4 experiments conducted between 1996 and 2001 (**Table D-1**). Plants were exposed to constant salinity treatments (n=two mesocosms per treatment) for periods of 3 to 10 weeks. The exact salinity treatments depended on whether the purpose of the experiment was to measure growth at low salinity or tolerance to high salinity. Numbers of blades and shoots were counted on a weekly basis. These weekly measurements were used to determine net (production – loss) rates of blade and shoot growth. Data taken on a given day in each mesocosm were averaged across tubs, yielding two data points per treatment per week of the experiment. Net growth was modeled using the exponential growth equation (Nt = N0ert) were N0 is the number of blades or shoots at the beginning of exposure and Nt is the number after t days.

A program to *monitor V. americana* on a monthly basis at Stations 1 - 4 (**Figure D-1**) was instituted in 1998. At each station, a pair of 100-m transects (one parallel to shore, one perpendicular to shore) was established at two sites. On each sampling date the number of blades and shoots was counted in 5 0.1 m^2 quadrats placed randomly along each transect (n=5 quadrats per transect, n=10 quadrats per site, n=20 quadrats per station). A detailed analysis of the first year of data may be found in Bortone and Turpin (2000). Data reported here encompass the time period January 1998 – April 2001.

Both field and laboratory data were used to select tolerable salinity thresholds that could be used to calculate minimum and maximum flows (see above). Field salinity tolerances were identified from plots of plant density as a function of salinity on the day of sampling. Tolerable, threshold salinities were those associated with marked or rapid changes in plant density. Laboratory data were examined to identify a range of salinity where growth was low, and close to zero. Using non-linearities to identify thresholds is common in methods used to determine flow requirements for streams and rivers (Estevez 2000b).

Results

Salinity Tolerance of *Vallisneria*

For *V. americana*, the net growth rates of shoots and blades in the laboratory decreased as salinity increased, with mortality occurring at salinities greater than 15 o/oo (**Figure D-2**). At 18 o/oo a 50% loss of shoots would occur in 38 days. At 20 o/oo a 50% loss would occur in 16 days. In the region between 10 o/oo and 15 o/oo , the change in growth in response to a change in salinity was very small. This lack of response was especially evident for the number of blades: growth rates at 10 o/oo and 15 o/oo were virtually identical. In this zone, plants survived but net growth rates of shoots and blades were low and relatively unchanging.

Data from field monitoring agreed well with results from the laboratory (**Figure D-3**, upper panel). The distribution of points in the four quadrants defined by the reference lines on the graph of shoot density and salinity may be treated as cells in a 2 x 2 contingency table. Higher densities in the field (> 400 shoots m-2) occurred at salinities less than about 10 o/oo. Lower densities (< 400 shoots m-2) were more frequent at salinities above 10 o/oo (**Figure D-3,** upper panel, $X2 = 4.53$, $p<0.05$).

Effect of Discharge on Density of Plants in the Field

To investigate the potential effects of discharge on *Vallisneria* in the upper estuary, plant density data collected during the monitoring program was plotted as a function of the average discharge at S-79 for the 30 days prior to sampling. Field monitoring data indicated that higher shoot densities (> 400 m-2) occur at 30-day average discharges greater than 8.5 m3 sec-1 (300 cfs) (**Figure D-5**, $X2 = 7.98$, $p<0.01$).

Discussion

The use of marine and estuarine SAV for management purposes appears to be a well-accepted practice (Batiuk et al. 1992; Dennison et al. 1993; Stevenson et al. 1993; Tomasko et al. 1996; Johansson and Greening 2000; Virnstein and Morris 2000). This stems in part from their sensitivity to pollutants of interest (e.g. nutrients, Tomasko et al. 1996) and in part from their ecological significance.

Although *V. americana* is considered a freshwater species, it is salt tolerant. Salinity tolerances of *V. americana* reported in the literature vary (Doering et al. 1999). Bourn (1932; 1934) found that growth declined with increasing salinity until it ceased at 8.4 $^{o}/_{oo}$. Haller et al. (1974) reported growth at 3.33 $^{o}/_{oo}$, no growth at 6.66 $^{o}/_{oo}$ or 10 $^{o}/_{oo}$ and death at 13.3 $^{o}/_{oo}$. After 5 weeks, Twilley and Barko (1990) found no effect of salinity on growth over the range 0 $^{o}/_{oo}$ to 12 $^{o}/_{oo}$. Our laboratory results suggest that for V. americana from the Caloosahatchee, growth is low or nil in the 10 $^{o}/_{oo}$ – 15 $^{o}/_{oo}$ range with mortality occurring at salinities greater that 15 $^{o}/_{oo}$. This agrees well with transplant experiments conducted in the Caloosahatchee that indicated mortality at salinities greater than 15 $^{o}/_{oo}$ (Kraemer et al. 1999). Adair et al. (1994) found the distribution of V. americana in Trinity Bay, Texas limited to salinities less than 10 $^{o}/_{oo}$. In outdoor mesocosm experiments, French (2001) observed minimal growth of Vallisneria from the Chesapeake Bay at 10 $^{o}/_{oo}$ and 15 $^{o}/_{oo}$.

The combination of results from field monitoring and laboratory experiments conducted by District and other investigators agree that 10 o/oo is a critical threshold salinity for growth. The thirty day averaging period is consistent with laboratory experiments which show that Vallisneria can survive exposure to 10 o/oo for periods exceeding a month (Doering et al. 1999; French 2001).

The daily average salinity limit of 20 o/oo was included in the rule to avoid acute exposure to high salinity. Laboratory experiments (1/5/1998, Table 1) showed that mortality occurs after a 20 day exposure to 18 o/oo . Shorter exposure (1, 5, or 11 days) retarded growth but did not cause mortality (Doering et al. 2001). Recently completed experiments (5/20/2001, Table 1) suggest that a 50 % loss of shoots would occur after 16 days of exposure to 20 o/oo. At the earliest, mortality began after 3 days exposure to 20 ppt (One-way ANOVA, $p<0.05$, **Figure D-4**). Therefore, a one day exposure to 20 ppt appears to be a reasonable limit for acute exposure.

Mean monthly flows less than 300 cfs are associated with low densities in the field (**Figure D-3**). These monitoring data indicate that 300 cfs should maintain Vallisneria in the upper Caloosahatchee estuary.

Acknowledgements

For all the help in the laboratory and field the authors thank Callie McMunigal, Matthew Crane and George Jones from Florida Atlantic University, Keith Donohue and Michael McMunigal from Harbor Branch Oceanographic Institution, and Kathleen Haunert and Julian DiGialleonardo from the South Florida Water Management District.

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Table 1. Summary of salinity tolerance experiments conducted with *Vallisneria americana*. Date refers to the beginning of an experiment. Exposure refers to the number of days plants were exposed to a given constant salinity treatment ($^0/_{00}$).

Species	**Date**	**Salinity Treatments ($^0/_{00}$)**	**Exposure (Days)**
Vallisneria	3/1/1996	0, 3, 9, 12, 15	43
	7/11/1996	0, 3, 9, 12, 15	43
	1/5/1998	18	20, 30, 50, 70
	5/20/2001	3, 10, 20, 25, 30	36

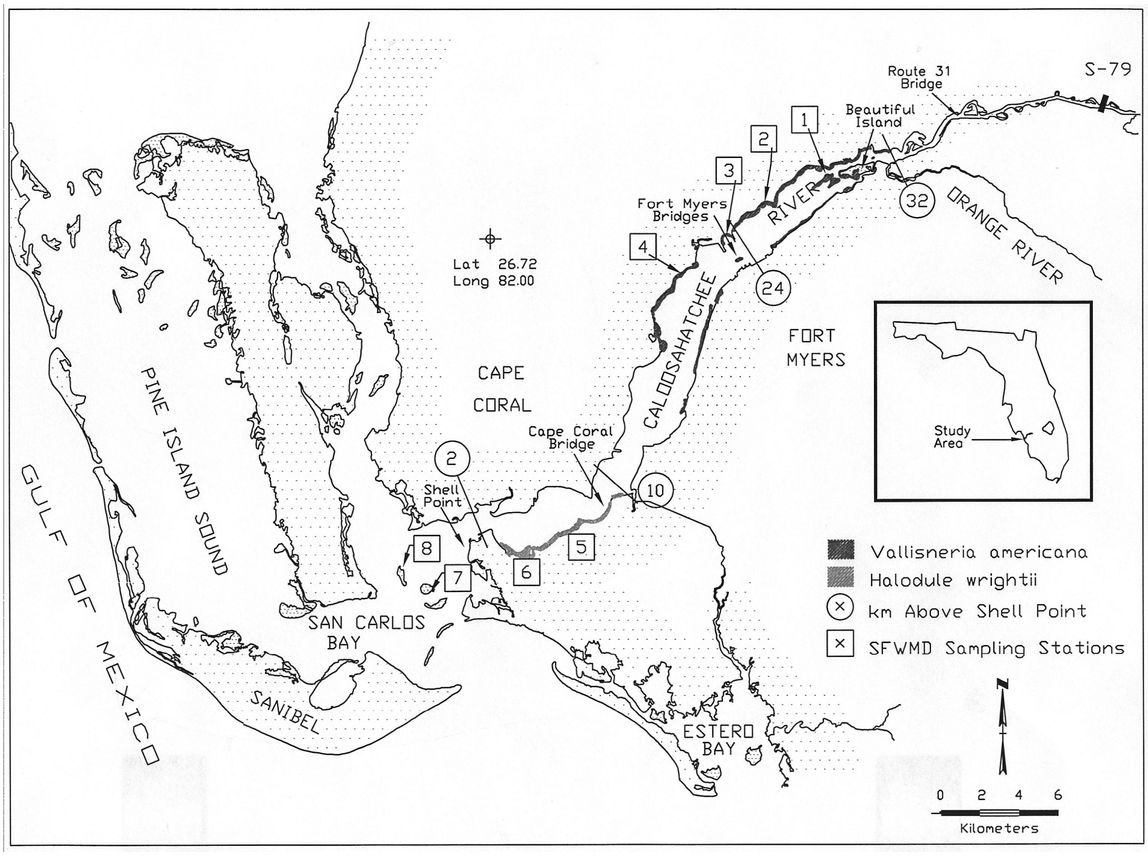


Figure D-1. Distribution of Vallisneria americana and Halodule wrightii in the Caloosahatchee Estuary. Also shown are the locations of grass bed monitoring stations and the general locations of salinity recorders at S-79, Rt. 31 Bridge, Fort Myers Bridges, and Shell Point.

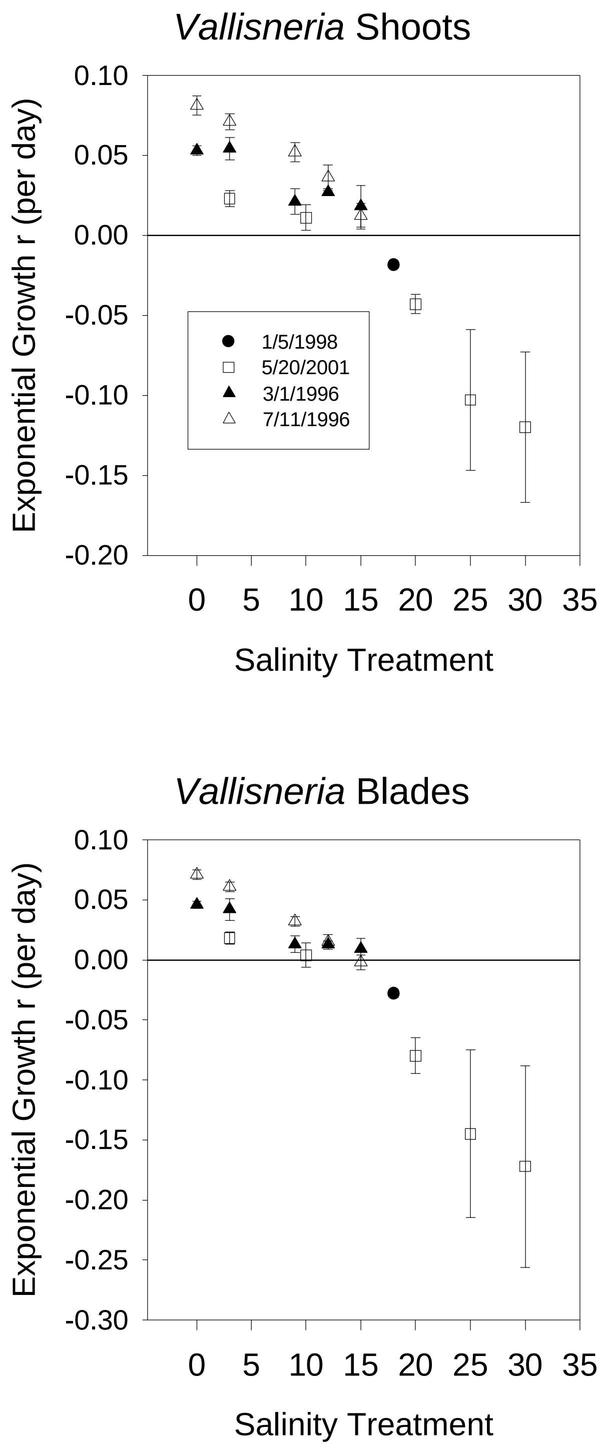
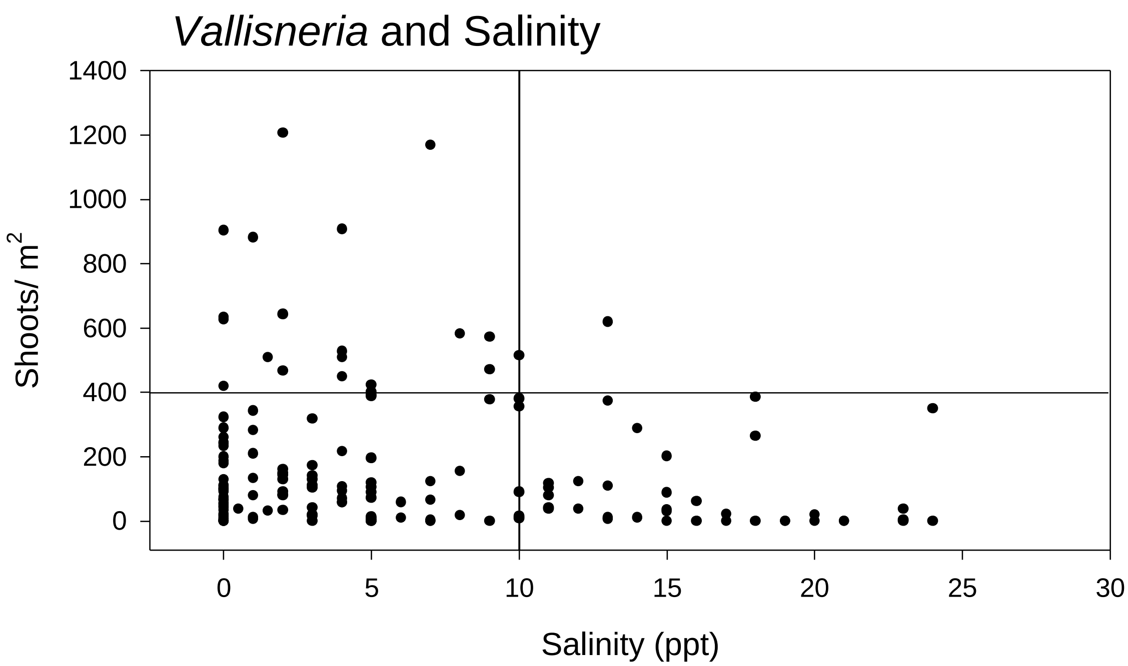


Figure D-2. Net exponential growth rates (r ± 95% C.I.) of Vallisneria americana measured in laboratory mesocosms during constant exposure to different salinities. A negative value of r indicates mortality.



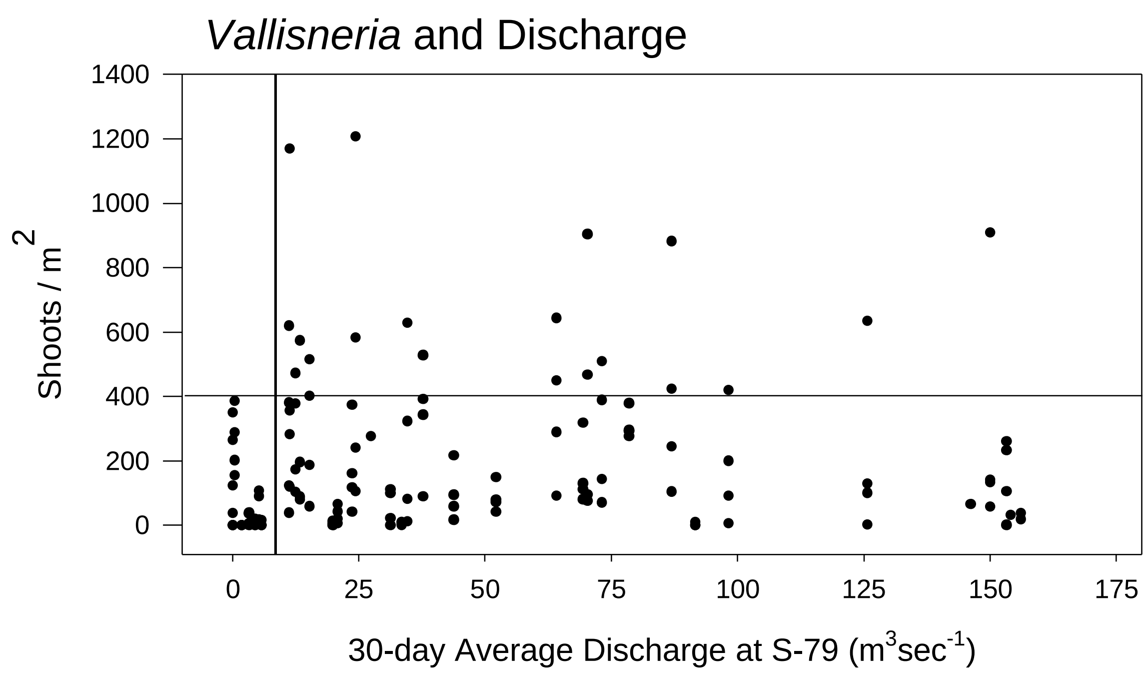


Figure D-3. Shoot density of Vallisneria americana at monitoring stations 1, 2, 3 and 4 as a function of salinity on the day of collection (top panel) and average discharge at S-79 for the 30 days prior to the day of collection (bottom panel).

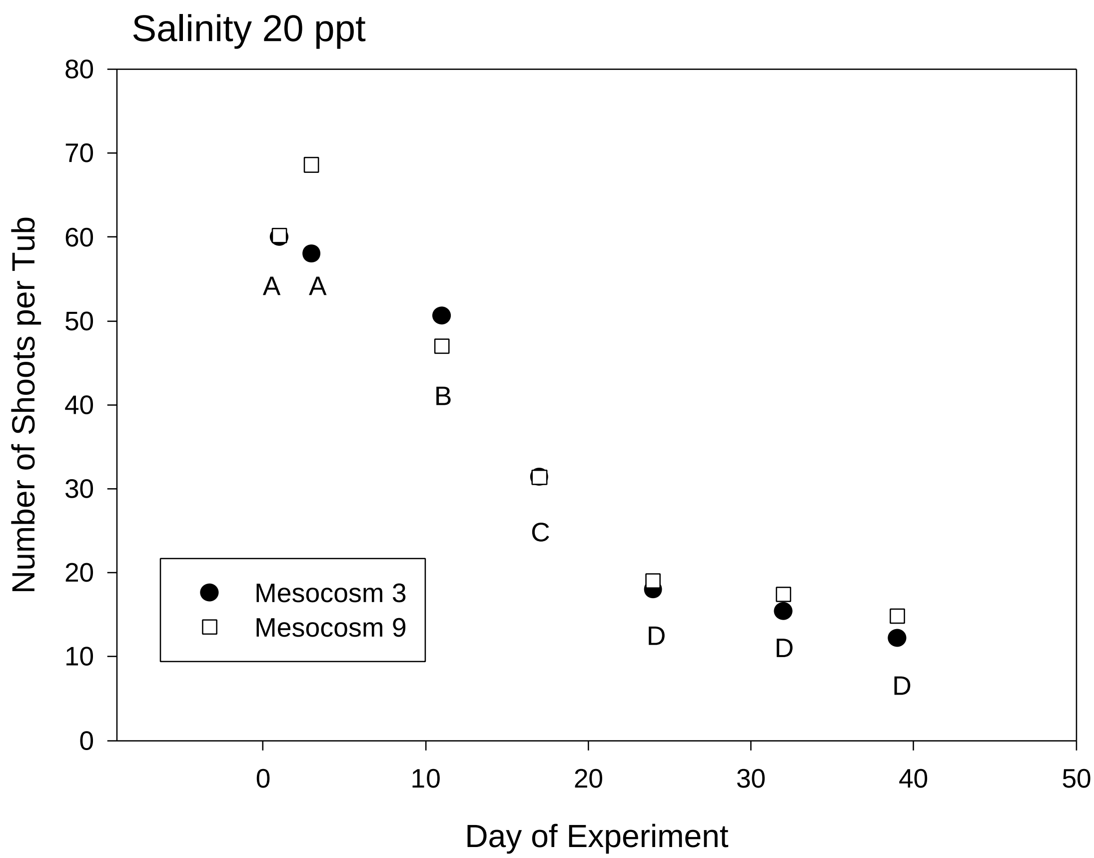


Figure D-4. Average number of shoots per tub in two replicate mesocosms exposed to 20 ppt. Letters indicate results of a comparison of daily means using the Student -Newman-Keuls test. Days with different letters are statistically different ($p<0.05$).

Technical Documentation to Support Development of Minimum Flows and Levels for the Caloosahatchee River and Estuary

Appendix E

DRAFT

CERP Projects in the C-43 Basin

Contents

South Florida Water Management District

January 2003

CERP Projects in the C-43 Basin

Caloosahatchee River (C-43) Basin Aquifer Storage and Recovery -Pilot Project (2008)

Project Description: Aquifer Storage and Recovery wells are proposed in order to maximize the benefits associated with the Caloosahatchee River Storage Reservoir. A pilot project for these wells is necessary to identify the most suitable sites for the aquifer storage and recovery wells in the vicinity of the reservoir and to determine the optimum configuration of those wells. The pilot project will provide information regarding the characteristics of the aquifer system within the Caloosahatchee River Basin as well as determine the hydrogeological and geotechnical characteristics of the upper Floridan Aquifer. The pilot project will also determine the specific water quality characteristics of waters to be injected, the specific water quality characteristics and the amount of water recovered from the aquifer, and the water quality characteristics of water within the receiving aquifer.

Caloosahatchee Back-pumping with Stormwater (2014) Treatment Project

Project Description: This project includes pump stations and a stormwater treatment area with a total capacity of approximately 20,000 acre-feet located in the C-43 Basin in Hendry and Glades Counties. The initial design of the stormwater treatment area assumed 5,000 acres with the water level fluctuating up to 4 feet above grade. The final size, depth and configuration of this facility will be determined through more detailed planning and design. The purpose of this feature is to capture excess C-43 Basin runoff, which will be used to augment regional system water supply. Backpumping will only occur after estuary and agricultural/urban demands have been met in the basin and when water levels in the C-43 storage reservoir exceed 6.5 feet above grade. Further, Lake Okeechobee water levels must be within a a specified range to accept this water so as to not impact ecological resources. When these conditions are met, a series of pump stations will back-pump excess water from the reservoir and the C-43 Basin to Lake Okeechobee after treatment through a stormwater treatment area. The stormwater treatment area will be designed to meet Lake Okeechobee phosphorus and other pollutant loading reduction targets consistent with the Surface Water Improvement and Management Plan for the Lake and future appropriate pollution load reduction targets which may be developed for the Lake and the watershed in which the facility is to be located.

C-43 Basin Storage Reservoir Project, Part 1 (2011)

Project Description: This project is the first part of the C-43 Basin Storage Reservoir and ASR component. The project includes an above ground reservoir with a total storage capacity of approximately 160,000 acre-feet located in the C-43 Basin in Hendry, Glades, or Lee Counties. The initial design of the reservoir assumed 20,000 acres with water levels fluctuating up to 8 feet above grade. The final size, depth and configuration of this facility will be determined through more detailed planning and design. The purpose of this project is to capture C-43 Basin runoff and releases from Lake Okeechobee. The reservoir will be designed for water supply benefits, some flood attenuation, to provide environmental water supply deliveries to the Caloosahatchee Estuary, and water quality benefits to reduce salinity and nutrient impacts of runoff to the estuary. It is assumed that, depending upon the location of the reservoir and pollutant loading conditions in the watershed, the reservoir could be designed to achieve significant water quality improvements, consistent with appropriate pollution load reduction targets. Excess runoff from the C-43 Basin and Lake Okeechobee flood control discharges will be pumped into the proposed reservoir. Lake Okeechobee will meet any estuarine demands, not met by basin runoff as long as the lake stage is above a pre-determined level. Lake water will also be used to meet the remaining basin demands subject to supply-side management. The C-43 reservoir will also be operated in conjunction with the Caloosahatchee Back-pumping project, which includes a stormwater treatment area for water quality treatment. If the level of water in the reservoir exceeds 6.5 feet and Lake Okeechobee is below a pre-determined level, then water is released and sent to the back-pumping facility.

C-43 Basin Aquifer Storage and Recovery Project, (2018) Part 2

Project Description: This project is the second part of the C-43 Basin Storage Reservoir and ASR component. This project includes aquifer storage and recovery wells with a total capacity of approximately 220 million gallons per day and associated pre- and post-water quality treatment located in the C-43 Basin in Hendry, Glades, or Lee Counties. The initial design of the wells assumed 44 wells, each with the capacity of 5 million gallons per day with chlorination for pre-treatment and aeration for post-treatment. The level and extent of treatment and number of the aquifer storage and recovery wells may be modified based on findings from a proposed aquifer storage and recovery pilot project (U.S. Environmental Protection Agency, 1999). The purpose of this project is to capture C-43 Basin runoff and releases from Lake Okeechobee. The wells will be designed for water supply benefits, some flood attenuation, water quality benefits to reduce salinity and nutrient impacts of runoff to the estuary, and to provide environmental water supply deliveries to the Caloosahatchee Estuary. Excess runoff from the C-43 Basin and Lake Okeechobee flood control discharges will be pumped into the C-43 Basin Reservoir. Water from the reservoir will be injected into the aquifer storage and recovery wellfield for long-term (multi-season) storage. Any estuarine demands, not met by basin runoff and the aquifer storage and recovery wells, will be met by Lake Okeechobee as long as the lake stage is above a pre-determined level. Lake water is also used to meet the remaining basin demands subject to supply-side management.

Technical Documentation to Support Development of Minimum Flows and Levels for the Caloosahatchee River and Estuary

Appendix F

Hydrodynamic and Salinity Modeling

Chenxia Qiu, Staff Engineer

Contents

Florida Bay and Lower West Coast Division
Southern District Restoration Department

South Florida Water Management District

January 2003

Hydrodynamic and Salinity Modeling

Chenxia Qiu, Staff Engineer
September 2002

Summary

The MFL update utilized CH3D hydrodynamic and salinity model and a regression model to investigate the salinity distribution in Caloosahatchee River. The Tidal Caloosahatchee basin model was applied to estimate the ground water and tributary input. The steady state simulation confirmed the previous MFL rule. Under current conditions, the 300 cfs at S-79 is matched by an additional 200 cfs or greater of tidal watershed inflow about 50% of the time. At the steady state, the combined flow of 500 cfs produces a salinity of about 10 ppt at Ft. Myers. An assessment of the recommended CERP alternative indicated that modified flows would create desirable salinity levels at Bird Island and Site 2 for the 2020 with Restudy scenario.

Background

A Minimum Flow and Level Rule (MFL) for the Caloosahatchee River and Estuary was adopted in September 2001. Best available information indicted that a mean monthly flow of 300 cfs at the Franklin Lock and Dam was required to maintain sufficient salinity to prevent a 30-day average salinity concentration exceeding 10 parts per thousand (ppt) at the Ft. Myers salinity station.

A peer review of the technical documentation supporting the rule endorsed the general approach. However, the review panel concluded that the uncertainty in the estimate of the needed freshwater inflows was too large but this deficiency could be remedied by further research in key areas. The statistical approach used by the District indicated that 300 cfs would maintain a salinity of about 10 ppt at Ft. Myers. However, the error surrounding this estimate was large (95% confidence ranged 5.4-17.4 ppt). The panel concluded that the statistical approach was flawed and strongly recommended that a mass balance modeling approach be used in predicting salinity and assessing minimum flows (Edwards et al. 2000). They further suggested that a mass balance model of Charlotte Harbor being developed at the University of Florida be used to refine the salinity simulations for the Caloosahatchee Estuary once it is available (Edwards et al. 2000).

The simulation of Caloosahatchee River MFL update utilized partial deliverables from the above project. The Caloosahatchee River portion of the Charlotte Harbor Model was further calibrated to derive the relationships between the fresh water discharge and the distribution of salinity.

The original technical documentation of the Caloosahatchee MFL concluded that under present conditions, the MFL could not be met. The recovery strategy for attaining the MFL relies on construction projects to be completed by CERP. An additional goal of the modeling effort was to predict the effect of CERP projects on salinity in the downstream estuary.

Modeling Approach – CH3D Model & Regression Model

The salinity model for Caloosahatchee River was developed from a CH3D Charlotte Harbor model (Sheng, 2002), a 3-dimensional fully coupled hydrodynamic and salinity model on curvilinear grids. The Charlotte Harbor model was calibrated using data collected during the summer of 1986 at 6 stations located in Pine Island Sound and around the Peace River in Charlotte Harbor. The hydrodynamic model was calibrated with a 2 months of data, while the salinity model was calibrated with a 2 weeks of data. The Caloosahatchee and San Carlos Bay portion of the model were not calibrated.

This study calibrated the Caloosahatchee River portion of the model using a 2.5 months period of data, collected every 15 minutes at five stations. Equilibrium relationships between fresh water discharge and salinity in the estuary were derived from a series of steady state simulations. In turn, a regression model was constructed based on these salinity discharge relationships. The regression model was calibrated with a 10-year period of salinity records at Bridge 31 (BR31) and Ft. Myers, as well as a 6-month record at Bird Island.

CH3D model

The CH3D model is three-dimensional and employs curvilinear grids. The model simulates time-dependent circulation in estuaries, lakes, and coastal waters. It solves the three-dimensional equations of motion in a non-orthogonal boundary-fitted coordinate system with given computational domain, initial conditions, and boundary conditions. For the present application to the Charlotte Harbor estuarine system, the model solves the conservation equations for the following hydrodynamic variables: surface elevation, 3-D velocities, salinity, and density. The detailed model equations and description can be found in Sheng (1987, 1989, and 2001).

Description of the grid

The computational grid and bathymetry used for the Caloosahatchee River and Charlotte Harbor estuarine system are shown in **Figure F-1**. It contains 145 by 225 horizontal cells and 8 vertical layers. This grid was generated using a grid generation program originally developed by Thompson (1985). The depth information was based on the raw data obtained from the Geophysical Data System of the National Geophysical Data Center. Bathymetry for navigation channels in San Carlos Bay and the vicinity of Sanibel Causeway were based on the latest data provided by Lee County in December 1999. The depths were converted to NAVD88 datum level with 12 benchmarks near Charlotte Harbor. The model has intensive grids, extending from the north at Charlotte Harbor to the south at Estero Bay. It has eight tributary inflows with four rivers in Estero Bay, 3 rivers in Charlotte Harbor and 1 river in San Carlos Bay. Total grid is about 130,000 with horizontal grids 32,000 and 8 vertical layers. The smallest grid cell is about 100 to 150 m. The model extends to the Gulf of Mexico eliminating the boundary effects (**Figure F-1**).

Figure F-2 is the detailed view of Caloosahatchee River portion and the location of monitoring stations. The bathymetry was modified based on the cross-section profile data from Scarlatos (1988).

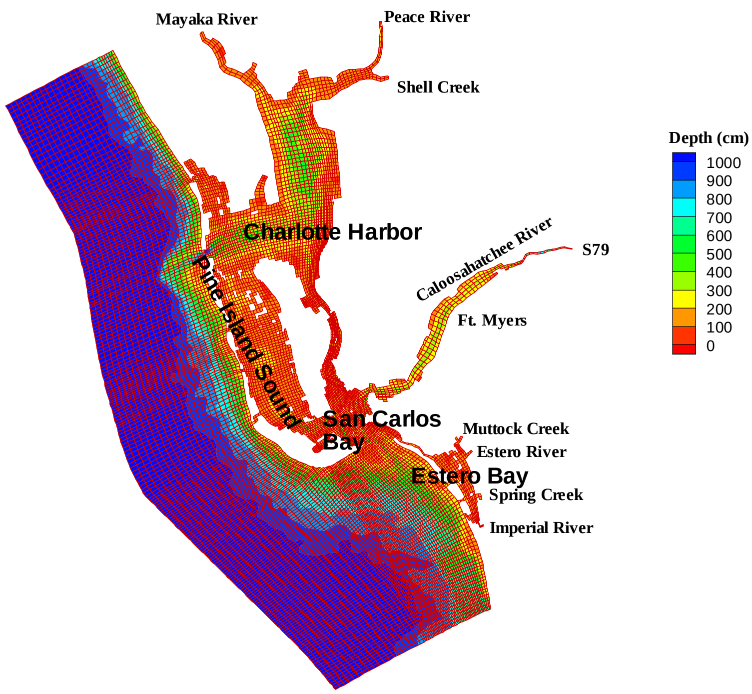


Figure F-1 Computation grid and bathymetry

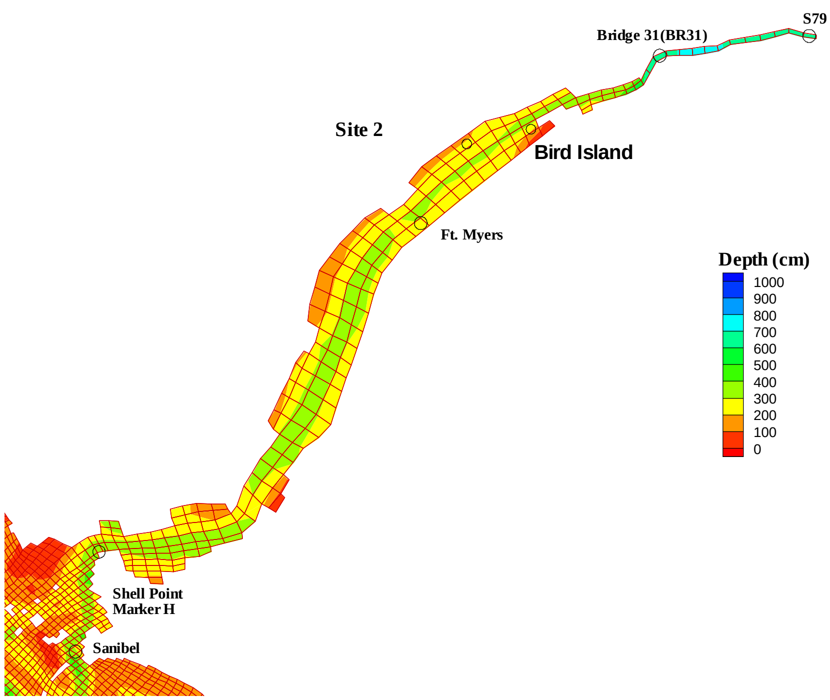


Figure F-2. Bathymetry on Caloosahatchee River and location of monitoring stations -- **Salinity monitoring stations:** S79, Bridge 31 (BR31), Ft. Myers, Shell Point (Marker H) and Sanibel; **Seagrass monitoring stations:** Bird Island and Site 2.

Model calibration

Description of the calibration scenario

The calibration encompassed the dry season period from October 15th to December 31th 2000. The calibration data set was composed of 2 water surface elevation monitoring stations and 5 salinity stations. The water surface elevation stations are located at Shell Point (maintained by the district), and Ft. Myers (maintained by NOAA). Five (5) salinity monitoring stations are located at S79, Bridge 31 (BR31), Ft. Myers, Shell Point (Marker H), and Sanibel. The tidal boundary condition was derived from Shell Point water surface elevation monitoring data. The driving forces included freshwater discharge at S-79, tide, wind, rainfall and evaporation.

Calibration results

Figure F-3 shows the calibration of water surface elevation at Shell Point: the downstream boundary of the Caloosahatchee estuary. The solid line is the model result, and the dotted line is the monitoring data. The modeling results are close to the monitoring data.

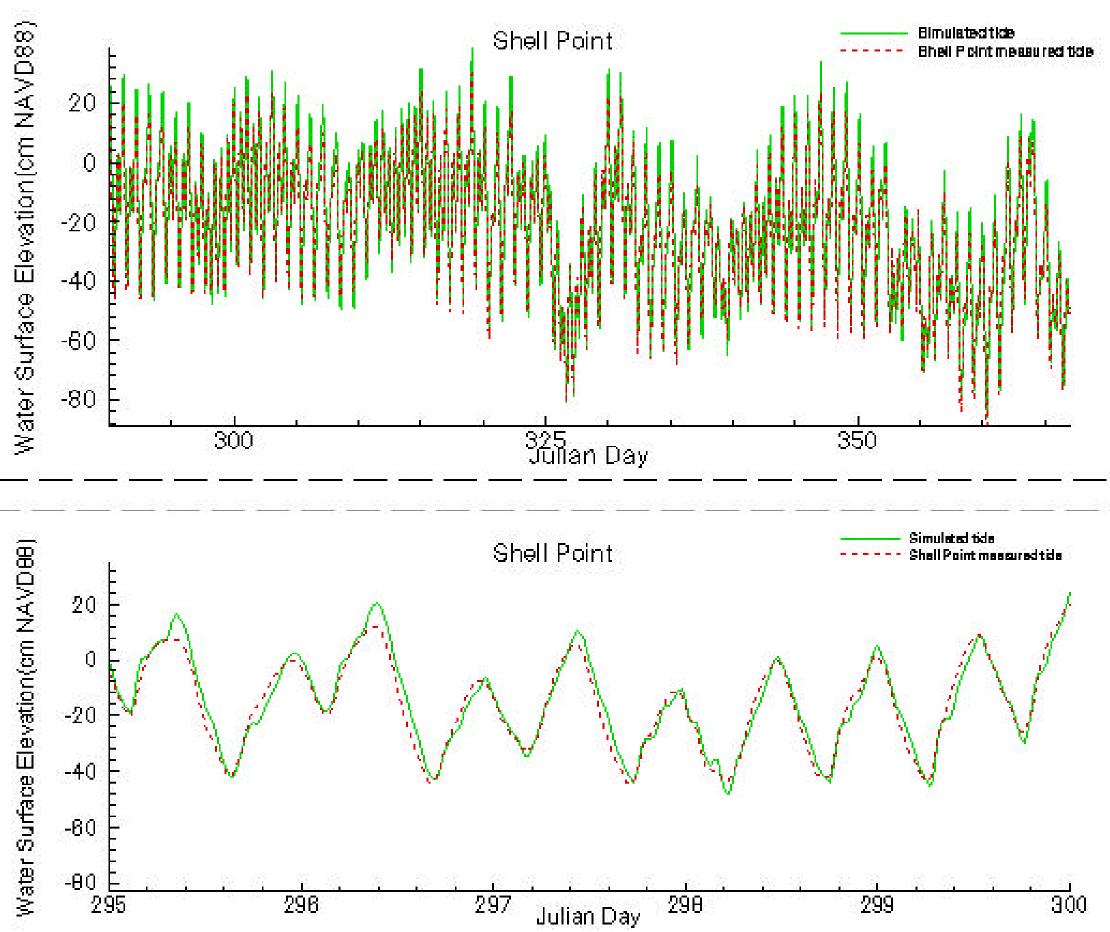


Figure F-3 Water surface elevation calibration at Shell Point (Marker H)

Figure F-4 shows the calibration of water surface elevation at Ft. Myers. This station data reflects the tide upstream on the River. The simulated tide range is close to the real data but a little larger than the real data.

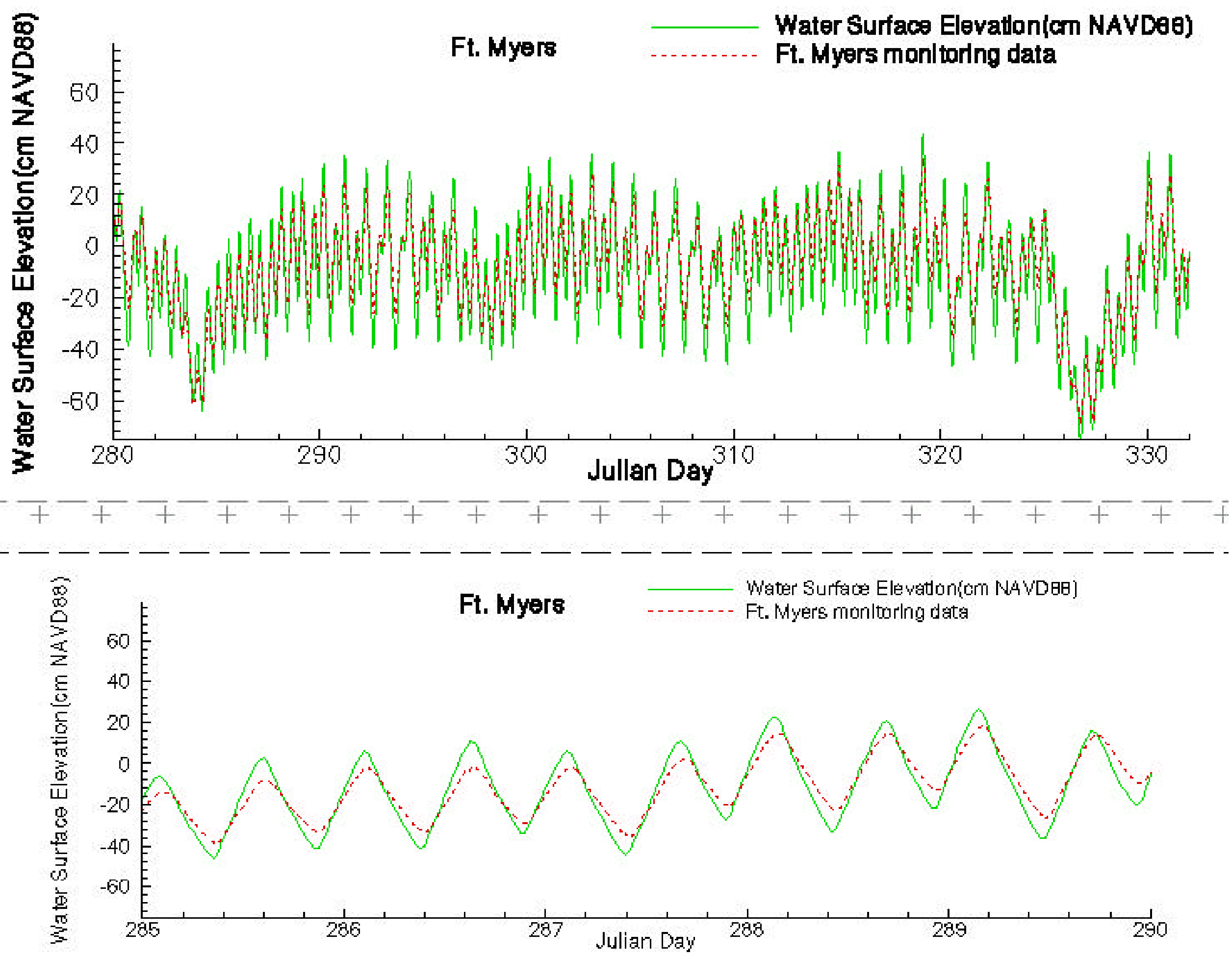


Figure F-4 Water surface elevation calibration at Ft. Myers

Figure F-5 presents the salinity calibration results at S79, down stream of the lock structure, and Bridge 31, located between S79 and Ft. Myers. The thick solid line is the simulated salinity at the second layer from the water surface (25% of the total depth), while the thin solid line is the simulated salinity at the second layer from the bottom (75% of the total depth). The dotted line is the real data at the surface sensor, while the dashed line is the real data at the bottom sensor. In November, the only discharge event was from the 22nd to 26 th (Julian days 327-332). So the salinity kept rising until the discharge began.

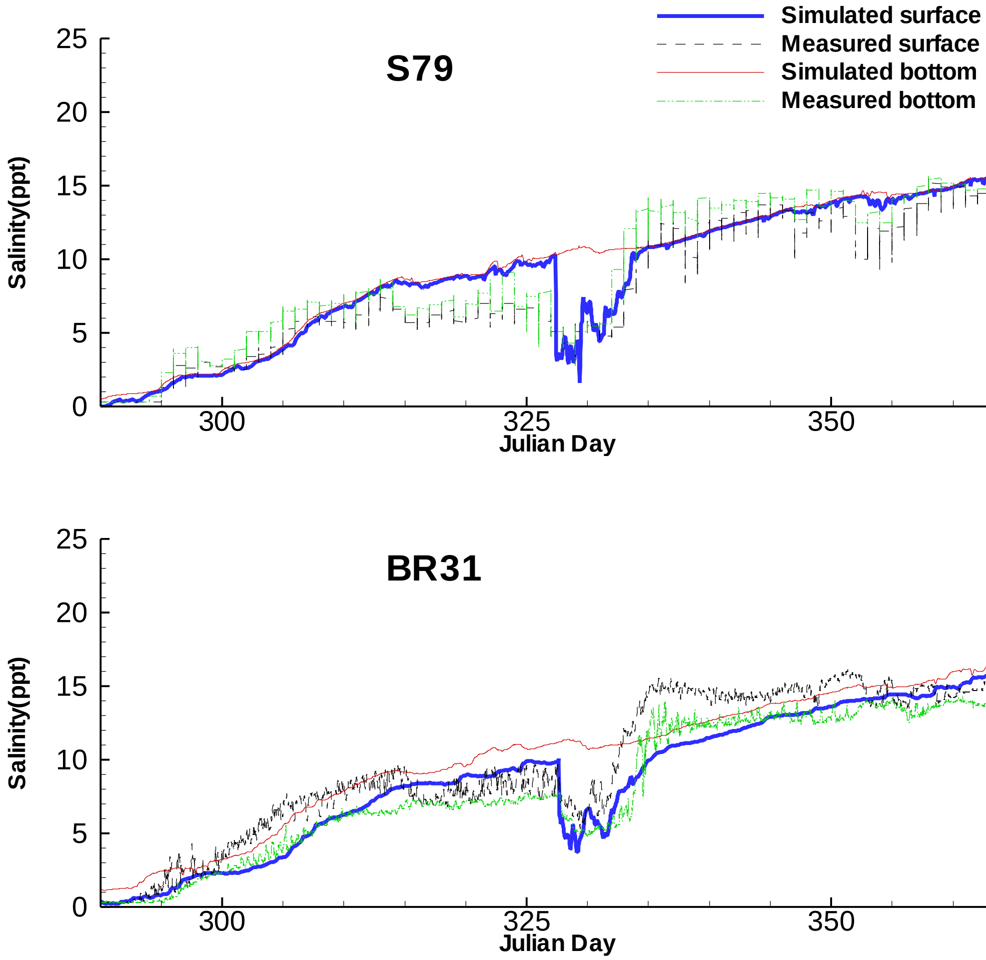


Figure F-5 Salinity calibration at S79 and BR31

Figure F-6 shows the simulation results at Ft. Myers, Shell Point and the Sanibel station in San Carlos Bay. The daily salinity fluctuation range is close to the monitoring data. The model results show good agreement with the monitoring data. At the Sanibel station during a very dry period (December 2000), the salinity in the surface layer was higher than in the bottom layer. The salinity could reach up to 38 ppt. This indicates that evaporation plays a key role in San Carlos Bay. To solve this problem, accurate evaporation data, along with coincident salinity monitoring data in San Carlos Bay and Charlotte Harbor will be needed. It will slightly affect the salinity in the upstream River.

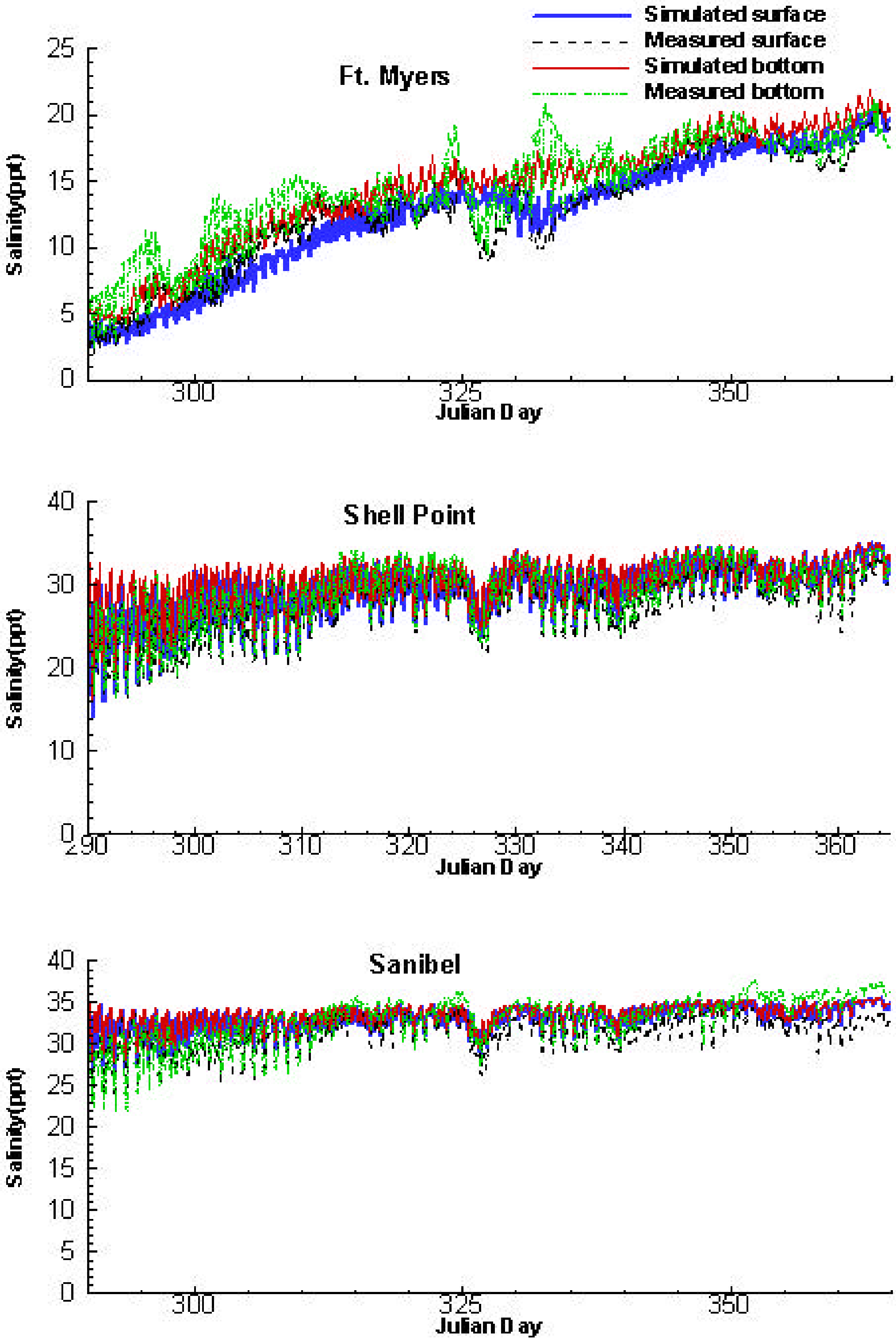


Figure F-6 Salinity calibration at Ft. Myers, Shell Point and Sanibel

Equilibrium relations between salinity and discharge

Based on the calibrated parameters, a group of curves describing the relationships between total discharge and salinity distribution were generated. Eight (8) scenarios (discharges at 50cfs, 100cfs, 200cfs, 300cfs, 500cfs, 1000cfs, 1500cfs and 2000cfs) were simulated for 40 days. Forty-day simulations allowed the model to reach equilibrium conditions. For convenience, all discharges were simulated as entering at S79; rainfall, evaporation and ground water input were not included as separate variables. The last 10 days of the 40 days simulation results were averaged to obtain the salinity at 4 locations, S79, BR31, Ft. Myers and Shell Point.

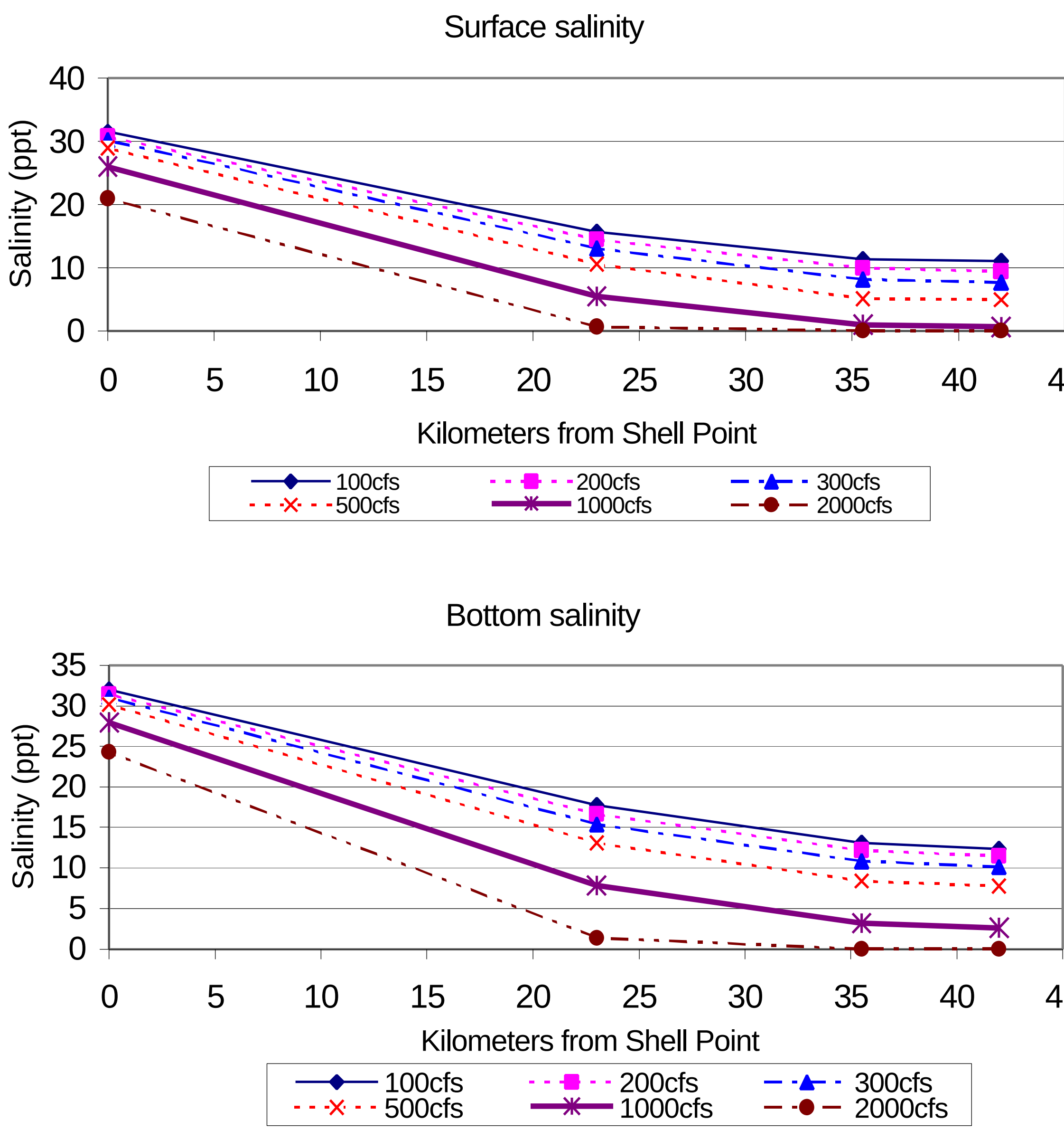


Figure F-7. Salinity as a function of total discharge to the estuary

Estimating total estuarine inflow

The dominant source of inflow to the Caloosahatchee estuary is runoff from the East and West Caloosahatchee Drainage Basin – which enters the estuary at the S-79 structure. However, flows from the tidal watershed are also significant. Previous empirical modeling established relationships between flows at S-79 and salinity within the estuary but specific information on tidal Caloosahatchee flows and direct rainfall and evaporation were only included implicitly in the statistical model through observed salinity data. The hydrodynamic modeling used in this analysis requires explicit knowledge of all waters entering estuary.

Unfortunately, few tidal Caloosahatchee inflows are monitored. However, a watershed hydrologic/hydraulic model has been recently been developed for the Tidal Caloosahatchee Watershed (Peterson, 2002) that can predict tidal inflows. A special simulation of the watershed model was conducted to generate daily estuary inflows by source over the length of the estuary in three years.

Model results were used to develop a characteristic relationship between S-79 flows and total inflows. (Details on the hydrologic assessment are discussed in a separate appendix of the 2002 MFL report.) S-79 flows dominate under high flow conditions while local tidal inflows dominate under low flow conditions. Under current conditions, a discharge of 300 cfs at S-79 corresponds to a total inflow of 500 cfs or greater about 50% of the time. Under current conditions, a mean monthly discharge of 300 cfs would be expected to prevent an exceedance of the 10 ppt criteria about half of the time.

Regression model

The CERP project in the C-43 basin comprises the recovery strategy for the Caloosahatchee MFL. When completed, these projects should supply the supplemental flow required to protect tape grass in the upper estuary.

In the original technical documentation, this proposition was evaluated using two 31 year (1965-1995) estimates of discharge at S-79. These were (1) the common 1995-base case which assumes 1995 land use and current water management operations in the C-43 basin and (2) a future base case (2020 with Restudy) which includes predicted 2020 land uses and the majority of CERP projects in the C-43 basin (reservoirs, aquifer storage and recovery wells (ASR), and back pumping).

Sine the hydrodynamic model cannot be run for 31 years, a regression model was developed to generate a 31-year record of salinity over Vallisneria beds at 2 stations in the upper estuary. The stations are in the 640-acre area to be protected by the MFL and Vallisneria has been monitored at these sites since 1998. The sites are referred to as Bird Island (upstream) and Site 2 (see **Figure F-2**).

A regression model was constructed and calibrated at Ft. Myers and Bridge 31 where 15-minute of salinity data were monitored. The salinity at Bird Island and Site 2 (**Figure F-2**) were interpolated with the salinity results from regression model at Ft. Myers and Bridge 31.

The spatial interpolation of salinity at Bird Island and Site 2

Since 1998, the District started seagrass sampling at Bird Island and Site2 monthly. During each monthly sampling event, salinity was taken from Hydrolab reading. In addition, the District started monitoring salinity data at Bird Island at 15-minute interval since December 2001. To get the interpolation parameters at Bird Island and Site 2, 15-minute of salinity data at Ft. Myers and Bridge 31 were averaged daily to obtain daily salinity variation. Then, the spatial interpolation was conducted to fit the monthly sampling data at Bird Island and Site 2, as well as a 6-month daily salinity data at Bird Island. The interpolation results are presented in **Figure F-8** and **Figure F-9**. The interpolated salinity data was used for calibration of seagrass model. The spatial interpolation formulae are:

At Bird Island, $S_{\text{Bird Island}} = 0.2 * S_{\text{Ft. Myers}} + 0.8 * S_{\text{BR31}}$

At Site 2, during salinity increases, $S_{\text{Site 2}} = 0.6 * S_{\text{Ft. Myers}} + 0.4 * S_{\text{Bird Island}}$

during salinity decreases, $S_{\text{Site 2}} = 0.4 * S_{\text{Ft. Myers}} + 0.6 * S_{\text{Bird Island}}$

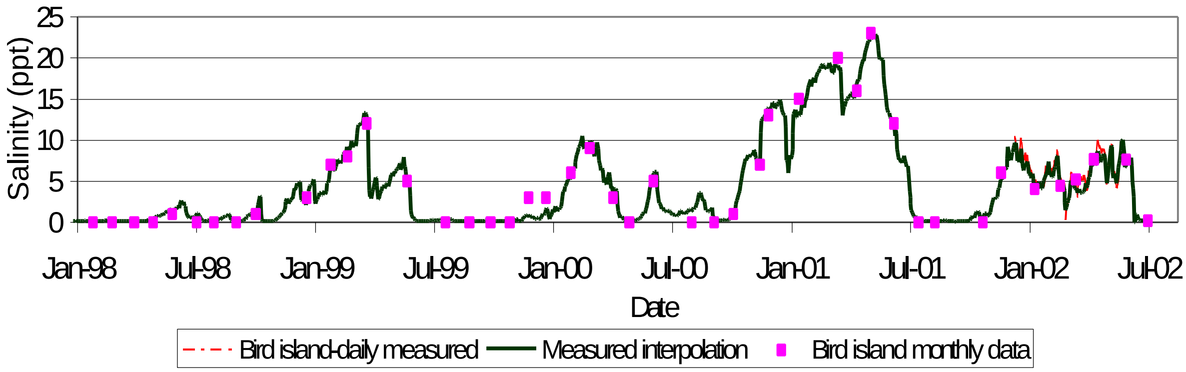


Figure F-8 Spatial interpolation of measured salinity for Bird Island

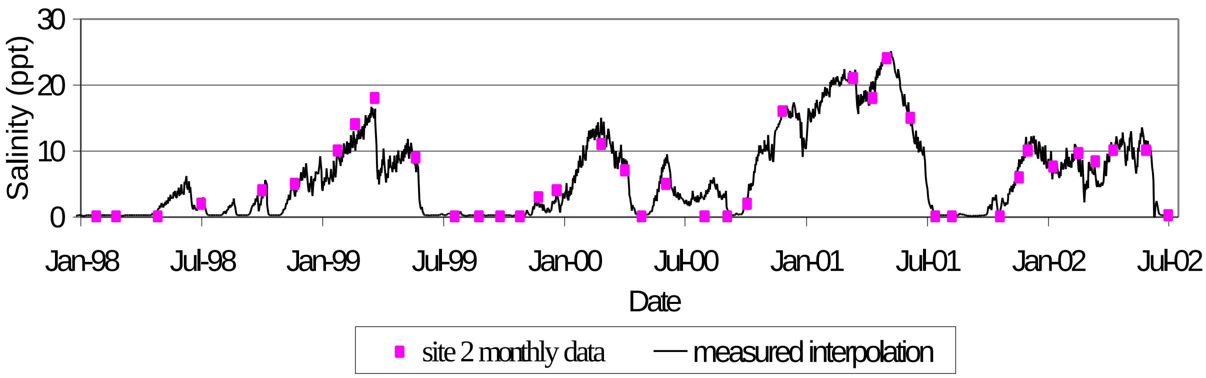


Figure F-9 Spatial interpolation of measured salinity for Site 2

Regression model formulae

The regression model calculated salinity in two steps. Firstly, salinity was calculated from surface layer equilibrium relations between salinity and discharge derived from the steady state simulations with CH3D model. Secondly, salinity was further corrected based on the estuary storage effect and tidal flushing. The total discharge was composed of S-79 discharge, and 50% of total basin runoff and the ground water flow to the entire Caloosahatchee River, since 50% of the tidal basin runoff enter into the River at the upstream of Ft. Myers. The ground water and tributary flow was calculated with rainfall driven formula based on tidal Caloosahatchee hydrology model (Peterson, 2002). Salinity at Ft. Myers station.

At the time step n+1, the salinity at Ft. Myers station (S^{n+1}) was calculated with the following formulae .

$S^{n+1'} = 0$ — $1300\text{cfs} < \text{flow}$

$S^{n+1'} = 5E\text{-}06*(\text{total flow})^2 - 0.0184*\text{total flow} + 18.566$ — $50\text{ cfs} < \text{flow} < 1300\text{ cfs}$

$S^{n+1'} = 35 - (35 - 19.5)*\text{total flow}/50\text{cfs}$ — $0 < \text{flow} < 50\text{ cfs}$

$S^{n+1'} = 35$ — $\text{flow} = 0$

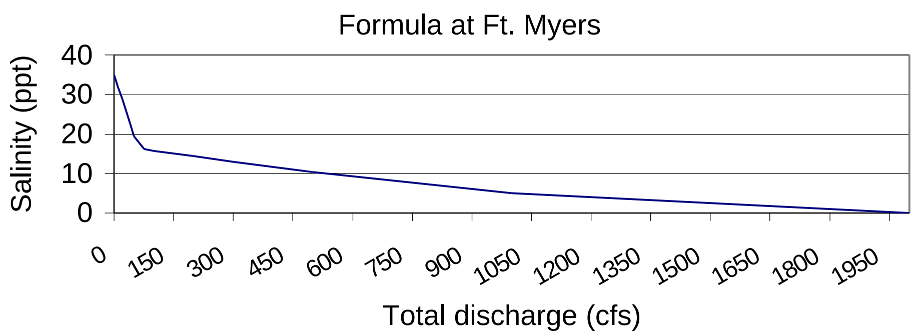


Figure F-10 Formula for preliminary calculation of salinity at Ft. Myers

To include the estuary flushing effect,

$S^{n+1} = S^n + (S^{n+1'} - S^n)*\text{Ratio\_up}$ if $S^{n+1} > S^n$

$S^{n+1} = S^n + (S^{n+1'} - S^n)*\text{Ratio\_down}$ if $S^{n+1} < S^n$

Ratio_up=0.05,	Ratio_down=0.05	$S^{n+1} < 10$ ppt
Ratio_up =0.03,	Ratio_down=0.02	10 ppt $< S^{n+1} <$ 15 ppt
Ratio_up =0.07,	Ratio_down=0.1	15 ppt $< S^{n+1} <$ 20 ppt
Ratio_up =0.02,	Ratio_down =0.01	20 ppt $< S^{n+1} <$ 25 ppt
Ratio_up =0.012,	Ratio_down =0.01	25 ppt $< S^{n+1} <$ 30 ppt
Ratio_up =0.001,	Ratio_down =0.001	30 ppt $< S^{n+1}$

Salinity at Bridge 31 station

At the time step n+1, the salinity at Bridge 31 station (S^{n+1}) was calculated with the following formula.

$S^{n+1'} = 0$ — $700\text{cfs} < \text{flow}$

$S^{n+1'} = 2E\text{-}05*(\text{total flow})^2 - 0.0297*\text{total flow} + 15.223$ — $50\text{ cfs} < \text{flow} < 1300\text{ cfs}$

$S^{n+1'} = 35 - (35 - 15)*\text{total flow}/50\text{cfs}$ — $0 < \text{flow} < 50\text{ cfs}$

$S^{n+1'} = 35$ — $\text{flow} = 0$

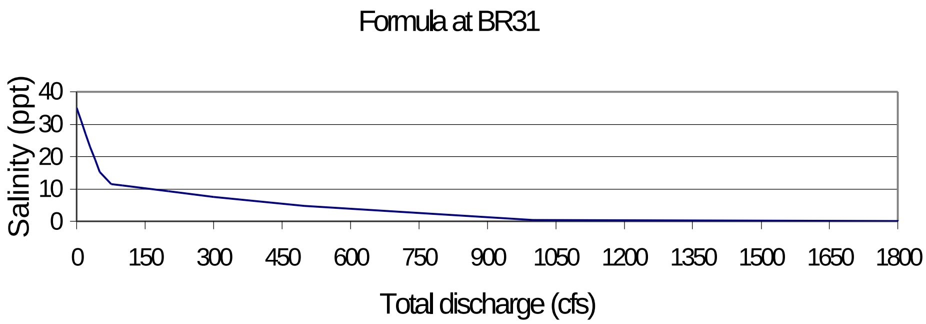


Figure F-11 Formula for preliminary calculation of salinity at BR31

To include the inertial effects of storage and flushing,

$S^{n+1} = S^n + (S^{n+1'} - S^n)*Ratio\_up$ if $S^{n+1} > S^n$

$S^{n+1} = S^n + (S^{n+1'} - S^n)*Ratio\_down$ if $S^{n+1} < S^n$

Ratio_up=0.02,	Ratio_down=0.03	$S^{n+1} < 5$ ppt
Ratio_up =0.02,	Ratio_down=0.1	5 ppt $< S^{n+1} <$ 10 ppt
Ratio_up =0.05,	Ratio_down=0.01	10 ppt $< S^{n+1} <$ 15 ppt
Ratio_up =0.03,	Ratio_down =0.015	15 ppt $< S^{n+1} <$ 20 ppt
Ratio_up =0.03,	Ratio_down =0.03	20 ppt $< S^{n+1} <$ 25 ppt
Ratio_up =0.0005,	Ratio_down =0.005	25 ppt $< S^{n+1}$

If flow > 4500 cfs, $S^{n+1} = 0$

Regression model calibration results

The regression model was calibrated with a 10-year period of daily salinity data at Ft. Myers and BR31. The calibration results are presented in **Figures F-12** and **F-13**.

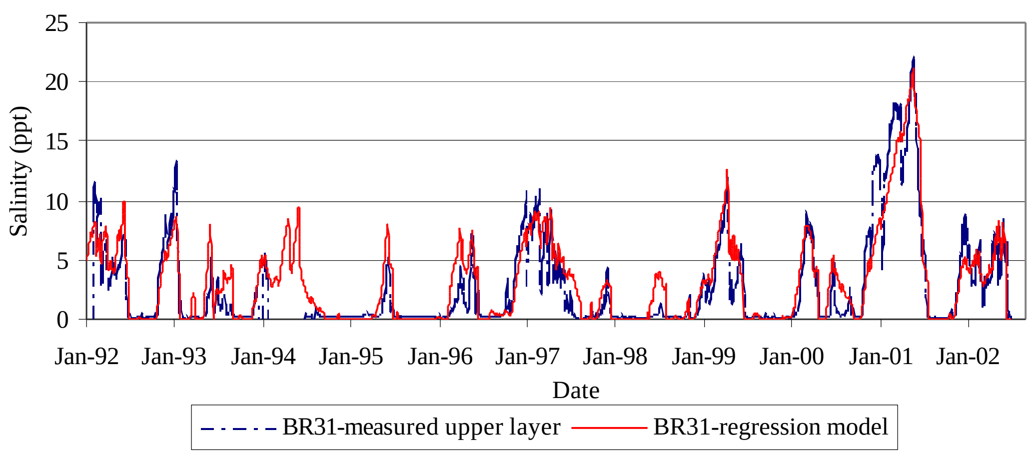


Figure F-12 Temporal calibration of regression model at BR31

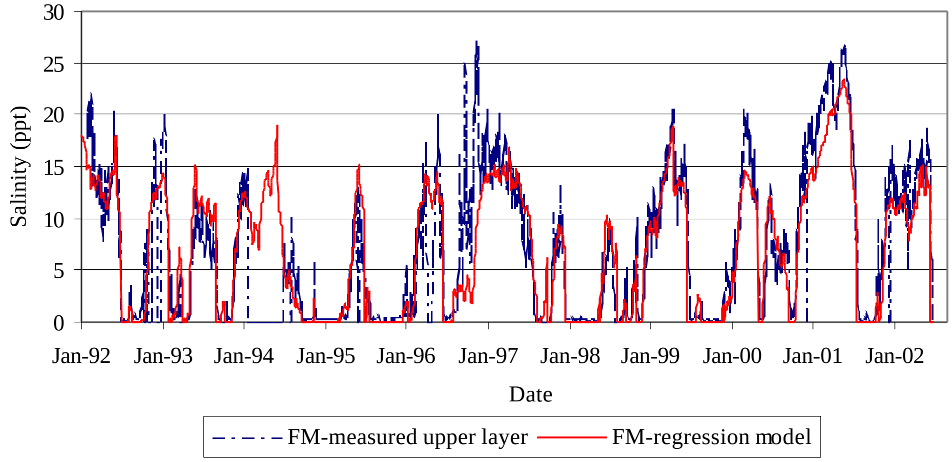


Figure F-13 Temporal calibration of regression model at Ft. Myers

To predict salinity at Bird Island and Site 2, which lie between BR31 and Ft. Myers, the regression model results were spatially interpolated. The interpolated model results at Bird Island and Site 2 were compared with a 5-year period of monthly sampling data and 6-months of daily salinity data at Bird Island (**Figure F-14**). The regression model under predicted salinity during the period from December 2000 to May 2001. It is due to the large amount of tidal basin runoff predicted by tidal Caloosahatchee watershed model.

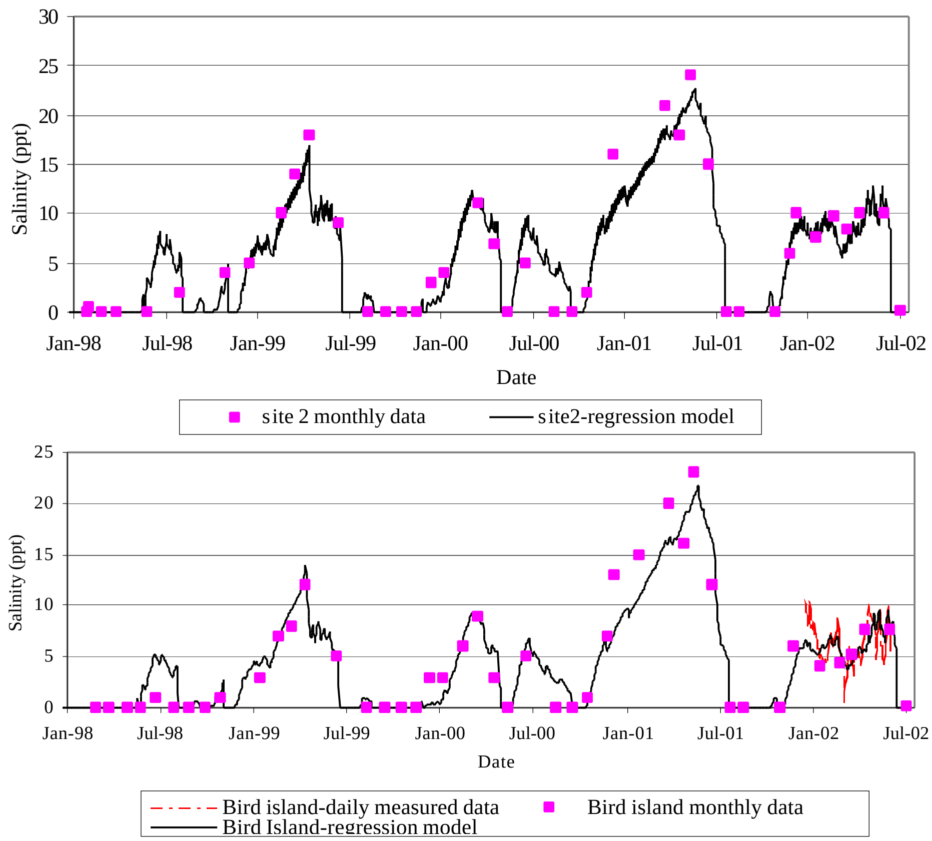


Figure F-14. Spatial interpolation of regression model results at Bird Island and Site2

Assessing CERP: Prediction of salinity for without project (95 base) and with project (2020 with Restudy)

Two scenarios, pre-CERP (95 base) and post-CERP 2020 with Restudy components (2020 with Restudy scenario), were designed by the District to reflect the change of discharge to the estuary due to the CERP projects. The 95 base describing the current drainage basin condition indicates higher peak flow discharge. 2020 with Restudy demonstrates the change of discharge after the completion of CERP projects. In 2020 with Restudy, the storm water is stored in reservoirs and ASR and the fresh water is discharged more evenly with smaller peaks during wet season and larger flow during dry season.

The calibrated regression model was applied to assess CERP project impacts to the salinity variation at Bird Island and seagrass Site 2. The total discharge of these two scenarios are compared and presented in **Figure F-15**. **Table F-1** shows the frequency analysis of the flow discharge under 95 base and 2020 with Restudy. 95 base has 38% of the total flow under 300 cfs. 2020 with Restudy improves the discharge at low flow conditions. The frequency of flow between 300 to 600 cfs has increased from 9% under 95 base to 37% under 2020 with Restudy. Total flow, including discharge from S-79 and flows from ground water and other tributaries, was used as the driving input to the regression salinity model.

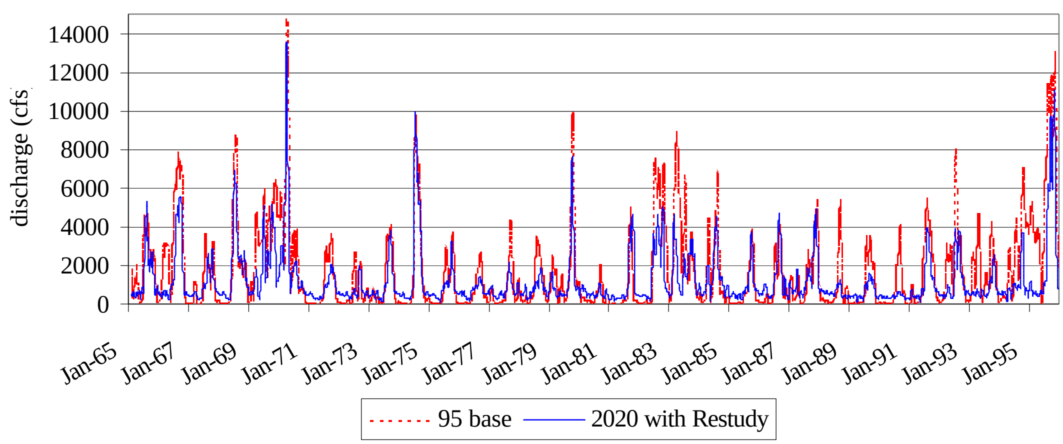


Figure F-15., Comparison of total discharge under 95 base and 2020 with Restudy (30-day moving average)

Table F-1 Frequency analysis of discharge

30 day moving averaged flow (cfs)	95 base total (%)	95 base S79 (%)	2020 with restudy total (%)	2020 with restudy S79 (%)	Ground water(%)
< 300	38	42	6	13	82
300~600	9	8	37	43	7
600~1000	7	7	25	19	6
1000~2500	20	19	19	15	5
2500~5000	18	16	10	8	0
5000~10000	7	7	3	2	0
>100000	1	0	0	0	0

The predicted salinity variations are presented in **Figure F-16** and **F-17** at Bird Island and Site 2 respectively. Both figures show that 2020 with Restudy has lower salinity at the peak than 95 base.

Table F-2 presents the frequency analysis of daily salinity and 30 day moving averaged salinity at Bird Island and Site 2. At Bird Island, 27% of the daily salinity under 95 base condition are over 10 ppt, while under 2020 with Restudy only 2% of the daily salinity values are over 10 ppt. At Site 2, 41% of daily salinity are over 10 ppt for 95 base, compared with 14% of daily salinity exceeding 10 ppt under 2020 with Restudy. The results demonstrate that CERP projects improve salinity in the estuary by lowering high peaks.

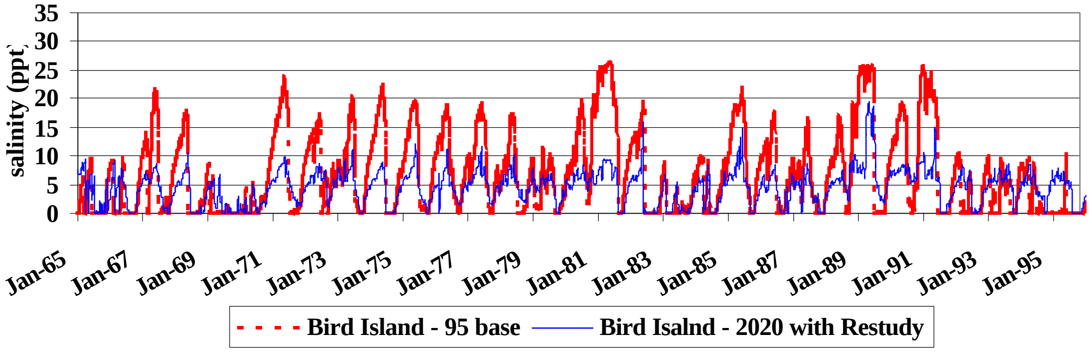


Figure F-16 Predicted salinity at Bird Island

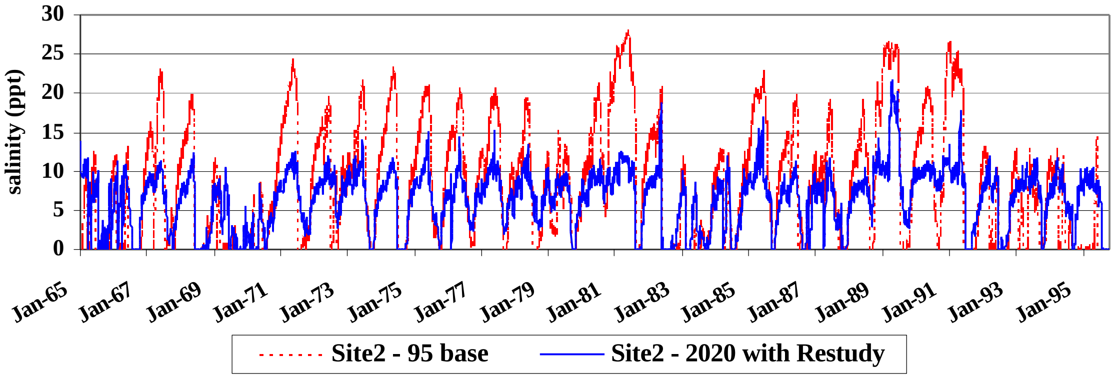


Figure F-17 Predicted salinity at Site 2

Table F-2 Frequency analysis of predicted salinity at Bird Island and Site 2

	Bird Island				Site 2			
	95 base		2020 with Restudy		95 base		2020 with Restudy	
salinity (ppt)	daily (%)	30-day moving average (%)	daily (%)	30-day moving average (%)	daily (%)	30-day moving average (%)	daily (%)	30-day moving average (%)
0~5	49	49	53	53	42	41	33	33
5~10	23	24	45	46	17	19	53	54
10~13	7	8	1	1	14	13	12	11
13~15	3	4	0	0	5	6	1	0
15~20	11	10	1	1	13	12	1	1
20~25	4	4	0	0	6	6	0	0
25~30	2	1	0	0	3	2	0	0

Figure F-18 presents the daily salinity and 30 day moving averaged salinity at Ft. Myers. **Table F-3** shows the frequency analysis of the daily salinity and 30 day moving averaged salinity at Ft. Myers. The MFL rule states that the daily salinity at Ft. Myers should not exceed 20 ppt, while the 30 day moving averaged salinity at Ft. Myers should not exceed 10 ppt. For 2020 with Restudy scenario, 1% of the daily salinity values at Ft. Myers are over 20 ppt (Table 2), and 52% of the 30 day moving averaged salinity values are less than 10 ppt. Of the remaining exceedance, 38% are between 10 ppt and 12 ppt. This range of salinity is linked to low flow (300 to 600 cfs) discharge (**Table F-1**). The predicted salinity at Ft. Myers marginally meet the assumed MFL rules, considering the uncertainty in the results. The point where meets the 30 day MFL rule occurs near Site 2 (**Table F-1**), which is 3 kilometers upstream of Ft. Myers, or 2 kilometer from the lower boundary of the protected seagrass area. Of the 31 year period of simulation time, the predicted salinity meet the 30 day MFL rule in three entire years, 1970, 1983 and 1984 (Figure 18). Due to the lack of groundwater input in CH3D calibration, the model might predict the salinity higher than the real values. Continuing work will improve the modeling performance.

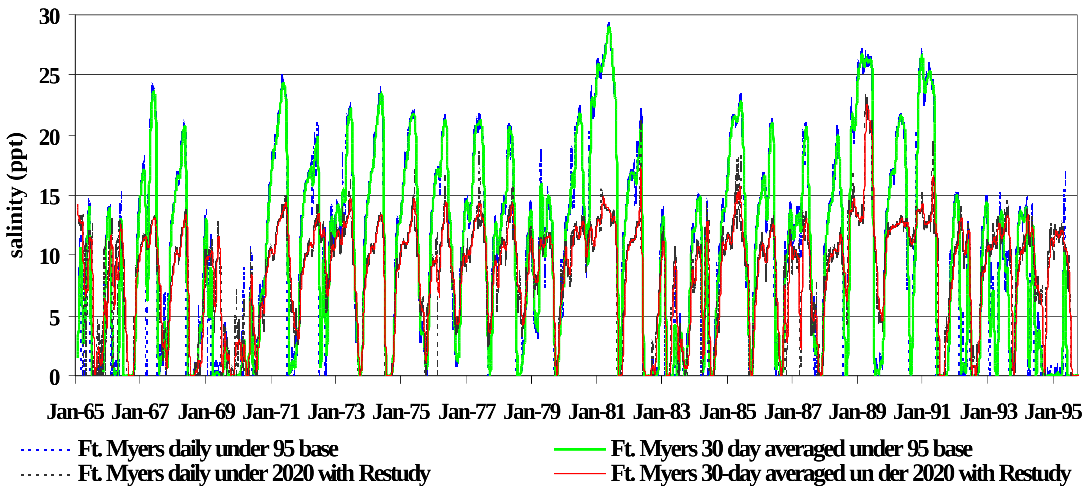


Figure F-18 Predicted salinity at Ft. Myers

Table F-3 Frequency analysis of predicted salinity at Ft. Myers

Ft. Myers salinity (ppt)	95 base		2020 with Restudy	
	daily (%)	30 day moving average (%)	daily (%)	30 day moving average (%)
0~5	37.9	36.7	25.3	24.5
5~10	8.6	12.0	25.1	27.2
10~13	12.5	11.7	39.1	37.6
13~15	12.5	10.9	8.3	9.2
15~20	11.6	13.9	1.3	0.8
20~25	13.4	11.2	0.9	0.7

Conclusions

The CH3D hydrodynamic and salinity model and a regression model based on the 3-D model results were utilized to investigate the salinity distribution in the Caloosahatchee River. The 3-dimensional model was calibrated with a two and half months of data. Then, a series of constant discharges from S-79 were simulated with CH3D model to establish the equilibrium relations between salinity and total flow. A regression model was constructed based on the equilibrium relations. The regression model was further calibrated with a 10-year period of daily salinity data at Ft. Myers and BR31. The regression model results were spatially interpolated to Bird Island and Site 2, and compared with 5-year monthly sampling data. The impacts of the CERP project on salinity variation were evaluated with a regression model based on salinity simulations in a 31-year period.

Under current conditions, a discharge of 300 cfs at S-79 corresponds to a total inflow of 500 cfs or greater about 50% of the time. Under current conditions, a mean monthly discharge of 300 cfs would be expected to prevent an exceedance of the 10 ppt criteria about half of the time. The assessment of CERP project indicates reduced peak salinity at Bird Island and Site 2 for 2020 with Restudy compared with 95 base.

The MFL update incorporated several projects and modeling efforts. The hydrodynamic and salinity model is one of its components. The tidal Caloosahatchee basin model (MIKESHE) was calibrated by Danish Hydraulic Inc. to provide the ground water and tributary flow information to the salinity model. The output of salinity model was used to drive Vallisneria seagrass model to assess the seagrass growth.

The prediction and simulation of these results are limited with data and approaches. No fine resolution bathymetry data exists on the Caloosahatchee River portion, except cross-section profile information. The tidal Caloosahatchee basin model providing ground water and tributary flows needs improvement. 3-d hydrodynamic and salinity model requires further validation with ground water information. The regression model is a simple approach to estimate the estuary flushing and storage factor.

The District is working on several aspects to continue the modeling efforts. The bathymetry survey on the Caloosahatchee River is underway. A grid editing software tool is under contract to be used to edit the existing grid. The MFL salinity prediction will be enhanced with new bathymetry data, the improvement of basin model, and a fast 2-d model with fewer grids to replace the regression model.

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Technical Documentation to Support Development of Minimum Flows and Levels for the Caloosahatchee River and Estuary

Appendix G

The Significance of Tidal Runoff on Flows to the Caloosahatchee Estuary

By Ken Konyha

Contents

Florida Bay and Lower West Coast Division
Southern District Restoration Department

South Florida Water Management District

January 2003

The Significance of Tidal Runoff on Flows to the Caloosahatchee Estuary

Ken Konyha

Summary:

This paper provides the first hydrologic summary of the entire Caloosahatchee Watershed. Until recently, there was neither measured nor modeled data for the tidal portion of the watershed. Recently, however, a coupled surface water – groundwater model was developed by DHI for the Tidal Caloosahatchee. In this paper, an empirical model of the Tidal Caloosahatchee is calibrated to the DHI model and used to estimate tidal inflows for the extended time-periods needed for ecological analyses. The estimates of tidal runoff are combined with upstream flows (estimated by CERP models) to assess the distribution of total inflows to the Caloosahatchee estuary.

The Tidal Caloosahatchee makes up 30% (268,000 acres) of the watershed area (903,000 acres) and generates 28% (340,000 acre-feet per year) of the total watershed runoff 1,234,000 acre-feet per year). Historically, regulatory releases from Lake Okeechobee add an additional 24% (297,000 acre-feet per year) – mostly at damaging high rates of inflow.

CERP restoration will eliminate most regulatory releases and a substantial amount of non-beneficial basin runoff will be captured and redirected to beneficial uses: some to agricultural demands and some to restoring a natural estuarine flow pattern. The flow distribution for total watershed hydrology is developed for three situations: historic data, the CERP '1995 Base' scenario, and the CERP '2020 with Restudy Components' scenario. The '2020 with Restudy' scenario shows a more natural flow distribution than today's watershed.

Past work on estuary restoration, including current MFL flow targets, have been based on conditions in the upstream watershed (S-79 flows). Recent hydrodynamic salinity modeling shows that total freshwater inflows to the estuary of 500 cfs is more likely to keep salinities below 10 ppt throughout the Vallisneria seagrass beds. In a comparison of S-79 flows against total freshwater inflows it was found that, under current conditions (1995 Base), the 300 cfs flow criterion at S-79 provides and acceptable estimate of 500 cfs total inflows; correlating to total flows below 500 cfs 43% of the time and to total flows above 500 cfs 57% of the time. The

criteria of 300 cfs at S-79 flow will become less acceptable as Restudy components are constructed. Under the 2020 with Restudy scenario 300 cfs flows at S-79 correlate to total flows above 500 cfs only 19% of the time.

Introduction:

As part of the Southwest Florida Feasibility Study, DHI Water & Environment was contracted to develop a hydrologic model of the Tidal Caloosahatchee Watershed. This model, an application of the MikeShe code, has been completed (Petersen et al, in review). Completion of this model makes it possible, for the first time, to estimate inflows for the entire Caloosahatchee watershed. Section 1 presents a brief summary of the Tidal Caloosahatchee model.

The ecology of the estuary is known to depend on freshwater inflows and many problems in the estuary have been attributed to poor management of these freshwater inflows. The C&SF Comprehensive Restudy has proposed the construction of several water management facilities to restore freshwater flows to the estuary.

The objective of this paper is to assess freshwater inflows over a wide variety of climate conditions using a long (thirty-one year) simulation. Unfortunately, results from Tidal Caloosahatchee Watershed were only available for three years. Therefore, an application model, calibrated to the MikeShe model, was created. The application model is based on linear reservoir theory. Section 2 paper describes the linear reservoir model and compares it to the MikeShe model. Section 3 applies the model to the entire thirty-one year period of simulation.

In section 4, thirty-one year time-series of Caloosahatchee Estuary inflows are created by combining Tidal Caloosahatchee runoff with flows from the rest of the watershed (S-79 flows). Three different sets of estuary flows are created and compared: measured data, the C&SF '1995 Base' scenario, and the 'C&SF 2020 with Restudy Components' scenario. Measured data show historic conditions; '1995 Base' shows conditions as they exist today in the watershed; '2020 with Restudy Components' shows conditions in 2020 after the proposed water management facilities are constructed.

Section 5 uses the '1995 Base' and '2020 with Restudy Components' hydrology to examine the suitability of the current MFL flow criterion of 300 cfs at S-79.

Summary of the MikeShe Tidal Caloosahatchee Basin Model

The Tidal Caloosahatchee Basin Model (Petersen et al, in review) is an application of the MikeShe code. The model is a fully coupled surface water and groundwater model intended to accurately simulate all significant hydrologic process in the watershed including evaporation, runoff, stormwater detention, river hydraulics, stream water management, groundwater withdrawals and recharge, etc.

The area modeled is shown in **Figure G-1**. **Table G-1** shows the areas of the drainage basins within the study area that drain into the Caloosahatchee. The Tidal Caloosahatchee watershed is 268,000 acres (30%), compared to the portion of the non-tidal portion of the Caloosahatchee, which is 634,000 acres.

The consultant was requested to make a special simulation examining the spatial distribution of inflows into the estuary and describing inflow sources (Petersen and Copp, 2002). The MikeShe runoff time-series is shown on **Figure G-2**. Although measured stream flow data in the basin are sparse, DHI calibrated to all available data: flows, groundwater elevation data and stream stage data. For the purposes of this paper, the MikeShe flow data are assumed to be accurate.

The spatial distribution of flows entering the estuary are shown in **Figure G-3** and tabulated in **Table G-2**. The largest single inflow (30% of the total) comes from Orange River (river segment 3: six miles downstream of S-79). Substantial volumes (17%) enter far downstream (segment 10: twenty-six miles downstream of S-79). This spatial distribution was relatively constant over the simulation period.

The Linear Reservoir Model for the Tidal Caloosahatchee Basin

A linear reservoir (LinRes) model was developed for the Tidal basin because MikeShe results were only available for a three-year simulation period while flows are needed for a thirty-one year period of simulation. The Linear Reservoir Model was developed because it is fast, reliable, and easily calibrated against the MikeShe model.

The model has three cascading reservoirs and a root zone. Rainfall and evaporation fill and empty the root zone with excess root zone water recharging the storage zones (linear reservoirs). The storage zones drain at a rate exponential to storage. There is also a term for rain falling directly on the streams and estuary. The equations are:

Root Zone:
potential change = max(0, Rain – PET + root zone storage)
root zone storage = min(max(0,(potential change)),root zone capacity)
actual ET = PET - max(0,-(potential change))
water to add to zone 1= max(0, potential change - root storage capacity)

For Each Zone:
addwater : excess water defined in previous zone
storage = min(max(0,(addwater + storage –outflow)),maximum capacity)
ouflow = (storage) *(1-exp(-1/ storage coefficient))
addwater for next zone = max(0,(addwater + storage –outflow)) - maximum capacity

[Fluxes are measured in inches per day and are converted to acre-feet per day by multiplying by the watershed area.]

The LinRes model was calibrated to MikeShe results, using the same rainfall and PET data. Since MikeShe simulates three flow types: aquifer flow (AQ), shallow drainage flow (DR) and overland flow (OVL), the conceptual reservoirs of LinRes were calibrated to match each MikeShe flow type. Time-series for each flow type (not shown here) were developed; the average annual flow for each type is shown on **Table G-4**. [Note: Reservoir 1 simulates AQ flow, Reservoirs 2 and 3 simulate DR flow, OVL flow is simulated best using the direct rainfall.] **Table G-3** shows the calibrated model parameters.

The final model matched the MikeShe model well and had a Pearson correlation coefficient of 0.878. Figure 2 shows the time-series for both the MikeShe and the LinRes model over the three-year simulation.

Tidal Hydrology over a Thirty-Six Year Period of Simulation

The calibrated LinRes model was used to generate a thirty-six year (1965-2000) time-series of tidal watershed runoff. Rainfall and PET data came from Ft Myers (prepared for regional modeling efforts). A general summary of the hydrology is shown in **Table G-4**. Note the variability of rainfall and runoff. The three-year calibration period averaged 65.1 inches per year of rain and 26.1 inches per year of runoff (584,000 acre-foot per year) while the thirty-six simulation period had only 56.2 inches per year of rainfall and 16.2 inches per year of runoff (362,000 acre-feet per year). Slow draining aquifer flow (AQ) makes up 23% (84,000 acre-feet per year) of the total. Aquifer drainage is about the same magnitude as the rainfall that falls directly onto the open-water of estuary (90,000 acre-foot per year).

Figure 4 shows daily tidal basin runoff for the thirty-one year simulation period (1965-1995). This simulation period matches the CERP simulation period. Local basin runoff averages 340,000 acre-foot per year and peak daily runoff rates regularly exceed 5000 cfs.

Comparing Estuary Hydrology for Three Scenarios

Salinities in the Caloosahatchee Estuary depend on total estuary inflow. Flows from the tidal basin (above) are combined with flows from the rest of the watershed to generate time-series of total estuary inflows. The Caloosahatchee Estuary receives distributed flows from the Tidal Watershed and a very large point source at the S-79 structure (aka Franklin Lock and Dam) at the downstream end of the C-43 canal. Flows at S-79 are generated within the upstream watershed: i.e. the East Caloosahatchee Basin, the West Caloosahatchee Basin, and the S-4 Basin; S-79 flows also include occasional but substantial (and damaging) regulatory releases from Lake Okeechobee that pass through the C-43 canal into the estuary.

Three time-series for S-79 flows are combined with tidal basin flows and examined: measured S-79 data, 1995 Base, and 2020 with Restudy Components. ‘Measured’ data represent the historic watershed; ‘1995 Base’ data represents the current conditions; ‘2020 with Restudy Components’ represents the proposed CERP solution. [One of the CERP objectives is to restore conditions within the Caloosahatchee Estuary via reservoirs, STAs, etc. The ‘2020 with Restudy Components’ models the ‘yellow book’ components. (These components are being refined as part of the C-43 PIR process. No refined hydrology is yet available.)]

Figure G-5 shows the time-series for total freshwater inflows to the estuary for the ‘1995 Base’ and ‘2020 with Restudy Components’ scenarios. Notice the variability in both time-series; several years in a row without large runoffs and also several years with many large runoffs in the same year. This variability is rain-driven and natural. Also notice the difference between the two time-series. The '2020 with Restudy Components' has raised the baseflow components and reduced peak flows.

Figure G-6 shows the probability flow-distribution of freshwater inflows for '1995Base' and '2020 with Restudy Components' scenarios. The same data is shown in tabular form in **Table G-6.** The frequency analysis shows that today's estuary is frequently exposed to low flows. [These result in high salinities that stress the Vallisneria sea-grasses. Recent hydrodynamic-salinity modeling has found that total freshwater inflows of 500 cfs are needed to keep salinities below 10 ppt throughout the productive Vallisneria sea-grass beds. (Qiu, personal communications).]

Under 1995 Base 41% of the months have flows below the 500 cfs threshold needed to protect the seagrass beds. Severe stress is also common with 32% of all months having flows below 325 cfs. Flows are much better for the '2020 with Restudy Components' scenario. Only 18% of the months have flows below the 500 cfs threshold and severe stress is almost eliminated with only 2% of months having flows below 325 cfs.

Total Caloosahatchee Flows under Current MFL Criteria

Existing minimum flow criteria are 300 cfs at S-79. These criteria were established without quantitative consideration of inflows from the unmonitored tributaries and groundwater inflows of the tidal basin. Now that hydrology is available for the entire watershed, this minimum flow value can be reassessed.

Hydrodynamic modeling shows that a combined flow of 500 cfs is necessary to keep salinities below 10 ppt throughout the critical seagrass beds. The combined watershed hydrology can be examined under current MFL conditions (300 cfs) to determine how well the MFL flow correlates to the target watershed flow of 500 cfs.

Table 7 looks at monthly watershed inflows, for all scenarios, when monthly S-79 flows are near 300 cfs (275 to 325 cfs). The frequency analysis of 1995 Base shows that 300 cfs at S-79 correlates reasonably well to the 500 cfs total flow target. When S-79 flows are near 300 cfs, total flows are between 325 cfs and 500 cfs about half of the time (43%) and between 500 cfs and 800 cfs about half of the time (43%).

The correlation of S-79 flows of 300 cfs and total flows of 500 cfs breaks down under the '2020 with Restudy Components' scenario. Under this scenario, when S-79 flows are near 300 cfs, total flows are below 500 cfs most of the time (80%) and between 500 cfs and 800 cfs only 20% of the time.

It is not surprising that the correlation of S-79 flows and total flows changes in the 2020 scenario; reservoirs and ASRs upstream of S-79 are designed to deliver base flows to the estuary. This shifting of sources is demonstrated in Figure 7. Figure 7 shows the contribution of upper basin flow as a percentage of total estuary inflow for both 1995 base and 2020 with Restudy scenarios. Under 1995 Base, upper basins contribute 42% of flows in the 325 cfs - 500 cfs range and 62% of flows in the 500 cfs – 800 cfs range. Under 2020 with Restudy, upper basins contribute 78% of flows in the 325 cfs - 500 cfs range and 70% of flows in the 500 cfs – 800 cfs range.

In summary, it would be better to base protection criteria on total estuary inflows (500 cfs) than on S-79 flows (300 cfs). Under current conditions (1995 Base), the 300 cfs flow criterion at S-79 is an acceptable surrogate for total estuary inflows of 500 cfs; correlating to total flows below 500 cfs 43% of the time and to total flows above 500 cfs 57% of the time. The criteria of 300 cfs at S-79 flow will become less acceptable as Restudy components are constructed. Under the 2020 with Restudy scenario 300 cfs flows at S-79 correlate to total flows above 500 cfs only 19% of the time.

References:

Tidal Caloosahatchee Basin Model - Model Calibration and Validation, Michael J. Petersen, Joseph D. Hughes, Jeremy McBryan, Roger Copp and Torsten V. Jacobsen, DHI Water & Environment, Project 51189, July 2002

Summary Descriptions of Groundwater and Tributary Flows to the Caloosahatchee River. Michael J. Petersen, and Roger Copp, DHI Water & Environment, Project 51189, August 22 2002

Table G-1. SFWMD Drainage Basins in Caloosahatchee Watershed

	Acres	**Mi^2**
Basins draining directly into Tidal Caloosahatchee Estuary		
Tidal Caloosahatchee Basin	196,140	306
Telegraph Basin	56,474	88
Caloosahatchee Estuary	15,376	24
SUB-TOTAL	267,990	418
Basins draining into Estuary at S-79		
East Caloosahatchee Basin	226,631	354
West Caloosahatchee Basin	356,928	558
S4 Drainage Basin	50,269	79
SUB-TOTAL	633,828	990
TOTAL	901,818	1409

Table 2. Spatial Distribution of Tidal Caloosahatchee Inflows (MikeShe estimates)

River Segment	**Station (Miles Downstream of S-79)**	**Fraction of Flow Entering at each Station**
1	0.44	9%
2	5.09	7%
3	7.13	29%
4	8.16	3%
5	9.09	8%
6	11.69	5%
7	15.11	7%
8	18.66	7%
9	21.84	8%
10	25.93	17%

Table 3. Parameters of Linear Reservoir Model of Tidal Caloosahatchee Basin

Area of Basin	267,990 acres		
Rainfall	1965-2000 measured data (Thiessen polygon average of 10 stations)		
Evapotranspiration	1965-2000 pseudo-Penman data for Fort Meyers		
Root Zone	6.85 inches		
Direct Flow	100% of rainfall over 19,207 acres		
Linear Reservoirs		Maximum Storage (in)	Storage Coeff (in/d)
	Rapid Flow	5	8
	Moderate Flow	1	100
	Slow Flow	2.6	110
Pearson GOF v MikeShe Results	R = 0.878		

Table 4. Comparing Tidal Caloosahatchee Models

Model	p.o.s.	Rainfall (inches per year)	Runoff (inches per year)	Runoff (acre-foot per year)			
				Total	AQ	DR	OVL
MikeShe	1998-2000	65.1	26.1	583,298	104,949	373,531	104,819
LinRes	1998-2000	65.1	26.1	584,092	119,630	360,421	104,042
LinRes	1965-2000	56.2	16.2	362,488	83,856	188,605	89,927

Table 5. Annual Flows into the Caloosahatchee Estuary: 1965-1995

	Measured	1995 Base	2020 with Restudy
	Average Annual Flow (af/year)		
Tidal Caloosahatchee Basins	339,471 (22%)	339,471 (24%)	339,471 (32%)
S-79 Flow	1,190,097 (78%)	1,070,637 (76%)	717,705 (68%)
E & W Caloos Basins	893,387 (58%)	703,322 (50%)	689,217 (65%)
Regulatory Releases	296,710 (19%)	367,314 (26%)	28,488 (3%)
TOTAL	1,529,568	1,410,108	1,057,176

note: 1995 Base is from Regional Modeling (95BSRR)

note: '2020 with Restudy Components' is from Regional Modeling (2020R1)

Table 6. Frequency Distribution of Total Estuary Inflows (see also Figure 5).

Flow Range	Probability of Monthly Flows within Flow Range		
	measured	1995 Base	2020 with Restudy Components
<325 cfs	23%	32%	2%
325 to 500 cfs	9%	9%	16%
500 to 800 cfs	12%	6%	32%
800 to 1500 cfs	13%	12%	25%
1500 to 2800 cfs	17%	13%	10%
2800 to 4500 cfs	11%	14%	9%
4500 to 8000 cfs	11%	9%	4%
>8000 cfs	4%	4%	1%

Table 7. Evaluating watershed inflows when S-79 monthly flows are near 300 cfs (275 to 325 cfs)

	probability total flow in range (cfs)		
Total Flow	measured	95base	2020 with Restudy Components
<325 cfs	7%	0%	13%
325 to 500 cfs	53%	43%	68%
500 to 800 cfs	33%	43%	20%
800 to 1500 cfs	7%	14%	0%
1500 to 2800 cfs	0%	0%	0%
2800 to 4500 cfs	0%	0%	0%
4500 to 8000 cfs	0%	0%	0%
>8000 cfs	0%	0%	0%
months is in range	15	14	40

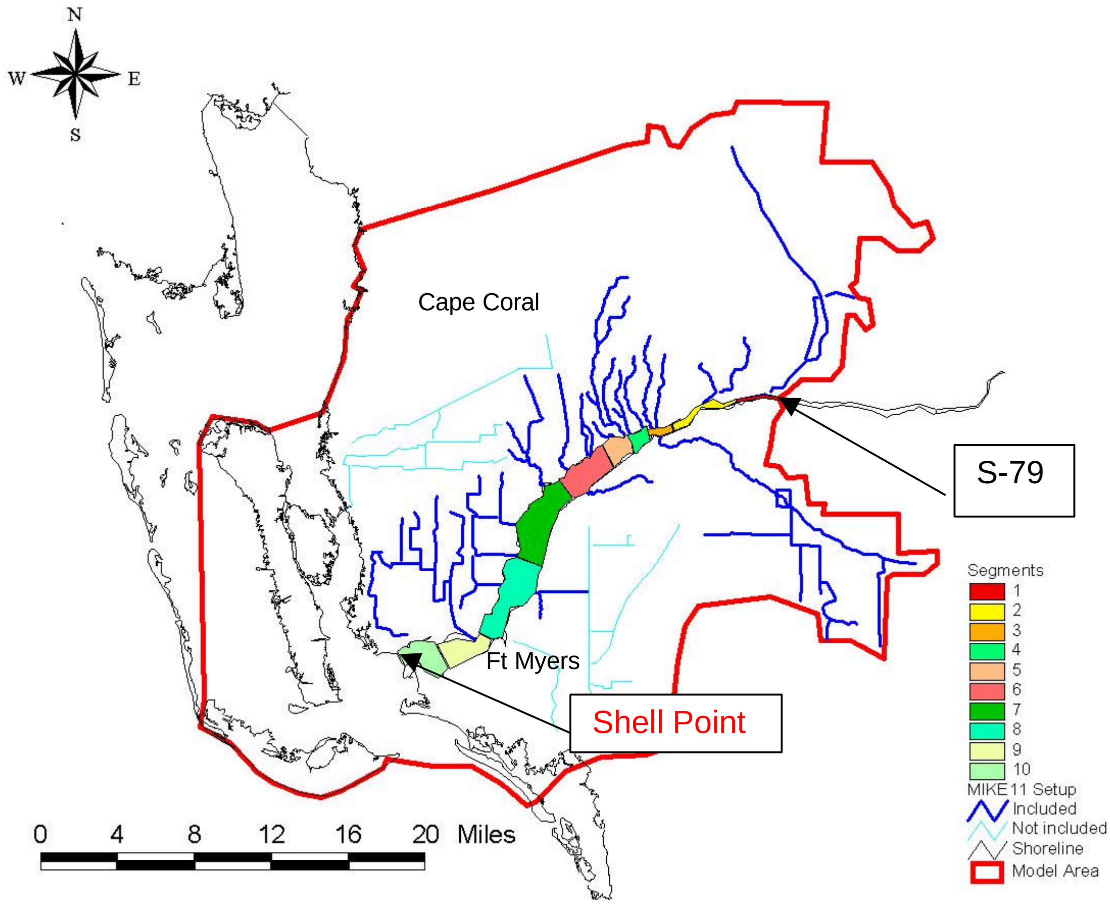

Figure G-1 – Segments of the Caloosahatchee River Estuary Receiving Inflows from the Tidal Caloosahatchee River Watershed

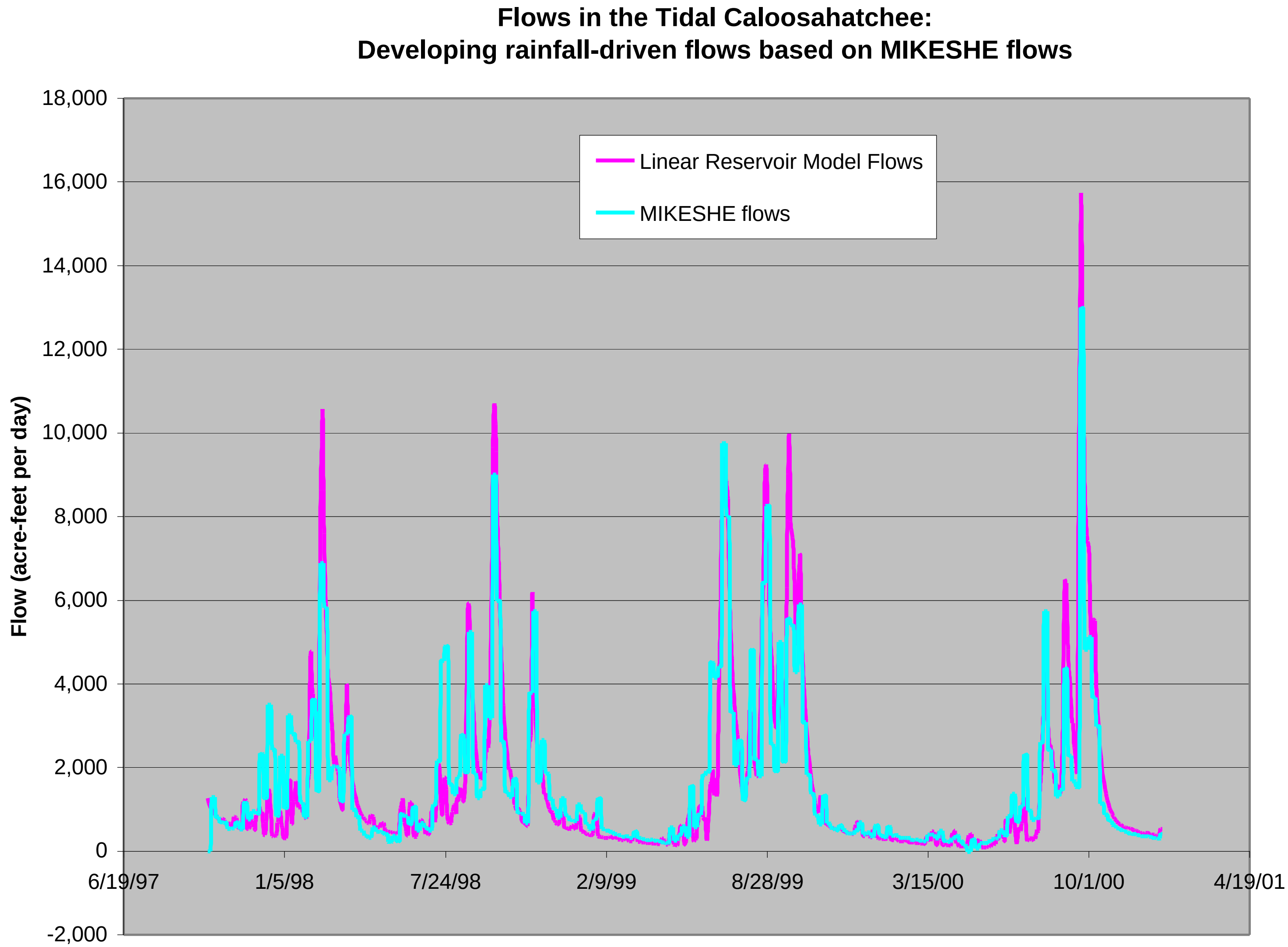

Figure G-2. Comparison of 5-day flows: MikeShe Model for the Tidal Caloosahatchee Basin and Calibrated Linear Reservoir Model.

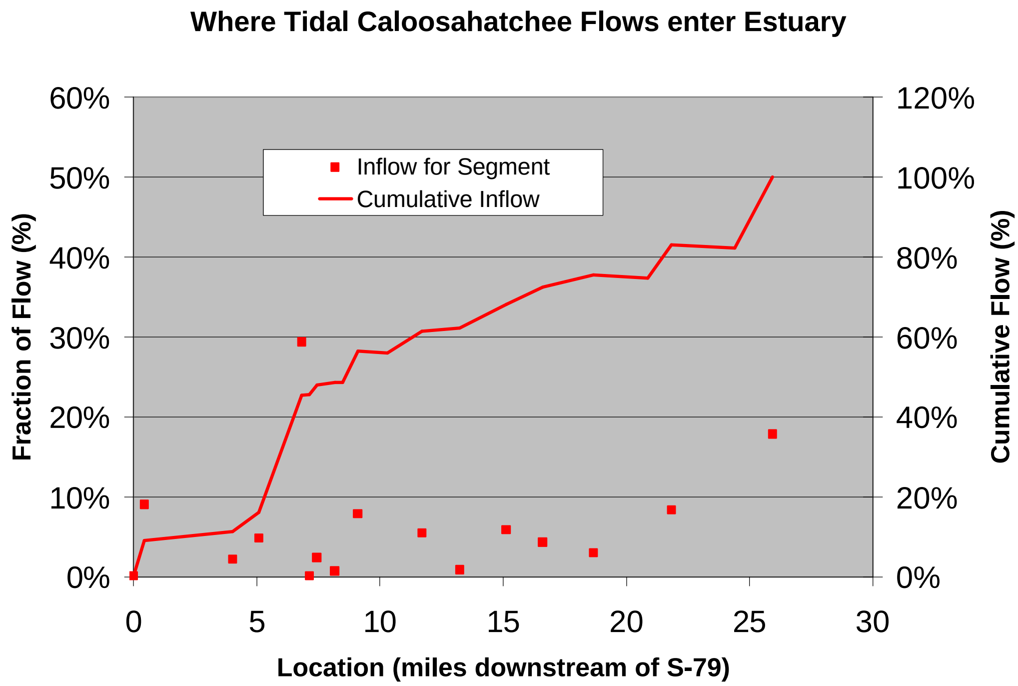

Figure G-3. Typical Spatial Distribution of Tidal Caloosahatchee Inflows

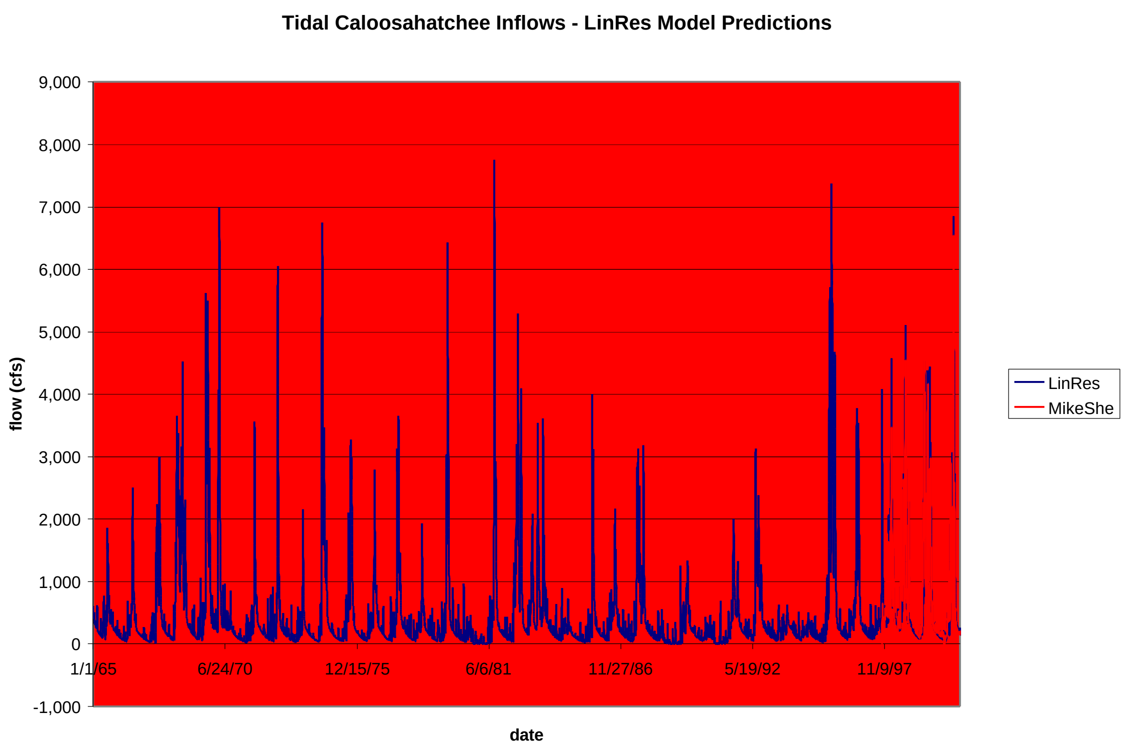

Figure G-4. Tidal Caloosahatchee Daily Flows predicted by LinRes model

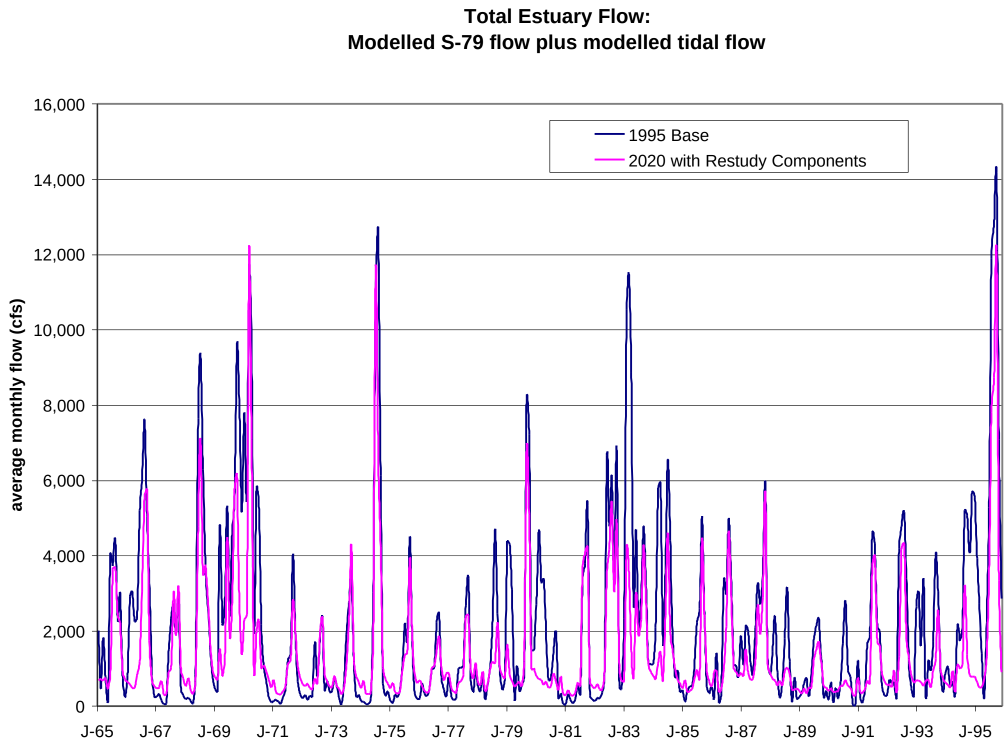

Figure G-5. Average Monthly Caloosahatchee Estuary Inflows: modelled S-79 flow for 1995 Base and 2020 with ReStudy - each combined with LinRes estimates of tidal flow.

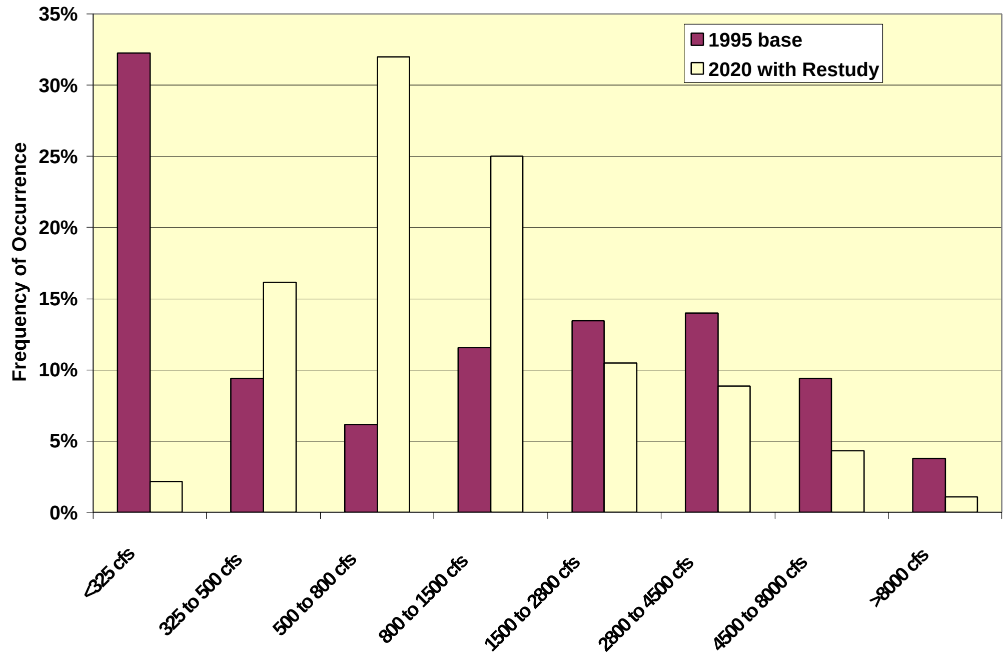

Figure G-6. Distribution of Average Monthly Caloosahatchee Estuary Inflows – 1965 to 1995. Inflows include Upper Basins, Tidal Basin, and Lake Okeechobee regulatory releases.

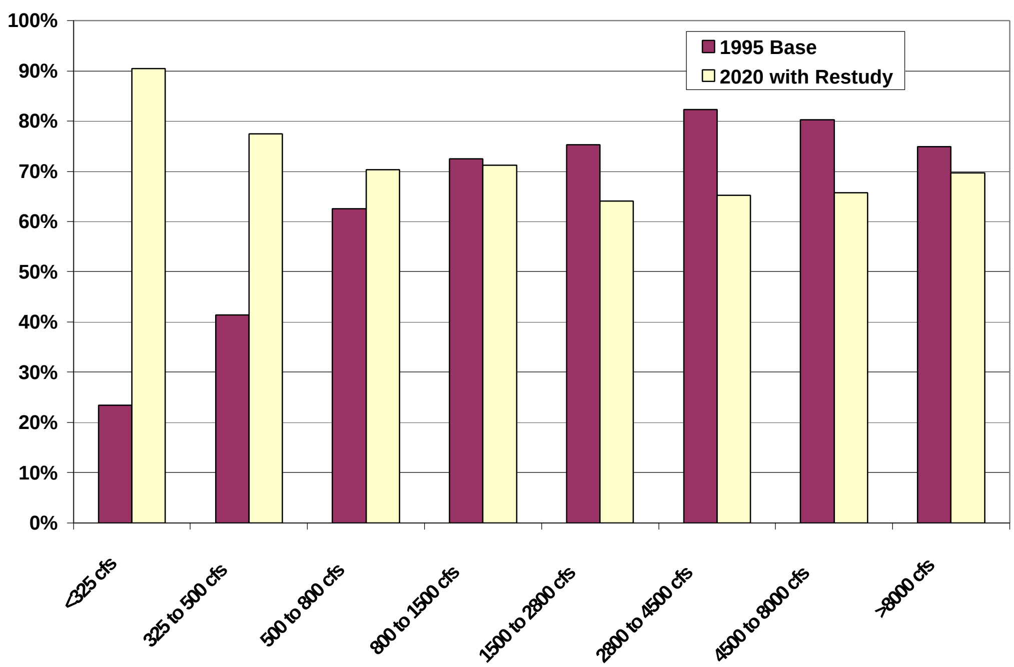

Figure G-7. Percentage of Average Monthly Caloosahatchee Estuary Inflows contributed by Upper Basins.

Technical Documentation to Support Development of Minimum Flows and Levels for the Caloosahatchee River and Estuary

Appendix H

Development of an Ecological Model to Predict *Vallisneria americana* Michx. Densities in the Upper Caloosahatchee Estuary: MFL Update

Melody Hunt

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Florida Bay and Lower West Coast Division
Southern District Restoration Department

South Florida Water Management District

January 2003

Development of an Ecological Model to Predict *Vallisneria Americana* Michx. Densities in the Upper Caloosahatchee Estuary -- MFL Update

Summary

The density of *Vallisneria americana* Michx. is estimated using a numerical model developed for the upper Caloosahatchee Estuary. The density is estimated based on responses to light, salinity and temperature at two sites within the upper estuary. Monthly field monitoring of *V. americana* density and water quality parameters has been conducted at these sites since 1998. The model is calibrated based on measured *V. americana* densities, water temperature, and transparency at each station for the period 1998-2001. Daily salinity input is estimated from flows generated by hydrodynamic modeling. Daily incident PAR was obtained from a continuous recording station in Estero Bay. Long–term computations for *V. americana* are developed using predicted salinity regimes from both the 95 base scenario (Pre-CERP) and the D13R (Post-CERP) scenario.

Background

V. americana Michx. in the upstream fresh and brackish water portion of the Caloosahatchee Estuary has been identified in the "Technical Documentation to Support Development of Minimum Flows and Levels for the Caloosahatchee River and Estuary" (SFWMD, 9/00 Draft) as a key species to be protected against significant harm. The proposed approach for determining the minimum flows and levels (MFLs) described in this document included the development of daily growth rate algorithms for *V. americana* relating changes in shoot density with salinity. Because the growth model presented was not intended to reproduce the annual cycle of *V. americana* growth or abundance, the shoot density was "reset" each year to a specified constant value. Additionally, salinity was the only environmental variable considered in this *V. americana* growth model. While a scientific review panel endorsed the approach of utilizing *V. americana* as an environmental indicator to establish MFLs, they identified areas where further work was required to validate the MFL. In their final review report, the scientific panel stated that the "*V. americana* approach should be refined, improved and made more robust" (Edwards et al., 2000). The primary criticisms stated by the review panel in the proposed *V. americana* model included:

1. using salinity as the global limiting factor to *V. americana* survival and growth,
2. the lack of variability in spatial and demographic factors,
3. the lack of variability in salinity input regimes,
4. setting annual shoot recovery densities to constant values.

Specifically the review panel recommended that an energetically based *V. americana* model be developed to allow prediction of the complete annual cycle of growth, reproduction, senescence, and overwintering with consideration for multiple environmental factors. Additionally, it was recommended that a hydrodynamic model be utilized to provide salinity input to the *V. americana* model thus permitting the evaluation of a wide range of salinity regimes on SAV growth and survival.

Model Description

A mechanistic, process based ecological model has been developed to investigate growth responses of *V. americana* to varying environmental conditions in the upper Caloosahatchee Estuary. Due to the limited amount of time available for development and calibration, the model presented here is in the preliminary stages of development and future modifications are anticipated. The model consists of a system of 3 simultaneous differential equations (finite difference), one for each of three state variables, solved by Euler numerical integration with a time step of 1 day. State variables represented in the model are the following: total mass, number of shoots and number of blades. The domain of the model is a spatially averaged $1m^2$ single layer water column. Forcing functions are water temperature, incident PAR, secci disk depth, and salinity. The water column is modeled as a non-stratified, homogeneous layer. A conceptual model (**Figure H-1**) illustrates the core processes that control plant growth and abundance in the model.

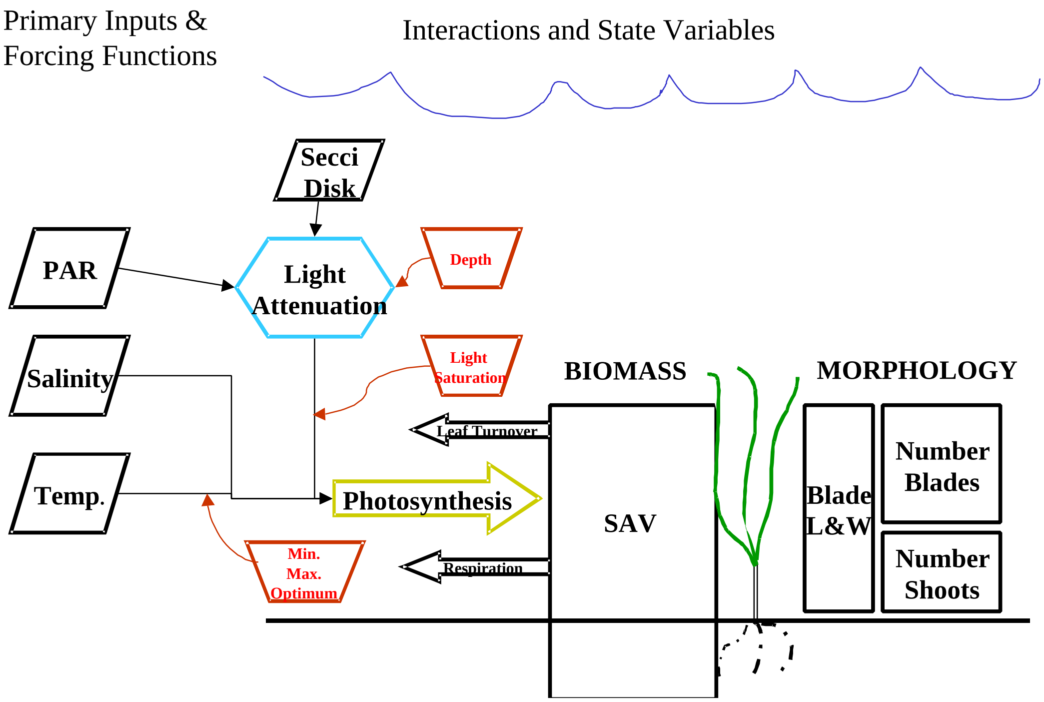


Figure H-1. Conceptual *V. americana* Model for the Upper Caloosahatchee Estuary

State Variable Equations

The equations for mass (g dry weight Carbon/m^2), blade (number of blades/m^2) and shoot density (number of shoots/m^2) were all formulated similarly for each of the state variables. The equation is parameterized for each state variable and repeated three times in the model. The discussion herein shows the equations for blade density. The basic equations are the same for the remaining state variables with a simple substitution of these variables. The equation representing blade density is:

Blade Density (t) = Blade Density (t-dt) + Productivity – Loss

Where:

Productivity = *f* (Blade Density, Salinity, Temperature, Light)

and

Loss = *f* (Senescence, Stress Mortality, Respiration)

Loss

Senescence is considered seasonal and is triggered by day and temperature cues, which are based on both observations in the Caloosahatchee Estuary and the four-year calibration data set. Losses from respiration and stress mortality are temperature dependent and have the following form:

$$(\text{Stress Mortality Coefficients} * \text{Respiration Coefficient}) * (\text{Blade Density}^2) * [0.63*\exp^{(0.092*\text{water temperature})}].$$

Stress mortality terms include a separate coefficient for light and salinity. They are utilized only when conditions fall below tolerance levels for light or salinity. The cues for these coefficients are currently based on the calibration data set. It is anticipated that this algorithm will be refined with the quantification of these stresses from a recent mesocosm experiment (Hunt et al., 2002). If conditions are not outside the tolerance levels, only the base-line respiration coefficient is used in the calculation.

Productivity

Maximum productivity is multiplied by a series of reduction factors that range from 0-1, with 1 representing productivity at optimal environmental conditions and 0 representing conditions that prevent productivity. The reduction factors include the effects of salinity, light, and temperature. Maximum productivity is a density – dependent, self-limitation term determined by calibration that represents the carrying capacity of the environment. Relative growth effect relationships for salinity, light and temperature were developed based on field data, experimental studies using *V. americana* obtained from the Upper Caloosahatchee Estuary, and from information reported in the literature (**Table H-1)**.

Table H-1: Summary of Productivity Variables

VARIABLE	INPUT DATA	RELATIONSHIP	PARAMETERS REQUIRED	SOURCE
Salinity	Salinity, Water-Temperature	Graphical	Growth rate at different salinities for two different temperature ranges (corresponding to wet /dry seasons)	Doering et al., 1999
Light	Incident PAR Secci Disk Depth Water Depth	P/I curve	Ik = 200 $\mu E/m^2*s$	Harley and Findlay, 1994: Reported Range 100-279
Temperature	Water-Temperature	Empirical equation (O'Neill et al.,1972)	Q10 = 2 Optimum Temp. = 33 ^oC Maximum Temp.= 50 ^oC	Wilkinson, 1963

Salinity Effect

V. americana is a salt-tolerant freshwater species that often occurs in the fresh, oligohaline and mesohaline reaches of estuaries in the Northeastern and Southeastern United States (Bourn, 1932; Lowden, 1982). Salinity is an important environmental variable regulating the growth and distribution of *V. americana* in the upper Caloosahatchee Estuary (Doering et al., 1999). Relationships were developed relating relative growth to salinity in the range of 0 to 15 based on mesocosm studies using *V. americana* obtained from the Caloosahatchee Estuary (Doering et al., 1999). These researchers report two different rates based on wet season or dry season experiments. A combined salinity effect was developed in the model for shoots and blades based on these data and differentiated in the model according to incubation temperatures **(Figure H-2)**.

If the water temperature is > 25 ^{o}C then the salinity effect formulated for the wet season is used and if the water temperature is < 25 ^{o}C then the salinity effect formulated for the dry season is used.

Light Effect

The central role of light availability for submerged aquatic vegetation (SAV) has been demonstrated in numerous, field, laboratory, and modeling studies. Changes in water clarity can impact density, depth distribution and species able to grow in a given area. *V. americana* is generally considered light adaptable as it acclimates rapidly to increasing light and efficiently uses low light (Titus and Adams, 1979; Meyers et al., 1943; Harley and Findlay, 1994**)** However, its limited elongation potential may be a disadvantage in deep turbid water (Barko et al., 1984; 1991) and water clarity may an important factor regulating growth and survival especially for seedlings or immature rosettes (Kimber et al. 1995).

The light available for photosynthesis is modeled based on a simple linear photosynthetic versus irradiance (P/I) relationship (Blackman, 1905). In the models present formulation, the amount light reaching the bottom at any given location is assumed to be the amount of light available for photosynthesis. It is recognized that this is a conservative formulation most appropriate for small immature plants and likely underestimates the amount available for mature established plants with leaves extending into the water column.

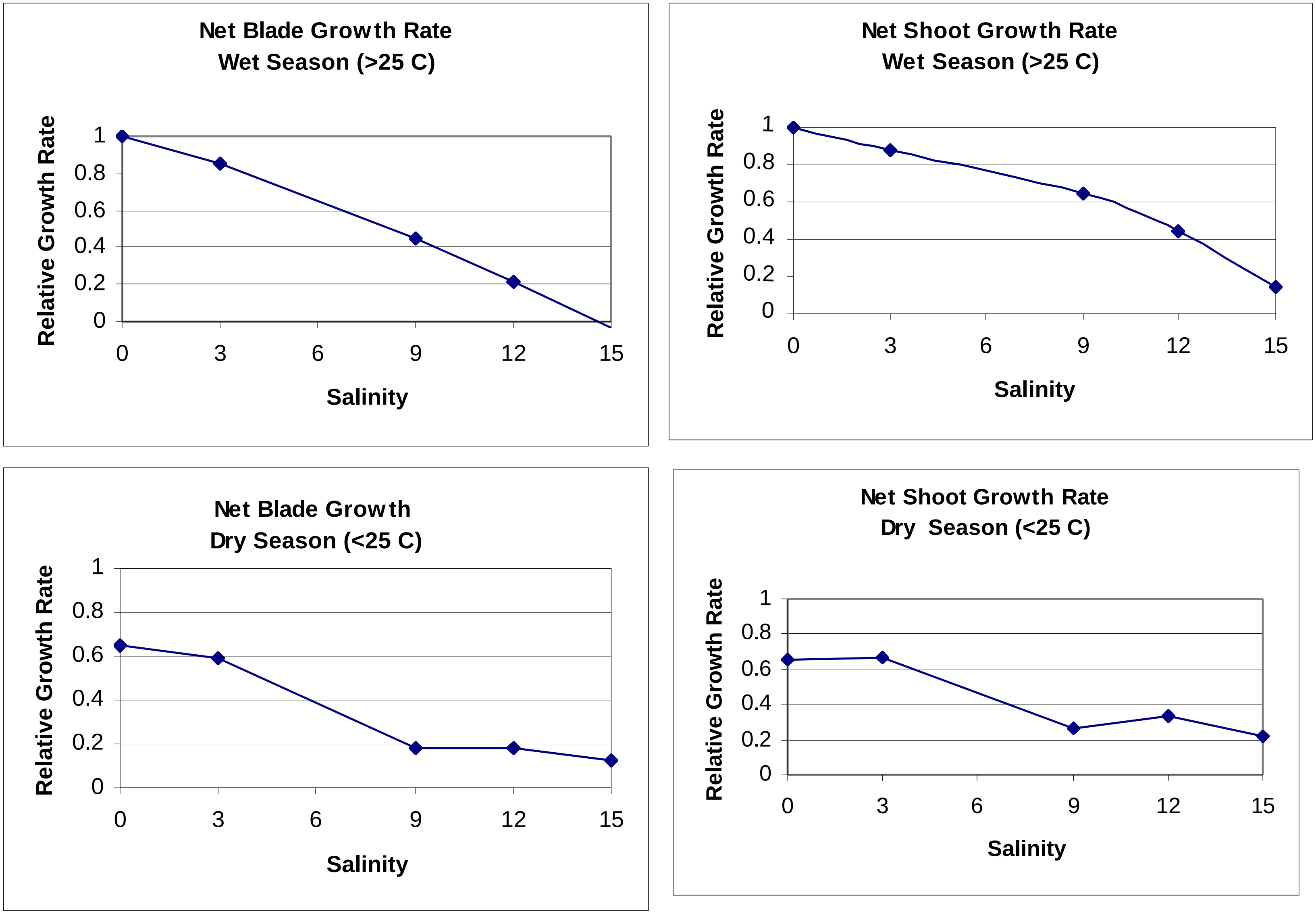


Figure H-2: Combined Salinity Effect for Shoots and Blades.

The amount of light reaching the bottom is determined by the following computation:

$$\text{Bottom PAR} = [\text{PAR}*(1\text{-Surface Reflectance})]*\exp^{(-Kd*\text{Bottom Depth})}$$

where:

surface reflectance = 0.10

and:

Light attenuation = 1.65/secci disk depth.

The relationship for light attenuation (kd) and secchi disk depth is an average conversion based on measurements made by 8 independent researchers (Giesen et al., 1990) valid in the range 0.5 to 2.0 meters (USEPA, 1992). Differences in conversion factors lead to small changes (5% discrepancy) in the determination of light attenuation in very turbid waters. Additionally researchers have suggested that use of secchi disk may not provide accurate estimates of light attenuation in highly colored waters (Dennison, 1990). The model does not differentiate between the various components that cause reduced availability (i.e. color, suspended solids, algae) which may influence the productivity of *V. americana* in different ways. Colored water absorbs the various wavelengths of water differently and algal blooms block sunlight used for photosynthesis. Suspended solids in the water column also physically block the penetration of irradiance through the water column. In addition suspended particles may be harmful when deposited on leaf surfaces by reducing light transmission and possibly blocking gas and nutrient exchange. Large amounts of suspended particles may change the depth and bury existing beds of submerged vegetation. All of these factors are possible and may play a slightly different role in reduced light in the upper Caloosahatchee Estuary at any given time. Contingent on the availability of additional information, it is anticipated that algorithms will be developed to individually represent these components. The calculated bottom PAR is then used to calculate the effect of light changes to relative growth by the following:

$$\text{Light Effect} = \text{Bottom PAR} / I_k$$

Light saturation (I_k) is set at the fixed value 200µE/m^2/s. When bottom PAR is greater than I_k then light effect is assumed to be 1 (optimal available light). The effect of any possible photoinhibition is not considered in this formulation. Additionally, it is assumed that P/I relationship is static and does not change with varying environmental factors. However, P/I curves may vary with depth and season for seagrasses (Drew, 1978; Dawes and Tomasko, 1988) and specifically for *V. americana* (Harley and Findlay, 1994). Recent mescosm experiments (Hunt et al., 2002) indicates that the P/I relationship for *V. americana* in the Caloosahatche Estuary may also change with salinity and plant age. Other factors, which may influence photosynthesis at a particular light level include: the age of the leaves, the orientation of the leaves with respect to the light field, and the psysiological health of the leaves (Fourqurean and Zieman, 1991). It is anticipated that the light relationships for the model in the future will be formulated to include dynamic conditions for salinity and plant age.

Temperature Effect

Temperature changes primarily influence growth of SAV over predictable seasonal cycles. In the upper Caloosahatchee Estuary water temperature ranged from 15 ^{o}C during winter months to 32 ^{o}C in summer months during the period 1998 - 2001. Assuming other conditions are appropriate for growth, *V. americana* can be observed throughout the year, with small rosettes persisting during the winter months. Consistent with the southern ecotype of *V. americana* reported by Smart and Dorman (1993), no over-wintering buds (turions) have been reported for *V. americana* in the Caloosahatchee Estuary. The effect of temperature on relative growth is modeled using the following equation (O'Neill, 1972):

$$kt=kmaxU^{x}e^{(XV)}$$

where:

$$U = (Tmax-T) / (Tmax-Topt)$$

$$V = (T-Topt) / (Tmax-Topt)$$

$$X = (W^{2} (1+(SQT(1+40/W))^{2}) / 400$$

$$W = (Q10-1)*(Tmax-Topt)$$

In this formulation kt is the rate of process at temperature T, and kmax is the rate of process at the optimum growth temperature (Topt). In the model kmax is 1, Q10 is 2, optimum growth temperature (Topt) is 33 ^{o}C, and the upper lethal temperature (Tmax) is 50 ^{o}C (Wilkinson, 1963).

It is important to consider that there are varying temperature growth ranges (minimums to maximums) reported for *V. americana* (Barko et al., 1982, 1984; Hunt, 1963; Meyer et al., 1943;

Wilkinson et al., 1963). This is not surprising considering values are determined in populations growing in different climates and under different environmental conditions. Titus and Adams (1979) report a temperature optimum for *V. americana* obtained from University Bay, Madison, WI. to be 32.6 ^{o}C. In laboratory tests (Wilkinson et al., 1963) *V. americana* grew best within a water temperature range of 33 ^{o}C to 36 ^{o}C. In this same study arrested growth occurred below 19 ^{o}C and plants became limp and disintegrated above 50 ^{o}C. The optimum growth temperature was determined under saturating light conditions and is assumed to be a constant value in the model. Bultus, (1987) reports that under non-saturating and low light conditions, temperature optimums may not remain constant values for marine SAVs. He reports lower values during periods of low light conditions relative to higher or saturating conditions. Future work may need to be initiated relating temperature to growth of *V. americana* under the range of conditions specific to the Caloosahatchee Estuary.

Model Calibration

V. americana densities were calibrated to monthly field measurements of shoot and blade density at two Stations within the Upper Caloosahatchee Estuary during the period 1998 – 2001 (**Figure H-3**). Due to limited collection of mass data, calibrations are shown for shoot and blade density. Mass was calibrated to the 1 year of available above ground mass (1998) and was observed for the subsequent years to be consistent with blade and shoot density results (data not shown). The following input data was used: water temperature, secchi disk, water depth, PAR, and salinity (**Table H-2**).

Table H-2: Input Data Summary For Calibration

INPUT DATA	SOURCE (FREQUENCY)
Salinity (ppt)	Regression model developed from field data (daily avg.) see **Appendix F** this document
Water Transparency (m)	Field measurement at each station (monthly)
Incident Par	Estero Bay Station with continuos recording (daily avg.)
Water Depth (m)	Field measurement at each station (monthly)
Water Temperature (^{O}C)	Field measurements at each station (monthly)

The four-year data set includes a range of environmental conditions in the Estuary. The first year 1998, produced a large standing crop of *V. americana* and as salinity was relatively low and

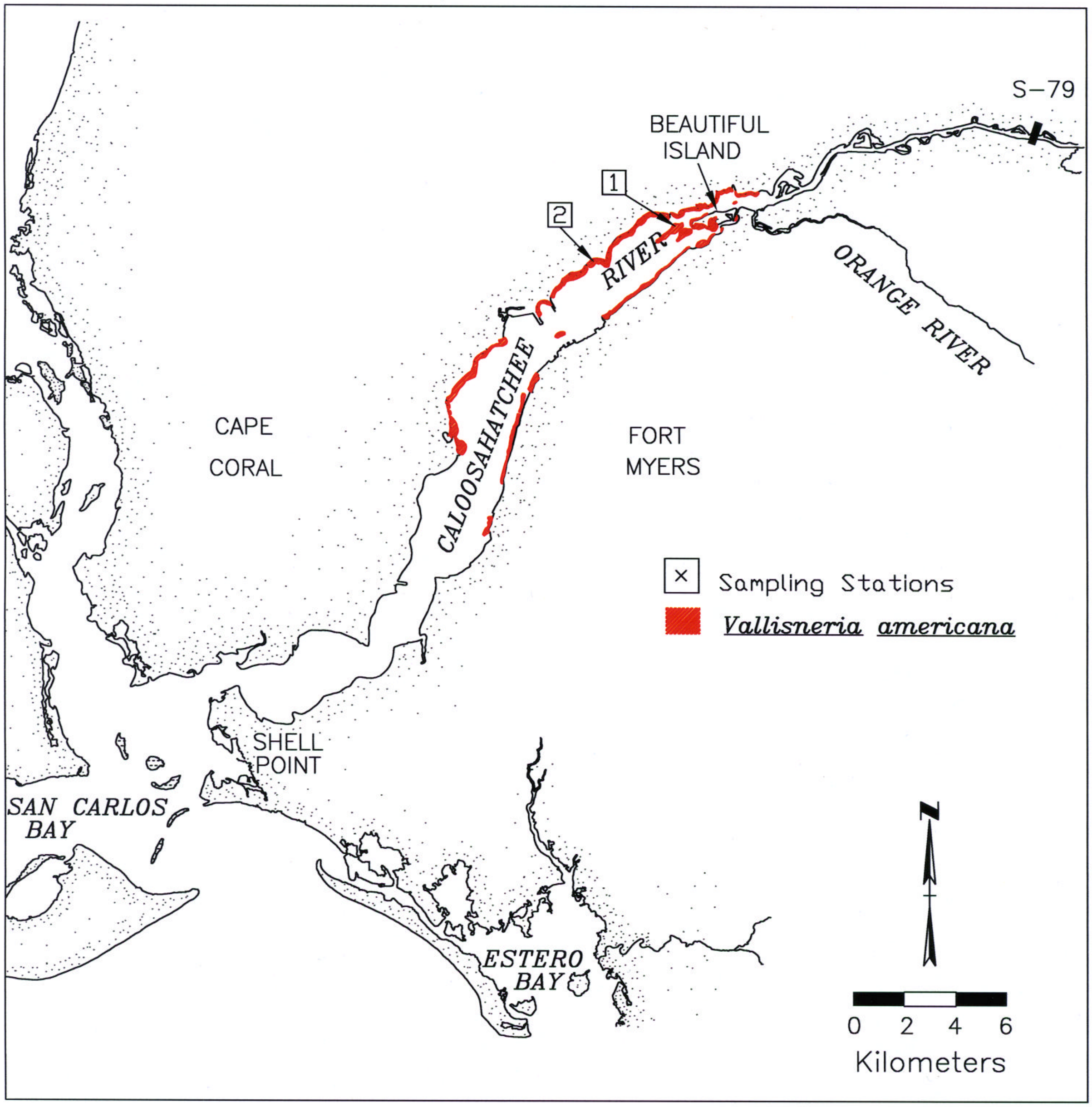
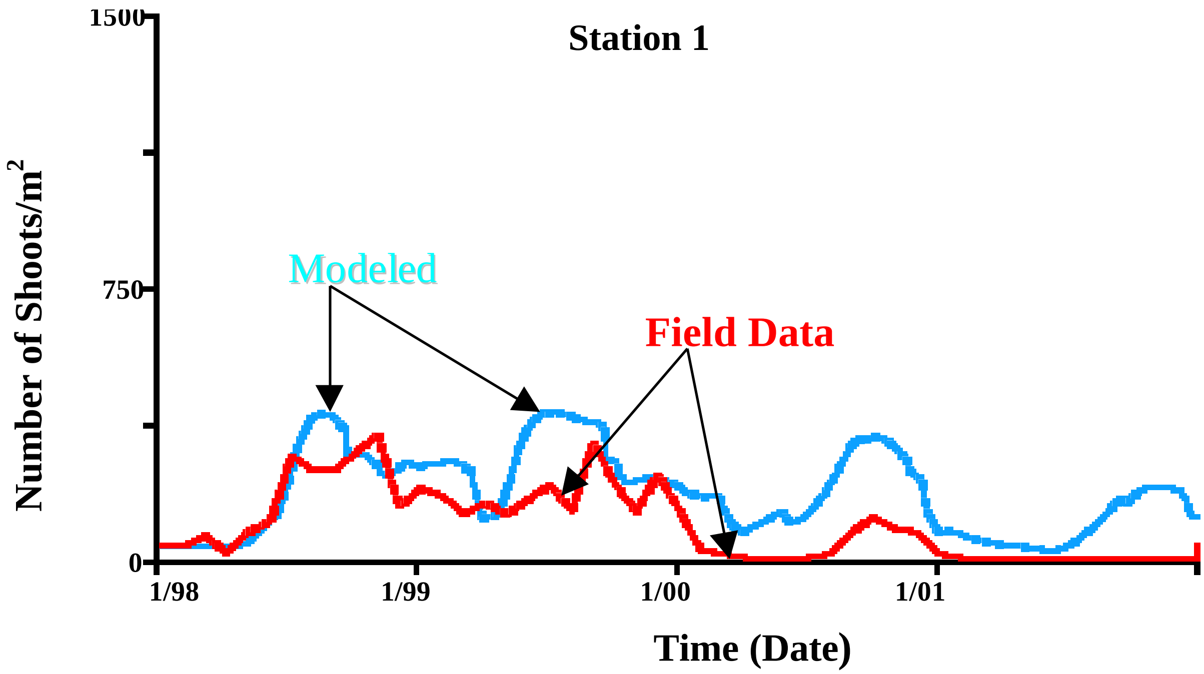


Figure H-3: Calibration Site Locations

water transparency was relatively high, representing ideal conditions for growth (**Figures H-4 and H- 5**). The initial annual densities were low due to reduced growth the previous year. Restricted growth of *V. americana* to varying degrees resulted in the years subsequent to 1998, due to both elevated salinity and reduced water transparency (**Figures H-6, and H-7**).



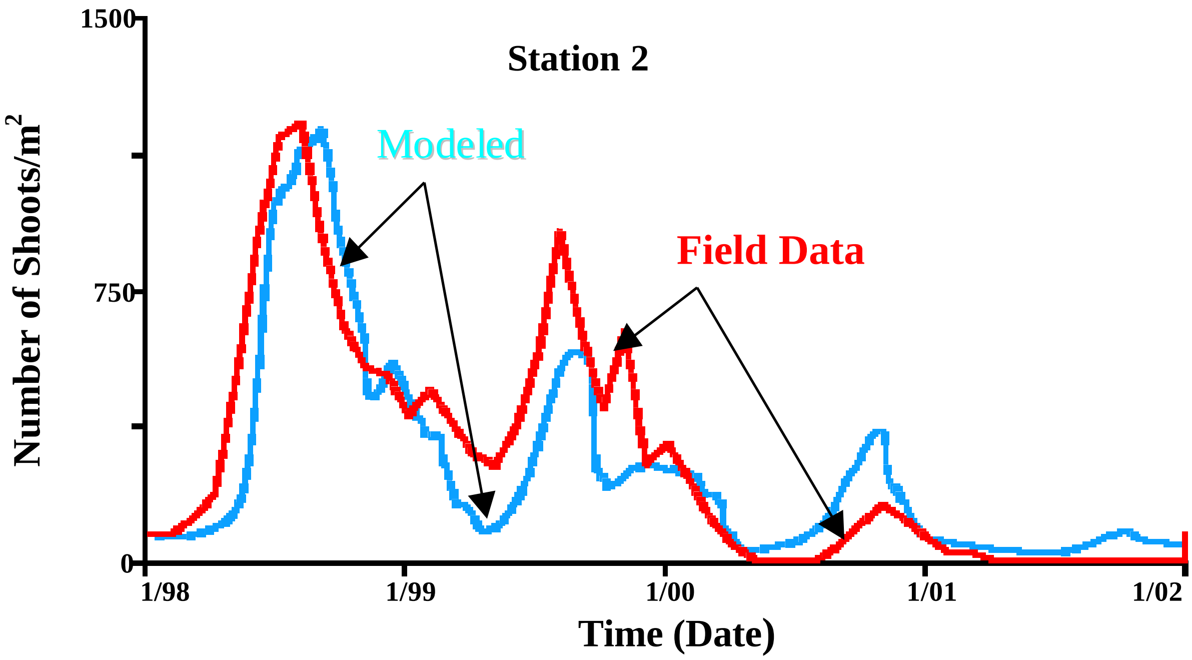


Figure H-4. Results of Calibration - Shoot Densities

In 1999, there was a salinity stress at the beginning of the growing season. Densities decrease slightly then resume growth when salinity returns to a more favorable level. In 2000, the salinity remained fairly low, however algal blooms created light limiting conditions at certain times. These blooms were noted by SFWMD field personal and measured as reduced transparencies in

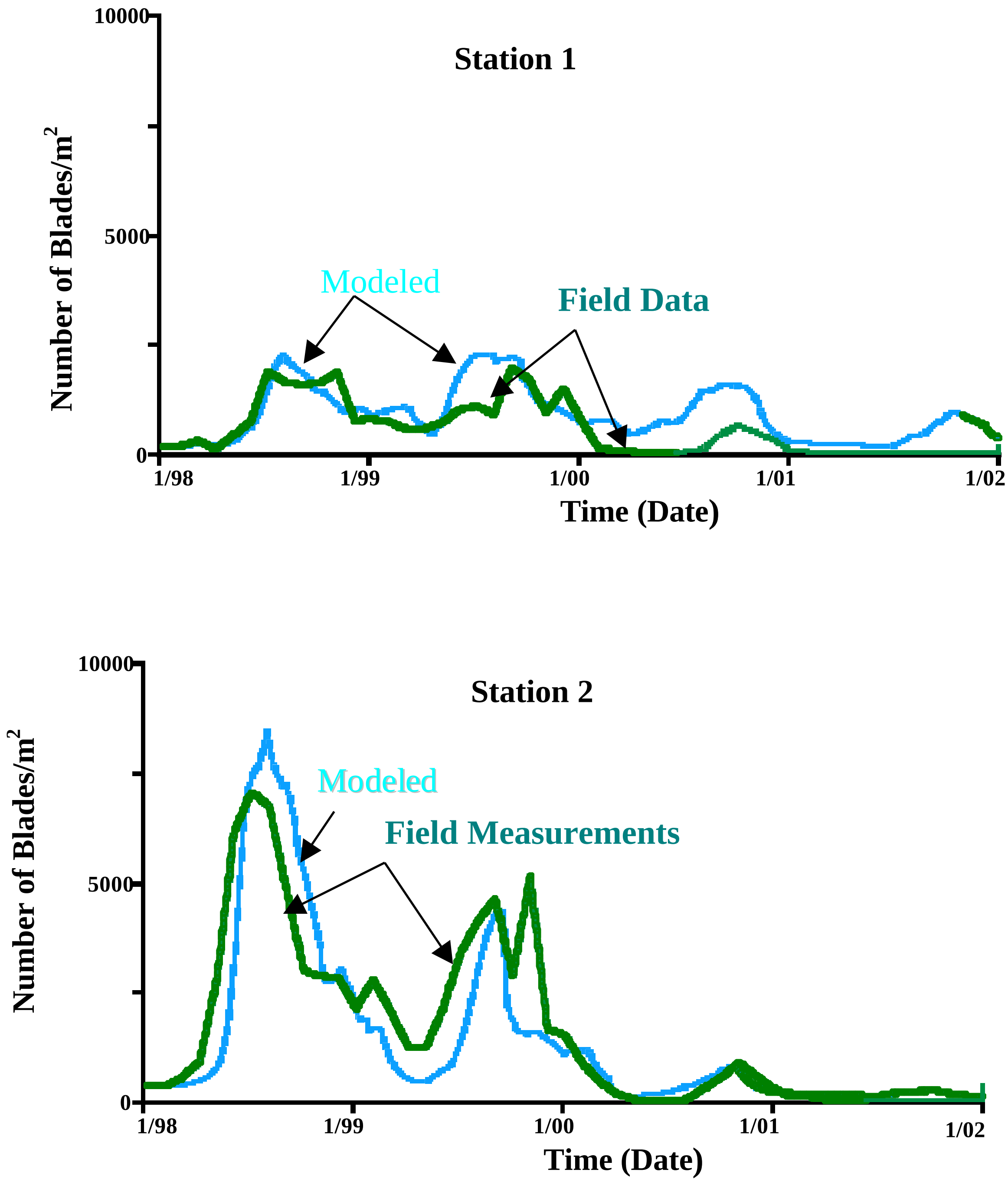
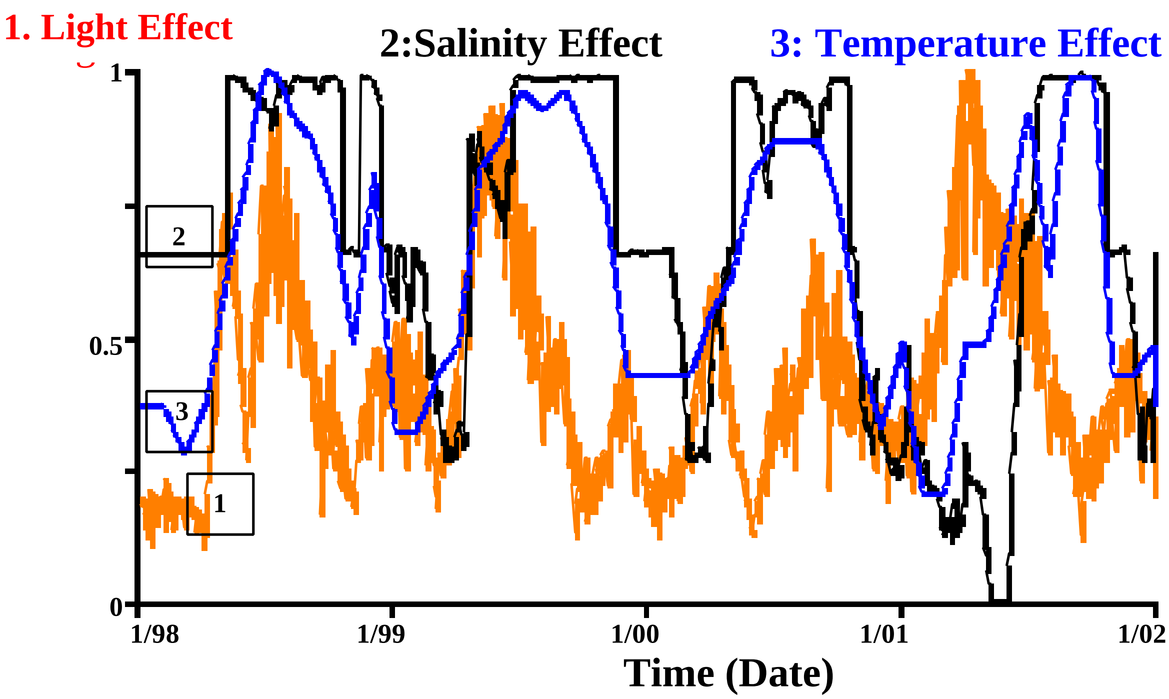


Figure H-5. Results of Calibration - Blade Densities.

the water column. Densities dropped and stayed very low throughout this year. By the end of 2000, *V. americana* was reduced significantly. Due to drought conditions in South Florida high salinity conditions were present throughout most of 2001 and *V. americana* beds did not recover.

Station 1



Station 2

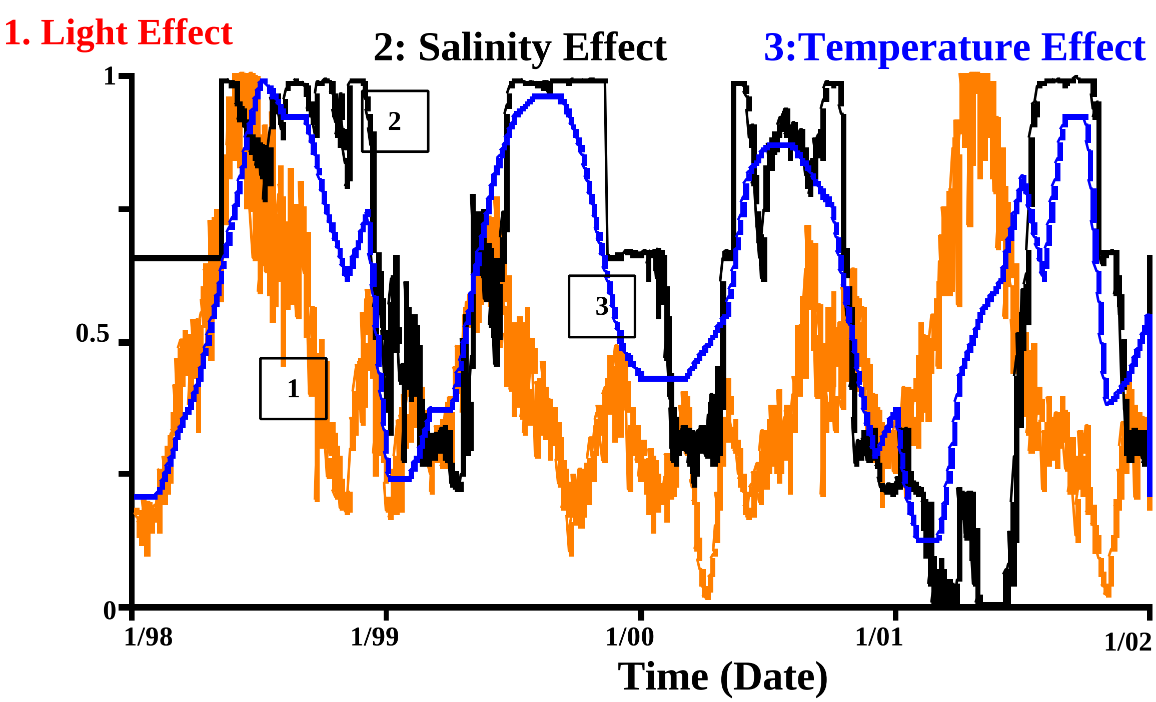


Figure H-6. Results of Calibration - Blade Densities.

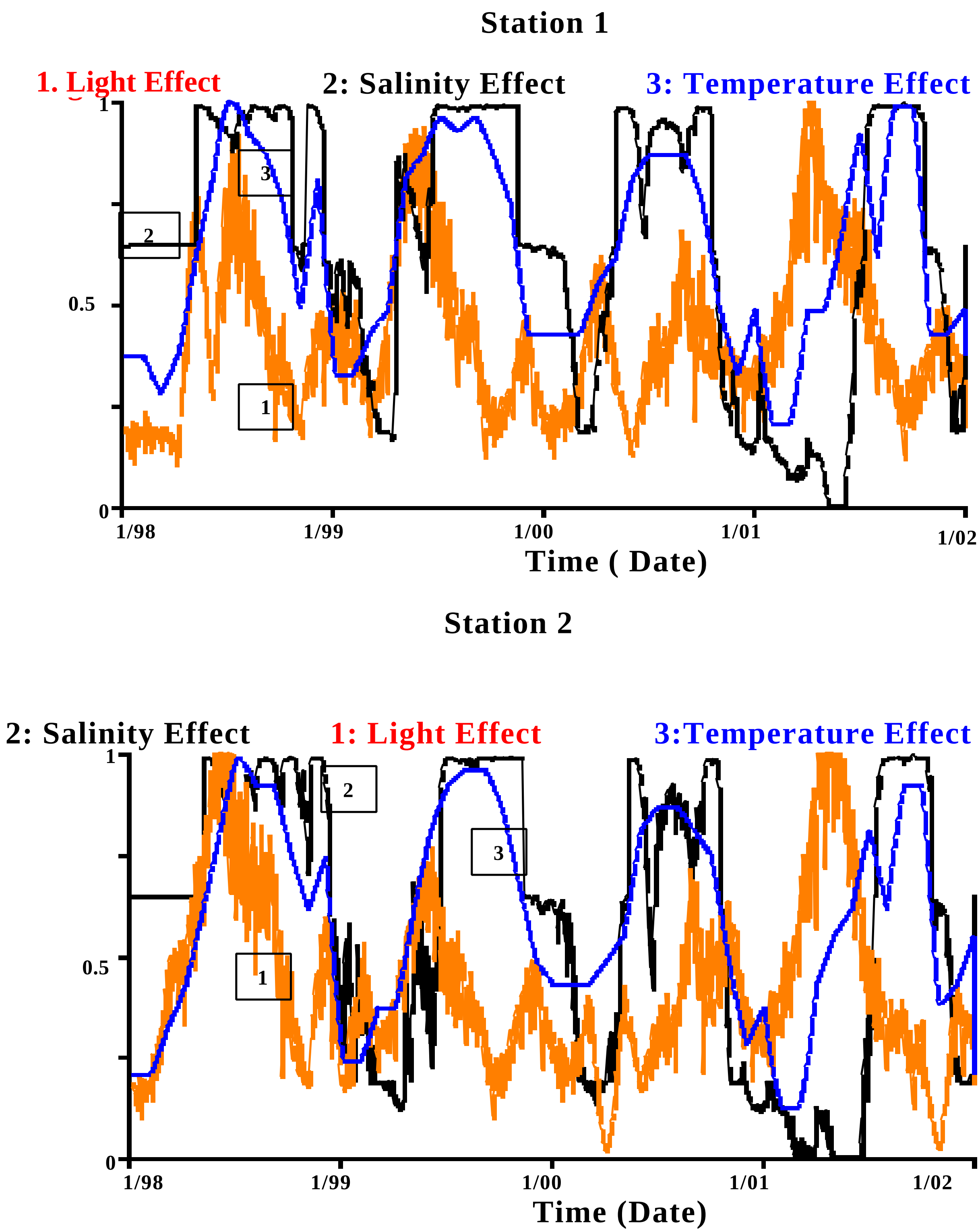


Figure H-7. Results of Calibration- Salinity, Light, and Temperature Effects for Blades.

At Station 1, the modeled computations predict field measurements reasonably well for 1998 and 1999. However the modeled results over-predict *V. americana* densities in the years 2000, 2001. The complete loss of *V. americana* 2001 is not well represented in the model computation at Station 1. At Station 2, the modeled results compare reasonably for all years (1998-2001), with a slight under- estimation of densities occurring in 1999. The calibration data set at Station 2 illustrates the importance of both salinity and light on *V. americana* growth in the Estuary. In 2000 a severe light limitation occurs and although the salinity and temperature become very favorable for growth immediately subsequent to the light restriction, *V. americana* does not recover that year. In 2001, severe salinity conditions are apparent and prevent growth even though light and temperature return to near optimums levels for growth (**Figures H4 to H-7**). Temperatures are below known growth minimums for *V. americana* (Wilkinson, 1963) at Station 2 in the initial two months of the year (14^{o}C) which may also have been inhibitory to growth/ establishment of this year. The temperature calculation does not specify a minimum value and may overestimate density at very low temperatures (**Figures H-6 and H-7**).

Assumptions and Limitations: Calibration

1. Nutrients or other water quality parameters are not represented in the model and assumed to be constant.

2. No epiphytic growth is considered. This would require considerations for nutrient cycling to be added to model.

3. A reduced carrying capacity coefficient (maximum density coefficient) is necessary at Station 1 relative to Station 2. This result indicates that factor(s) other than salinity, light, or temperature may be impacting growth potential at this location. Possibilities include: sediment characteristic(s) such as type, composition, nutritional status, slope, and toxics and/ or physical characteristics such as depth, angle, flow velocity, grazing or other physical disturbance. Future investigation is needed to determine the cause of this difference.

4. It is assumed that a viable seed bank is present for population reestablishment after a significant decline and there is no lag period for growth to commence once

environmental conditions become favorable. No over-wintering buds for *V. americana* have been found in Caloosahatchee Estuary and it is assumed that reestablishment occurs by exclusively by seed germination. Population factors representing seed production or dispersal are not represented in the model.

5. Light availability is calculated based on the light reaching the bottom. This is an appropriate assumption for immature plants with leaves near the bottom. However, this assumption may underestimate available light to larger more mature plants with leaves extending up into the water column.

6. The P/I relationship and associated parameters (i.e. I_k) is assumed to remain the same throughout all possible environmental conditions.

7. The various components that cause changes in water transparency (i.e. color, algal blooms, suspended solids) are not differentiated. The effect is assumed to be the same for all types of light reductions as measured by secci disk depth.

8. Grazing or other potential physical disturbances are not explicitly represented in the model.

9. The effect of temperature changes on productivity is assumed to remain the same throughout all possible environmental conditions (such as salinity or light changes).

10. The temperature minimum is not explicitly represented in the temperature formulation and may overestimate growth if temperatures fall below the minimum growth temperatures.

Sensitivity Analysis

Input Data

The quality, type, location and variability associated with the input data are important considerations when interpreting model results. Field measurements should be used whenever possible and the error associated with obtaining and processing the measurements should always be considered. Unfortunately, creating input files using field data from the locations under consideration is not always possible. This may be the case when: there is limited field data in the area of interest, for long-term simulations, and for future scenario analysis. Developing approximations for input data during years when field data is not available is often necessary. However, this introduces an additional source of error in the analysis. The potential impact of using a form of input approximation (averaged data input files) verses field data during the 4-year calibration period is illustrated by substituting the calibration files with the following:

- daily salinity input calculated from a regression model (**Appendix F**),
- 4-year water transparency averaged input files,
- 4-year temperature averaged input files.

In the latter two instances, the averaged input file was developed by averaging the four years calibration data to create one "average year" input file.

Parameters

The sensitivity of input parameters is an additional factor to consider. Constant values obtained from the literature are used in both the temperature and light functions. These values were obtained under defined experimental conditions and do not necessarily represent the range of conditions possible in the Caloosahatchee Estuary. Sensitivity analysis for the following parameters are provided:

- Light saturation (I_k),
- Optimum temperature,
- Maximum temperature,
- Q10 coefficient used in temperature equation.

Sensitivity Analysis Discussion

For discussion purposes blade densities are specifically discussed in the sensitivity analysis. The same analyses were performed for shoot densities with comparable results (data not shown.)

Salinity

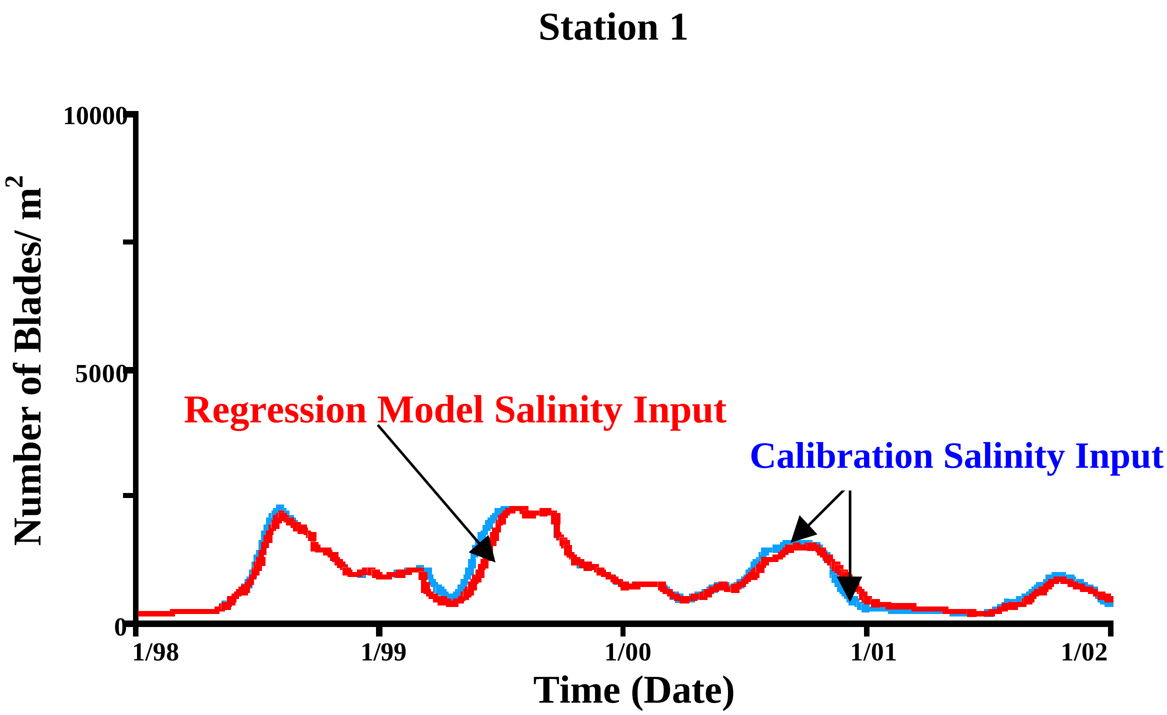
Use of salinity data interpolated from the field data (input to the calibration runs) or salinity input from the regression model, (**Appendix F**) does not produce a significant impact on *V. americana* densities at either Station 1 or Station 2 during the four-year of calibration period (**Figures H-8 and H- 9**).

Light

The use of an averaged annual secci disk depth input file produced differences compared to the calibrated model, which uses field measurements at both Station 1 and 2. (**Figure H-10**). The blade density at both stations 1 and 2 is overestimated in 2000 and 2001. This is due to underestimation of true water transparency using the averaged annual input file and illustrates the importance of light limitation in these two years. Additionally at Station 2, the average annual input file results in an underestimation of blade density in 1998 due to increased water transparency relative to the four-year average (**Figure H-11**).

The averaged annual data files resulted in secci disk depths ranging from 0.9 m to 1.3 m at Station 1 during the course of a year. The field data for the four-year calibration period shows a greater degree in variability in measurements ranging from 0.5 to 1.75m (**Figure H-11**). At Station 2, field measurements fall below 0.3m (data not shown). Thus the averaged data files do not account for the variability and extremes events such as phytoplankton blooms or highly colored water from basin discharge nor do they represent years that have very high water transparency such as that of 1998. It is these extreme values that may have the greatest impacts on *V. americana* growth.

The parameter I_k derived from P/I relationships is used directly in the determination of the light effect. The sensitivity of blade density to raising or lowering I_k within ranges reported in the literature (Harley and Findlay, 1994) is shown in **Figure H-12.** At both stations variations in I_k simply raised or lowered the peak density values. The model currently assumes this value to be constant over all environmental conditions. As discussed previously, research has indicated that P/I relationships (and thus I_k) are dynamic and can potentially change with water temperature, salinity, and prior exposure. Due to lack of quantifiable information available at the present time, this value remains constant in the current model. Analysis of recent experimental work (Hunt et



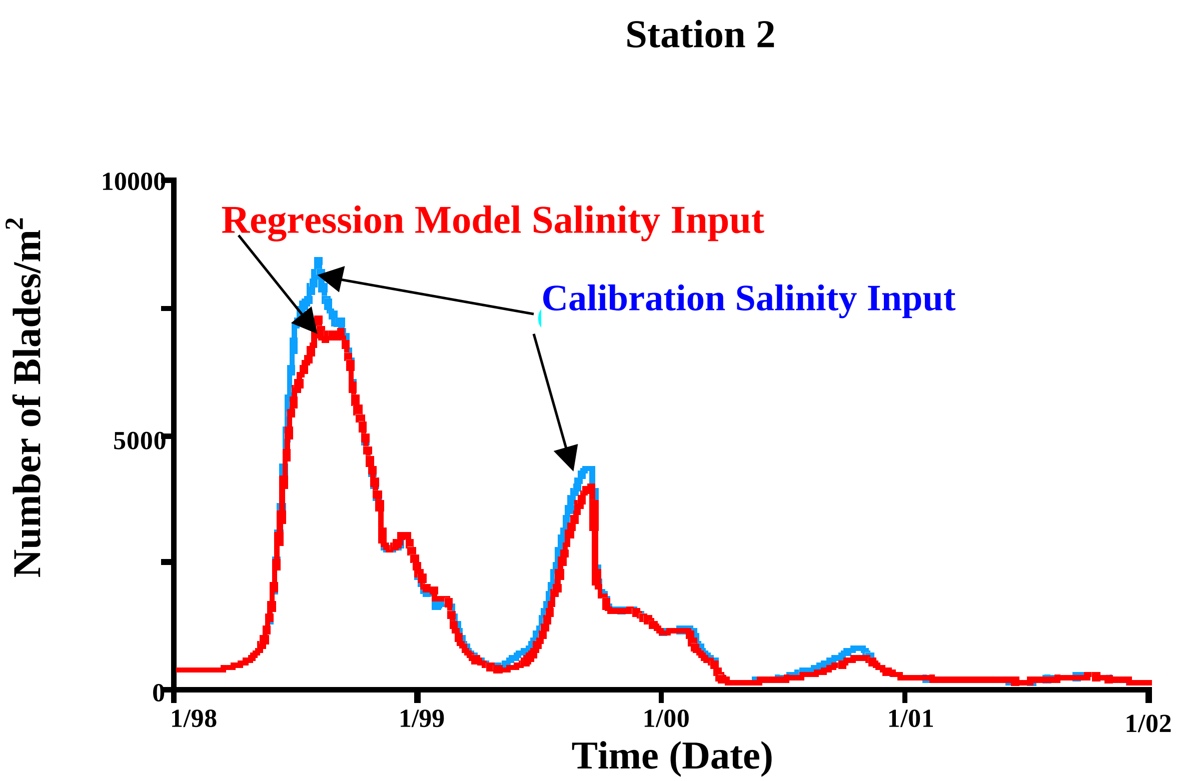
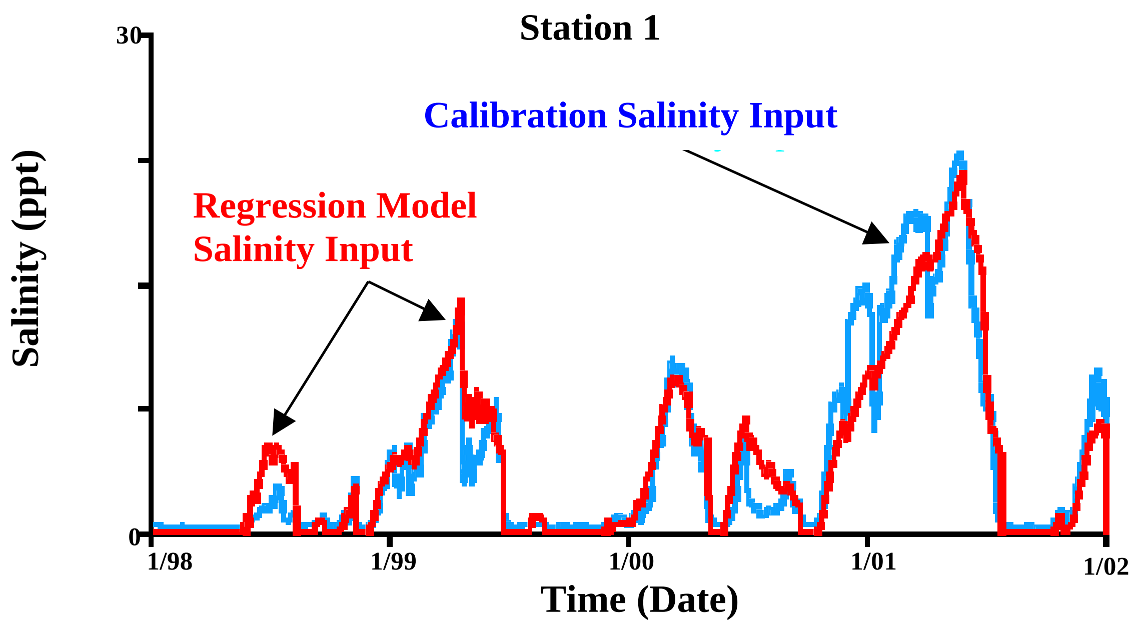


Figure H-8: Results of modeled *V. americana* Blade Densities Using Different Salinity Input



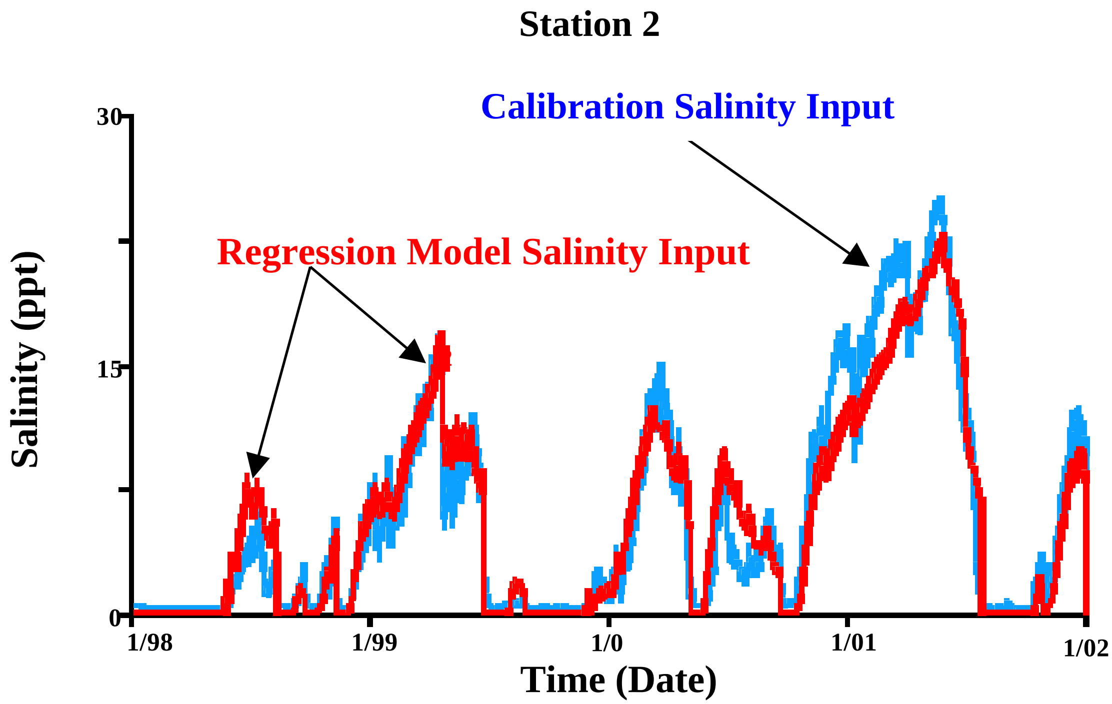
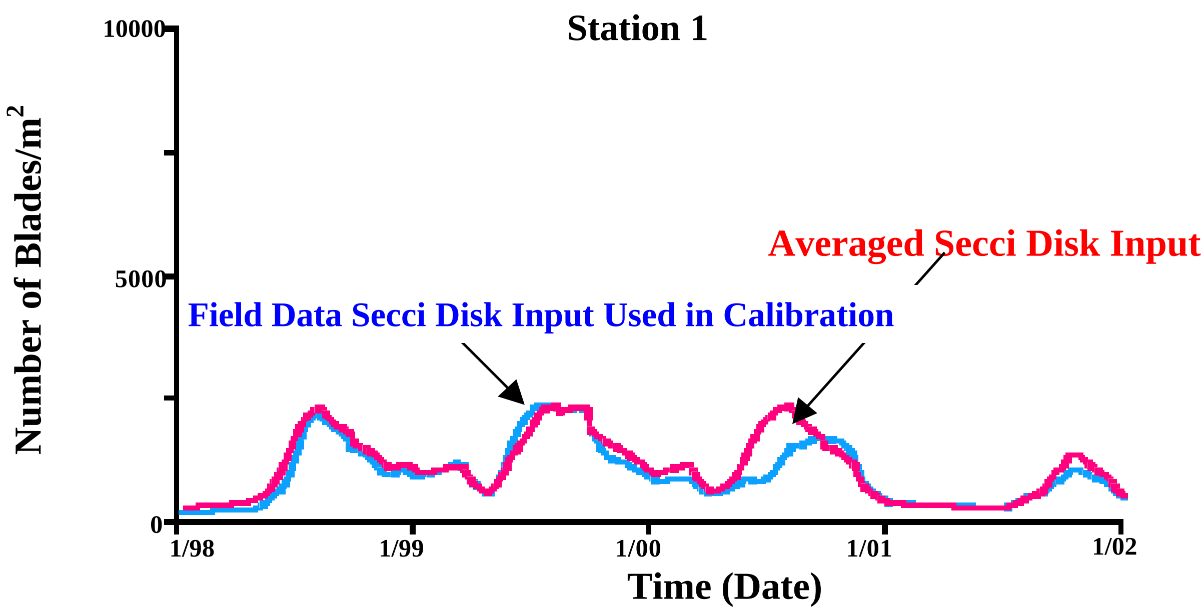


Figure H-9. Comparison of Salinity Input Data



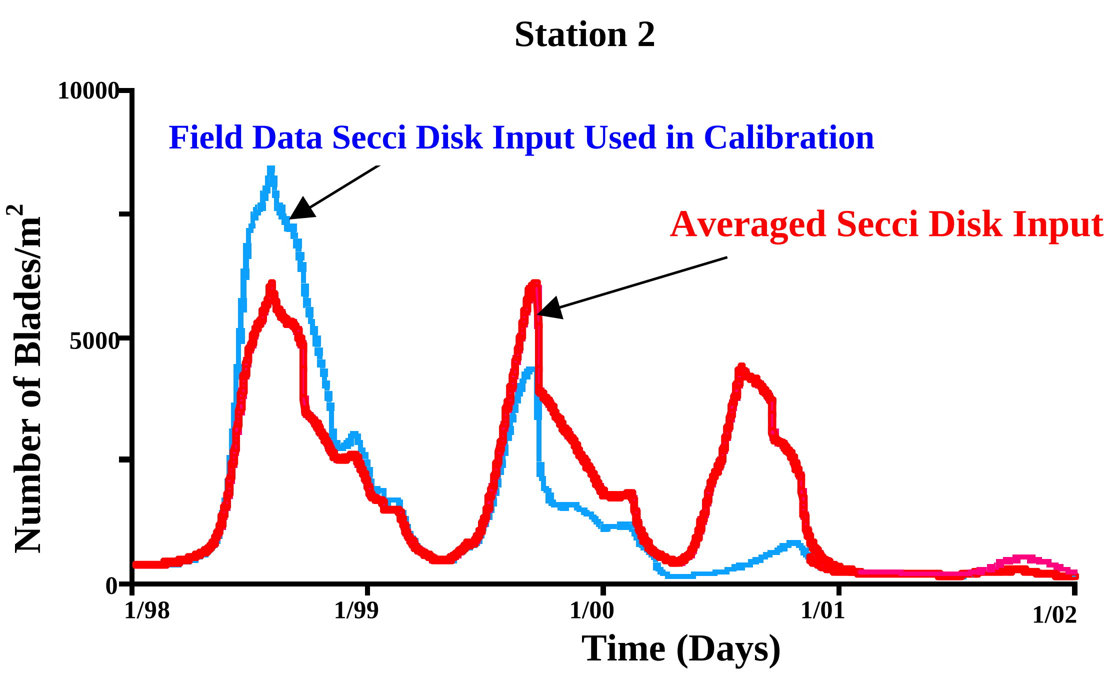
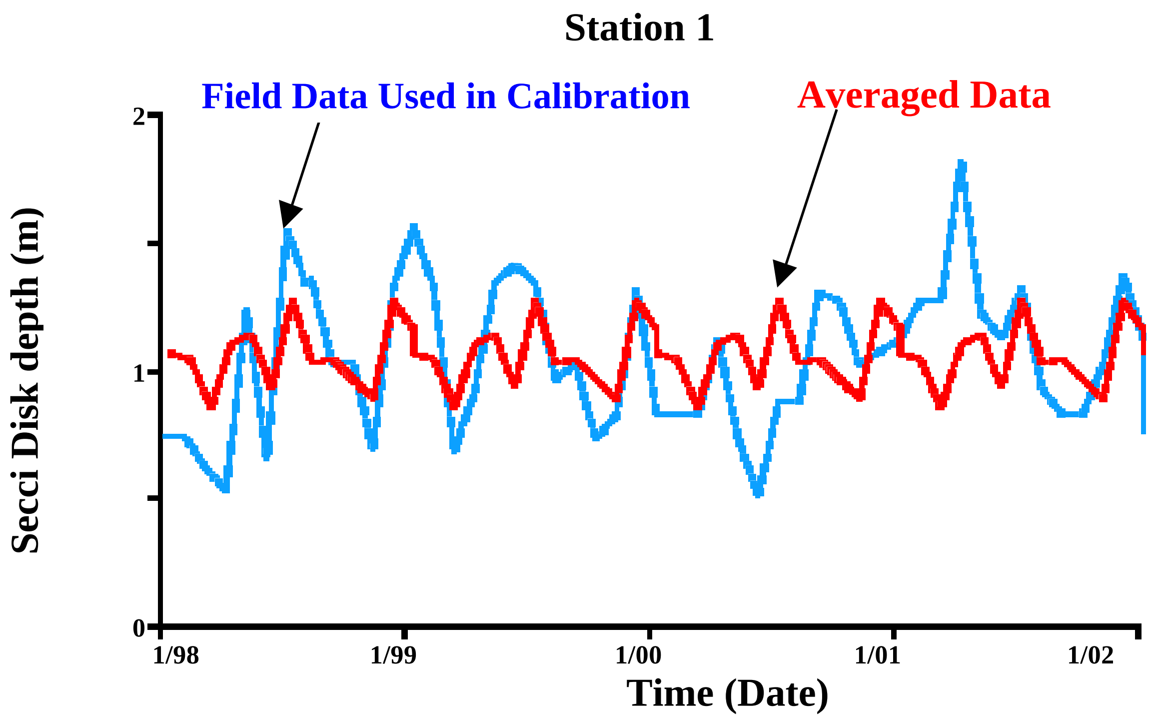


Figure H-10: Results of modeled *V. americana* Blade Densities Using Different Water Transparency Input.



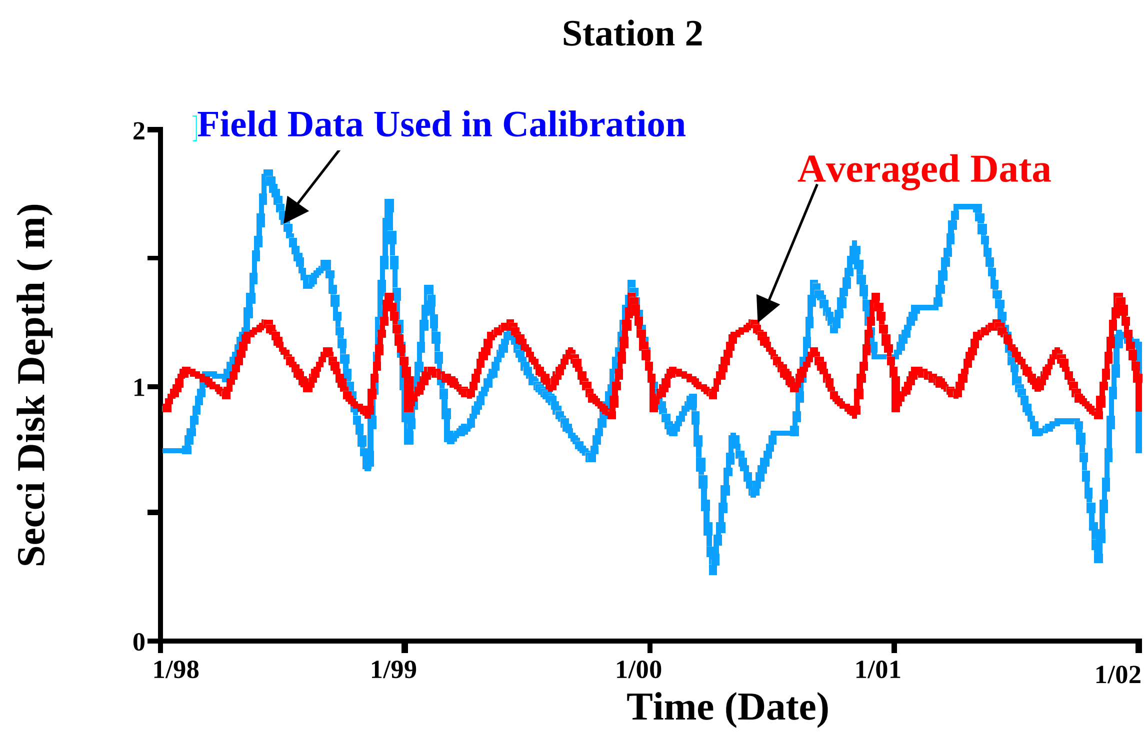
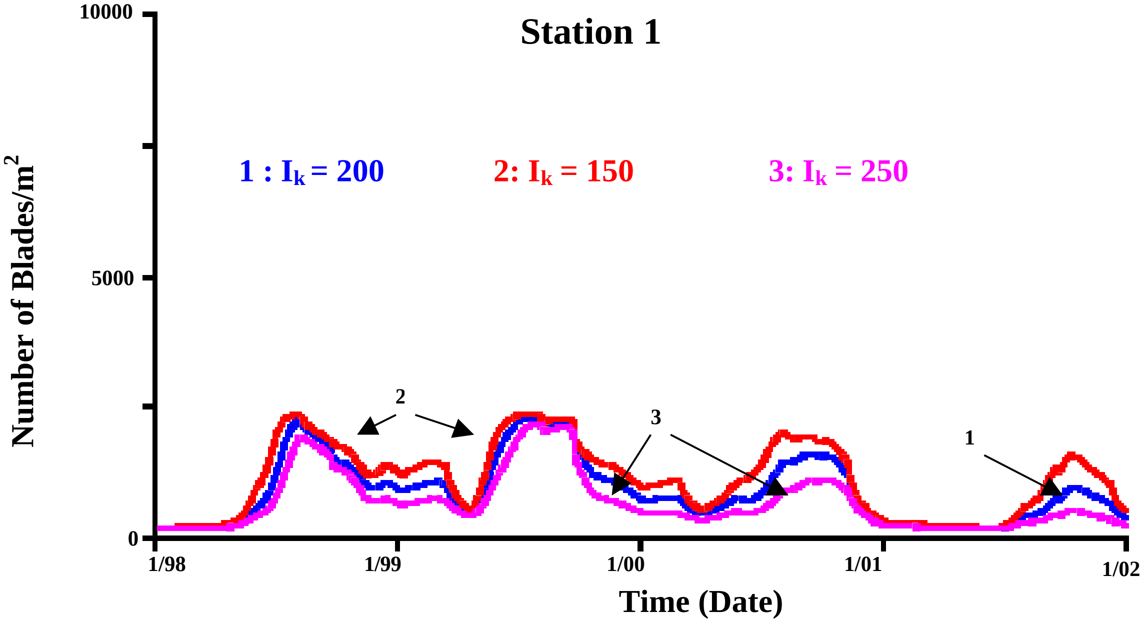


Figure H-11: Comparison of Water Transparency Input Data.



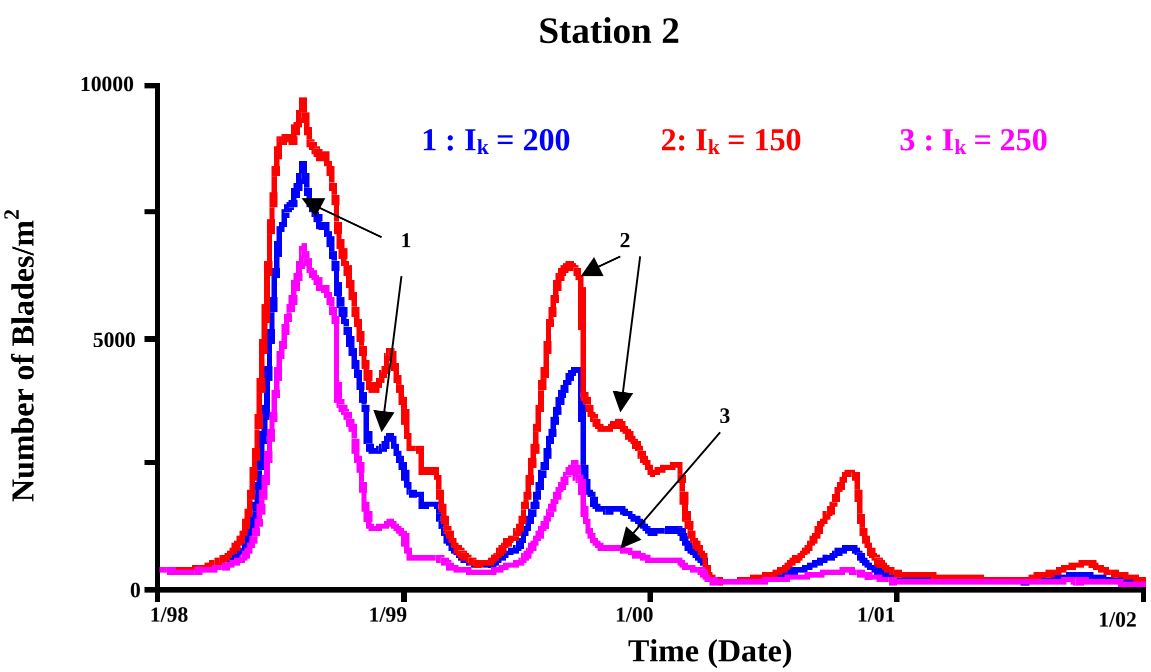


Figure H-12: Light Saturation Parameter (I_k) Sensitivity for Blade Density.

al. 2002) is expected to produce refinements in the way the P/I curve is formulated: both in terms of differences in respiration and photosynthesis under high and low salinity as well as prior light exposure/acclimation.

Temperature

Comparison of averaged temperature input file and the field data does not show a significant impact on the computed *V. americana* densities for either Station 1 or Station 2 during the four-year calibration period (**Figures H-13** and **H- 14**). In addition, raising optimal growth temperature to 36 ^{o}C, reducing maximum growth temperature to 45 ^{o}C or changing the Q10 values did not have significant impacts (data not shown).

31-Year Scenarios

To evaluate plans for watershed management, *V. americana* computations for Station 1 and Station 2 were generated under the following two scenarios:

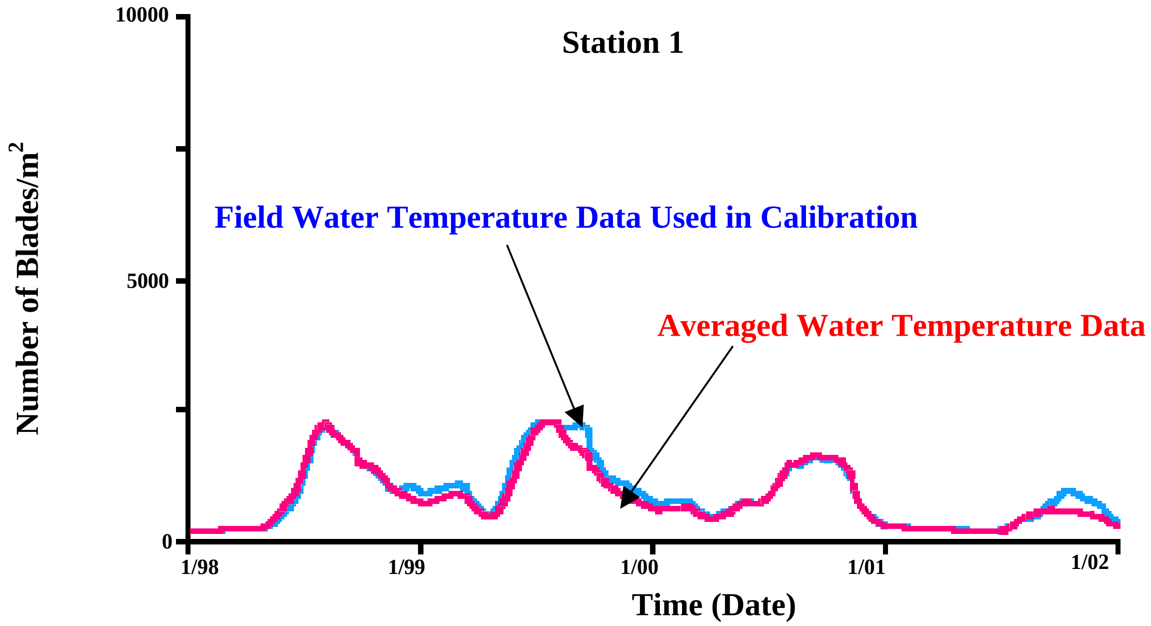
- 31-year period simulation using 1995 Base Case condition flows,
- 31-year period using CERP D13R project condition flows.

Data Needs

The input data is summarized in **Table H-3.** In both simulations, daily salinity predicted by a regression equation derived from a 3-D hydrodynamic model (**Appendix F**), served as input to the *V. americana* model. Input water temperature, secci disk depth, and PAR were determined using averaged annual data sets (determined from the calibration period). Therefore salinity was the only dynamic variable in these simulations and the remaining inputs were maintained as “average conditions” throughout each annual cycle.

Table H-3. Input Data Summary For 31-Year Scenarios

INPUT DATA	SOURCE (FREQUENCY)
Salinity (ppt)	Regression model based on hydrodynamic model (daily avg.) see **Appendix F** this document
Water Transparency (m)	Averaged data set used for calibration from 1998-2001 (monthly)
Incident PAR ($\mu E/s*m^2$)	Averaged data set used for calibration from 1998-2001 (average daily)
Water Temperature (^{o}C)	Averaged data set used for calibration from 1998-2001 (monthly)



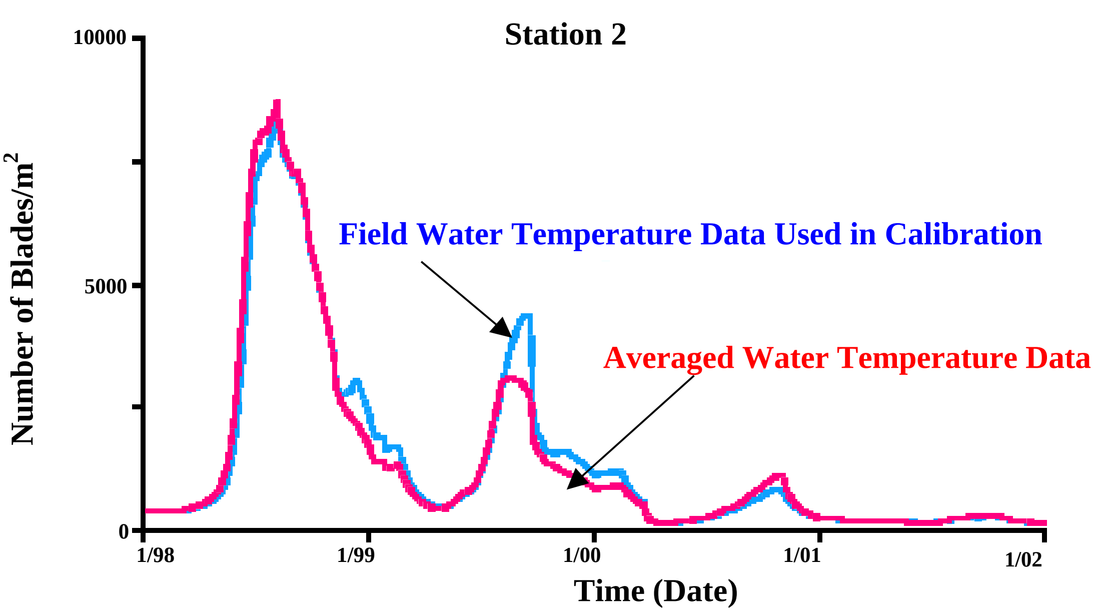


Figure H-13: Results of Modeled *V. americana* Blade Densities Using Different m Water Temperature Input

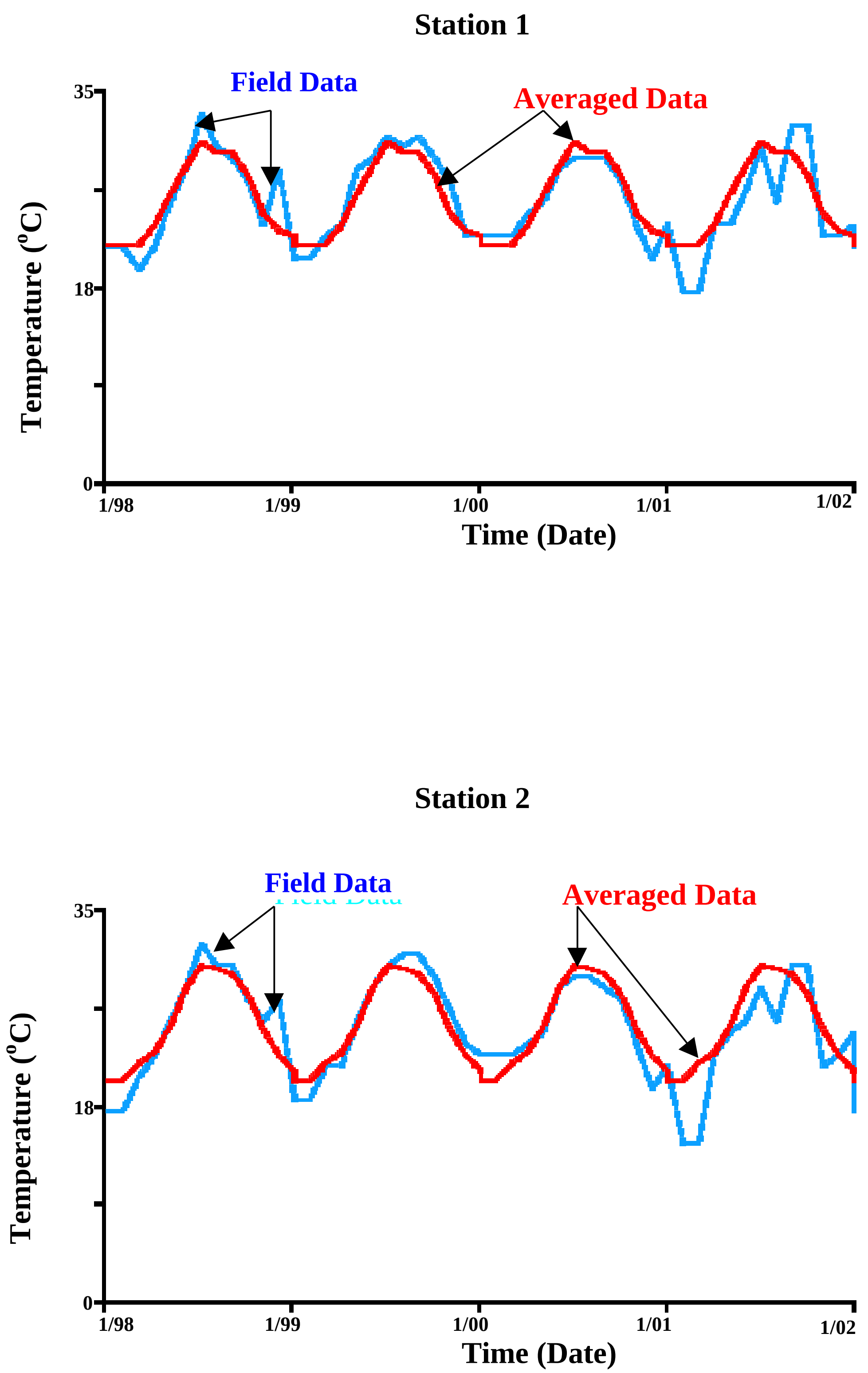


Figure H-14: Comparison of Water Temperature Input Data

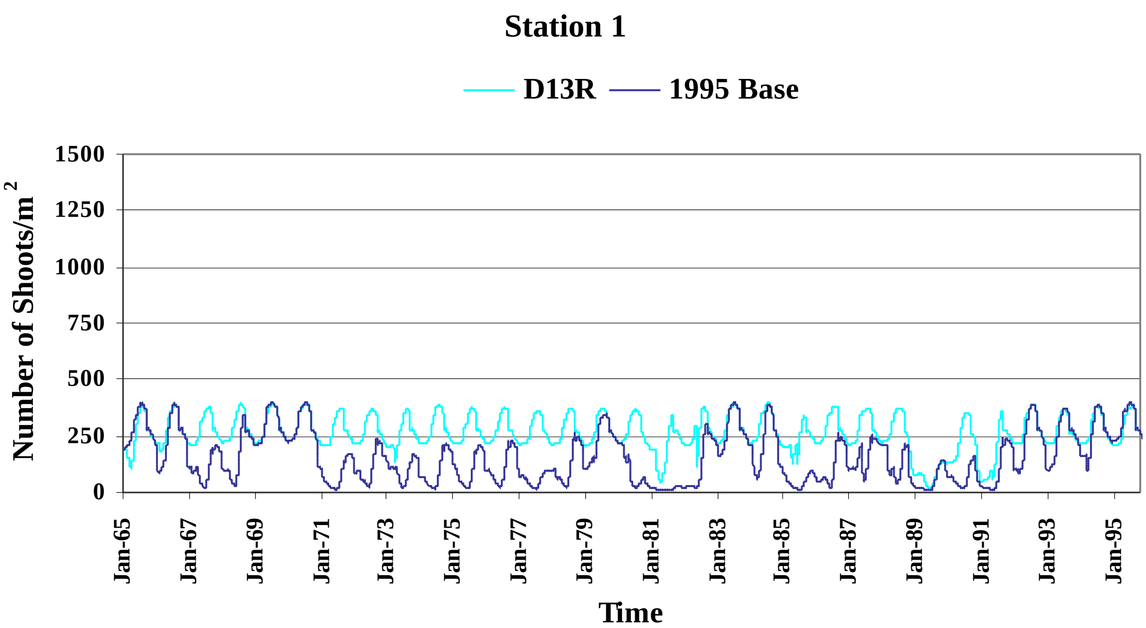
The simulations using the CERP D13R project flow conditions show more favorable *V. americana* densities than the 95 base case at both Station 1 and Station 2 **(Figures H-15** and **H-16).** Specifically, there is a 68% increase in total number of shoots produced for the 31 year period modeled at Station 1 and 51 % increase at Station 2 in the D13R scenario compared to the 95 base case. For blade density, there is a 74% increase at Station 1 and 23% at Station 2 in the D13R scenario compared to the 95 base case.

Assumptions and Limitations

In addition to the general model limitation and assumptions stated previously there are further considerations when evaluting the outcome of the 31-year scenarios.

1. Due to the fluctuation of salinity within small timesteps, daily input is preferred. In order to accommodate this scale, salinity input to the *V. americana* model was provided using a regression equation model derived from a 3-D Hydrodynamic model **(Appendix F)**. Thus the model is calibrated using salinity data that is predicted from a model and carries with it the errors associated with this input data.

2. The model also requires direct input data for water temperature, incident PAR and water transparency. Field measurements of these variables are directly input in the four-year calibration runs. In the 31 scenarios, these three variables are estimated based on yearly averages from the 4-year calibration data and are assumed to be constant from year to year. Thus, there are no light-limiting conditions or temperature extremes represented in the 31-year scenarios. As illustrated in the sensitivity analysis, use of the averaged annual input files can result in differences in computed *V. americana* density than those using dynamic field data **(Figures H-10 and H-11).** Specifically, a notable limitation of the 31-year simulations is that these simulations do not represent deviations in transparency that may occur in the upper portions of the Estuary. Such deviations that would be expected to negatively impact growth may occur due to algal blooms, highly colored discharges or sediment transport. Specifically the scenario, which is occurs in the third year of calibration (2000) is not represented by the 31-year scenarios shown (**Figures H-4 to H7)**. Similarly, periods of high water clarity such as are represented in



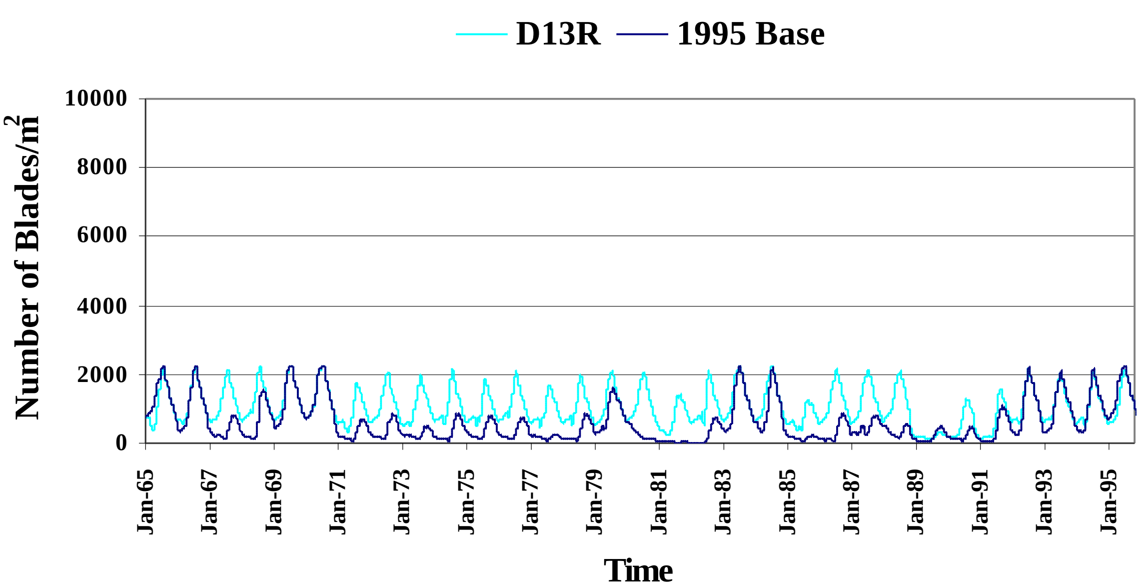
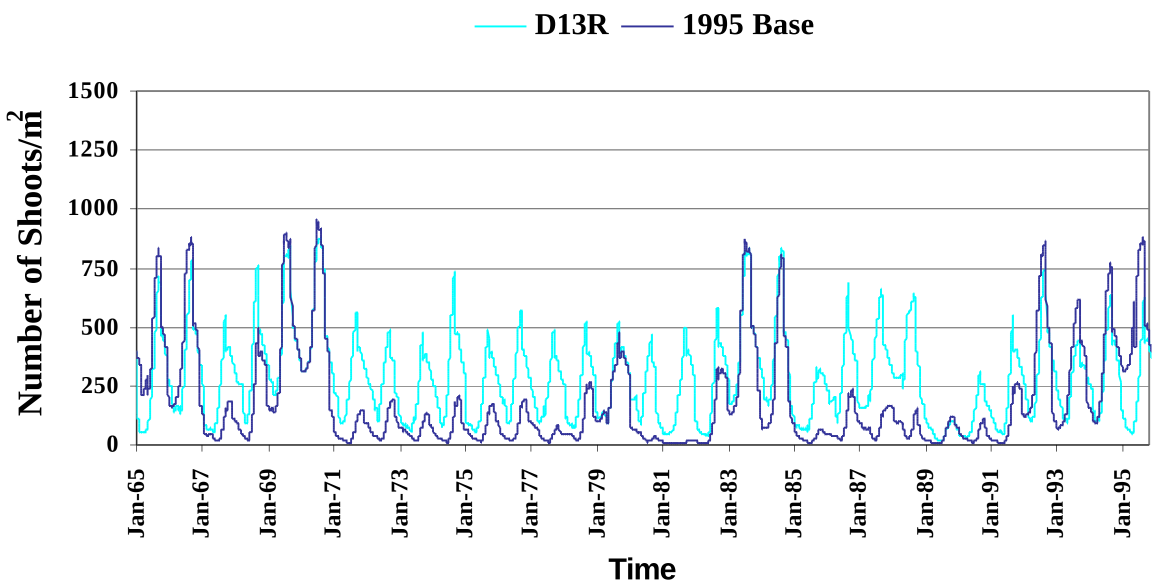


Figure H-15: Results of 31-Year Scenarios - Shoot Density

Station 2



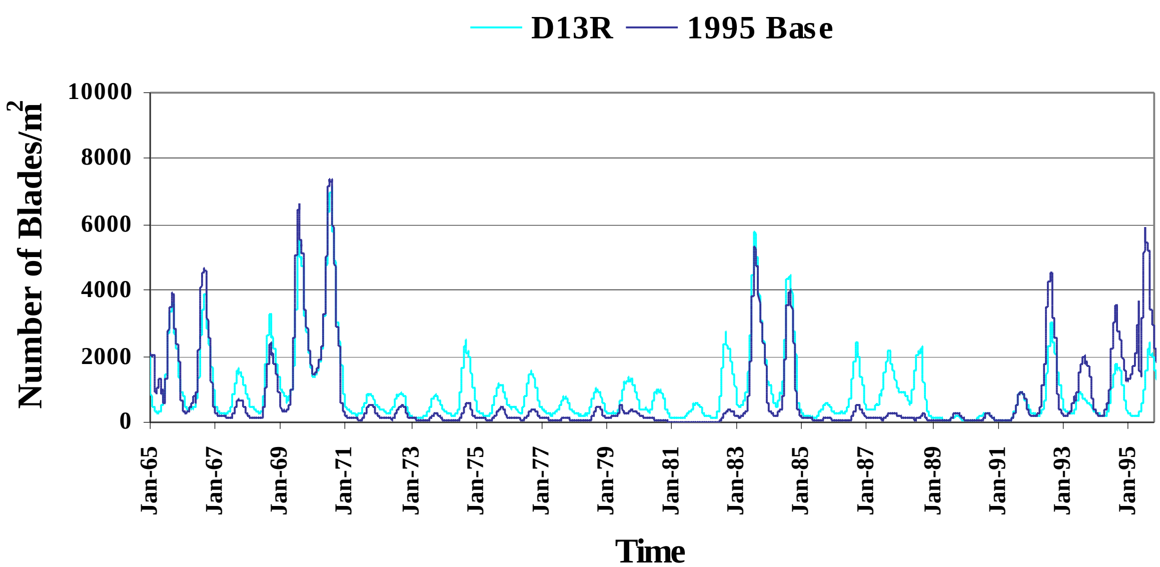


Figure H-16: Results of 31-Year Scenarios - Blade Density

the calibration period during the summer of 1998 may produce exceptional growth conditions and is not represented in the 31-year simulations.

3. The water depth at each site is assumed to be constant over the 31-year period.

Future Improvements

Due to the limited amount of time available to construct and calibrate the *V. americana* model, improvements are anticipated. It is necessary that all field monitoring be continued and the calibration period be extended to include the new data. The extended calibration period will permit improved prediction of *V. americana* recovery after severe conditions. Additional input data and information concerning the growth and survival of *V. americana* in the Caloosahatchee Estuary will be required to make the model more robust. Information is needed for validation of some existing equations, refinements to salinity, light and temperature effects as well as development of additional state variables. Equations representing additional important ecosystem components will be incorporated into the model. Potential examples include: sediment characteristics, current, sediment diagensis, biogeochemical rate processes, sulfide, flowering, and competition for light and nutrients by plankton and microphytobenthos. The relative importance of these variables and the information needed to quantify these effects are currently under review. Additional forcing functions may be added such as color, chlorophyll-a, suspended solids, and nutrients. State variables describing additional plant morphologies such as canopy height, and below ground biomass may also be added. Future work, outlined below, falls into three broad categories, data analysis, model development, and experimental or site work.

Data analysis

- Develop a method to predict variation in water transparency for long-term or other simulations.
- Quantify input data error and perform additional sensitivity analysis.
- Develop relationships to relate mass to blade and shoot densities, and blade length with existing data.

Model Development

- Quantify existing experimental work (Hunt et al., 2002) and develop improved algorithms for light and salinity.

- Incorporate blade length as a state variable to more accurately represent light availability for mature plants.

- Add nutrient cycling/ water quality impacts.

- Add population and demographic characteristics to describe seed production and dispersal.

Experimental /Site Work

- General areas of data needs include: above and below ground biomass measurements at existing sampling stations, levels and influence of pore water salinity and sulfide, and direct light attenuation measurements. Field measurements should be obtained under differing environmental conditions.

- Identify the factor(s) responsible for reduced carrying capacity in Station 1 relative to Station 2. Some factor(s) other than light attenuation (as measured by secci disk), salinity or temperature governed the growth of *V. americana* at Stations 1 during the four-year calibration period.

- Develop criteria and cues (including lag times) for reestablishment of *V. americana* growth after population has been substantially reduced. The assumption that reestablishment occurs via a seedbank should be verified.

CONCLUSIONS

The ecological model described, although still in the developmental stages, synthesizes known information about the growth and survival of *V. americana* in the Upper Caloosahatchee Estuary. Calibration of the 4- year period 1998-2001 indicates reasonable agreement with field data. It is expected that improvements will be forthcoming as the model is further developed.

The four primary criticisms (listed previously) of the peer reviewers for the Draft MFL Document of September 2000 (SFWMD, 2000) are being addressed by the development of the ecological model. This model includes the effects of multiple environmental variables: salinity, light, and temperature. Additional variables such as nutrient cycling and sediment diagenesis will be added to the model as appropriate. The issue of spatial variability is addressed by verifying and calibrating the model at two locations within the Upper Caloosahatchee Estuary. Additional locations further downstream may be added in the future. In terms of demographic variability, the model predicts several measures of growth including shoot density, blade density and, biomass. The capability to predict average canopy height will also be included in the future. Long-term (31-year) simulations with variable input salinity regimes derived from a hydrodynamic model are presented addressing another criticism. Finally the panels concern regarding the annual shoot recovery densities set as constant has also been addressed. The current model allows for the user to either input any desired starting density or calculate a density given a previous years growth by performing multiple-year simulations.

The model can be used as a tool to assess management strategies in the Upper Caloosahatchee Estuary. Information generated by the model can eventually be used to optimize timing and quantity of freshwater releases to the upper estuary as indicated by MFL criteria. The model can also be used to identify important factors influencing *V. americana* growth and survival. Simulations can be used to test hypothesis concerning the influence of freshwater flows on *V. americana* productivity and survival. Mechanisms responsible for habitat decline can be elucidated and conditions required for restoration and survival can be evaluated. A set of habitat requirements for *V. americana* survival and growth for target densities can be then established at different locations within the Upper Caloosahatchee Estuary. Compilation of existing data and sensitivity analysis within the model framework can highlight areas of data needs and be used guide and prioritize future work efforts.

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