FINAL PROJECT REPORT

CONTRACT NO. C-11818

SALINITY DISTRIBUTION
and
FLOW MANAGEMENT STUDIES
for
LAKE WORTH LAGOON

Prepared For:

South Florida Water Management District
3301 Gun Club Road
West Palm Beach, FL 33406

by

Environmental Consulting & Technology, Inc.
1901 S. Harbor City Blvd.
Melbourne, Florida 32901
Ph. 321.733.1333
and

Scientific Environmental Applications, Inc (SEA)
5575 Willoughby Dr.
Melbourne, Florida 32934
Ph/fax: 321.254.2708
Email seappl@aol.com

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EXECUTIVE SUMMARY

The watersheds of South Florida's coastal waterways have been extensively modified by drainage works and development. As a result, the quality, quantity, and timing of freshwater inflows to receiving water bodies have been altered. South Florida's marine estuaries and lagoons have been particularly impacted by these anthropogenic changes. In 1996, the South Florida Water Management District (District) working with the Palm Beach County Board of County Commissioners sponsored a study to develop a three-dimensional circulation model of Lake Worth Lagoon to use as a tool for analyzing existing and future variable controlled freshwater flows from canal discharge, rainfall, runoff, groundwater inflows, and tides. The Environmental Fluid Dynamics Code (EFDC) Model was used for the analysis. The study concluded that the model performed well in simulating and predicting salinity distribution for the Lagoon but recommended that additional data would greatly improve the calibration of the model. The results of this preliminary study were used to formulate salinity targets to protect estuarine fauna and was published as the 1998 Lake Worth Lagoon "White Paper".

In 2001, Environmental Consulting & Technology, Inc. (ECT) and Scientific Environmental Applications, Inc. (SEA), under the direction of the SFWMD obtained additional tidal amplitude, current velocity, salinity, and bathymetric data and incorporated these data into an updated hydrodynamic/salinity model for Lake Worth Lagoon. The Environmental Fluid Dynamics Code (EFDC) was applied to Lake Worth Lagoon for three-dimensional predictions of the salinity regime. During a field study conducted from mid-July to early November 2001 four monitoring stations collected salinity and water level data from key locations at the boundaries of the Lake Worth Lagoon. Two stations were situated within the interior of Lake Worth Lagoon where continuous salinity and current velocity data were collected for calibrating the EFDC Model. Additional model inputs were provided from meteorological data collected from a local weather station maintained by the National Buoy Data Center. Freshwater inflows to the model were provided by gauged data collected from the structures that control freshwater flows into the Lake Worth Lagoon. This additional data was used to improve the calibration of the model and provide detailed information on dry and wet season salinity distribution within the Lake Worth Lagoon.

The model calibration process consisted of adjustments to the mean elevations of water level time series at the model boundaries and local and regional adjustments of roughness height at the benthos boundary. Other calibration procedures included local adjustments to wind stress drag coefficients, quality control of measured data, and adjustments of local water depths. Statistical measures were used to quantify and verify the calibration. The average relative error of predicted salinity with respect to measured salinity values was between 9% and 14.5%. The overall average agreement for measured and predicted velocity data was within 15%.

Three distinct test cases were conducted using the calibrated EFDC model in order to compare the predicted salinity regime of the Lake Worth Lagoon under full and reduced freshwater inflow regimes. The 1995-Base test case represented the historical record and included freshwater inflows through major control structures that were similar to the gauging record. Two additional hypothetical cases were tested in which freshwater inflows were reduced by an average of 50%. Results of the model's 8-year hind cast runs using each of the freshwater scenarios indicated that magnitude and periodicity of salinity decreases in the Lake Worth Lagoon correlated with freshwater inflow events. Model results indicated that low salinity levels would be mitigated by 2 to 10 psu for the reduced freshwater cases. However, salinity levels for most events were predicted to be well below 20 psu, even under the reduced freshwater scenarios. This can be attributed to the fact that maximum rates during freshwater inflow events for all model test cases remained relatively high and comparable in magnitude.

A further finding of the model tests is that the Lake Worth Lagoon can be divided into three zones, each characterized by a distinctive salinity regime. A large central zone between Palm Beach Inlet and South Lake Worth Inlet is characterized by frequent low salinity events occurring at the meteorological time scale of a few days to a few weeks weeks. Salinity levels during these events dropped to values of 5 to 15 psu and generally rebound to levels at or below 25 psu, particularly after 1989 when maximum flows through the S155 Control structure increased in frequency and magnitude. A northern zone of relatively high salinity in the Lake Worth Lagoon is predicted to occur from the vicinity of Palm Beach Inlet and northward. Here low salinity events occur with the same frequency as in the central zone, but salinity values are predicted to remain above 20 psu and generally occur in the range of 20 to 25 psu. A third southern zone of the Lagoon is predicted to be subject to low salinity events similar to those of the central zone. However, salinity values generally rebound to levels between 25 and 30 psu compared to levels in the central zone where the rebound is between 15 and 25 psu. Cycles of Salinity variation in all zones of the Lake Worth Lagoon were predicted to occur over periods of a few days to approximately one month and correspond to variations in freshwater flows driven by weather systems moving through south Florida.

The ichthyofauna of the LWL is unlikely to be affected dramatically by low salinities resulting from the discharge of fresh water at the historical or proposed reduced level. Episodic spikes in freshwater discharge will likely result in localized mass mortality events, but most fishes are able to adapt or move out of the disturbed area. It is more likely that sustained low salinities will adversely affect marine invertebrates (particularly during spawning) and sea grasses (primarily from increased turbidity). The model analysis presented in this report clearly show compartmentalization of the LWL in terms of salinity. The modeling analysis and historical data show that prolonged (months) of low salinity are likely to occur in the LWL under all modeled scenarios, especially the Central section encompassing the S-155 discharge structure. Thus, the preliminary salinity targets previously suggested by others may not be practically achievable and may be overly conservative based on the vertebrate biology (and perhaps the invertebrate biology) of the LWL. The apparent compartmentalization of the LWL suggests that it is appropriate to establish salinity targets for each section of the LWL based on the observed dynamics, practical operating constraints, and ecosystem function.

Modeling Summary

The Environmental Fluid Dynamics Code (EFDC) model was applied to Lake Worth Lagoon for three-dimensional predictions of the salinity regime in response to freshwater inflow. Meteorological inputs to the model for 8-year hind cast runs were provided from meteorological data collected from a local weather station maintained by the National Buoy Data Center. Freshwater inflows to model were provided by hind cast data from the South Florida Water Management District (SFWMD) Regional Hydrologic Model. Water elevations at the ocean boundaries of the model offshore of Palm Beach Inlet and South Lake Worth Inlet included a combination of tidal constituents from a regional model of the North Atlantic Ocean and low frequency water elevation collected from long-term National Ocean Survey (NOS) water level gauges in the south Florida region. Salinity conditions at the ocean boundary and lateral boundaries of the EFDC model were set from the results of several preliminary 8-year hind cast runs of the model in which freshwater inflows from the S155, S44, and S41 were applied to predict model boundary salinity conditions.

Three distinct test cases were conducted using the calibrated EFDC model in order to compare the predicted salinity regime of the Lake Worth Lagoon under full and reduced freshwater inflow regimes. The 1995-Base test case represented the historical record and included freshwater inflows through major control structures that were similar to gauging record. Two additional hypothetical cases were tested in which freshwater inflows were reduced by an average of 50%. Results of model 8-year hind cast runs using each of the freshwater scenarios indicated that magnitude of salinity decrease in the Lake Worth Lagoon corresponding to freshwater inflow events would be mitigated by 2 to 10 psu for the reduced freshwater cases. However, salinity levels for most events were predicted to be well below 20 psu, even under the reduced freshwater scenarios. This can be attributed to the fact the that maximum rates during freshwater inflow events for all model test cases remained relatively high and comparable in magnitude.

A further finding of the model tests is that the Lake Worth Lagoon can be divided into three zones, each characterized by a distinctive salinity regime. A large central zone between Palm Beach Inlet and South Lake Worth Inlet is characterized by frequent low salinity events occurring at the meteorological time scale of a few days to two weeks. Salinity levels during these events dropped to values of 5 to 15 psu and generally rebound to levels at or below 25 psu, particularly after 1989 when maximum flows through the S155 Control structure increased in frequency and magnitude. A northern zone of relatively high salinity in the Lake Worth Lagoon is predicted to occur from the vicinity of Palm Beach Inlet and northward. Here low salinity events occur with the same frequency as in the central zone, but salinity values are predicted to remain above 20 psu and generally occur in the range of 20 to 25 psu. A third southern zone of the Lagoon is predicted to be subject to low salinity levels similar to those of the central zone. However, salinity levels generally rebound to levels between 25 and 30 psu compared to levels in the central zone where rebound is between 15 and 25 psu. Salinity variation in all zones of the Lake Worth Lagoon were predicted to occur over periods of a few days to approximately four weeks and correspond to variations in freshwater flows driven by weather systems moving through south Florida.

Table of Contents

1.0 Introduction and Goals

The salinity regime in Lake Worth is strongly influenced by episodic freshwater flows from the C-17, C-51, and C-16 Canals through their respective control structures. Other controlling factors and processes include salt intrusion from the Lake Worth tidal inlets, precipitation, and evaporation. Freshwater inflows combined with marine processes operating at tidal, meteorological, and seasonal time scales together determine the salinity regime of the Lake Worth Lagoon. In this project, the Environmental Fluid Dynamics Code (EFDC) model was applied to predict saltwater transport and salinity regime within the Lake Worth Lagoon as a function of conditions prescribed by three distinct cases of freshwater inflows. Case 1 includes conditions nearly identical to the historical measurements of flows from the watersheds of Lake Worth, which are largely directed into the Lagoon through the control structures of the C17, C51, and C-16 Canals. This case is termed 1995-Base and includes the 8-year period from the beginning of 1988 to the end of 1995.

The EFDC model hind cast of salinity regime from each of the freshwater inflow case will be used by the South Florida Water Management District to make management decisions as basin discharge characteristics change over time. The EFDC model has been used extensively in Florida estuaries and lakes, as well as in other similar environments in the U.S. and Europe (Zarillo and Surak, 1994, Zarillo and Yuk, 1997, Zarillo, 1998, 1998, 1999, 2001). Within Florida, applications have included the Indian River Lagoon (Zarillo and Yuk, 1997, Lake Jesup (Zarillo, 1998, 2000) in addition to an earlier Lake Worth application of the EFDC model in 1996 (Tomasello Consulting Engineers, 1996).

2.0 Overview of EFDC Formulation

The formulation and features of EFDC are well described by Hamrick (1992, 1995) and Zarillo (1997). Thus the formulation is only briefly described here. Similar to other 3-D hydrodynamic models, the EFDC formulation assumes the water is incompressible, and invokes the hydrostatic and Boussinesq approximations. For shallow marine environments like Lake Worth or the Indian River Lagoon the characteristic length in the vertical is two to three orders of magnitude smaller than the horizontal dimension. A simple order of magnitude argument can be used to reduce the z-momentum equation to the so-called hydrostatic Boussinesq approximation. The Boussinesq approximation assumes that density is a constant except in terms involving horizontal pressure gradient.

The governing equations of the model, which were reviewed by Hamrick, (1992) are closed by a turbulence closure scheme that relates turbulent correlation terms to the mean variables. The EFDC model, similar to the Princeton Ocean Model, employs Mellor and Yamada's (1982) level 2-1/2 closure scheme. All numerical constants in the level 2-1/2 closure scheme are analytically predetermined, and require no further adjustment. In addition to the specification of the turbulent correlations appearing in the governing equations, the appropriate initial and boundary conditions must be given. Typically, at the air-water interfaces, no fluxes of mass or conservative solutes are permitted. Further, the loss of momentum at the water-sediment interface is given in a form of bottom stress (turbulent boundary layer).

In shallow estuaries, the ratio of vertical length scale to horizontal length scale is very small. The horizontal mixing terms are orders of magnitude smaller than the vertical mixing terms. Therefore, the use of a sophisticated turbulence closure model for horizontal mixing terms is generally not warranted. As a result, EFDC treats the horizontal eddy viscosity-diffusivity coefficients as constants.

The EFDC Model integrates the governing equations in the time domain by a finite difference method (referred to as a time-stepping integration). The EFDC model uses both explicit and implicit schemes, and thus allows for a longer time step and a lesser constraint on the minimum grid size compared to a completely explicit scheme. This approach provides greater flexibility, allowing the model user to specify more cells in areas where more detail is needed (for example, sharp salinity gradient regions), and still run faster than an explicit scheme. The details of model formulation and procedures for model setup and grid generation can be found in technical publications by Hamrick (1992, 1995).

3.0 Model Setup for Long-Term Simulations

Table 1 identifies the three scenarios applied to long-term simulations of salinity regime in the Lake Worth Lagoon. The setup of the EFDC model for long-term simulations includes procedures similar to those used for the setup of the calibration and validation runs for the Lake Worth application (SEA, 2002). However, the long-term simulations used to test three distinct freshwater discharge scenarios used modeled data for both surface water and groundwater inputs. The District's Regional Hydrological model was used to generate both surface water and groundwater flows that were applied as model boundary conditions. The types of input data files required to set up the initial conditions of the physical domain and to provide boundary conditions during long-term simulations are the same as those used in the model calibration/validation runs. Boundary conditions for model runs include time series of water surface elevation, salinity, water temperature, freshwater inflow, meteorological parameters and other measured water quality parameters that may be available.

Table 1. Freshwater runoff test cases applied to long-term simulations

Case	Period	Freshwater runoff	Data Source
1995_Base	1988-1995	Full historical	SFWMD Hydrologic Model
D13R	1988-1995	Reduced Historical	SFWMD Hydrologic Model
Tsp	1988-1995	Reduced Historical	SFWMD Hydrologic Model

The same master input file was used to direct the long-term runs in terms of the location of input time series to a specific cell within the model domain. Data for the long-term runs were provided by a combination of measured time series, tidal constituents from the East coast 2001 Database of Tidal Constituents (Mukai et al., 2002), and model-predicted freshwater inflows.

3.1 Topographic Data and Grid Generation

Model setup for the Lake Worth project area required topographic data and boundary (shoreline) coordinates. These data were supplied in digital form (GIS) by the District. The overall grid is shown on a photo mosaic of Lake Worth in Figure 1. The final version of the computation grid consists of 2,366 cells including cells extending into the coastal ocean for numerical stability (See Figure 2). The open boundaries of the model include a cell at the south end of Lake Worth, a cell at the north boundary near Indiantown Bridge and the cells bounding the model domain in the offshore extension of the model. In addition to the horizontal cells, the vertical dimension was set to contain 5 layers over which momentum exchanges were calculated using the 2 1/2 level turbulent closure scheme.

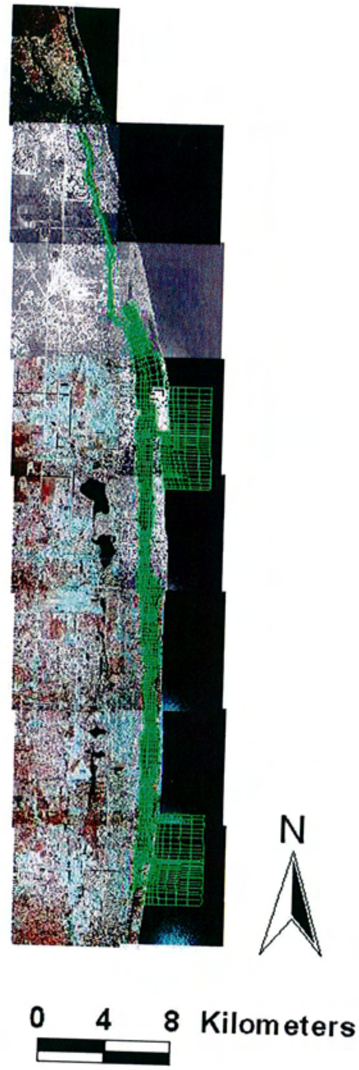

Figure 1 Schematic of the model computational grid superimposed on photo mosaic assembled from 1999 USGS digital imagery.

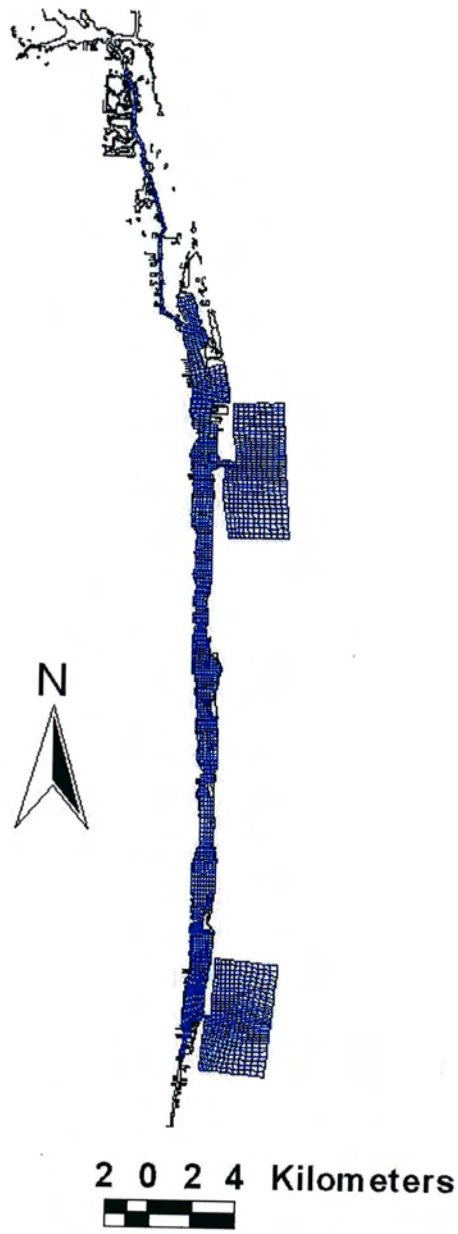

Figure 2. Model computational grid consisting of 2,366 computation cells in the horizontal Dimension.

3.2 Water Level Forcing at Model Boundaries

Similar to the calibration version of EFDC, forcing of the model at the ocean boundary was provided by both measured and predicted data. Tidal constituents for the coastal ocean offshore of Lake Worth were provided from the Eastcoast 2001 Database of Tidal Constituents (Mukai et al., 2002). Details of this database were included in the calibration report (SEA, 2002). Comparisons between tidal constituents from the Tidal Data Base and tidal constituents extracted by harmonic analysis from measured water level data at Lake Worth Pier closely agreed with the amplitude and phase of the various constituents. In the long-term application of EFDC to the Lake Worth Lagoon, six tidal constituents provided forcing at the appropriate tidal frequencies. Comparisons between tidal constituents from the Tidal Data Base and tidal constituents extracted by harmonic analysis from measured water level data at Lake Worth Pier closely agreed with the amplitude and phase of the various constituents. Furthermore, in the calibration process of the EFDC model, comparisons were made between tidal constituents calculated from measured and predicted water level data from the interior of the model, well within the Lagoon. The comparisons showed that the predicted and measured tides closely agreed. This was further confirmed for the interior of Lake Worth by measured and predicted water levels that agree within approximately 3% at two calibration stations. The details of these and other calibration parameters are given in the Calibration Report (SEA, Inc, 2002).

Tidal constituents also provided forcing of the tidal frequencies at the interior of the north and south boundaries of the model. In this case, however, the constituents were derived from measured data rather than the East Coast Database. Tidal constituents were extracted from the water level time series collected during the monitoring phase of the project. A description of the data collection procedures and measured data can be found in the data collection report (ECT, 2001)

In addition to forcing at tidal frequencies, low frequency water level variations were also included in the model. These data were largely provided from water level records collected by the National Ocean Survey's long-term water level gauges located at Miami Beach and Virginia Key. It was considered important to include these lower frequency water level changes since they can exceed 2 feet on a seasonal basis, and are large compared to the total depth of Lake Worth. To include these data in the EFDC Lake Worth model, the local tide record from the stations was removed using a digital filter. The resulting low frequency water level was then reduced to a long-term mean sea level and readjusted to the local NAV88 vertical datum near Lake Worth. This was accomplished by examining the relationship of mean sea level and NAV88 from a local benchmark description available from the NOS. Figure 3 shows the adjusted low frequency water elevation records applied to the EFDC long-term simulations in Lake Worth. Figure 4 shows the combination of the tidal signal from constituents and the measured water level data applied at the offshore model boundary cells adjacent to Palm Beach Inlet.

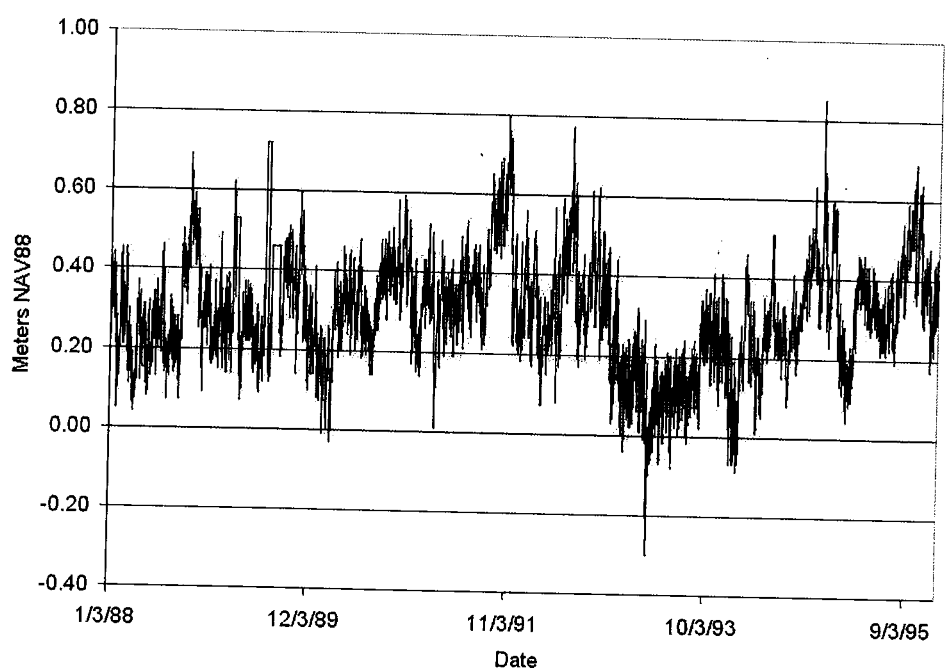

Figure 3. Low frequency water elevation combined with tidal constituents to force boundaries of the EFDC model.

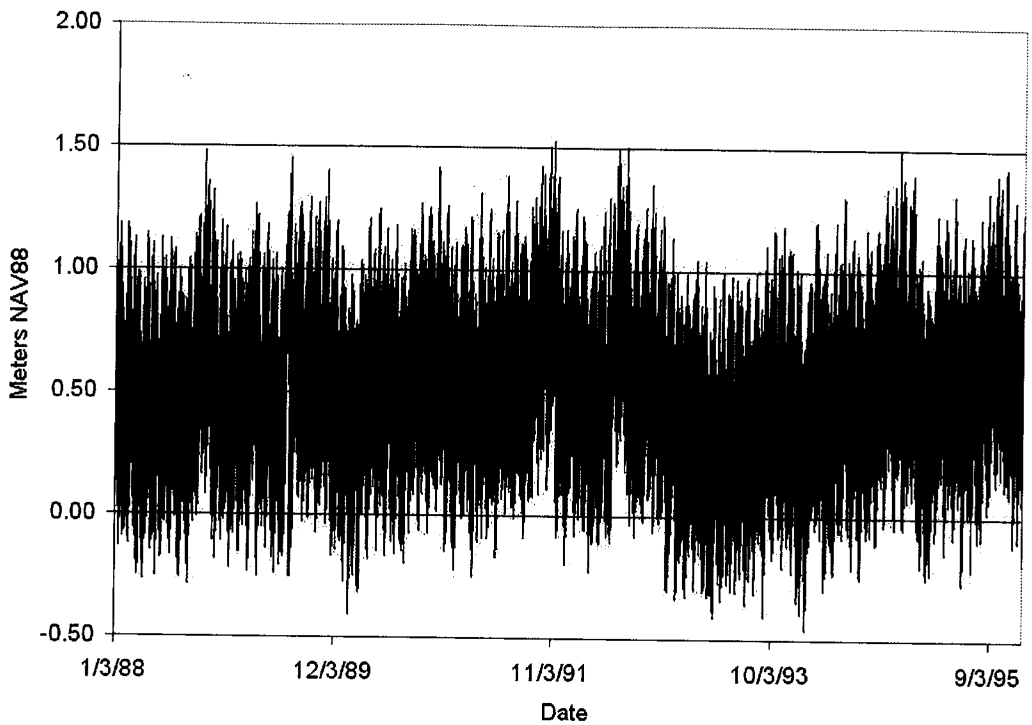

Figure 4. Water level time series at tidal and low frequency applied to open boundary conditions offshore of Palm Beach Inlet.

The low frequency portion of the record includes water level changes that are a large percentage of the mean tidal range. The low frequency water level changes are not damped at the inlets and weekly to monthly water level changes in the Lagoon driven by low frequency sea-level changes in the coastal ocean ranges from approximately 10 cm to more than 30 cm (about 1 foot).

Figure 5 shows the combined tidal and water level time series applied to offshore boundary cells at South Lake Worth Inlet. The low frequency and tidal records are similar except for the tidal phase between the two areas. Generally, high tide occurs about 30 minutes later near South Lake Worth Inlet than at Palm Beach Inlet.

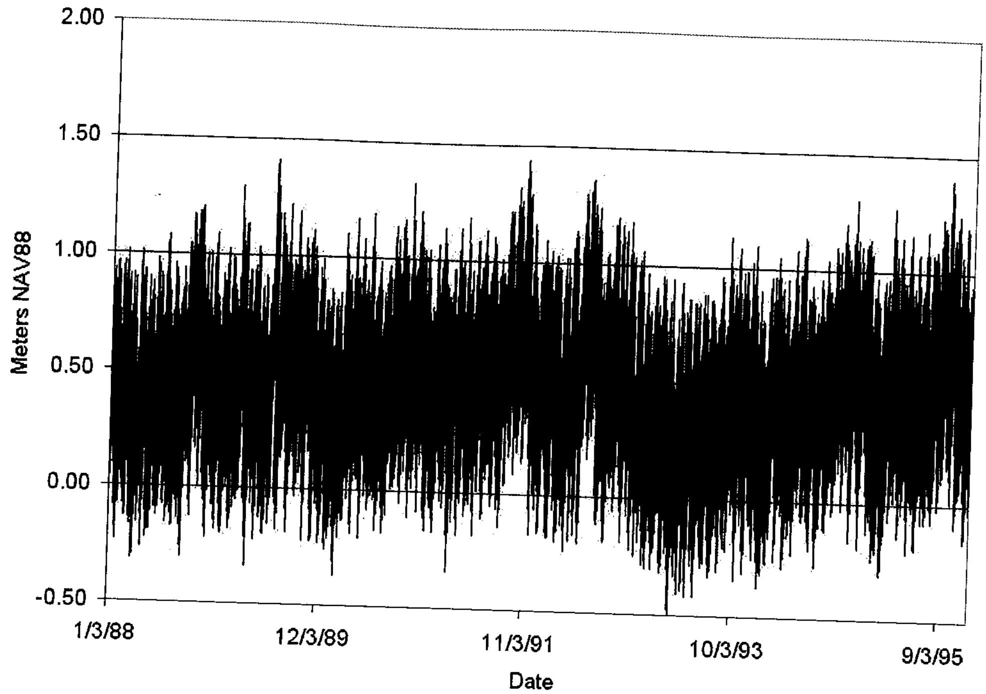

Figure 5. Water level time series at tidal and low frequency applied to open boundary conditions offshore of South Lake Worth Inlet.

3.3 Salinity Time Series at Model Boundaries

Historical salinity time series for the open boundaries of the EFDC long-term simulation of Lake Worth were not available. Therefore to establish realistic values for salinity at model boundaries for the 1988 to 1995 runs using the 1995 Base, tsp, and d13r cases, several preliminary runs of the long-term simulation were made to hind cast the appropriate salinity conditions. Hind casts for the surface water runoff through structures S155, S44, and S41 were combined into average daily values and applied to the appropriate cells as inputs along the west boundary of the EFDC model. Likewise hind cast groundwater inflows were combined into daily averages and applied as inputs into the bottom layer of the EFDC model cells in Lake Worth. The EFDC model was then run for the full eight year hind cast and predicted salinity values near the open boundary cells of the model were stored for further use. This process was repeated several times until the predicted salinity concentrations at the model boundary cells remained stable. This iterative process allowed the impacts of freshwater discharges to propagate to the model boundaries. The final values of predicted salinity at the model boundaries were then used in the final production runs to simulate the impact of the Base, tsp, and d13r test cases.

Figure 6 shows the time series of salinity concentration applied at the east column of boundary cells offshore of South Lake Worth Inlet. Figure 7 shows the salinity time series applied offshore of Palm Beach Inlet. Figure 8 shows the salinity time series applied at the south boundary of the model. Here the salinity levels are more directly influences by freshwater flows into the Lake Worth Lagoon and are generally lower than those at offshore boundary cells.

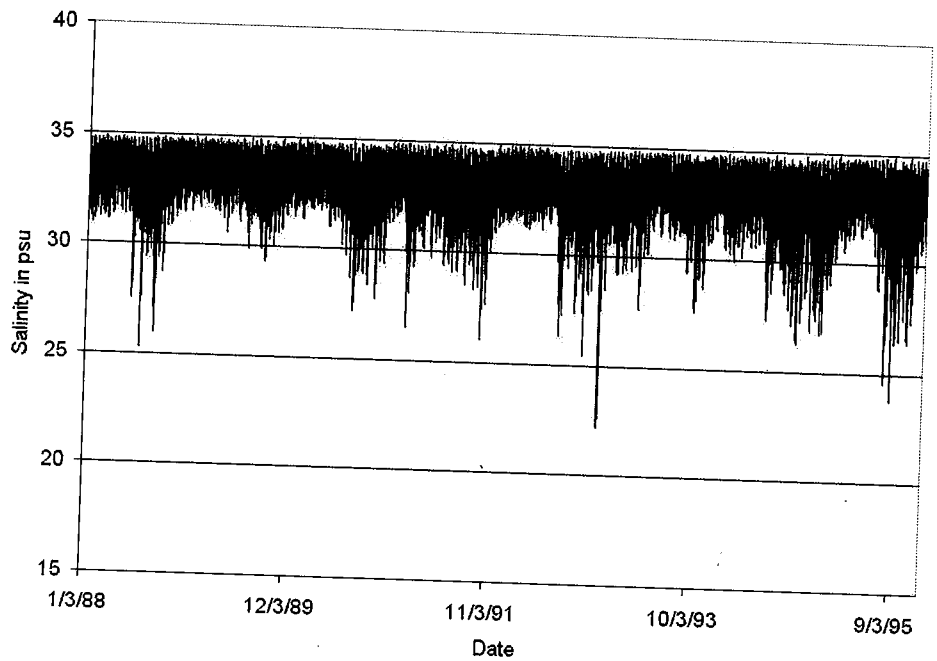

Figure 6. Salinity time series applied at the east boundary of the EFDC Model offshore of South Lake Worth Inlet.

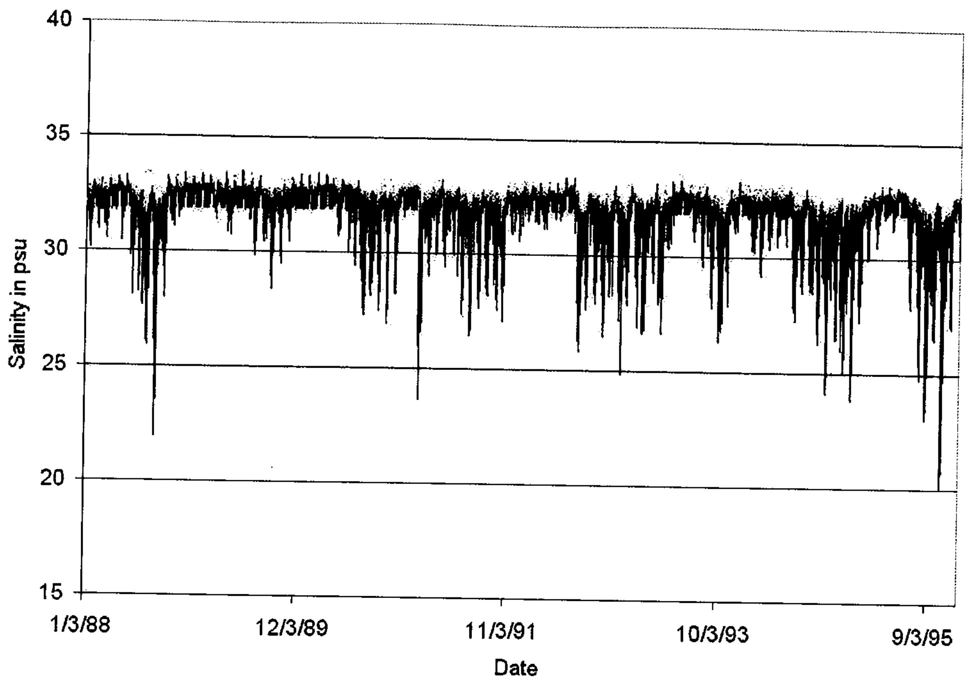

Figure 7. Salinity time series applied at the east boundary of the EFDC Model offshore of Palm Beach Inlet.

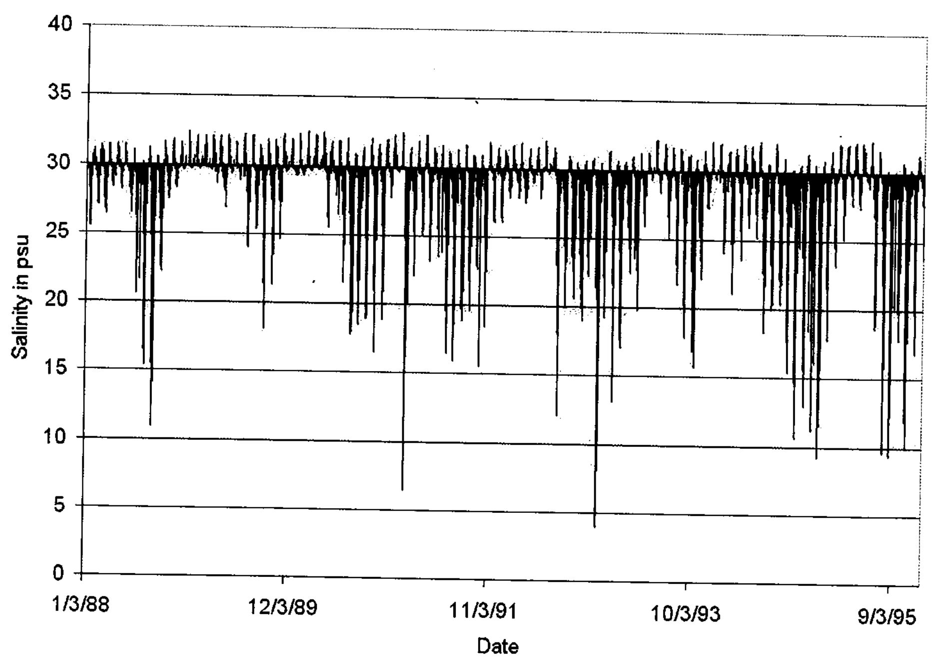

Figure 8. Salinity time series applied at the south boundary of the Lake Worth model.

3.4 Freshwater Inputs

Freshwater inflows to the Lake Worth Model were specified according to the hind cast data from the South Florida Water Management District's Hydrologic Model. Simulated runoff from the Lake Worth watershed basins were used to hind cast discharges at the control structures for the C-51, C-17, and C16 Canals. Figure 9 compares the predicted flows through the S155 control structures on the C51 Canal for the 1995-Base, tsp, and d13r test cases. On the average, flows for the tsp, and d13r cases are approximately 50% of the flows for the 1995-base test case. Reduced inflows were due to diversion and storage of freshwater in the Tsp and D13r simulations compared to the 1995-Base scenario. However, during periods of high freshwater runoff and discharge through the control structures, the magnitude of flow in all three test cases was similar.

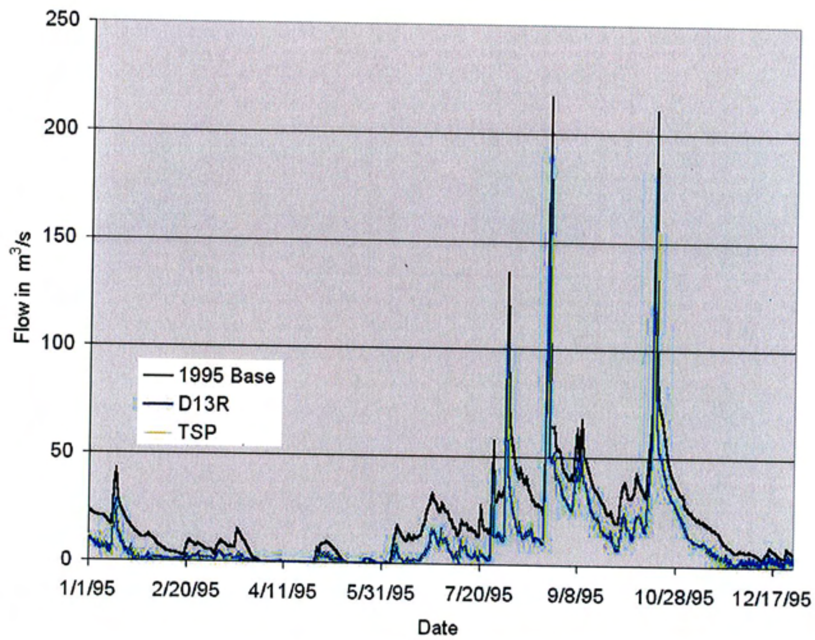

Figure 9. Flows through the S155 control structure for the model test cases predicted for 1995.

Among the three test cases the Base-1995 case essentially represents the historical record of the Lake Worth Lagoon from 1988 to 1995. Figure 10 compares a portion of the gauged historical flows and predicted freshwater flows at the S155 structure for this case. On the average, the predicted flows are slightly higher. In addition, several peak flow events are over-predicted at the maximum by approximately 50%, compared to maximum flow values for the events in the gauged data (Figure 11). However, the simulated data generally under predicts the later stages of these events as discharge levels return to lower values (Figure 11). The overall comparison between the historical data and simulated data at S155 is within 11.7 m^3/s according to a root mean square (RMS) error statistic. By comparing this to the range of gauged discharge values at S155 the comparison between the gauged and the 1995 Base data is within 7.6%. Therefore, the 1995 Base simulated data is considered to adequately represent the Historical case. Furthermore, there are significant gaps in the gauged data from 1988 through the end of 1995 that must be represented by estimated data in the historical record. Therefore, the simulated data is more continuous and eliminates the need to deal with gaps in the gauged data set.

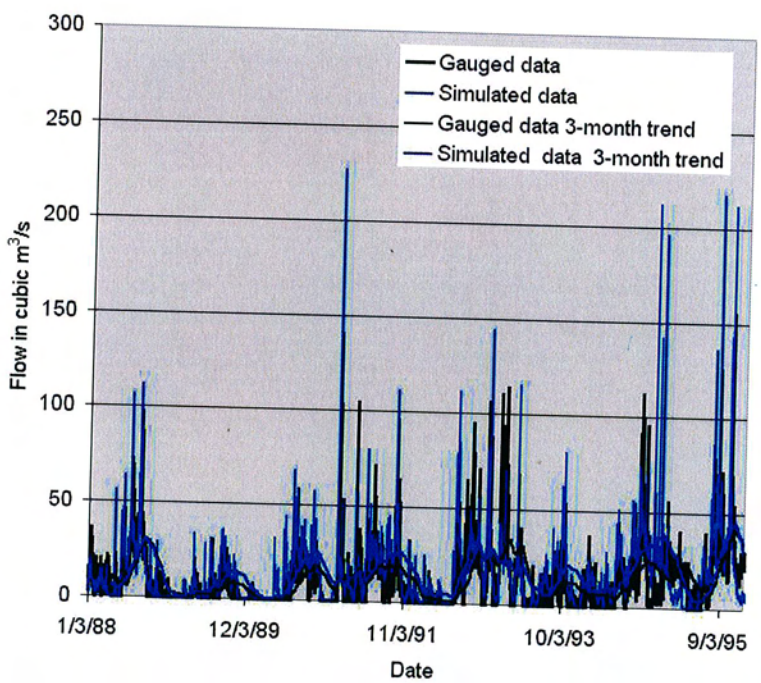

Figure 10. Comparison of gauged historical discharge and hind cast discharge at the S155 Structure.

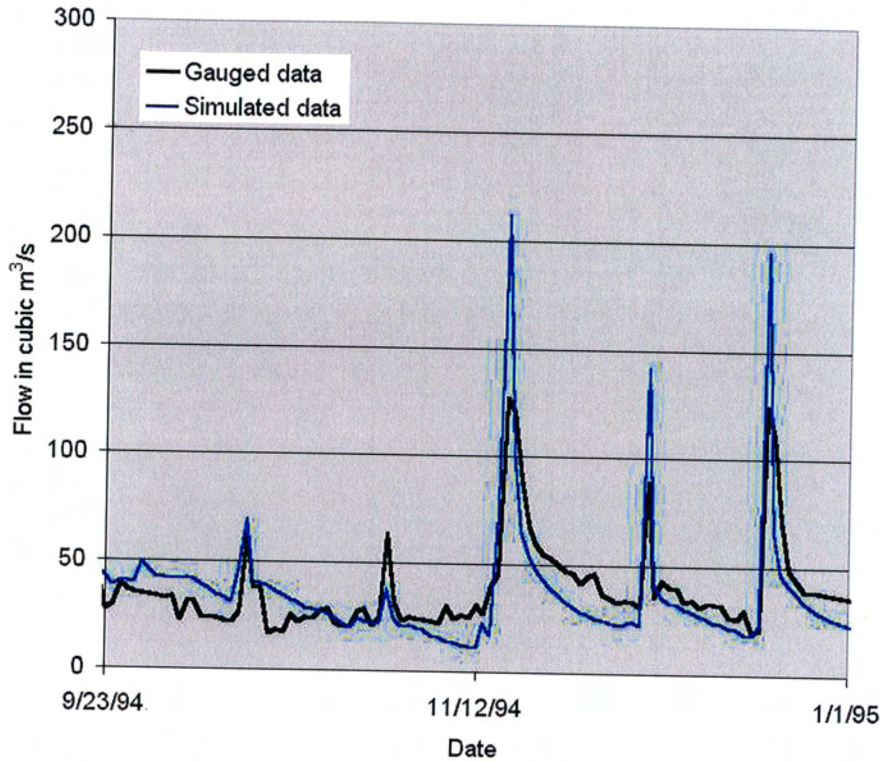

Figure 11. Comparison of high flow events in 1994 represented in the gauged historical discharge and hind cast discharge at S155.

In addition to surface inflows, groundwater inflows were specified according to simulated data provided by the District. Figure 12 shows a portion of the District's Regional Hydrologic Model grid in the region of Lake Worth from which groundwater predictions were calculated. The groundwater model output units were in terms of acre-feet per month were re-formatted into units of cubic meters per second for convenient input to the EFDC model. Predicted groundwater inflows from each of the three test cases (1995-Base, tsp, and d13r) were specified in more than 1400 of the 2366 computational cells of the EFDC Lake Worth Model.

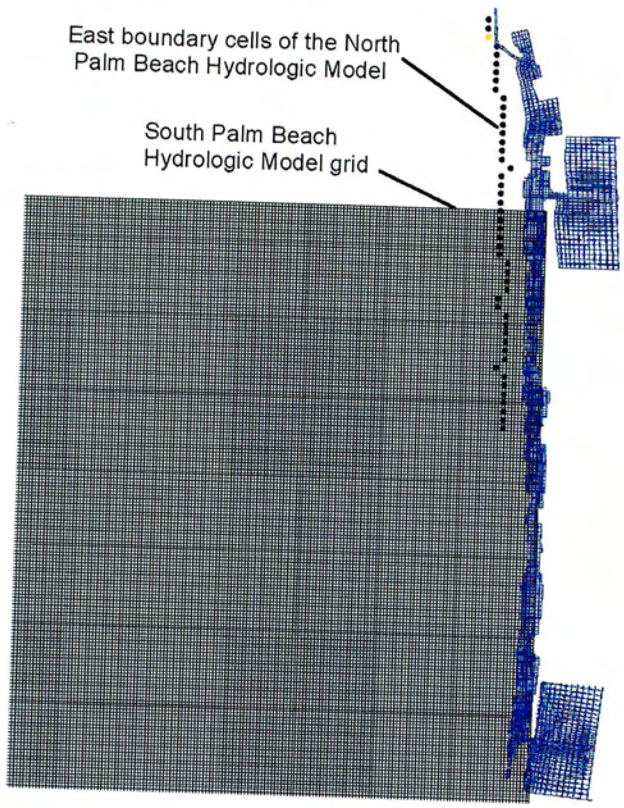

Figure 12. A portion of the SFWMD Hydrological Model computational grid used to simulate groundwater inflows to the Lake Worth Lagoon.

3.5 Meteorological Inputs

Wind velocity, atmospheric pressure, air temperature data, and rainfall data were used to specify meteorological inputs to the long-term EFDC simulation of Lake Worth salinity. Evaporation data were specified from pan evaporation data collected by the District. A major portion of the meteorological inputs were specified from the Lake Worth Weather Station (LKWF1), which is owned and maintained by the National Data Buoy Center and located on the Lake Worth Pier. Other stations that provided meteorological data included the Fowey Rocks Station (FWYF1, the Settlement Point Station (SPGF1), as well as selected data from District maintained facilities. Data from these stations were used for short periods when the Lake Worth Station was not in operation. Data from these sources listed in the meteorological input file to EFDC included, wind velocity, atmospheric pressure, air temperature, evapotranspiration, and rainfall rate. Figure 13 summarizes the wind and atmospheric pressure data applied for the 1988-1995 simulation.

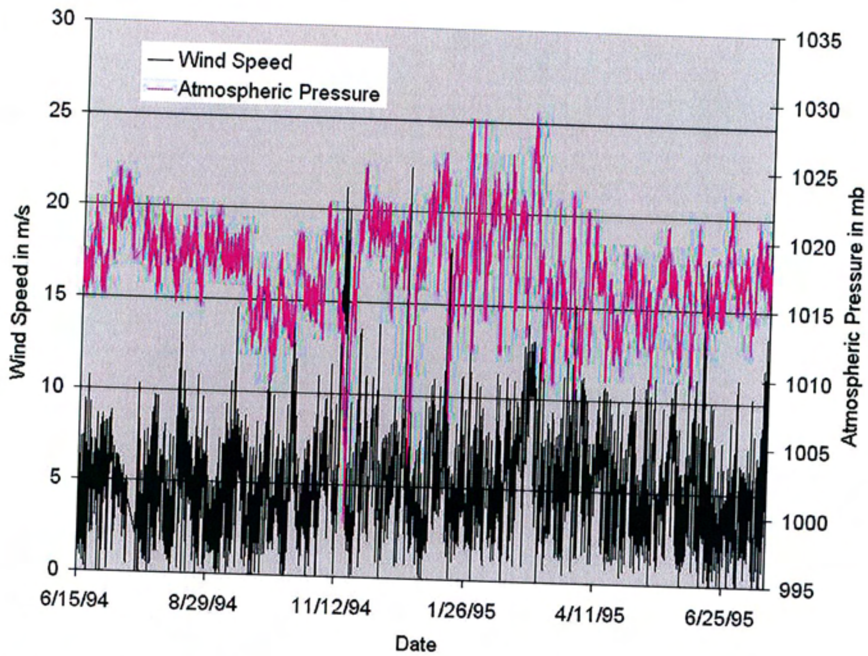

Figure 13. Example of wind and atmospheric time series data applied to the Lake Worth Lagoon hind cast simulations.

4.0 Salinity Regime Predictions

The results from the three test cases applied in the 8-year simulations are summarized as time series of salinity at ten numerical stations (Figure 14). In addition, still plots and animations of the horizontal salinity field and the along-estuary vertical salinity field were used to examine the results for each model test case (Table 2). The numerical stations are positioned to represent north, central and southern sections of the Lagoon. Figure 14 shows locations of the numerical stations, as well as the vertical profile of salinity at locations along the estuary. The calibration runs indicated that the salinity regime of the Lake Worth Lagoon varies strongly by region and a zone of persistently lower salinity occurs in the central region where the impacts of discharges from the S155 control structure dominate the salinity regime.

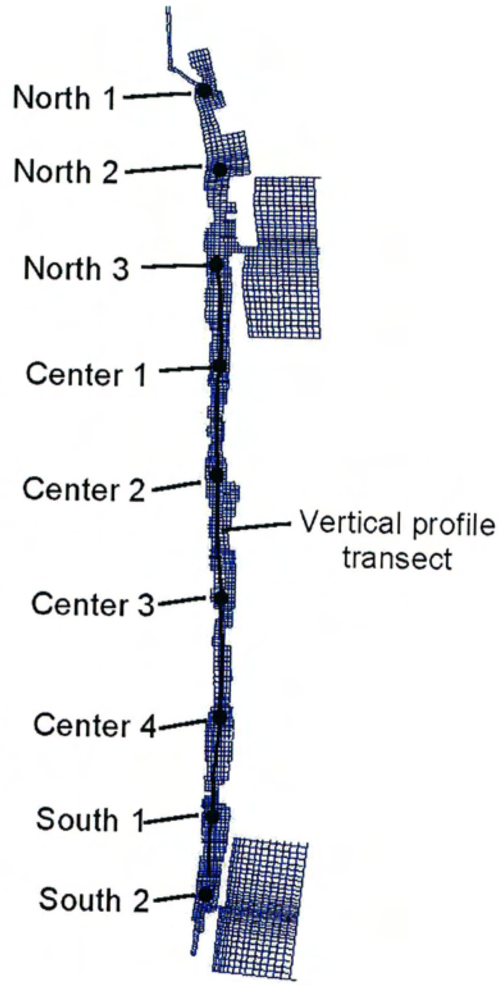

Figure 14. Numerical salinity recording stations and transect of vertical salinity profile used to analyze results of EFDC model test cases.

The calibration runs of the model showed that recovery to higher salinity after moderate freshwater inflow events can take 6 to 12 days in this central region. Furthermore, movement of the freshwater plume is controlled by the mean, non-tidal hydraulic or water level slope and the direction of wind stress during these events. The area of the Lake Worth Lagoon to the north of Palm Beach Inlet is less impacted by freshwater discharge from the S155 structure and is characterized by generally higher salinity levels compared with the central portion of the Lagoon. The S44 structure on the C-17 Canal in the north section of the Lagoon serves a much smaller basin compared with the C51-S155 combination. Likewise, the very southern segment of the Lagoon in the vicinity of South Palm Beach Inlet is characterized by higher salinity compared with the central section. Similarly the S41 Structure on the C16 Canal provides some freshwater flows directly into the southern segment of Lake Worth, yet serves a relatively small basin compared to the C51 Canal and S155 Structure.

Table 2. Animation files for the Lake Worth test cases included in the electronic appendix

Test case	Horizontal field	Vertical profile
1995- Base	Base88_92upper	Base88_92vertical
1995- Base	Base92_95upper	Base92_95vertical
1995- Base	Base88_92lower	Base88_92vertical
1995- Base	Base92_95lower	Base92_95vertical
Tsp	Tsp88_92upper	Tsp88_92vertical
Tsp	Tsp92_95upper	Tsp92_95vertical
Tsp	Tsp88_92lower	Tsp88_92vertical
Tsp	Tsp92-95lower	Tsp92-95vertical
D13r	D13r88_92upper	D13r88_92vertical
D13r	D13r92_95upper	D13r92_95vertical
D13r	D13r88_92lower	D13r88_92vertical
D13r	D13r92-95lower	D13r92-95vertical

4.1 Salinity Regime Predictions – Central Zone

Salinity predictions in the central portion of Lake Worth, between Palm Beach Inlet on the north end and South Lake Worth Inlet at the south end of the Lagoon, show this region is strongly affected by freshwater flows through the S155 Structure. Figure 15 compares salinity in the bottom layer of the model (layer 1 among 5 layers) predicted at numerical station "Center 2", which is located approximately 5 km south of Palm Beach Inlet and 5 km to the north of where the S155 discharges reach the west bank of Lake Worth.

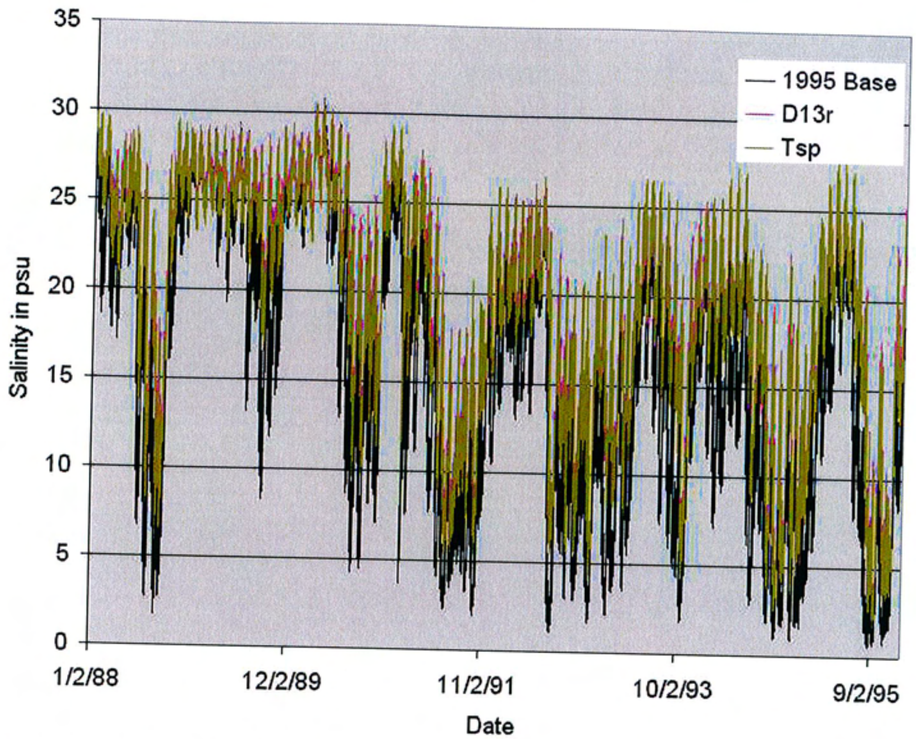

Figure 15. Comparison of predicted salinity at numerical station Center 2 for each model test case.

Figure 16 shows the details of predicted salinity at station Center 2 for all three test cases for the 1992 and a portion of the 1993 wet season, which included multiple high discharge events from S155 between July and October of 1992 (see Figure 10). Strong variations in salinity occurred over periods of a few days to a month. Recovery from individual low salinity events occurred over periods of approximately 6 days to 14 days. The tidal variation in salinity is also apparent in the simulations and occurs over a range of less than 10 psu. From the predicted record is can be seen that the 1995-Base test case yields salinity values that are distinctly lower compared to the results of the d13r and tsp test cases. The tsp and d13r model results are nearly identical and all three cases result in salinity values less than 20 psu for periods of one month or longer.

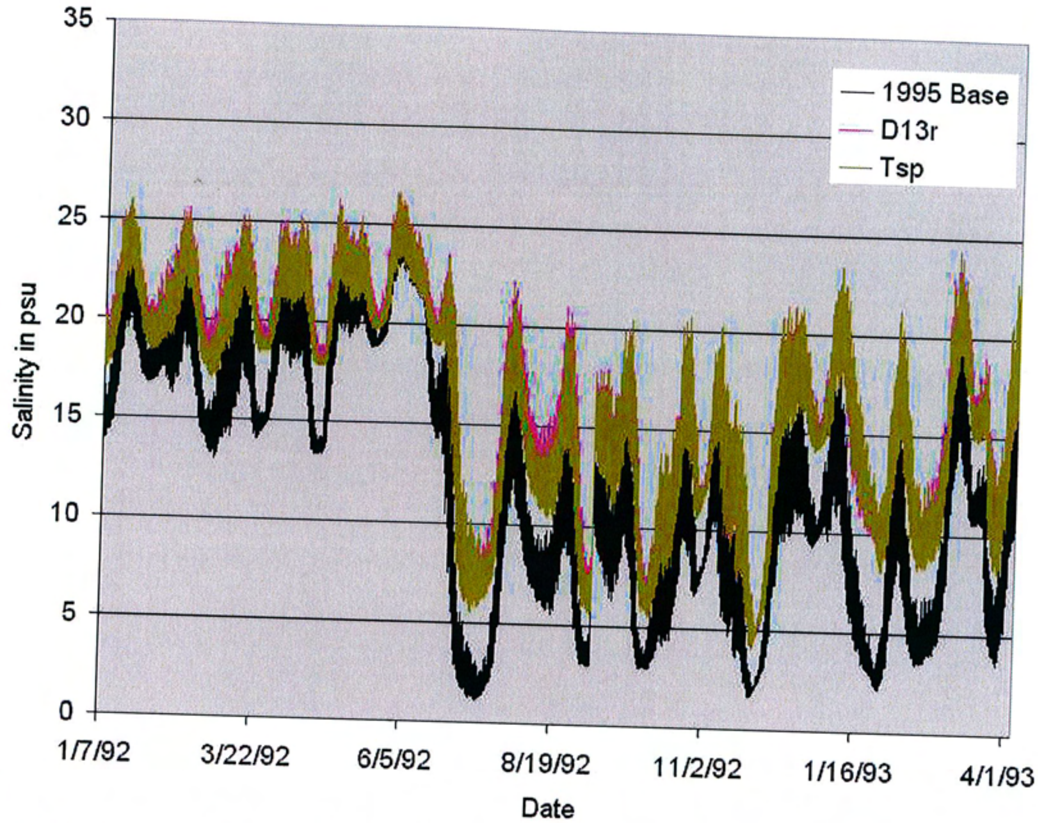

Figure 16. Comparison of predicted salinity for each test case numerical station Center 2 for 1992-1993.

Figure 17 shows a vertical profile for the 1995-Base Test Case along the centerline of Lake Worth on July 15, 1992, during one of the more severe reductions of salinity. Likewise, Figure 16 shows the prediction for the same period according to the D13r test case. The location of numerical station Center 2 is also shown in the figure. Comparison of the figures show that D13r and Tsp test cases provided a considerable improvement with respect to the salinity level and the lateral extent of low salinity region along the axis of the estuary. Figure 19 shows the predicted salinity distribution in Lake Worth according to the results of the Tsp test case. The results of this case are nearly identical to those of the D13r case.

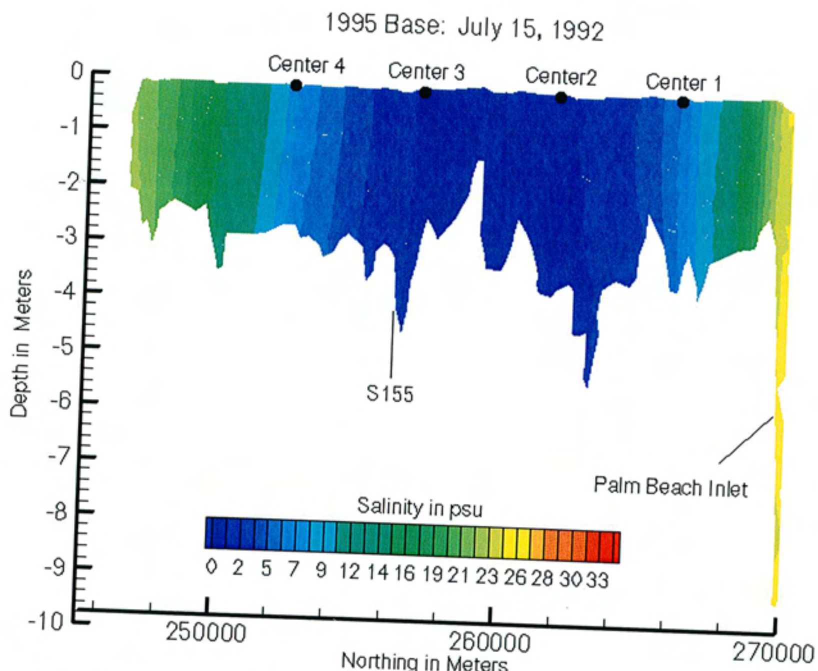

Figure 17. Predicted vertical salinity distribution along the Lake Worth Lagoon for July 15, 1992 under the 1995-Base test case. Locations of numerical recording stations Center 1-4 are also shown.

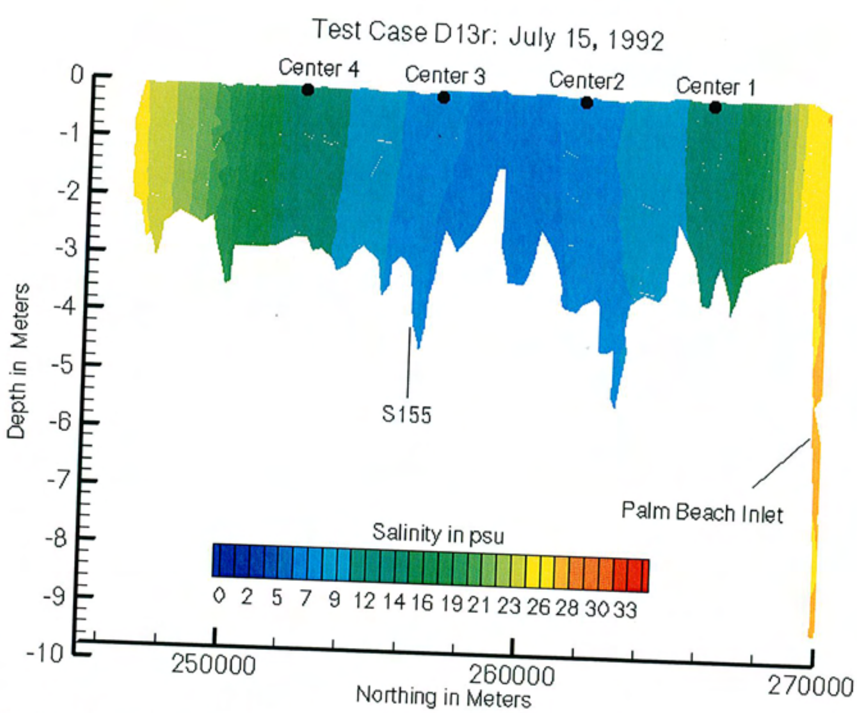

Figure 18. Predicted vertical salinity distribution along the Lake Worth Lagoon for July 15, 1992 according to the D13R test case.

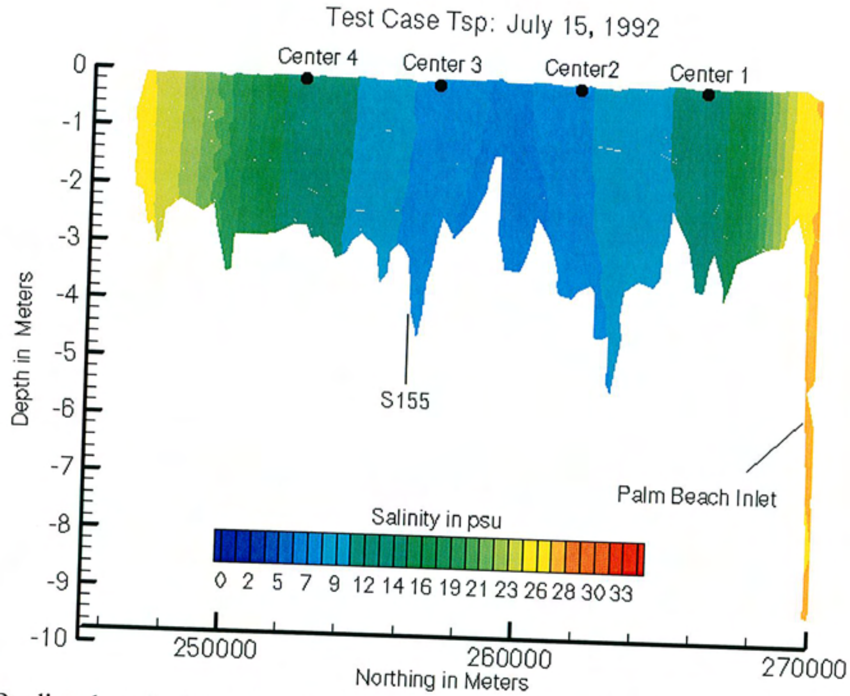

Figure 19. Predicted vertical salinity distribution along the Lake Worth Lagoon for July 15, 1992 according to the TSP test case.

4.2 Salinity Regime Predictions – Northern Zone

The salinity regime of the northern zone of the Lake Worth Lagoon is characterized by consistently higher salinity, fewer periods of low salinity, and shorter duration of low salinity periods. Figure 20 compares predicted salinity values for the three test cases for numerical Station North 3, which is just to the south of Palm Beach Inlet. Salinity variations occur over periods of a few days to approximately two weeks, coinciding with flows from both the S155 and S41 Control Structures. Figure 21 shows a series of predicted salinity events for 1991, which demonstrate the frequency and strength of salinity variations in the north region of the Lake Worth Lagoon. As with the central region of the Lake Worth Lagoon strong salinity variations occur at the meteorological frequency. Tidal salinity variation in this region of the Lagoon is predicted to be between 1 and 5 psu.

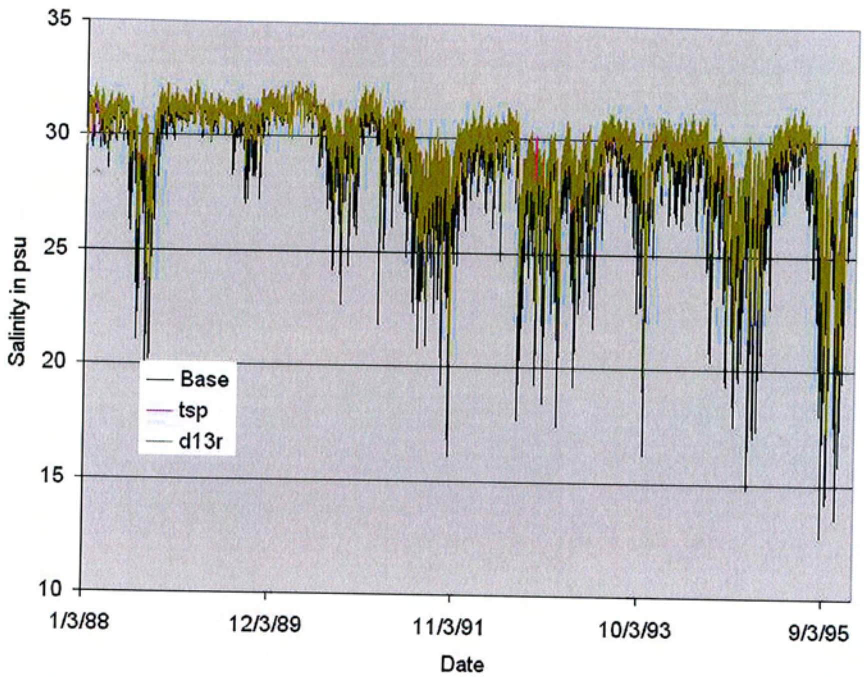

Figure 20. Comparison of predicted salinity at numerical station North 3 for each model test case (See Figure 13 for station location).

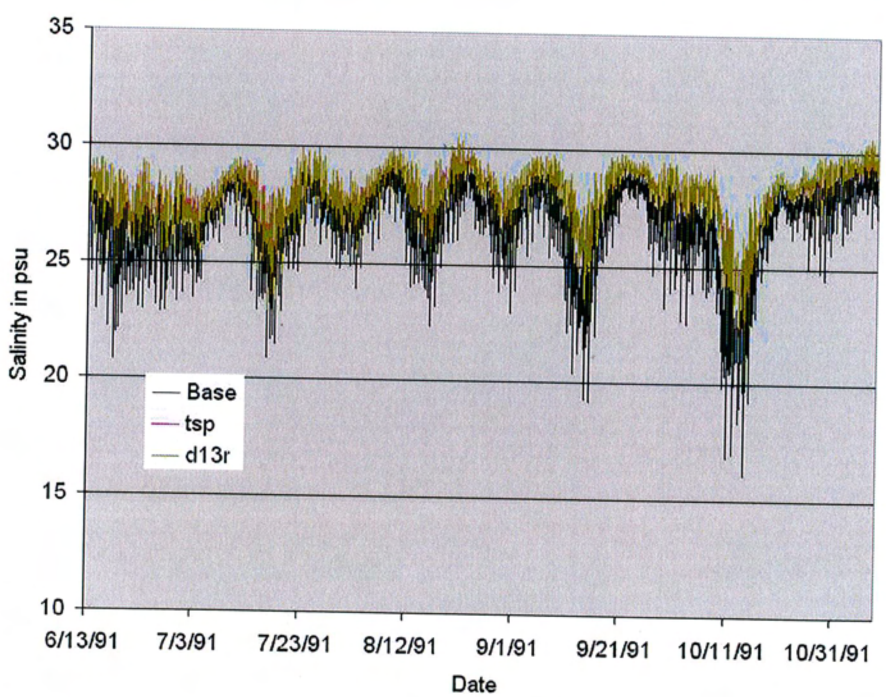

Figure 21. Salinity variations predicted at numerical station North 3 between June and October of 1991 for the three model test cases (See Figure 13 for the location of Station North 3).

North of Palm Beach Inlet, model predictions for the 1988 to 1995 test period show that salinity values rarely drop below 20 psu for any of the three test cases. Figure 22 shows that over the course of the 8-year simulation, salinity values dropped below 20 psu only once near the end of the model test.

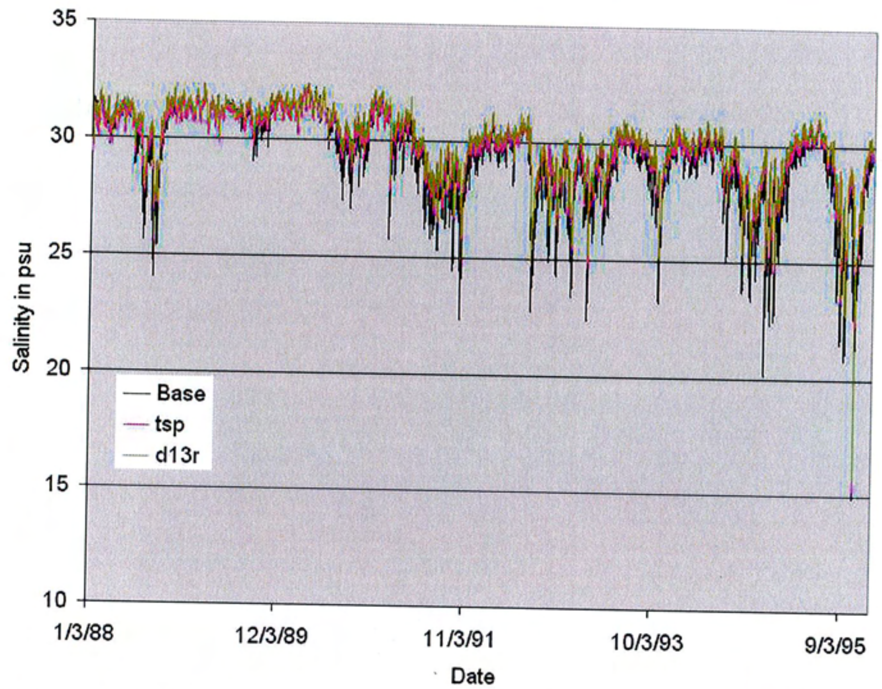

Figure 22. Comparison of predicted salinity at numerical station North 2 for each model test case (See Figure 13 for station location).

4.3 Salinity Regime Predictions – Southern Zone

The southern zone of Lake Worth in the EFDC model is a 5 km long section that includes South Lake Worth Inlet (See Figure 13). This zone is similar to the central zone of Lake Worth Lagoon in having low salinity events at the same frequency of meteorological forcing (a few days to four weeks). Figure 23 shows predicted salinity for all three test cases at numerical station South 1 over the 8-year simulation period. Figure 24 shows the predicted salinity record for all three cases for 1991. The major difference between the south zone and the central zone is the level of predicted rebound. By comparing Figures 23 and 24 with 15 and 16, which characterize the central zone it can be seen that salinity rebounds to values between 25 and 30 psu in the southern zone of the Lagoon. Gary, I don't understand what is meant by rebound Figures 22 and 23 show salinity in the south dips from just above 0 to30 psu. In the central zone maximum salinity values reach approximately 25 psu, especially after 1989 when the frequency and magnitude of large discharge events through S155 increased (see Figure 10). In the south zone salinity rebounds to 25 psu or higher between a majority of events for the entire 8-year simulation period (Figure 23).

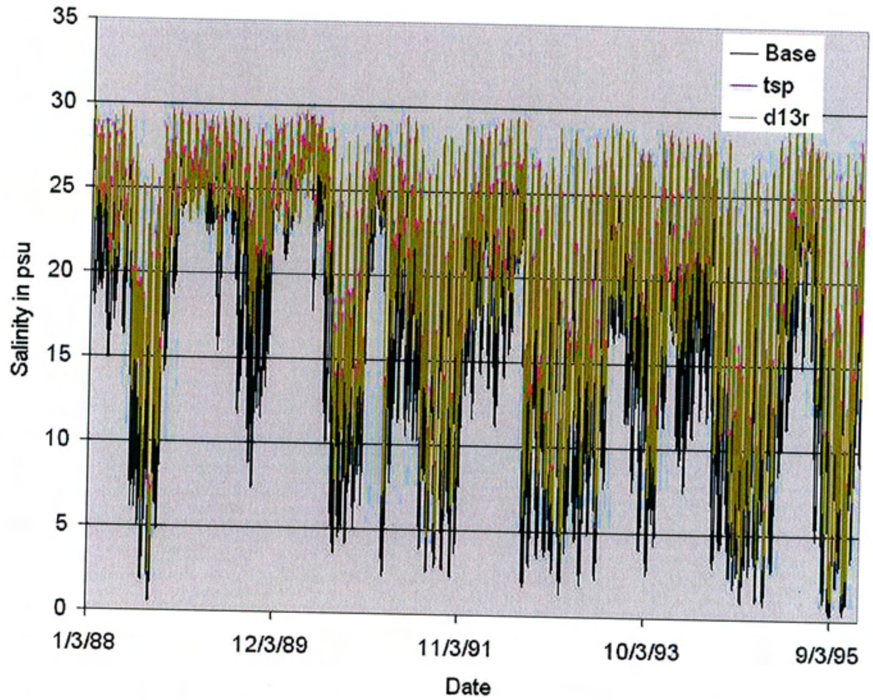

Figure 23. Comparison of predicted salinity at numerical station South 1 for each model test case (See Figure 13 for station location).

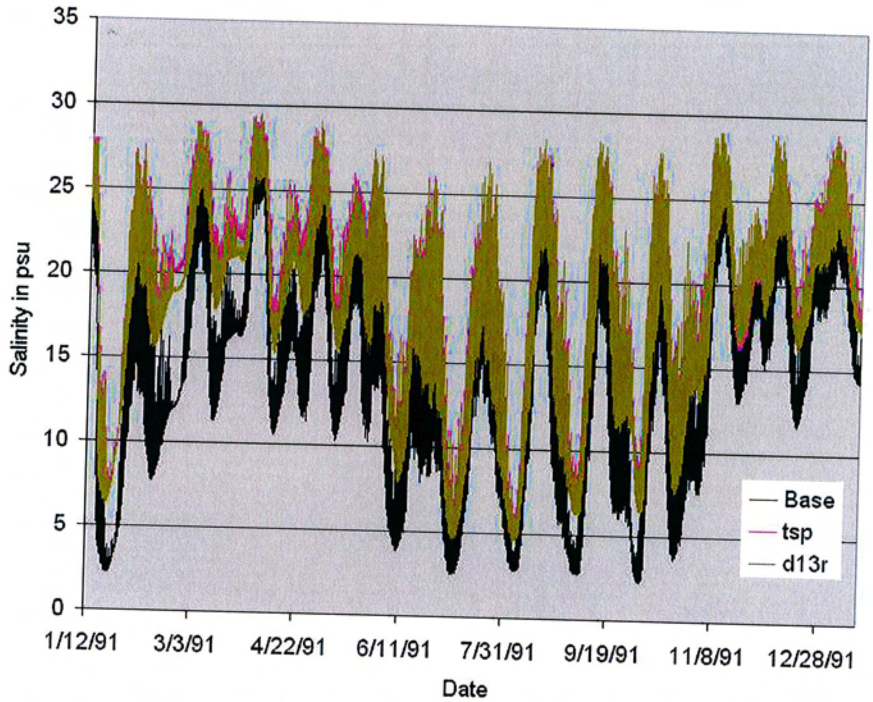

Figure 24. Salinity variations predicted at numerical station South 1 during 1991 for the three model test cases (See Figure 13 for the location of Station South 1).

5.0 Summary of Lake Worth Salinity Regime Predictions

The major findings of the 8-year hind cast simulations of salinity in the Lake Worth Lagoon are: 1) The salinity regime can be characterized according to three major zones; 2) variations in salinity correspond to variations in freshwater flows driven by weather systems moving through south Florida.; 3) Simulations involving reduced freshwater inflows result in some improvement in salinity levels during discharge events, but still result in salinity levels that are frequently below 20 psu in the central region of the Lagoon; 4) The spatial extent of extremely low salinity levels is markedly smaller for the D13r and Tsp reduced flow test cases.

Figure 25 compares predicted salinity at numerical station Center 2 from the three model test cases with the freshwater discharge through the S155 Control Structure for the 1995_Base scenario. Two frequencies of variation are seen in both the salinity record and the discharge record. The salinity and discharge are inversely correlated at both frequencies. The higher frequency of variation has a period of approximately 20 to 30 days and represents the cycle of meteorological systems that move through south Florida. Runoff and rainfall that correlate with these weather systems increase freshwater inputs to Lake Worth Lagoon and drive down salinity levels over a period of a few days to 2 weeks. The rebound from low salinity then occurs over the next few days to 2 weeks. The complete cycle usually occurs over a time interval of 20 to 30 days. The lower frequency pattern that is obvious in Figure 25 is the seasonal pattern of high freshwater inflows to the Lake Worth Lagoon along with the corresponding seasonal decrease in salinity levels. The higher frequency 20 to 30 day cycle of salinity is superimposed on the lower frequency seasonal cycle. The difference between the wet and dry season salinity can be seen for 1993, 1994, and 1995 in Figure 25. Salinity levels begin to decline in mid to late summer months to a minimum that usually occurs during October or November. Comparison of salinity predictions for all three test cases shows that the D13r and Tsp reduced flow scenarios increased salinity values between approximately 2 and 5 psu.

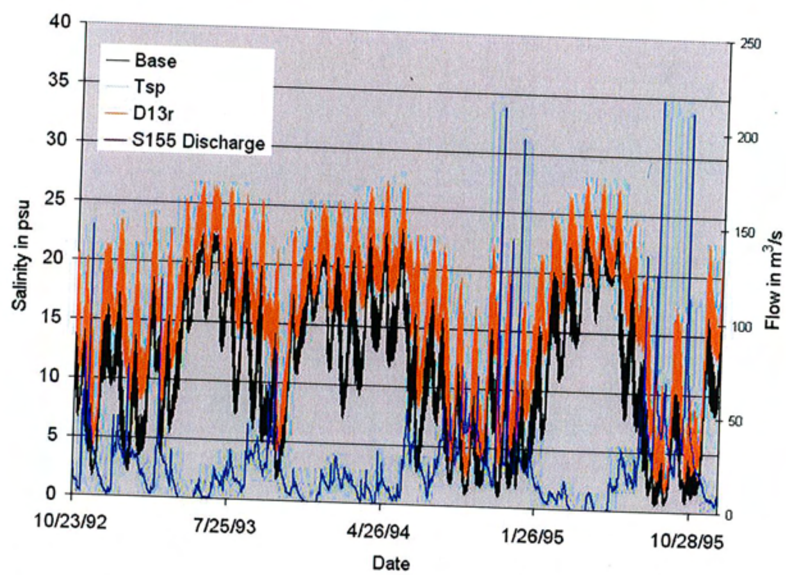

Figure 25. Comparison of predicted salinity record with the freshwater discharge at the S155 Control Structure.

Figure 26 shows a vertical cross-section of salinity along the north-south axis of Lake Worth on November 20, 1995 predicted for the 1995-Base test case. This date corresponds with a period of strong freshwater inflow though the S155 Control Structure. The central zone of low salinity corresponds with the direct influences of inflows from the S155 Structure (See Figure 25). Figure 26 shows the horizontal distribution of salinity predicted in the surface layer of the EFDC model for the same date and case. The three zones of Lake Worth Lagoon are apparent Figure 26. The northern zone beginning in the vicinity of Palm Beach Inlet is characterized by relatively high salinity levels even during period of high freshwater inflow. Very low salinity levels and strong horizontal stratification characterize the central zone. Moderate to high salinity levels characterizes the southern zone in the vicinity of South Lake Worth Inlet.

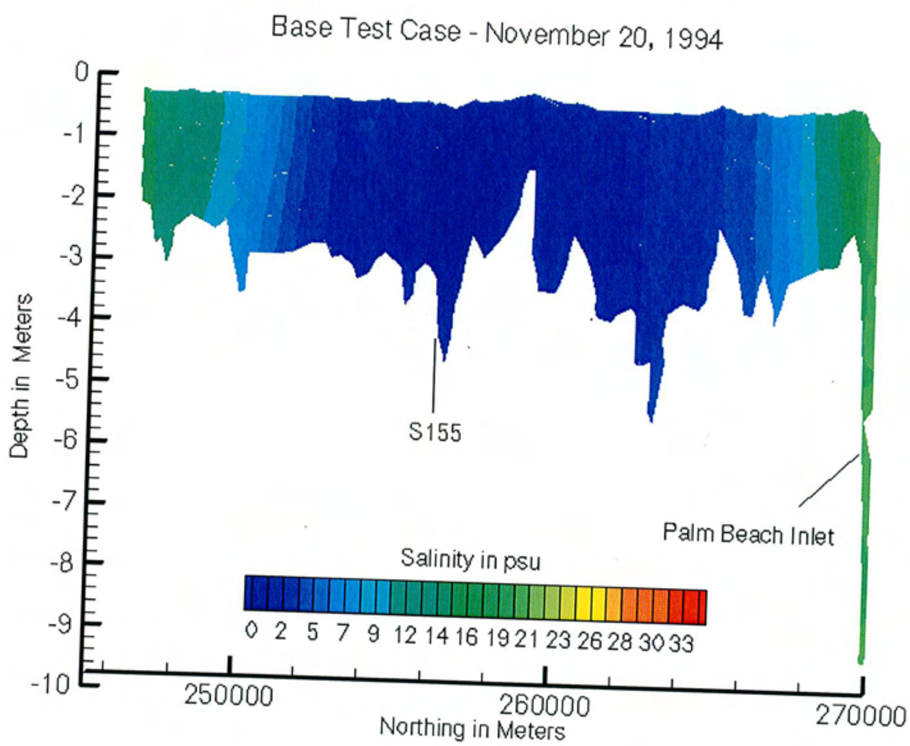

Figure 26. Vertical profile of salinity along the axis of Lake Worth Lagoon on November 20,1994 according to predictions of the Base test case.

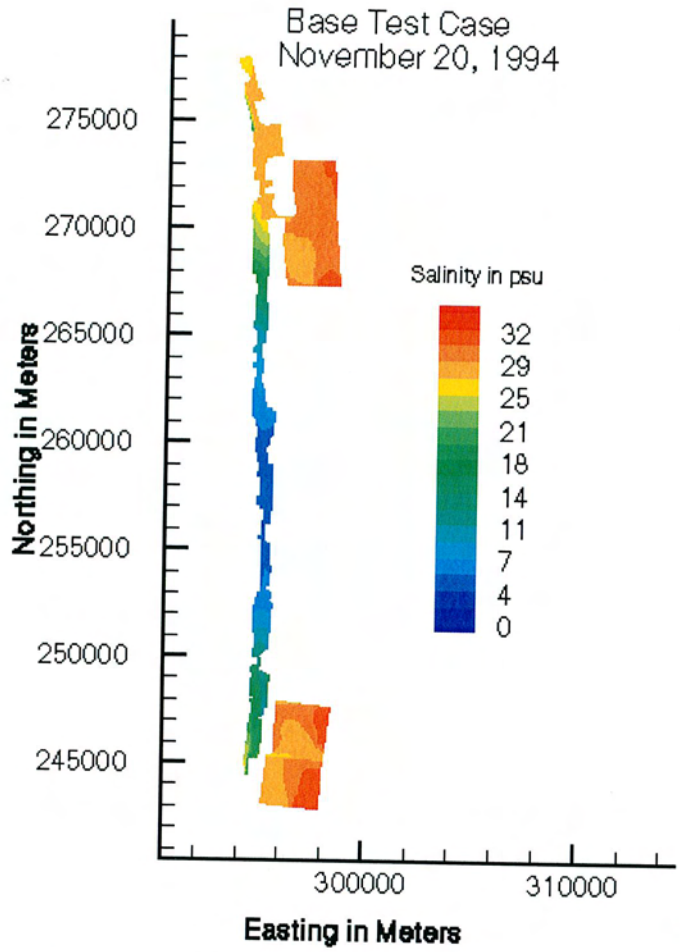

Figure 27. Horizontal distribution of salinity in Lake Worth Lagoon on November 20,1994 according to predictions of the Base test case.

Figures 28 and 29 illustrate salinity distribution in the Lagoon for November 20, 1994 for the D13R reduced flow test case. The overall pattern of salinity distribution is similar to the full flow 1995-Base test case, but the overall lateral extent of salinity is less than 10 psu, markedly smaller under the D13R test case (compare Figures 26 and 28).

A complete record of salinity predictions in the horizontal and vertical dimensions of the model can be viewed in the animations of the EFDC model results included in an electronic appendix to this report (see Table 2)

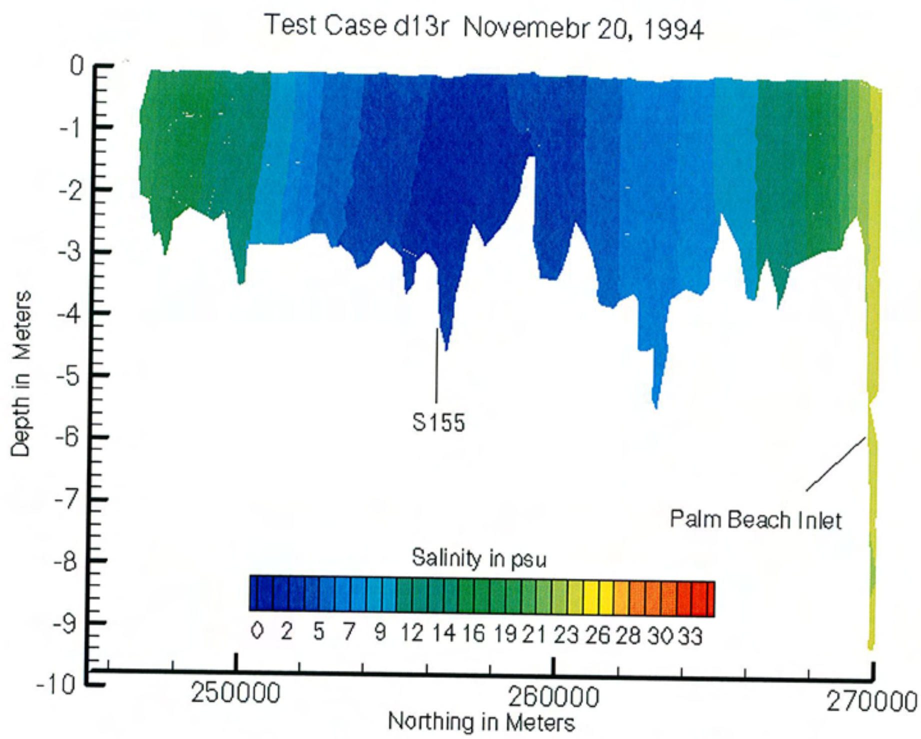

Figure 28. Vertical profile of salinity along the axis of Lake Worth Lagoon on November 20,1994 according to predictions of the Tsp test case.

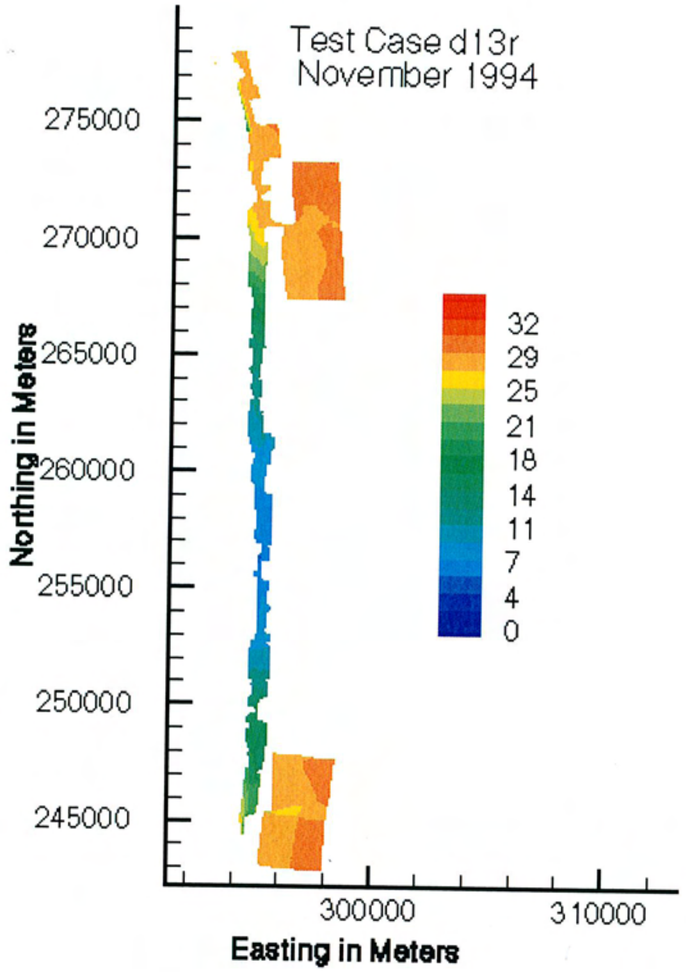

Figure 29. Horizontal distribution of salinity in Lake Worth Lagoon on November 20,1994 according to predictions of the TSP test case.

6.0 Salinity Tolerances of the Ichthyofauna in Lake Worth Lagoon, Southeast Florida.

6.1 Introduction

Palm Beach County (the County) has recommended that specific goals for maximum and minimum discharges of freshwater into the Lake Worth Lagoon (LWL) be established (1998 Lake Worth Lagoon "White Paper"). The measure for success of the freshwater discharge goals is the bottom salinity of the LWL as measured at ½ mile north of the S-155 discharge structure of C-51 canal. The County is primarily concerned with wet season discharges (June through September) and the need to hold back large quantities of freshwater from discharging into the LWL so as not to adversely affect ecosystem function in the estuary. This section discusses the salinity tolerances of the vertebrate ichthyofauna of the LWL.

The County and the South Florida Water Management District (the District) have established salinity targets based on historical salinity conditions and general ecological theory of estuarine ecosystem structure and function. These salinity goals have taken into account the requirements of specific communities, habitats, species, and life stages within the LWL. Broad salinity targets have been established as a minimum bottom salinity range of 23 to 30 ppt at a distance of ½ to 2 miles north of the S-155 discharge structure during the wet season. Further, the bottom salinity should not fall below 23 ppt for more than 2 weeks. Though dry season (November through April) discharges are not a primary concern, the County recommends that maximum bottom salinity not exceed 36 ppt during those months (average seawater salinity: 35 ppt).

The County has recommended that the optimal salinity range for LWL be considered as 30-36 ppt. By maintaining interior salinity levels above 30 ppt, it is believed that the LWL will be inhabited by more marine species while still allowing traditional estuary species to survive. Thus, the ecological objectives of the salinity goals are to maximize species abundance and richness. Species abundance refers to the number of effectively reproducing individuals within a species. Species richness refers to the diversity of species present in an ecosystem.

This report presents data on the salinity tolerance of vertebrate ichthyofauna of the LWL. This report also presents general background information on the osmoregulatory mechanisms of fishes. Thus, the biological imperative for the maintenance of the salinity targets can be better understood in the context of the fishes known to be associated with the LWL. Many factors affect the implementation of the salinity goals. The history, hydrological and hydraulic regimes, salinity distribution models, techniques for optimizing salinity, and the physical properties of the LWL are all important to consider, but are beyond the scope of this review.

6.2 Osmoregulation

Background

Living cells require internal ionic concentrations to be maintained within narrow tolerances in order to function properly. Plasma membranes and integrated structures that enclose the cells are used to maintain the proper ionic balances inside of the cell relative to the external environment. Organisms must regulate this internal environment by physiological or behavioral mechanisms in order to survive. Since the internal ionic constituents of cells are essentially dissolved in water, fishes are challenged to maintain the proper balances of ionized salts, alkalinity, and dissolved organic compounds despite an external environment that may have substantially different concentrations. Thus, fishes must osmoregulate in order to maintain the proper hydromineral balance within their cells.

Traditionally, fishes have been classified as either stenohaline or euryhaline based on their ability to withstand variations in ionic concentration in the external environment. Stenohaline fishes are able to withstand a narrow range of salinities. Euryhaline fishes are able to withstand a wide range of salinities. Though much research has been done on the affects of salinity on fishes, often fishes are categorized based on their ecological preference since robust data is available for only a limited number of species. Woo and Chung (1990) suggested that the traditional definitions of stenohaline and euryhaline are too restrictive to accurately reflect the biology of fishes and suggest that a distinction be made between ecological and physiological tolerances. Though physiological adaptations may exist that allow the preferential exploitation of a particular niche, the organism may be able to tolerate a physical environment that is substantially different.

Most fishes have adapted to an environment where salinity is maintained within narrow limits. However, many other fishes live in environments that have large variations in salinity, such as estuaries. Changes in salinity may affect metabolism, endocrine function, osmotic balance, reproduction, habitat selection, and niche utilization. Outside of the adaptive niche the energy costs associated with osmoregulation may be high.

Fish can acclimate to salinity changes through behavioral and physiological means. The time required for acclimation ranges from hours to days and varies by species (Parry 1966). The limits of salinity tolerance are determined by physiological constraints of the individual organism as determined by its genetics, the dynamic changes of the environment, and the interaction between the fish's genetics and the environment. Some fishes that are generally considered to be stenohaline can be acclimated to salinities well outside the normal range by very gradual changes. For example, *Tilapia mossambica*, a freshwater species, has been acclimated to salinity as high as 69 ppt (Parry 1966). Fish eggs and larvae generally have more restrictive salinity ranges than do adult fishes, since early life stages can not osmoregulate as effectively as adults (Parry, 1966). However, data for early lifestages are limited.

Slow changes in salinity can be expected to select individuals and strains with increased salt tolerance. These adaptations depend on the rate of change in the environment, the magnitude of the change, the duration of the change, the vagility of the organism, the generation time of the organism, and the degree of variability in the population for traits that influence salinity tolerance. Selection potential is a difficult parameter to forecast and little data exists. Theoretical approaches are possible. Heuts (1947) found that the rate of development of eggs of *Gasterosteus aculeatus* in different salinities depended on the sub-species of the female parent. Genetic potential can be evaluated with laboratory studies, but these experiments are costly and time-consuming since many generations must be reared in order to accurately estimate the population genetics parameters that affect salinity tolerance.

6.2 Strategies

Fishes can be categorized into 4 groups by the strategies used to regulate internal water and total solute concentrations. The first strategy is no osmoregulation at all (osmoconformers as opposed to osmoregulators). The only vertebrates that use this strategy are the hagfishes (Agnatha: Myxinniformes). These primitive, jawless fishes occur only in marine environments that have relatively constant salinity. The body fluids of hagfishes are almost isotonic with sea water, though they do exhibit some ability to regulate sodium ion concentration.

The second strategy is to maintain internal salt concentrations at about 1/3 that of sea water (typical for most vertebrates) by concentrating organic salts (e.g. urea and Trimethylamine oxide) in the blood. The total salt concentration of the animal is thus maintained near that of sea water. All marine elasmobranchs (sharks, skates, rays, and chimeras) and the coelacanth (*Latimeria chalumnae*) use this method of osmoregulation. Elasmobranchs exhibit considerable ability to regulate individual ion concentrations.

The third strategy is to maintain the internal salt concentration at about 1/3 that of sea water (hyposmotic) by actively transporting excess salt out of the organism while ingesting large quantities of sea water. This strategy is employed by marine teleosts. These fishes continually ingest sea water to counter the effect of water diffusing to the environment. The excess salt ingested with the sea water is then excreted by specialized chloride cells in the gill filaments and opercular skin epithelia. Teleost kidneys cannot produce urine that is more salty than the blood.

The fourth strategy is to maintain the typical internal salt concentration of about 1/3 that of sea water by excreting large quantities of dilute urine. This strategy is employed by freshwater teleosts and elasmobranchs and is an adaptive synapomorphy for a hyperosmotic environment. These fishes continually gain water by diffusion from the environment. The well developed kidneys of these fishes are capable of excreting a volume of urine equivalent to 1/3 of the fish's body weight each day. The endocrine system (e.g. the pituitary hormone arginine vasotocin) regulates urine production to maintain the correct hydromineral balance. The pituitary hormone prolactin minimizes diffusional losses of salts in the urine and across the gill epithelia. Salts are primarily replaced by active transport mechanisms from the environment across the gill epithelia, though some salts are replaced by ingestion of food items. The chloride cells found in freshwater fishes are functionally the reverse of those from salt water environments. Freshwater fishes display a remarkable array of adaptations to the hyperosmotic environment.

6.3 Trophic Considerations

Ecosystems can be characterized by the complex interactions of populations that live in them. Beyond the consideration of the salinity tolerance of a particular species, it is important to acknowledge that the interactions between species are integral to survival. These tropic relationships can be affected by changing environmental parameters, such as salinity. Changes in the natural salinity regime of the LWL could effect fishes indirectly well before reproductive failure or mortality of adult fish occurs. The LWL, like most estuaries, is an extremely complex system and food webs are poorly characterized. Thus, predictions about changes to trophic structure are likely to be speculative without rigorous study. However, changes in the lower trophic levels, can dramatically affect abundance of top predators such as Snook and Tarpon. For example, many juvenile fishes depend on copepods for forage. Copepods depend almost entirely on algae for food. Any change in salinity that affects the distribution and abundance of algae to the extent that copepod abundance was influenced would feed back up the food web affecting the survivorship of top predators. Juvenile fishes may be able to switch to an alternate prey source, but this scenario is illustrative of the interactions between the physical environment and all of the organisms that constitute the ecosystem. Because of behavioral or distributional characteristics of predator and prey, switching may not always be possible (Hagar, 1984; Kitchell and Crowder, 1986; Jude et al. 1988).

More important trophic links may be found in the LWL plankton community. Trophic relations of the early life stages of these planktonic species may be critical and may cause changes well before salinity reaches critical levels for the fishes. Although adult fishes may feed on a variety of prey items, the juveniles must subsist on copepods, barnacle nauplii, other zooplankton and nereid worms. These trophic interactions must be considered in anticipating the likely effects of changes in salinity yet they are extremely difficult to quantify and difficult to predict in any rigorous way.

In general, salinity values outside of the optimal range will result in the decline of species richness, though abundance of remaining species may be great (Carpelan 1967, Copeland 1967, Hammer 1986). Plankton species differ in their tolerance to salinity with some preferring fresher waters, some preferring high salinity, and some having a very wide range of tolerance. The pattern is consistent for phytoplankton, zooplankton and other invertebrates. Under conditions of variable salinity it is expected that planktonic species community composition could change over time if the duration of the change was sufficient and that an overall trend to fewer species would occur if the salinity was maintained outside of the optimal range for normal function. These changes would necessitate modified food webs. For example, Carpelan (1964) found that the distribution of algae in hypersaline ponds limited the distribution of *Artemia* feeding on it in spite of suitable salinities for *Artemia*. Also, hypersaline waters tend to concentrate nutrients by evaporation and may lead to high levels of productivity (Copeland and Nixon 1974, Hammer 1986). Conversely, hyposaline waters will favor a shift in species composition to freshwater forms and may lead to a decrease in planktonic productivity for the LWL.

6.4 Biology of the Lake Worth Lagoon

The LWL is an ecologically and economically important shallow lagoon located in urbanized Palm Beach County of southeast Florida. Though originally a freshwater lake, the LWL has been transformed over the last century by anthropogenic impacts associated with developing the area. Dredging of submerged land to create channels and inlets along with filling of previously submerged lands has resulted in the formation of the estuary as it is today. Pollution and nutrient loading associated with human activities is an important concern to resource managers. One indicator of the pollution level is the species richness of benthic macroinvertebrates. The LWL has species richness values that are comparable to other moderately polluted estuaries (Rudolf, 1989).

Palm Beach County Department of Environment and Natural Resources (DERM) conducted a natural resources inventory (DERM, 1990). That inventory characterized the biological community in the LWL. According to the report, the LWL was found to have 261 species of fish either within the lagoon proper (195 species), or in the vicinity of the inlets (66 species). This species richness is comparable to other estuaries in the region: Loxahatchee River Area (267 species; Christensen, 1965), Indian River Lagoon (286 species; Gilmore, et al., 1981), and Biscayne Bay (193 species; DERM, 1984). Six species of seagrass beds were identified covering approximately 2110 acres (35%) of submerged area. Ten species of macro-algae were identified. Twenty seven animal species and 13 plant species that were listed as endangered, threatened, or rare. All listed plant species occurred either in the John D. MacArthur State Recreation Area or the Gemini Botanical Gardens. Additionally, habitats for oysters, coral, and sponges were identified.

6.5 Salinity Tolerance

Challenges of Estuaries

Estuaries are defined by their dynamic salinity regimes. Cameron and Pritchard (1963) define estuaries as "a semi-enclosed coastal body of water having free connection with the open sea and within which the sea water is measurably diluted with freshwater deriving from land drainage". Thus, estuaries are transitional environments between salt and freshwater. Fish species that utilize estuarine environments do so because they are physiologically adapted to, and have access to the niches in the estuary. Typically, these fish species are a mix of euryhaline species from both freshwater and marine environments, species migrating from one environment to another, species that utilize portions of the estuary during specific life stages, and a few resident species. The dynamic physicochemical changes in estuaries limit the species richness. Conversely, the abundant productivity of estuaries tends to support high species abundance, often of commercially or recreationally important fishes.

Gradients created by the mixing of fresh and sea water are not stable, but move up and down the estuary on a daily basis under tidal and freshwater input influences. Seasonal influences can be oceanic storms that push sea water into the estuary and rainfall that directly dilutes the estuary. Dissolved oxygen and turbidity gradients are also common features of estuaries since the inflowing water often contains suspended organic and inorganic matter. As a result of this dynamic environment, fishes that inhabit these areas must expend a considerable amount of energy adjusting to the changing conditions, either physiologically or behaviorally.

The energy costs incurred by fishes as they adjust to changing conditions in an estuary are easily compensated by the concentration of nutrients and abundant prey items that are typical in lagoons. Nutrient availability is generally a result of detrital transport from the freshwater inflows or decay of organic material in associated marshes or mangrove swamps. Salt marshes and mangrove swamps can be an important source of nutrients for estuaries, as well as providing valuable nursery habitat for many fishes. The LWL, being an urbanized lagoon, lacks a normal associated wetland regime in that the majority of the lagoon has bulk headed banks. Photosynthesis in estuaries is generally limited by high turbidity but phytoplankton production can be an important energy source for fishes. Anthropogenic nutrient loading (i.e. runoff, stormwater, and sewage) is another important consideration. Estuaries recycle nutrients efficiently as a result of constant mixing and zooplanktonic feeding on detritus. Major nutrient losses usually only occur during floods. Copepods feeding on detritus and phytoplankton are, in turn, food for fishes. Copepod and fish fecal pellets are deposited on the bottom where they become part of the organic ooze that supports the benthic invertebrates. Amphipods and neried worms that inhabit the benthos are important food sources for fishes in that many species rely on these invertebrates as a primary food source during some lifestage. Oysters, which filter-feed in the water column, occur in beds in the nutrient-rich estuarine water. Oysters are an important resource in the LWL and are a good indicator of water quallity since they are sessile. Oysters can survive short exposure to freshwater (days to weeks) depending on their stored energy reserves, but individual health and survivorship start to drop-off below about 7.5 ppt. Oysters seem to do best at salinities between 16 and 24 ppt and salinities above 12 ppm are required during spawning.

Though the benthos is often abundantly inhabited, the upper layer usually has the highest concentration of nutrients, phytoplankton, and zooplankton. These resources have been correlated to the lower salinity portions of the estuary since the mechanism that concentrates the nutrients is the mixing of fresh and salt that creates the gradients described above. The same processes that concentrate nutrients in estuaries can also concentrate pollutants. Estuarine fishes may survive exposure to pollutants, since they are already adapted to the stressful estuarine environment, and still pass on the toxic effects to humans who consume them for food.

6.6 Fishes of the Lake Worth Lagoon

Fishes that live in estuaries do so because they are able to benefit from this diverse ecosystem at some lifestage or during some environmental condition. Estuarine fishes can be broadly divided into 5 categories. These five categories are usually represented in a typical estuary, though the relative abundance of each category varies from seasonally and spatially within the estuary.

Freshwater fishes are often found in the upper reaches of estuaries. Though some freshwater fishes may complete their entire life cycle in an estuary, but typically they are ephemeral residents that may have been washed in over a discharge structure. The distributions of true freshwater fishes are typically restricted to salinities less than 5 ppt. The most euryhaline of traditionally classified freshwater fishes are restricted to water below 15 ppt. Examples of freshwater fishes that may be found in estuaries include the genera *Gambusia*, *Ictalurus*, and *Cyprinus*.

Diadromous fishes are found in estuaries as they transit between salt and freshwater systems. Diadromous fishes either spawn in salt water and move into freshwater at some life stage or vice versa. Some fishes, such as striped bass (*Morone*), may spawn in the freshwater adjacent to the estuary and use the estuary as a nursery habitat. These fishes that utilize the estuary for nursery habitat before moving into the preferred habitat can be called semi-diadromous.

True estuarine fishes are those species that are usually found in the lower reaches of estuaries. There are few species that fit into this category though those that do may be important components of the fish fauna. For example, the spotted sea trout (*Cynoscion nebulosus*) is a true estuarine fish found in the LWL that is of considerable importance to sport fisherman.

Non-dependent marine fishes are those species that are commonly found in the lower reaches of estuaries but that do not depend on the estuary to complete their lifecycles.

These fishes are generally important in shallow-water marine environments and may be important in estuaries too. Most of the fishes found in the LWL fall into this category.

Dependent marine fishes are those species that spend at least one stage of their life cycle in estuaries. These fishes use estuaries for spawning, nursery habitat, or feeding grounds for adults. There are few fish species that use estuaries for spawning. However, many marine species that spawn outside of estuaries have larval or juvenile lifestages that recruit into the estuary to take advantage of the abundant food supplies. Croakers (Sciaenidae) and tarpon (Megalopidae) are examples of fishes that use this strategy.

Physiochemical dynamics are the primary factors affecting the distribution and abundance of fishes within an estuary. Biological factors are of secondary importance in the distribution and abundance of ichthyofauna within estuaries. Physiochemical factors exert such a strong influence because most species that inhabit estuaries are either transient or vagile enough to alter their distribution to compensate for the dynamic environment. Fishes can occupy an estuary when conditions are favorable and then move out of the estuary when environmental conditions become severe (Dahlberg and Odum, 1970). Temperature and salinity are the two most important variables affecting the distribution and abundance of fishes in estuaries. Other factors affecting abundance and distribution may include dissolved oxygen, predation, interspecific competition, and available habitat. Only salinity is considered here.

The intermediate and fluctuating salinities found in estuaries serve to limit the types of fishes that can inhabit them. Species richness is depressed since stenohaline freshwater and marine fishes are limited in their ability to penetrate the estuary. Most estuarine fishes are euryhaline. Some fishes found in estuaries are able to tolerate abrupt salinities changes, such as a sudden increase in freshwater inflow, and remain in the area; whereas, other fishes may move to a more saline area. Salinity tolerances may also vary by lifestage within a species. For example, juvenile fishes with low vagility that are caught by an abrupt salinity decrease caused by a sudden freshwater inflow may experience mass mortality due to osmotic shock or from being flushed to an unsuitable habitat elsewhere in the estuary.

The fishes of the LWL were inventoried by DERM (1990) and published as a Natural Resources Inventory. The complete list of fishes from that inventory have been compiled into a single table (Table 1) and are presented below. Table 1 shows that 292 species of fishes have been found either within the LWL proper or in the vicinity of the inlets. These fishes are considered to be stenohaline marine species (mostly around the inlets) or euryhaline. No stenohaline freshwater fishes are included in Table 1. This notable absence of freshwater fishes is probably an artifact of the artificial structure of the LWL. The LWL is a man-made estuary and lacks freshwater input from a natural river system. Thus, no freshwater habitat is available that can serve as a source for freshwater fishes. The fishes that are present in the LWL are able to cope with the dynamic salinity regime either physiologically (i.e., osmoregulation) or behaviorally (i.e., halotaxis). Following are several examples of salinity tolerances of several genera found in the LWL. These examples serve to highlight that the fishes in the LWL are capable of handling a broad range of salinities. The following examples illustrate the salinity tolerances for a euryhaline family, a stenohaline marine family, and a euryhaline marine family with stenohaline larvae.

Poeciliidae

Members of the family Poeciliidae are well known for their broad salinity tolerance. Species in this family are found in pure freshwater to full strength seawater. Nordlie and Mirandi (1996) demonstrated that freshwater collected *Gambusia holbrooki* could be acclimated to salinities in excess of 25 ppt with relatively low mortality (39.7%) over a 14 day period and some fishes were able to survive in salinities above 30 ppt (64.6% mortality). In an earlier study, Nordlie et al. (1992) found that *Poecilia latipinna* had upper salinity tolerance limits of 70 to 80 ppt. Chervinski (1982) found that Gambusia affinis were able to tolerate the direct transfer from freshwater to salinities as high as 19.5 ppt with no mortality. These fish were able to withstand a salinity of 39 ppt with 35% mortality after 7 days. 50% mortality was not reached until salnity reached 58.5 ppt.

Fish that had been held at 39 ppt for 7 days showed no mortality when transferred directly to 0 ppt water.

Table 1. Fishes In and Around the LWL. Table is compiled from Tables 6 and 7 from DERM (1990) with corrections to recent changes in taxonomy.

Family	Genus	Common Name	Location
BRANCHIOSTOMIDAE			
	Asymmetron sp.	lancelet	
	Asymmetron lucayanum	sharptail lancelet	I
ORECTOLOBIDAE			
	Ginglymostoma cirratum	nurse shark	I
CARCHARHINIDAE			
	Carcharhinus brevipinna	spinner shark	I
	Carcharhinus leucas	bull shark	T
	Carcharhinus limbatus	blacktip shark	I
	Carcharhinus obscurus	dusky shark	I
	Negaprion brevirostris	lemon shark	I
SPHYRNIDAE			
	Sphyma tiburo	bonnethead	I
PRISTIDAE			
	Pristis perotteti	largetooth sawfish	I
TORPEDINIDAE			
	Narcine brasiliensis	lesser electric ray	I
RAJIDAE			
	Raja eglanteria	clearnose ray	I
DASYATIDAE			
	Dasyatis americana	southern stingray	T
	Dasyatis sabina	Atlantic stingray	T
	Dasyatis sayi	bluntnose stingray	T
	Gymnura micrura	smooth butterfly ray	T
MYLIOBATIDAE			
	Aetobatus narinari	spotted eagle ray	T
	Rhinoptera bonasus	cownose ray	T
MOBULIDAE			
	Manta birostris	Atlantic manta (juveniles)	T
ELOPIDAE			
	Elops saurus	ladyfish	T
MEGALOPIDAE			
	Megalops atlanticus	tarpon	T
ALBULIDAE			
	Albula vulpes	bonefish (rare in Lake Worth)	I
MURAENIDAE			
	Echidna catenata	chain moray	I
	Gymnothorax funebris	green moray	T
	Gymnothorax moringa	spotted moray	I
	Muraena miliaris	goldentail moray	I
	Uropterygius diopus	marbled moray	I

Family	Genus	Common Name	Location
OPHICHTHIDAE			
	Myrophis punctatus	speckled worm eel	T
CLUPEIDAE			
	undertermined sp.		
	Brevoortia smithi	yellowfin menhaden	T
	Brevoortia tyrannus	Atlantic menhaden	T
	Harengula sp.	sardine	
	Harengula clupeola	false pilchard	I
	Harengula humeralis	redear sardine	I
	Harengula jaguana	scaled sardine	T
	Jenkinsia lamprotaenia	dwarf herring	I
	Jenkinsia majua	little-eye herring	
	Opisthonema oglinum	Atlantic thread herring	T
	Sardinella aurita	spanich sarding	T
ENGRAULIDAE			
	Anchoa sp.	anchovy	
	Anchoa cayorum	Key anchovy	
	Anchoa hepsetus	striped anchovy	T
	Anchoa lamprotaenia	longnose anchovy	
	Anchoa lyolepis	dusky anchovy	T
	Anchoa mitchilli	bay anchovy	T
SYNODONTIDAE			
	Synodus foetens	inshore lizard fish	T
	Trachinocephalus myops	snakefish	I
CYPRINIDAE			
	Notropis maculatus	taillight shiner	T
ARIIDAE			
	Ariopsis felis	sea catfish	T
	Bagre marinus	gafftopsail catfish	T
BATRACHOIDIDAE			
	Opsanus beta	gulf toadfish	T
ANTENNARIIDAE			
	Antennarius ocellatus	ocellated frogfish	I
	Antennarius scaber	splitlure frogfish	T
	Histrio histrio	sargassum fish	I
OGCOCEPHALIDAE			
	Ogcocephalus nasustus	shortnose batfish	I
	Ogcocephalus radiatus	polka-dot batfish	I
EXOCOETIDAE			
	Cypselurus heterurus	Atlantic flyingfish	I
HEMIRAMPHIDAE			
	Hemiramphus brasiliensis	ballyhoo	I
	Hyporhamphus unifasciatus	halfbeak	I
BELONIDAE			
	Strongylura sp.	needlefish	
	Strongylura marina	Atlantic needlefish	T
	Strongylura notata	redfin needlefish	T

Family	Genus	Common Name	Location
	Strongylura timuca	timucu	T
	Tylosurus acus	agujon	T
CYPRINODONTIDAE			
	Floridichthys carpio	golspotted killifish	T
	Fundulus confluentus	marsh killifish	T
	Fundulu grandis	gulf killifish	T
	Rivulus marmoratus	rivulus	T
POECIILIDAE			
	Heterandria formosa	least killifish	T
	Poecilia latipinna	sailfin molly	T
ATHERINIDAE			
	Membras martinica	rough silverside	T
	Menidia beryllina	inland killifish	T
FISTULARIIDAE			
	Fistularia tabacaria	bulespotted cornetfish	I
SYNGNATHIDAE			
	Hippocampus erectus	lined seahorse	T
	Hippocampus zosterae	dwarf seahorse	T
	Syngnathus sp.	pipefish	
	Syngnathus florida	dusky pipefish	T
	Syngnathus louisianae	chain pipefish	T
	Syngnathus pelagicus	sargassum pipefish	I
	Syngnathus scovelli	gulf pipefish	T
SCORPAENIDAE			
	Scorpaena bergi	goosehead scorpionfish	I
	Scorpaena calcarata	smoothhead scorpionfish	I
	Scorpaena grandicornis	plumed scorpionfish	T
TRIGLIDAE			
	Prionotus sp.	Searobin	
	Prionotus ophryas	bandtail searobin	I
	Prionotus scitulus	leopard searobin	I
	Prionotus tribulus	bighead searobin	I
CENTROPOMIDAE			
	Centropomus pectinatus	tarpon snook	T
	Centropomus undecimalis	common snook	T
SERRANIDAE			
	Alphestes afer	mutton hamlet	
	Diplectrum formosum	sand perch	I
	Epinephelus itajara	jewfish	T
	Epinephelus morio	red grouper	I
	Hypoplectrus unicolor	butter hamlet	I
	Serranus tigrinus	harlequin bass	I
	Serranus tortugarum	chalk bass	I
PRIACANTHIDAE			
	Pristigenys alta	short bigeye	I
APOGONIDAE			
	Apogon binotatus	barred cardinalfish	I

Family	Genus	Common Name	Location
	Apogon pseudomaculatus	twospot cardinalfish	I
	Apogon xenus	sponge cardinalfish	I
	Phaeoptyx pigmentaria	dusky cardinalfish	I
POMATOMIDAE			
	Pomatomus saltatrix	bluefish	T
RACHYCENTRIDAE			
	Rachycentron canadum	cobia	I
ECHENEIDAE			
	Echeneis naucrates	sharksucker	I
CARANGIDAE			
	Caranx sp.	jack	
	Alectis ciliaris	African pompano	I
	Caranx bartholomaei	yellow jack	I
	Caranx crysos	blue runner	I
	Caranx hippos	crevalle jack	T
	Caranx latus	horse-eye jack	T
	Caranx ruber	bar jack	I
	Decapterus macarellus	mackerel scad	I
	Decapterus punctatus	round scad	I
	Elagatis bipinnulata	rainbow runner	I
	Oligoplites saurus	leatherhacket	T
	Selar cramenophthalmus	bigeye scad	I
	Selene vomer	lookdown	T
	Seriola dumerili	greater amberjack	I
	Trachinotus sp.		
	Trachinotus carolinus	Florida pompano	I
	Trachinotus falcatus	permit	T
	Trachinotus goodei	palometa	
CORYPHAENIDAE			
	Coryphaena hippurus	dolphin	I
LUTJANIDAE			
	Lutjanus analis	mutton snapper	I
	Lutjanus apodus	schoolmaster	T
	Lutjanus cyanopterus	cubera snapper	I
	Lutjanus griseus	mangrove (gray) snapper	T
	Lutjanus synagris	lane snapper	T
	Ocyurus chrysurus	yellowtail snapper	I
	Rhomboplites aurorubens	vermillion snapper	I
LOBOTIDAE			
	Lobotes surinamensis	tripletail	T
GERREIDAE			
	Diapterus sp.		T
	Diapterus auratus	Irish pompano	T
	Diapterus plumieri	striped mojarra	T
	Eucinostomus sp.	mojarra	T
	Eucinostomus argenteus	spotfin mojarra	T

Family	Genus	Common Name	Location
	Eucinostomus gula	silver jenny	T
	Eucinostomus harengulus	tidewater mojarra	T
	Eucinostomus jonesi	slender mojarra	I
	Eucinostomus melanopterus	flagfin mojarra	T
	Gerres cinereus	yellowfin mojarra	T
	Gerres sp.	mojarra	
	Ulaema lefroyi	mottled mojarra	T
HAEMULIDAE			
	Anisotremus birginicus	porkfish	I
	Haemulaon sp.	grunt	
	Haemulaon album	margate	I
	Haemulaon aurolineatum	tomtate	T
	Haemulaon flabolineatum	French grunt	I
	Haemulaon macrostomum	Spanish grunt	I
	Haemulaon parrai	sailors choice	T
	Haemulaon plumieri	white grunt	I
	Haemulaon sciurus	bluestriped grunt	I
	Haemulaon striatum	striped grunt	I
	Orthopris chrysoptera	pigfish	T
SPARIDAE			
	undetermined sp.		
	Archosargus probatocephalus	sheepshead	T
	Archosargus rhomboidalis	sea bream	T
	Calamus sp.	porgy	I
	Calamus penna	sheepshead porgy	I
	Diplodus argenteus	silver porgy	
	Diplodus holbrooki	spottail pinfish	T
	Lagodon rhomboides	pinfish	T
SCIAENIDAE			
	Sciaenops sp.	drum	
	Bairdiella chrysoura	silver perch	T
	Cynoscion arenarias	sand seatrout	T
	Cynoscion nebulosus	spotted seatrout	T
	Equetus acuminatus	high-hat	I
	Equetus lanceolatus	jackknifte-fish (rare)	I
	Leiostomus xanthurus	spot	T
	Menticirrhus americanus	southern kingfish	I
	Micropogonias undulatus	Atlantic croacker	T
	Odontosicon dentex	reef croacker	I
	Pogonias cromis	black drum	T
	Sciaenops ocellata	red drum	T
	Umbrina coroides	sand drum	I
MULLIDAE			
	Mulloidichthys martinicus	yellow goatfish	I
KYPHOSIDAE			
	Kyphosus sectatrix	Bermuda chub	T
EPHIPPIDAE			

Family	Genus	Common Name	Location
	Chaetodipterus faber	Atlantic spadefish	T
CHAETODONTIDAE			
	Chaetodon capistratus	foureye butterflyfish	I
	Chaetodon ocellatus	sppotfin butterflyfish	I
	Chaetodon sedentarius	reef butterflyfish (rare)	I
	Chaetodon striatus	banded butterflyfish	I
POMACONTHIDAE			
	Holacanthus bermudensis	blue anglefish	I
	Holacanthus ciliaris	queen angelfish	I
	Holacanthus tricolor	rocky beauty	I
	Pomacanthus arcuatus	gray anglefish	I
	Pomacanthus paru	French anglefish	I
POMACENTRIDAE			
	Abudefduf saxatilis	sergeant major	I
	Chromis cyanea	blue chromis (rare)	I
	Chromis multilineata	brown chromis	I
	Microspathodon chrysurus	yellowtail damselfish (rare)	I
	Pomacentrus ? Diencaeus (juvenile)	longfin damselfish	I
	Pomacentrus dorsopunicans	dusky damselfish	I
	Pomacentrus leucostictus	beaugregory	I
	Pomacentrus planifrons	threespot damselfish	I
	Pomacentrus partitus	bicolor damselfish	I
	Pomacentrus variabilis	cocoa damselfish	I
LABRIDAE			
	Bodianus rufus	Spanish hogfish	I
	Bodianus pulchellus	spotfin hogfish (rare)	I
	Doratonotus megalepis	dwarf wrasse	I
	Halichoeres gamotic	yellowhead wrasse	I
	Halichoeres maculipinna	clown wrasse	I
	Halichoeres pictus	painted wrasse	I
	Halichoeres radiatus	puddingwife	I
	Hemipteronotus novacula	pearly razorfish	I
	Thalassoma bifasciatum	bluehead wrasse	I
SCARDIDAE			
	Cryptomus roseus	bluelip parrotfish	I
	Scarus croicensis	striped parrotfish	I
	Scarus quacamaia	rainbow parrotfish	I
	Scarus taeniopterus	princess parrotfish	I
	Scarus vetula	queen parrotfish	I
	Sparisoma sp.	parrotfish	
	Sparisoma chrysopterum	redtail parrotfish	I
	Sparisoma radians	bucktooth parrotfish	I
	Sparisoma rubripinne	redfin parrotfish	I
	Sparisoma viride	stoplight parrotfish	I
MUGILIDAE			
	Mugil sp.	mullet	
	Mugil cephalus	striped mullet	T

Family	Genus	Common Name	Location
	Mugil curema	white mullet	T
	Mugil gaimardiaus	redeye mullet	T
	Mugil trichodon	fantail mullet	T
SPHYRAENIDAE			
	Sphyaena sp.		
	Sphyaena barracuda	great barracuda	T
	Sphyaena borealis	northern sennet	T
	Sphyaena picudilla	southern sennett	T
POLYNEMIDAE			
	Polydactylus oligodon	littlescale threadfin	I
PISTOGNATHIDAE			
	Opistognathus maxillosus	mottled jawfish	T
CLINIDAE			
	Acanthemblemaria aspera	roughhead blenny	I
	Coralliozetus bahamensis	blackhead blenny (rare)	I
	Labrisomus nuchipinnis	hairy blenny	I
	Paraclinus fasciatus	banded blenny	T
	Paraclinus grandicomis	horned blenny	T
	Paraclinus nigricpinnis	blackfin blenny	I
BLENNIIDAE			
	Hypleurochilus aequipinnis	oyster blenny	I
	Hypleurochilus bermudensis	barred blenny	I
	Lupinoblennius nicholsi	highfin blenny	T
GOBIIDAE			
	undertermined sp.	goby	
	Bathygobius soporator	frillfin goby	T
	Coryphoterus glaucofraenum	bridled goby	I
	Gobionellus sp.	goby	
	Gobionellus bolesoma	darter goby	T
	Gobionellus saepepallens	dash goby	T
	Gobionellus smaragdus	emerald goby	T
	Gobiosoma sp.	goby	
	Gobiosoma bosci	naked goby	T
	Gobiosoma gemmatum	freckled goby	I
	Gobiosoma longipala	twoscale goby	I
	Gobiosoma oceanops	neon goby	I
	Gobiosoma robustum	code goby	T
	Lophogobius cyprinoides	crested goby	T
	Microgobius gulosus	clown goby	T
	Microgobius microlepis	banner goby	T
ACANTHURIDAE			
	Acanthurus chirurgus	doctor fish	I
	Acanthurus coeruleus	blue tang	I
SCOMBRIDAE			
	Scomberomorus cavalla	kngh mackerel	
	Scomberomorus maculatus	spanish mackerel	
	Scomberomorus regalis	cero	

Family	Genus	Common Name	Location
STROMATEIDAE			
	Psenes cyanophrys	freckled driftfish	I
BOTHIDAE			
	Bothus sp.	flounder	
	Bothus ocellatus	eyed flounder	I
	Citharichthys macrops	spotted whiff	T
	Citharichthys spilopterus	bay whiff	T
	Paralichthys albigutta	gulf flounder	T
	Syacium sp.	flounder	
	Syacium micrurum	channal flounder	T
	Syacium papillosum	dusky flounder	T
SOLEIDAE			
	Archirus lineatus	line sole	T
	Gymnachirus melas	naked sole	I
CYNOGLOSSIDAE			
	Symphurus sp.	tonguefish	
	Symphurus arawak	Caribbean tonguefish	T
	Symphurus plagiusa	blackcheek Tonguefish	T
BALISTIDAE			
	Balistes sp.	triggerfish	
	Canthidermis maculatus	rough triggerfish	I
MONACANTHIDAE			
	Aluterus scriptus	scrawled filefish	I
	Cantherhines pullus	orange spotted filefish	I
	Monacanthus sp.	filefish	
	Monacanthus ciliatus	fringed filefish	T
	Monacanthus hispidus	planehead filefish	T
OSTRACIIDAE			
	Acanthostracion quadricomis	scrawled cowfish	T
	Lactophrys sp.	trunkfish	
	Lactophrys bicaudalis	spotted trunkfish	I
	Lactophrys trigonus	trunkfish	T
	Rhinesomus triqueter	smooth trunkfish	T
TETRAODONTIDAE			
	Canthigaster rostrata	sharpnose puffer	I
	Sphoeroides sp.	puffer	
	Sphoeroides dorsalis	marbled puffer	I
	Sphoeroides nephelus	southern puffer	T
	Sphoeroides spengleri	bandtail puffer	T
	Sphoeroides testudineus	checkered puffer	T
DIODONTIDAE			
	Chilomycterus schoepfi	striped burrfish	T
	Diodon histrix	porcupinefish	I
	Cynoscion nebulosus	Spotted Seatrout	

Pomocanthidae

Angelfish have traditionally been considered stenohaline marine fishes; however, Woo and Chung (1994) present evidence that these fishes can tolerate salinities well below seawater concentrations. Woo and Chung found that *Pomocanthus* had 0% mortality at a salinity of 7 ppt; however, the lower limit was found to be 5 ppt where 100% mortality was observed after 3 days. At 7 ppt salinity *Pomocanthus* was unstressed. The fish still fed actively, displayed no abnormal behavior, and had serum cortisol and glucose levels comparable to fishes in 33 ppt salinity.

Megalopidae

Adult tarpon (*Megalops atlanticus*) are well known for their ability to withstand a broad range of salinity. Tarpon have been found in habitats with salinities ranging from 0 to 47 ppt (reviewed in Zale and Merrifield, 1989). This highly vagile marine fish has been found in freshwater impoundments, estuaries, and open ocean. However, the larval stage of tarpon has specific salinity requirements in order to recruit to the juvenile stage. Stage I larvae have only been collected in salinities between 28.5 and 39.0 ppt. By the time that the leptocephalus larvae recruit to Stage II and begin to move into estuaries to seek nursery habitat their salinity tolerance broadens considerably. Late Stage I and juvenile tarpon can withstand direct transfer from oceanic salinities to freshwater.

The general conclusion that most marine fishes can tolerate a broad range of salinities is well founded in the literature. Wu and Woo (1983) examined 13 marine fish species in 9 different families (including several coral reef inhabitants that are traditionally considered stenohaline such as Siganidae, Sparidae, Theraponidae, Letherinidae, and Pomadasyidae) and noted that most species can tolerate hypoosmotic salinities in the 3-5 ppt range. Evans (1984) listed 90 fish families (including coral reef families Blennidae, Serranidae, Theraponioda, Carangidae, Lutjanidae, Sparidae, Pomacentridae, and Bothidae) that contain euryhaline members. Though the underlying cause of this widespread euryhalinity in marine teleosts is poorly understood, the evolutionary history of fishes supports the notion that low salinity tolerance is an ancestral trait (pliesiomorphic) (Woo and Chung, 1994). Ocean salinity during the Devonion (the Age of the Fishes) was approximately 1/3 that of modern oceans. The ancestors of modern teleosts evolved in the low salinity environment of the ancient ocean and their descendant have likely retained this character (Moyle and Cech, 1988). A review of the salinity tolerance literature reveals that most recent research is in fact focused on the effects of the hypersaline environments (i.e., the Salton Sea and the Laguna Madre) or the effects of increasing salinity on stenohaline freshwater fishes, since these environments tend to be more challenging physiologically for the organisms that inhabit them (e.g. Walsh et al., 1997).

7.0 Conclusions

The ichthyofauna of the LWL is unlikely to be affected dramatically by low salinities resulting from the discharge of fresh water at the historical or proposed discharge levels. Episodic spikes in freshwater discharge will likely result in localized mass mortality events, but most fishes are able to adapt or move out of the disturbed area. It is more likely that sustained low salinities will adversely affect marine invertebrates (particularly during spawning) and sea grasses (primarily from increased turbidity). For example, American oysters can survive short duration (weeks) exposure to salinities around 5 psu, but will not grow. Extended periods (month) of low salinity will result in increasing mortality. Larvae and early juvenile stages of oyster show poor recruitment and increased mortality in salinities below 12 psu. Thus, 12 psu can be considered a lower limit for a viable American oyster population (reviewed in South Florida Water Management District, 1998).

The model analysis presented in earlier sections of this report clearly show compartmentalization of the LWL in terms of salinity. The LWL can roughly be divided into three sections: North, Central, and South. Each of these sections is distinct in salinity, habitat, and fauna. Further, the modeling analysis and historical data show that prolonged (months) of low salinity are likely to occur in the LWL under all modeled scenarios, especially the Central section encompassing the S-155 discharge structure.

Thus, the preliminary salinity targets previously suggested by others may not be practically achievable and may be overly conservative based on the vertebrate biology (and perhaps the invertebrate biology as suggested above) of the LWL. The apparent compartmentalization of the LWL suggests that it is appropriate to establish salinity targets for each section of the LWL based on the observed dynamics, practical operating constraints, and ecosystem function.

Monitoring salinity in each compartment of the LWL at 1 to 2 sampling stations and setting salinity targets at each station should allow managers to obtain a more realistic picture of the salinity dynamics and enhance their ability to make ecologically meaningful decisions. Sampling stations along the LWL could be distributed so as to overlap the modeling points shown in Figure 13. Salinity targets can be set to minimize impacts on biota while still allowing operation flexibility to managers. Sampling stations corresponding to North 2 and 3; Center 2, 3, and 4; and South 2 and 3 (Figure 13) are recommended sampling locations because these stations bracket and sample across the lowest salinity regions of the LWL and in the vicinity of the S-155 discharge structure. Table 2 presents the average salinities for several stations along the LWL for an eight month period from June 1994 through January 1995 for the 1995-Base and the D13r test cases. The average salinities from the model outputs for the values listed in Table 2 are representative of the salinity concentrations for the compartments observed in the LWL. As previously mentioned, prolonged periods of low salinity occur frequently during the wet season but salinity targets based on the average salinity for the compartment during the period of highest discharge and computed on a rolling average should maximize the salinity for biota, also be achievable in practice, and provide operational flexibility. Table 3 shows recommended salinity targets for each proposed sampling station in the LWL. It is recommended that these targets be computed on a 30-day rolling average so as not to over emphasize the importance of short duration depressions in salinity.

Table 2. Average Salinities for Several Sampling Points along the LWL during a Representative 8 Month Period Modeled Between June 1994 and January 1995. Average salinities are shown for

the base case and the base case reduced by 50%. Station labels correspond to Figure 13. Stations shown in bold are recommended sampling sites.

Station	Average Salinity (psu)	
	Base	D13r
North 2	**27.2**	**28.7**
North 3	**26.3**	**28.1**
Center 1	12.8	19.1
Center 2	**7.3**	**14.4**
Center 3	**4.0**	**10.9**
Center 4	**4.5**	**11.3**
South 1	**9.6**	**15.7**
South 2	22.2	24.9

Table 3. Recommended Minimum Salinity Targets (psu) calculated on a 30-day Rolling Average for Each Proposed Sampling Station. Station labels correspond to Figure 13.

Compartment	Station	Minimum Salinity Target (psu)
North	2	23
	3	23
Center	2	12
	3	8
	4	8
South	1	12

The recommended salinity targets shown in Table 3 are compatible with the enhancement and management goals outlined by the County with the exception of the Center Stations 3 and 4. The centrally located stations are adjacent to the S-155 discharge structure and the historic and modeled outflows from this structure severely limit the ability of this compartment to recover to salinities above 8 psu during high discharge episodes such as storm events and generally during years of high rainfall.

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