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A Simulation of Historic Hydrology and Salinity in Everglades National Park: Coupling Paleoecologic Assemblage Data with Regression Models

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Abstract Restoration of Florida's Everglades requires scientifically supportable hydrologic targets. This study establishes a restoration baseline by developing a method to simulate hydrologic and salinity conditions prior to anthropogenic changes. The method couples paleoecologic data on long-term historic ecosystem conditions with statistical models derived from observed meteorologic and hydrologic data that provide seasonal and annual variation. Results indicate that pre-drainage freshwater levels and hydroperiods in major sloughs of the Everglades were about 0.15 m higher and two to four times greater, respectively, on average compared to today's values. Pre-drainage freshwater delivered to the wetlands and estuaries is estimated to be 2.5 to four times greater than the modern-day flow, and the largest deficit is during the dry season. In Florida Bay, salinity has increased between 5.3 and 20.1 with the largest differences in the areas near freshwater outflow points. These results suggest that additional freshwater flows to the Everglades are needed for restoration of the freshwater marshes of the Everglades and estuarine environment of Florida Bay, particularly near the end of the dry season.

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Introduction

The Greater Everglades Ecosystem of South Florida is a globally unique combination of hydrology and resultant water-based ecology that supports many threatened and endangered species. Encompassed within the Greater Everglades Ecosystem are the wetlands and estuaries of Everglades National Park, including Florida Bay and the southwest mangrove estuaries; Biscayne National Park; Big Cypress National Preserve; and several wildlife refuges. This wetland area has been designated an International Biosphere Reserve, a World Heritage Site, and a Wetland of International Importance (Davis and Ogden 1994); however, the ecosystem has been greatly altered by human activities. Beginning around the start of the twentieth century, drainage projects for flood control and land reclamation in the surrounding areas altered the natural hydrologic patterns and negatively impacted the biota (Ogden et al. 2005; Sklar et al. 2005). Conversion of wetlands to uplands and the diversion of freshwater to the coast have reduced the spatial extent of the freshwater wetlands that existed around 1900 by about half (Davis et al. 1994; Renken, et al. 2005; Schaffranek et al. 2001; Ogden et al. 2005; Davis et al. 2005). The impact of altering the natural flow of water through the South Florida ecosystem was highlighted by Marjory Stoneman Douglas with the publication of "The Everglades: River of Grass" in 1947 and has since been documented widely in both scientific journals and the open press.

The operational control of freshwater flow has reduced the volume of stored freshwater within the natural Everglades wetland system and has significantly altered the hydrology and ecology of the entire region. In the remaining marshes, hydroperiods have been reduced and hydropatterns changed (Ogden et al. 2005; Davis et al. 2005; Sklar et al. 2005; Willard et al. 2006). Downstream in estuarine areas, this reduction in freshwater flow has increased average salinities. In some areas, however, the flood control component of the managed system causes rapid short-term reductions in salinity that are outside the temporal range of variability of the natural system (Montague and Ley 1993). This is particularly true in northeastern Florida Bay, Card Sound, Barnes Sound, and southern Biscayne Bay. In other areas, such as Whipray Basin, this diversion of freshwater to northeastern Florida Bay has resulted in an increase in hypersaline events (Browder et al. 2002; Marshall 2005).

The reduction in freshwater stored upstream has caused the salt/freshwater transition zone to migrate landward (Parker et al. 1955), resulting in the influx of phosphorous-rich saline water into the tidal wetlands of Florida Bay (Rudnick et al. 2005). Florida Bay provides significant habitat for many ecologically and commercially important species of marine wildlife and it serves as a nursery for Gulf of Mexico and Atlantic Ocean fisheries (Browder et al. 2002). The alteration of the natural hydrologic regime in South Florida has resulted in the decline of a unique productive environment that is not thought to be sustainable in its current form (Rudnick et al. 2005).

To address the complex hydrologic, environmental, and societal issues of water control in South Florida, a multiagency effort began in the 1990s that led to the development of the Comprehensive Everglades Restoration Plan (CERP; U. S. Army Corps of Engineers 1999, 2006), and the goal to restore the freshwater, estuarine, and marine environments, much of which are located in Everglades National Park (ENP). The primary goal of CERP is to restore the timing, quantity, quality, and distribution of freshwater to the remaining parts of the original ecosystem so that it approximates the predevelopment conditions as closely as possible. Determining what constitutes the spatial extent and temporal hydrologic variation of the original Everglades ecosystem is a source of debate, and scientific data sets prior to the 1950s are scarce. Almost all of the existing scientific data on the Everglades ecosystem were collected from an already altered landscape, with the exception of paleoecological data.

This research was initiated to couple paleoecologic data on pre-drainage salinity in Florida Bay with hydrology and salinity regression models. The purpose is to estimate through hindcasting the pre-drainage hydrology in the Everglades and the salinity in Florida Bay. The results can be used by resource managers as a benchmark in the development of targets for freshwater flow and stage in the upstream wetlands and salinity in the estuaries. The objective is to forecast the amount and timing of freshwater necessary to restore a more natural hydrologic pattern to the Everglades and salinity to the estuaries of South Florida.

Materials and Methods

Study Area

The area of study is Everglades National Park, which covers 5,662 km^2 (Fig. 1). The Park encompasses diverse wetland ecosystems such as sawgrass prairies, hardwood hammocks, marl prairies, ridge and slough, mangroves, estuaries, carbonate mudbanks, and mangrove islands (McPherson and Halley 1996). The research discussed in this paper is focused on the wetlands in Shark River Slough south of U. S. Route 41 (Tamiami Trail), the marshes of Taylor Slough downstream of the Taylor Slough Bridge, and the open water of Florida Bay. Specific monitoring sites utilized within this region where data were collected are listed in Table 1 and shown in Fig. 1. It is noted that this paper utilizes the UNESCO (1985) salinity guidelines and the Practical Salinity Scale. As such, values of salinity reported herein have no units.

A sediment core from Whipray Basin (WB) was selected to test and develop the methodology of linking regression models to paleoecologic data. The basin is located in north central Florida Bay (Fig. 1) and is surrounded by shallow mud banks and mangrove islands that restrict circulation and reduce the tidal influence (Boyer et al. 1999). These conditions have led to extended periods of hypersalinity in Whipray Basin that have recurred a number of times over the past several decades (Fourqurean and Robblee 1999). Whipray Basin is recognized as a nursery ground for pink shrimp (*Farfantepenaeus duorarum*), a commercially important species (Browder et al. 2002). A key question for this research is whether hypersalinity is a natural condition in Florida Bay, or whether it resulted from water management practices. The variation in salinity for both current and pre-drainage periods (i.e., never fresh) in Whipray Basin makes this site particularly advantageous for regression modeling.

Approach

Despite the volume of research done in South Florida in recent years, long-term data sets on physical and biological factors are generally limited to the last 30 years. Fourqurean and Robblee (1999) point out that paleoecologic data, which indicate changes over centuries, put “long term” in perspective. By comparison, monitoring stations established within the freshwater marshes and estuaries in ENP

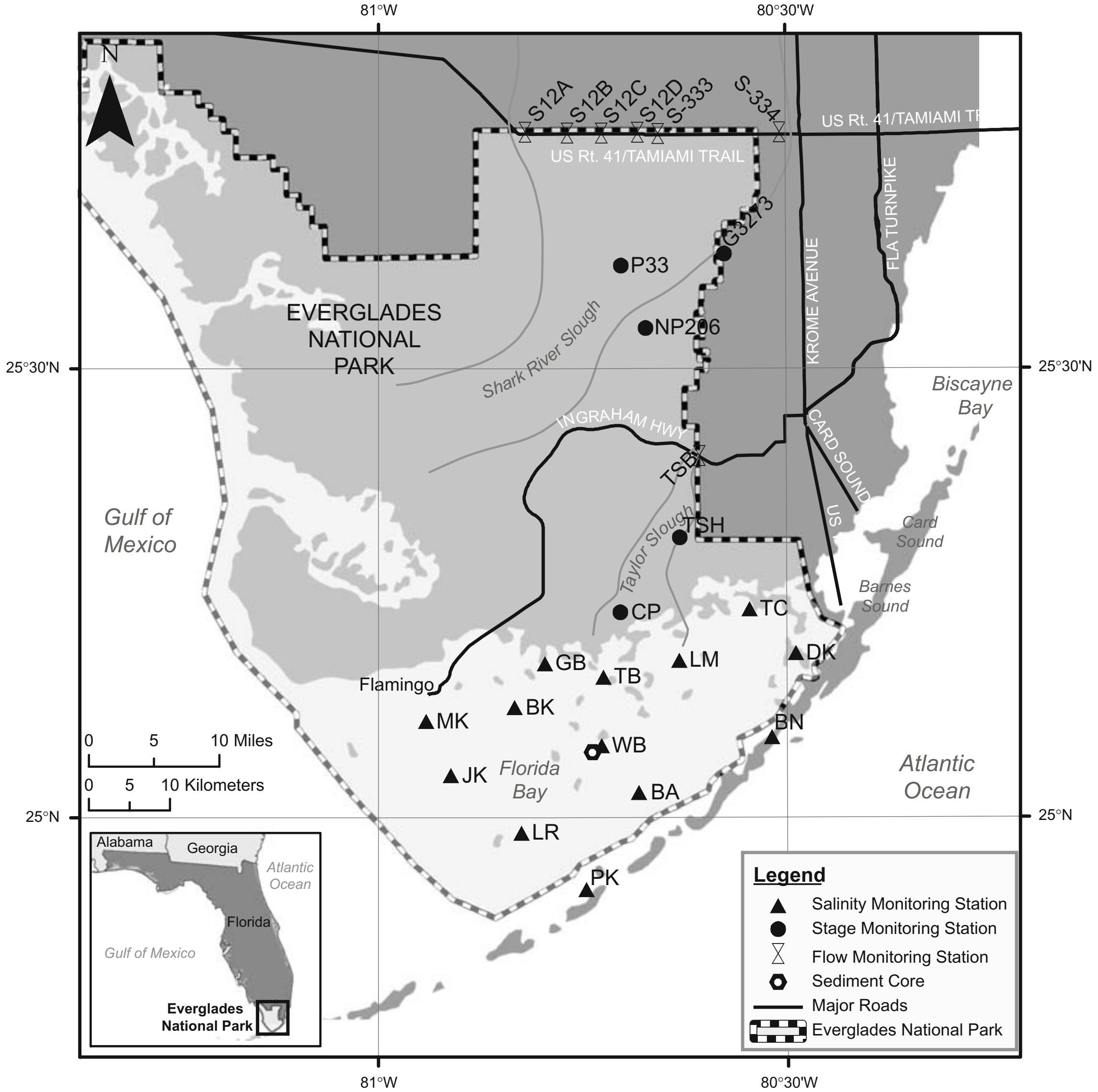

Fig. 1 Vicinity map showing the monitoring station locations in the Everglades and Florida Bay for salinity, stage, and flow data and the location of USGS sediment core (Whipray Basin Core FB697 25B) used in this study. Information on each monitoring station is provided in Table 1. Note: In South Florida, the term slough is typically applied to the broad channels of slow moving water that flow through the wetlands toward the coasts

during the 1980s and 1990s provide information on hydrologic parameters for this study. The physical responses of the system to climatic forcing factors and the effects of drainage operations is inferred from the observed water level (stage) and flow data collected at these stations.

Tabb (1967) was one of the first to document the relationship between salinity in South Florida tidal creeks and the stage measured in the upstream watershed. Water levels in the Everglades are a function of rainfall accumulation in the surrounding areas over the most recent period, water flow from upstream areas (surface and groundwater), and water loss due to evapotranspiration. Other physical factors affecting water levels include wind stress, tide effects, and water supply pumping. Surface water flow is a driving factor controlling salinity in the upper portion of the estuaries (Marshall and Nuttle 2008), and it is one of the primary quantities used for operating and managing the drainage system and for setting restoration targets. For these reasons, freshwater flow is one of the focal variables of this study.

The ability of linear regression modeling techniques to explain the connection between salinity conditions in Florida Bay and the hydrologic conditions upstream in the freshwater marshes of the Everglades has been clearly

Table 1 Data on variables (water level/stage, flow, salinity) from water monitoring stations and control structures in the Everglades and Florida Bay used to develop and verify the linear regression models

Monitoring station or structure	Symbol	Variable type	Raw data units[c]	Location	Latitude (Nad83)	Longitude (Nad83)	Date data begins	Model calibration period	Model verification period	Data source[d]
CP	CP	Water level	ft, NGVD 29	Craighead Pond	25:13:38	80:42:14	10/1/1978	1/1/91–12/31/01	1/1/90–12/31/90, 1/1/02–1/30/03	ENP (1)
P33	P33	Water level	ft, NGVD 29	Shark River Slough	25:36:48	80:42:09	2/15/1953	1/1/91–12/31/01	1/1/90–12/31/90, 1/1/02–1/30/03	ENP (1)
G3273	G3273	Water level	ft, NGVD 29	Shark River Slough	25:37:35	80:34:33	3/14/1984	1/1/91–12/31/01	1/1/90–12/31/90, 1/1/02–1/30/03	ENP (1)
NP206	NP206	Water level	ft, NGVD 29	Shark River Slough	25:32:38	80:40:20	1/1/1978	1/1/91–12/31/01	1/1/90–12/31/90, 1/1/02–1/30/03	ENP (1)
TSH	TSH	Water level	ft, NGVD 29	Taylor Slough	25:18:38	80:37:51	3/12/1994	3/1/94–12/31/01	1/1/02–1/30/03	ENP (1)
S12T[a]	S12T[a]	Flow	cfs	Tamiami Trail	25:45:43	80:43:33		1/1/91–12/31/01	1/1/90–12/31/90, 1/1/02–1/30/03	SFWMD (2)
S333	S-333	Flow	cfs	Tamiami Trail	25:45:38	80:40:27	12/24/1991	1/1/91–12/31/01	12/24/91–12/31/92, 1/1/02–1/30/03	SFWMD (2)
S334	S-334	Flow	cfs	Tamiami Trail	25:45:42	80:30:07	12/24/1991	1/1/91–12/31/01	12/24/91–12/31/92, 1/1/02–1/30/03	SFWMD (2)
SRS[b]	SRS[b]	Flow	cfs	Shark River Slough						
TSB	TSB	Flow	cfs	Taylor Slough	25:24:06	80:36:24		1/1/91–12/31/01	1/1/90–12/31/90, 1/1/02–1/30/03	ENP (1)
Bob Allen Key	BA	Salinity	µS/cm	Central FL Bay	25:01:34	80:40:54	9/9/1997	9/9/97–12/31/01	1/1/02–10/31/02	ENP (1)
Buoy Key	BK	Salinity	µS/cm	Central FL Bay	25:07:16	80:50:01	9/7/1997	9/7/97–12/31/01	1/1/02–10/31/02	ENP (1)
Butternut Key	BN	Salinity	µS/cm	East FL Bay	25:05:18	80:31:07	2/8/1990	2/8/90–12/31/01	1/1/02–10/31/02	ENP (1)
Duck Key	DK	Salinity	µS/cm	Northeast FL Bay	25:10:54	80:29:22	7/14/1988	7/14/88–12/31/01	1/1/02–10/31/02	ENP (1)
Garfield Bight	GB	Salinity	µS/cm	N. Central FL Bay	25:10:12	80:47:48	3/6/1996	3/6/96–12/31/01	1/1/02–10/31/02	ENP (1)
Joe Bay	TC	Salinity	µS/cm	Northeast FL Bay	25:13:28	80:32:27	7/14/1988	7/14/88–12/31/01	1/1/02–10/31/02	ENP (1)
Johnson Key	JK	Salinity	µS/cm	Western FL Bay	25:02:43	80:54:41	7/25/1989	7/25/89–12/31/01	1/1/02–10/31/02	ENP (1)
Little Madeira Bay	LM	Salinity	µS/cm	Northeast FL Bay	25:10:25	80:37:56	8/25/1988	8/25/88–12/31/01	1/1/02–10/31/02	ENP (1)
Little Rabbit Key	LR	Salinity	µS/cm	Western FL Bay	24:58:53	80:49:31	9/11/1997	9/7/97–12/31/01	1/1/02–10/31/02	ENP (1)
Murray Key	MK	Salinity	µS/cm	Western FL Bay	25:06:21	80:56:31	10/21/1997	10/21/97–12/31/01	1/1/02–10/31/02	ENP (1)
Peterson Key	PK	Salinity	µS/cm	Western FL Bay	24:55:06	80:44:45	7/25/1989	7/25/89–12/31/01	1/1/02–10/31/02	ENP (1)
Terrapin Bay	TB	Salinity	µS/cm	N. Central FL Bay	25:09:18	80:43:30	9/12/1991	9/12/91–12/31/01	1/1/02–10/31/02	ENP (1)
Whipray Basin	WB	Salinity	µS/cm	Central FL Bay	25:04:42	80:43:38	4/6/1989	1/1/91–1/30/01	1/1/90–12/31/90; 1/1/02–1/30/03	ENP (1)

Station locations are shown in Fig. 1.

[a] S12T = ΣS12A:S12D; the total flow through stations 12A, 12B, 12C, and 12D

[b] SRS = S12T+S333−S334

[c] NGVD 29 = National Geodetic Vertical Datum 1929. cfs = cubic feet per second. µS/cm = micro-Siemens/cm.

[d] Data from the following sources: (1) Everglades National Park; (2) South Florida Water Management District. All data available from: http://www.sfwmd.gov/org/ema/dbhydro/index.html

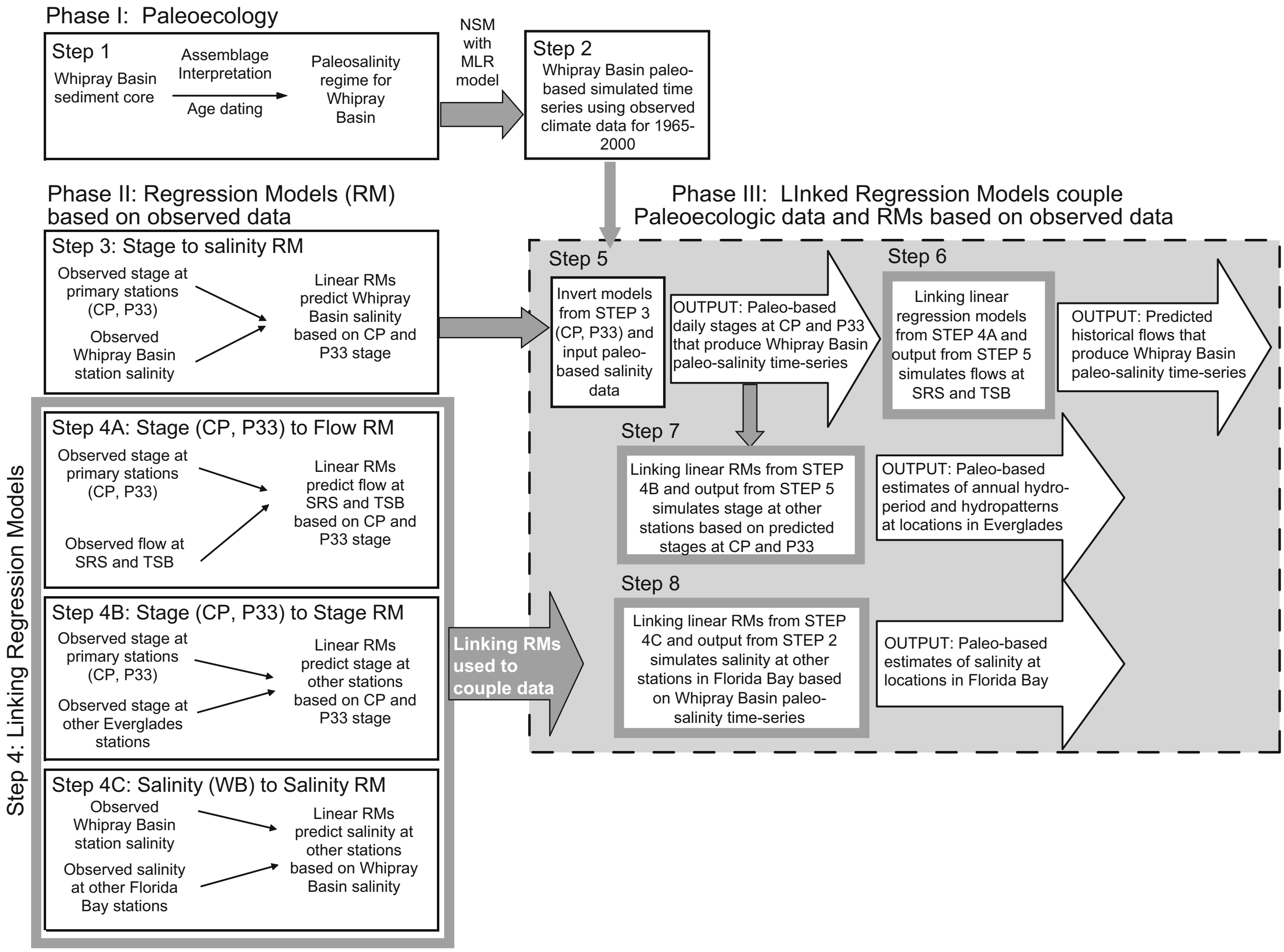

Fig. 2 Flow chart illustrating the steps involved in coupling the paleoecologic data (*phase I*) with the regression models (*phase II*) to produce estimates of flow, stage, and salinity conditions in the absence of drainage disturbances at locations within the Everglades

documented (Tabb 1967; Cosby 1993; Nuttle 1997; Marshall et al. 2004; Marshall 2005, 2008; Marshall and Nuttle 2008). Uncertainty in estimates made by regression models is easily quantified (Neter et al. 1990; Helsell and Hirsch 1991; Kashigan 1991) and regression model nomenclature is familiar to scientists in many fields. When the number of observations is large, as is the case in South Florida for stage, flow, and salinity, error is minimized and confidence in predictions is increased.

The predevelopment salinity regime for Florida Bay was developed using paleoecologic data collected by the US Geological Survey (USGS; Trappe and Brewster-Wingard 2001; Brewster-Wingard et al. 2001; Cronin et al. 2001). Paleoecologic studies provide a method of reconstructing pre-existing biological, physical, and chemical parameters of an ecosystem through quantitative analysis of biotic assemblages preserved in sediment cores. These methods have been successfully used in a number of environments (see for example Brush and Hilgartner 2000; Cole and Wahl 2000; Oswald et al. 2003; Parsons et al. 1999). Wingard et al. (2007a) provide a summary of paleoecologic studies done in Florida Bay through 2003.

In this study, a three-phase process is used to couple paleoecologic assemblage data with regression models (Fig. 2). In phase I, the paleoecological analysis establishes the target salinity regime for pre-drainage conditions. In phase II, regression models are developed from observed instrumental data. In phase III, the products of phases I and II are coupled to estimate the paleo-based hydrology (stage and flow) in the Everglades and the resultant paleo-based salinity conditions at locations throughout Florida Bay. The three phases, as well as details of the various steps involved in the approach presented in Fig. 2, are described below.

Phase I: Establishing Pre-drainage Salinity Conditions

The first phase of the approach uses the paleoecological analysis as shown by step 1 on Fig. 2. A sediment core was collected in Whipray Basin in 1997 by the USGS (Core FB697 25B, coordinates: N25.0712° W80.7385°; Fig. 1),

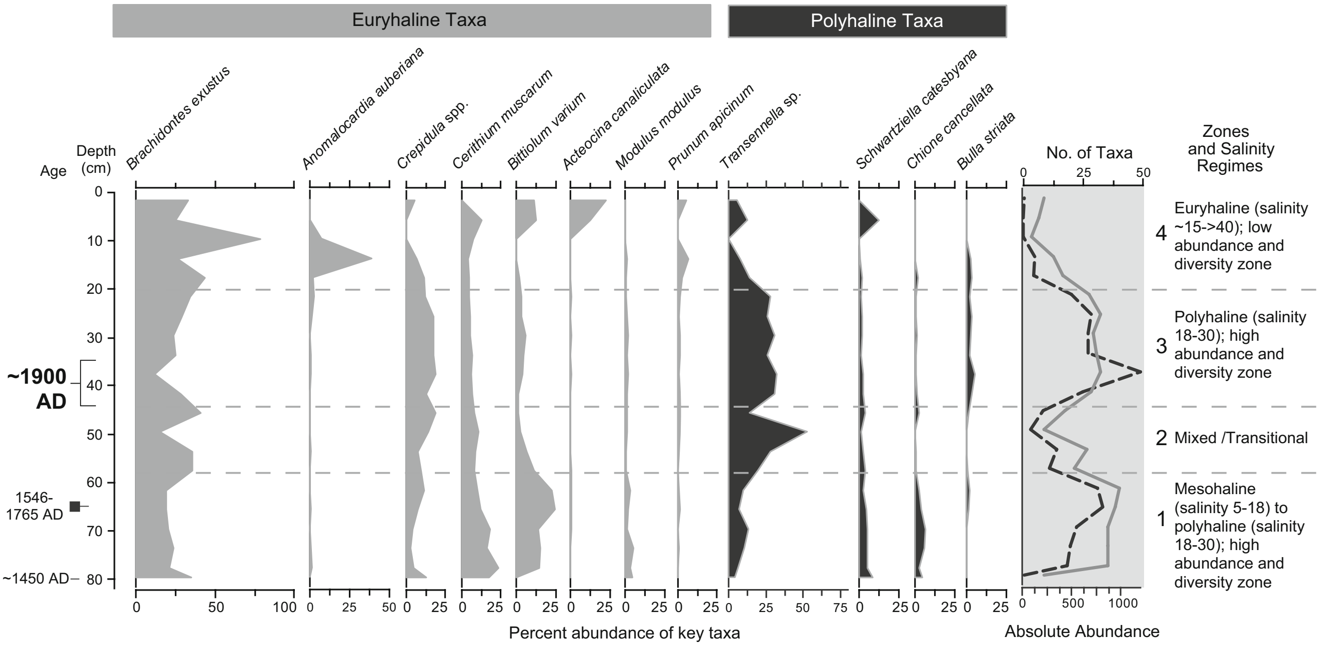

Fig. 3 Percent abundance of selected molluscan taxa from the USGS Whipray Basin Core (FB697 25B) plotted against core depth (cm). Absolute abundance (total number of individuals, *black dashed line*) and total number of taxa (a simple measure of diversity, *solid gray line*) for the mollusks in each sample are shown on the right. Zones and salinity regimes within the core are listed on the *right*. For complete description of the molluscan faunal data and analyses, see Trappe and Brewster-Wingard (2001). Age information is shown on the *left* (*black square* is carbon-14 date, rest based on lead-210 and age model); for age information, see Wingard et al. (2007b)

using a piston core with a 10.16-cm (4-in.) barrel. The core contained 88 cm of shelly calcareous mud, stopping just above the underlying peat. The core was sectioned into 2-cm segments and processed into three sizes: ≥850; ≥63 and <850; and <63 µm. The ≥850-µm fraction was analyzed for the mollusks reported herein and the <63-µm fraction was used for the lead-210 analyses; the 63–850-µm fraction was reserved for micropaleontological analyses not reported on here. Details on the processing and analyses of the Whipray Basin core can be found in Trappe and Brewster-Wingard (2001). The paleoecologic analyses of the Whipray Basin core are identical to methodologies successfully utilized on other cores from South Florida's estuaries (Brewster-Wingard and Ishman 1999; Brewster-Wingard et al. 2001; Ishman et al. 1998).

The geochronologic model is based on lead-210 analyses of the <63-µm sediment fraction from each core segment and on carbon-14 analysis of a single shell collected in the 64- to 66-cm-depth sample. The use of lead-210 to date twentieth century sediments is well documented (for example, Appleby and Oldfield 1978; Ducat and Kuehl 1995; Appleby 1997; Walling 2003) and the method used here follows Robbins et al. (2000). When the excess (unsupported) lead-210 reaches the background (supported) level present in the sediments, the sediments are approaching 100 years in age. This value provides a convenient marker for the approximate beginning of the twentieth century. In the Whipray Basin core, lead-210 approaches background levels between 35 and 45 cm depth in the core. The age model incorporates both lead-210 and carbon-14 data and was developed using a mixed effect regression model. Details on the development of the age model and all of the associated data are presented in Wingard et al. (2007b). This model provides a range of 1900–1940 AD at 35 cm depth and 1805–1912 at 45 cm depth in the Whipray Basin core. The average sedimentation rate for the post-1900 portion of the core is 0.37 to 0.43 cm year^{-1}.

Mollusks were sorted to species level from the ≥850-µm sediment fraction (data reported in Trappe and Brewster-Wingard 2001) and ostracodes were examined from the 63- to 850-µm fraction (data reported in Cronin et al. 2001). For this analysis, the molluscan fauna were used, but molluscan and ostracode faunal data consistently indicate the same salinity and substrate patterns at the Whipray Basin site. All identifiable molluscan remains were removed from every other 2-cm sample, identified to species level, counted, and converted to percent abundance data to standardize the counts. Figure 3 shows the down-core data for key molluscan salinity indicators.

The basis for paleoecological interpretations is the application of a modern calibration data set to the interpretation of biotic assemblages from sediment cores, using either the analytical transfer function (Imbrie and Kipp 1971) or the modern analog method (Hutson 1979). A modern molluscan faunal calibration data set has been developed for South Florida (Wingard et al. 2007c).

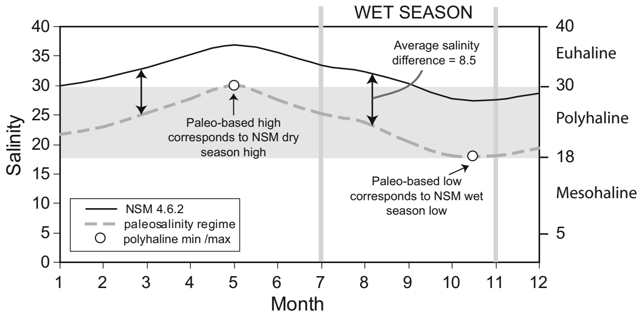

Fig. 4 Whipray Basin annual average monthly salinity based on Natural System Model (NSM, ver. 4.6.2) compared to the paleo-based polyhaline (18–30) salinity target (Trappe and Brewster-Wingard 2001; Pitts et al. 2005). Average difference between NSM and paleo-based salinity is 8.5. Annual paleo-based curve shown here was generated by distributing the minimum and maximum salinities within the polyhaline range (zone 3, Fig. 3) to correspond to typical annual wet and dry season salinities. Figure adapted from Pitts et al. (2005)

Preliminary tests of the calibration data set were conducted on modern samples, comparing the predicted salinity based on the data set to the observed salinity at the sample sites. These tests indicate the modern molluscan data set can accurately predict the known salinity with a correlation coefficient of about 0.8 (Wingard and Hudley 2008). A comparison of the assemblages in the Whipray Basin core with the calibration data set produced the salinity regimes indicated in Fig. 3.

Zone 3, from 46 to 20 cm in the core, indicates a polyhaline salinity regime (18–30), which spans approximately 65 years given the average sedimentation rate for the upper portion of the core. This zone incorporates the 35–45-cm section of the core that represents the ~1900 timeline within the core. Even allowing for the errors in the age model as discussed above, the 35–45-cm section of zone 3 is representative of pre-1940 salinity for Whipray Basin. The polyhaline paleosalinity regime (18–30) derived from the core assemblage data (Fig. 2, step 1) is exported for use in step 2.

The next step in the process was to develop a Whipray Basin daily paleo-based time series (Fig. 2, step 2) from an existing run of the Natural System Model (NSM; ver. 4.6.2; South Florida Water Management District and Interagency Modeling Center 2005), a derivative of the South Florida Water Management Model (SFWMM). The SFWMM is a regional hydrologic model for South Florida on a 2 by 2-mile grid. NSM simulates daily stage and flow in each of the 4-mi^2 grid cells assuming an unaltered landscape. NSM uses the observed climatologic data for 1965 to 2000 as input. NSM output was coupled with multivariate linear regression (MLR) models in a previous study (Marshall 2005, 2008) to produce estimates of NSM-based salinity at a number of locations in Florida Bay for 1965–2000, including Whipray Basin.

Pitts et al. (2005) noted that the NSM-based salinity curves at several locations in Florida Bay (including Whipray Basin) appear to be high compared to paleosalinity data for the ecosystem prior to anthropogenic changes to regional hydrology. At Whipray Basin, the average monthly salinity difference between NSM and the paleosalinity is about 8.5 (Fig. 4). Because the paleosalinity does not provide a time series, the NSM-based salinity simulation for the 1965–2000 time period for Whipray Basin was modified by subtracting this 8.5 difference from all salinity values. The resulting simulated daily paleosalinity time series for the 1965 to 2000 time period fits the polyhaline salinity regime indicated for the beginning of the twentieth century in the Whipray Basin core (Trappe and Brewster-Wingard 2001).

Figure 5 shows the daily paleo-based salinity regime at Whipray Basin produced by modifying the NSM-based salinity, as described above. This daily paleo-based salinity regime is coupled with regression models to produce the subsequent paleo-based simulations (Fig. 2, steps 5–8). The average monthly salinity values from this simulated series closely approximate the pre-drainage salinity regime in Whipray Basin (Trappe and Brewster-Wingard 2001; Pitts et al. 2005). In the following analysis, this daily salinity regime for 36 years at Whipray Basin is termed the "paleo-based" salinity, and the stage, flow, and salinity simulations produced by the regression models using the paleo-based input are termed paleo-based parameters.

This approach assumes seasonal patterns of rainfall for the early twentieth century were similar to the documented period from 1965 to 2000 used in the NSM/MLR simulations. Evidence indicates this is a reasonable assumption because patterns in the long-term regional

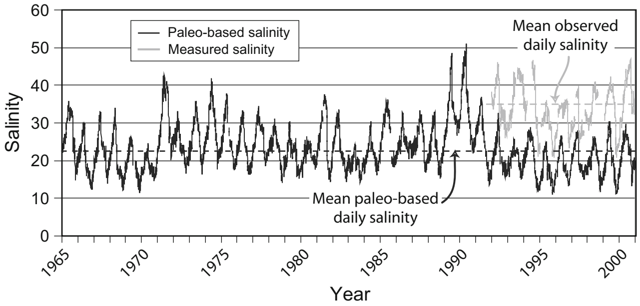

Fig. 5 Output from step 2 (Fig. 2): Whipray Basin paleo-based daily salinity (*black line*) compared to observed salinity in Whipray Basin (*gray line*). Daily mean paleo-based salinity (*black dashed line*) is 23.4, and daily mean observed salinity (*gray dashed line*) is 35.5. The paleo-based salinity was estimated using the stage output from the Natural System Model (NSM, ver. 4.6.2) as input to the multivariate linear regression equations for Whipray Basin salinity, then adjusting the output from the NSM/MLR model to compensate for the 8.5 salinity difference noted in Fig. 4. The resulting paleo-based daily salinity data simulated for the 1965–2000 model run were input into the MLR models

Table 2 Model parameters, number of values used for model development and coefficient of determination (adjusted) for simple linear regression models used in phase II (steps 3–4 on Fig. 2)

Step	Dependent variable	Independent variable	Number	Coefficient	Intercept	Adjusted R^2
3	Whipray Basin	P33	3,367	−25.96	86.31	0.53
3	Whipray Basin	CP	3,353	−22.15	43.82	0.33
4A	TSB	CP	2,707	14.25	−3.5	0.46
4A	SRS	P33	3,254	184.95	−325.69	0.58
4B	G3273	P33	3,788	1.36	−0.75	0.75
4B	NP206	P33	8,382	1.48	−1.19	0.61
4B	TSH	CP	2,260	0.93	0.26	0.71
4C	Bob Allen	Whipray Basin	1,506	0.84	4.23	0.83
4C	Buoy Key	Whipray Basin	1,424	0.8	5.99	0.73
4C	Butternut Key	Whipray Basin	3,757	1	−5.01	0.73
4C	Duck Key	Whipray Basin	3,498	0.91	−3.9	0.71
4C	Garfield Bight	Whipray Basin	1,971	1.4	−18.1	0.61
4C	Joe Bay	Whipray Basin	3,697	1.1	−24.54	0.45
4C	Johnson Key	Whipray Basin	1,573	0.62	13.18	0.69
4C	Little Madeira Bay	Whipray Basin	3,879	1.13	−17.13	0.73
4C	Little Rabbit	Whipray Basin	1,596	0.54	16.46	0.68
4C	Murray Key	Whipray Basin	1,438	0.6	12.58	0.75
4C	Peterson Key	Whipray Basin	3,700	0.36	22.42	0.63
4C	Terrapin Bay	Whipray Basin	3,419	1.58	−30.1	0.72

See Table 1 for the period of model development (calibration). Units of measure for the independent variable are stage in meters relative to NGVD29 datum for P33 and CP, and salinity stated as the Practical Salinity Scale (UNESCO 1985) for Whipray Basin

precipitation data in the upper watershed of the Everglades are similar for the periods 1895 to 1950 and 1960 to 2000 (Enfield et al. 2001; Basso and Shultz 2003). In addition, analysis of the Atlantic Multidecadal Oscillation (AMO) shows that the conditions for 1965 to 2000 were similar to the AMO conditions for the approximately 30-year period beginning with the turn of the century and that the AMO for the period from approximately 1930 to 1965 was different (Enfield et al. 2001).

Phase II: Development of Linear Regression Equations from Observed Data

Hydrologic and salinity data are collected by several agencies at locations throughout Everglades National Park (Table 1; Fig. 1). For the second phase of the procedure, the average daily values of these observed data were utilized to develop regression models for stage, flow, and salinity (Fig. 2, steps 3 and 4). Physical data obtained from each station are listed in Table 1.

The key regression models for this process are univariate linear regression models of Whipray Basin salinity as a function of stage at two primary upstream stations developed from the observed data (Fig. 2, step 3). Daily stage data from Craighead Pond (CP) and P33 were regressed against daily salinity data from the Whipray Basin station (see Fig. 1 for location) over a period of 11 years (Table 1). In previous work, CP and P33 were identified as important stage stations in the development of the MLR salinity models because of the relatively high correlation between stage at these two stations and salinity at a number of locations in Florida Bay (Marshall et al. 2004; Marshall 2005, 2008). In these studies, CP and P33 were consistently selected by the stepwise regression process as the independent variables explaining the greatest portion of salinity variation, as compared to the data from other stage monitoring stations in the Everglades. Model parameters for these two key regression models are presented in Table 2.

Three suites of regression models were developed (Fig. 2, step 4) to use the Whipray Basin paleosalinity-based stage output from step 5 to produce stage, flow, and salinity estimates. Regression models to link stage to flow were developed for Shark River Slough (SRS) at Tamiami Trail and Taylor Slough at Taylor Slough Bridge (TSB). Flow into western SRS (see Fig. 1) is estimated by a water budget using S12T (total flow through the S12 structures), S334, and S334 structure flows. Flow into Taylor Slough is measured directly at TSB. The net flow into western SRS across Tamiami Trail and the flow at TSB function as the independent variables in the flow regression models at SRS and TSB locations developed from the observed daily stage values at CP and P33 (Fig. 2, step 4A). Table 2 presents the model parameters and values of the coefficient of determination (adjusted R^2) for the flow regression models.

Stage-to-stage linking regression models also were developed between stations P33 and CP and other stage monitoring stations in ENP (Fig. 2, step 4B). Several gauges that are in CERP Indicator Regions that provide data for performance-measure purposes (U. S. Army Corps of Engineers 2006) were selected for hydroperiod analysis. In Shark River Slough, regression models were prepared for stage monitoring station G3273 in Indicator Region 147 (SRS—Rocky Glades East), station NP206 in Indicator Region 148 (SRS—Rocky Glades West), and Taylor Slough stage station TSH in Indicator Region 133 as a function of the stage at CP or P33.

Finally, salinity-to-salinity regression models were developed for salinity monitoring stations in Florida Bay as a function of Whipray Basin salinity (Fig. 2, step 4C). Details on all of the linking regression models are presented in Table 2.

Phase III: Coupling the Pre-drainage Salinity Regime and the Regression Models

For the third phase of the procedure, the various linking models were coupled with the paleo-based salinity regime to simulate paleo-based stage and flow in the Everglades and salinity in Florida Bay. To begin the simulations, the P33/Whipray Basin and CP/Whipray Basin regression models were solved for the independent variable (stage) as a function of the dependent variable (salinity), a process called inverse calibration (Neter et al. 1990; Kashigan 1991; Fig. 2, step 5). The inverse model stage values are estimates of the stage that existed for known salinity values at the Whipray Basin monitoring station. When the estimated paleo-based salinity regime is input in time series form to the inverse calibration models, the outputs are paleo-based stage at P33 and CP at the daily frequency for 36 years. The simulated P33 and CP stage values were then used in the flow models to estimate paleo-based daily flow at key locations (SRS and TSB) for 36 years (the output of Fig. 2, step 6). The paleo-based stage values at P33 and CP were also used to simulate the paleo-based stage at other stations in the Everglades using the regression models (Fig. 2, step 7). The outputs are annual hydroperiod durations that can be compared to the existing data. Finally, the paleo-based salinity at Whipray Basin was used with the salinity-to-salinity regression models to estimate the paleo-based salinity regime at other stations in Florida Bay (Fig. 2, step 8). In total, four outputs are produced that describe the paleo-based hydrologic and salinity conditions in the Everglades and Florida Bay based on the interpretation of the paleoecologic assemblage data.

Testing the Models

To insure that the use of linear regression models with these data sets did not violate the basic assumptions of regression modeling, model residual plots were evaluated (plots not shown). Minor deviation from normal distribution behavior was seen for some of the flow models when residual/normal plots were examined. Time plots of residuals showed that there is a seasonal pattern to the residuals; however, there were no significant deviations or other limitations that preclude the use of the developed regression models for simulation purposes (Neter et al. 1990). The addition of other independent variables to the linear regression models could account for the seasonal trend (Marshall et al. 2004), but multivariate models cannot be used for an inverse calibration function. The model output error was managed through the use of a high temporal resolution for simulations (daily) and a long simulation period (36 years) to take advantage of averaging techniques, as well as appropriate interpretation of results.

Results

Phase I: Paleoecology

A complete discussion of the statistical analyses of the molluscan fauna in the Whipray Basin sediment core can be found in Trappe and Brewster-Wingard (2001). The temporal distribution of significant indicator species, zones, and salinity regimes are shown in Fig. 3. Zone 1 (78–60 cm) is a zone of high faunal richness (number of taxa) and abundance and is characterized by fauna typical of mesohaline (5–18) to polyhaline (18–30) salinity environments. Zone 2 (58–44 cm) is a transitional zone, containing fauna typical of several salinity regimes. Species tolerant of a range of salinity conditions (*Brachidontes exustus* and *Transenella* sp.) dominate the assemblage and zone 2 is low in abundance and diversity. Zone 3 (42–20 cm) has high abundance and diversity and the fauna remain relatively constant throughout this zone; the assemblage is typical of a mid-estuarine polyhaline environment. The polyhaline salinity regime (18–30) from zone 3 existed at the beginning of the twentieth century and is used for the output to step 2 (Fig. 2). The latter half of the twentieth century is represented by zone 4 (18–0 cm), a low diversity, low abundance zone dominated by the opportunistic *B. exustus* and other species tolerant of rapid changes in salinity.

The paleo-based salinity regime that drives the models (step 2, Fig. 2) has a mean daily salinity value of 23.4 for the 1965 to 2000 time period—a difference of 12.1 compared to the observed Whipray Basin mean daily salinity of 35.5 over the 1990–2003 time period (dashed lines on Fig. 5). Over 600 values of simulated Whipray Basin paleo-based salinity over the 36-year period exceeded 35. Maximum values during the 1989–1990 drought period reached salinities above 50 for the paleo-based regime. This

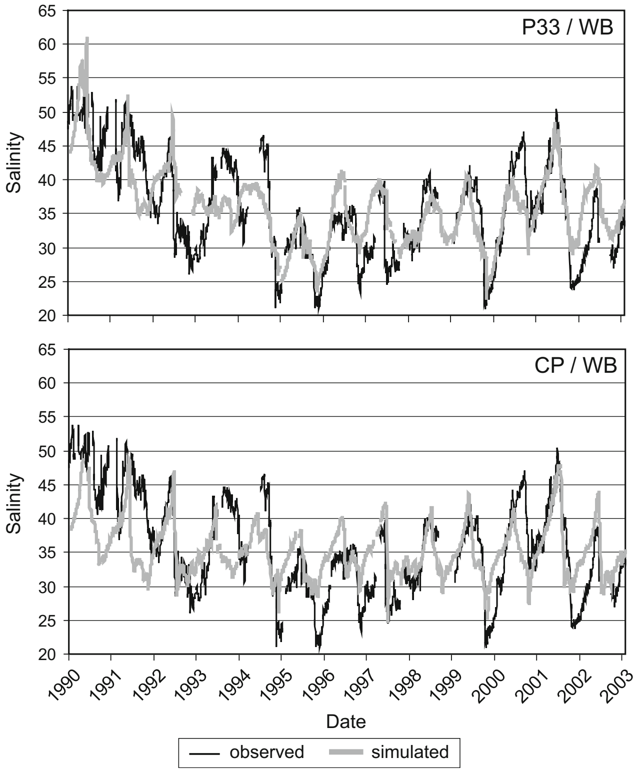

Fig. 6 Results of step 3 (Fig. 2). Comparison of observed Whipray Basin (*WB*) salinity and salinity simulated by regression models utilizing stage at P33 in Shark River Slough (*top*) and at Craighead Pond (*CP—bottom*)

provides evidence that hypersaline conditions can occur at Whipray Basin without an altered hydrologic regime. According to the Venice salinity classification system (Symposium on the classification of brackish waters 1958), the average salinity observed for Whipray Basin (1990–2003) is euhaline (30–40), but using the paleo-based simulation, Whipray Basin is polyhaline (18–30; Fig. 5; Swart et al 1999; Trappe and Brewster-Wingard 2001).

Phase II: Regression Models Based on Observed Data

Regression model development resulted in the estimation of salinity models for Whipray Basin as a function of the stage at P33 and CP. Plots that compare the observed and simulated salinity values produced by regression models using P33 and CP for both calibration and verification periods (see Table 1 for details) are presented in Fig. 6. The simulated salinity agrees closely with the observed except for a few notable time periods. For example, the P33 plot shows that during much of 1993, observed salinity is 5–10 lower than simulated, and in late 1993 through most of 1994, observed salinity was 5–10 higher than simulated. Similar differences between observed and simulated salinity appear in the verification plot for the salinity regression model developed from CP. A drought period occurred in South Florida in the late 1980s and early 1990s that is reflected in the low stage elevations, low flows, and hypersaline conditions indicated during that period by both observed and simulated data. The statistics on the salinity, flow, and stage regression models are presented in Table 2. The coefficient of determination values (adjusted R^2) in Table 2 (developed for the regression models in step 3 on Fig. 2) show that the Whipray Basin salinity model developed from P33 does a better job of explaining the variation in the observed Whipray Basin salinity data (adjusted R^2=0.53) than the CP station model (adjusted R^2=0.33).

Figure 7 presents the observed flow data compared to the simulated flow (from regression models) for SRS and TSB (Fig. 2, step 4A), for periods that are combined calibration and verification periods (see Table 1 for time periods). The plots generally show good agreement between observed and simulated flows for SRS and TSB. However, the results also show that the peak observed flow on some days was not reached by the SRS and TSB models (e.g., late 1994 in SRS and late 1999 in TSB). At other times, the simulated flows are higher than observed flows (e.g., most of 1996 in SRS and the last half of 1996 and 1997 in TSB). Table 2 presents adjusted R^2 values of 0.46 and 0.58 for SRS and TSB, respectively. Table 2 also summarizes the model parameters and presents the adjusted R^2 values for stage and salinity models at other locations in the Everglades and Florida Bay (Fig. 2, steps 4B and 4C), based upon the observed stage and salinity data. The adjusted R^2 values for these stage and salinity models ranged from 0.45 to 0.83.

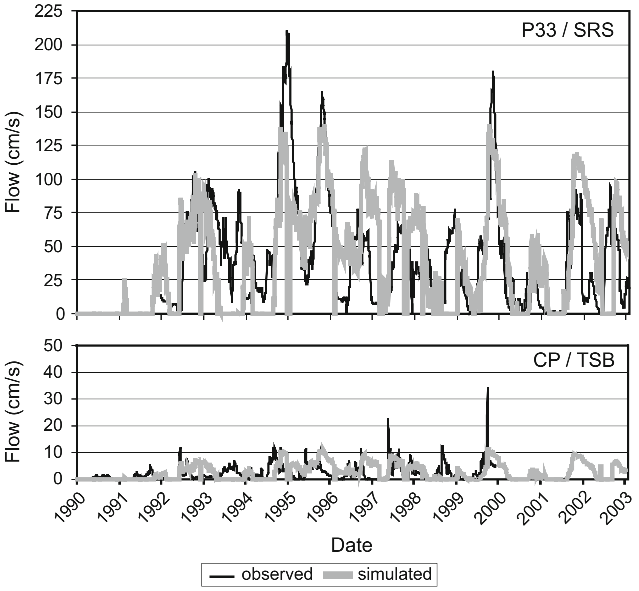

Fig. 7 Comparison of daily observed flow and flow simulated by regression models utilizing stage at P33 for Shark River Slough (*SRS—top*) and stage at CP for Taylor Slough Bridge (*TSB—bottom*; Fig. 2, step 4A). Note different *y*-axis scales

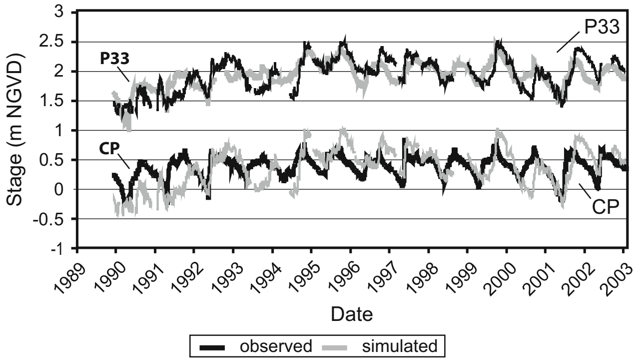

Fig. 8 Comparison of Craighead Pond (*CP*) and P33 daily observed stage values to values simulated by inverse calibration models (Fig. 2, step 5). *NGVD* National Geodetic Vertical Datum

Phase III: Coupling Paleoecologic Salinity with Regression Models

When the observed Whipray Basin salinity is input to the inverse calibration model to produce stage, both CP and P33 are simulated well, although there are notable differences in simulated and observed stages throughout the record (Fig. 8). Table 3 presents the results of this evaluation, including mean values, standard deviation, and percent error of the mean for both observed and simulated series. The statistics on stations P33 and CP represent the use of the inverse calibration model only to simulate stage (Fig. 2, step 5). In contrast, for verification of the SRS and TSB flow models, two models were coupled and the statistics reflect the coupled (two-model) procedure. The low error of the mean value for the P33 model contributes to the low error of the mean value for the two-model simulation of SRS flow. The higher error of the mean for the CP model is reflected in the higher error of the mean value for the two-model TSB simulations. A comparison of the percent error of the mean in Table 3 shows that the models are estimating higher values, with the exception of the CP station model. Overall, the percent error of the mean varies from about 1% to over 13% for the salinity-to-stage and the salinity-to-stage-to-flow coupled models.

After evaluating model performance through verification to understand the uncertainty in the estimation process, the paleo-based Whipray Basin salinity developed in step 2 was used to drive the suite of linear regression models described above to estimate paleo-based stage and flow in the Everglades and salinity throughout Florida Bay. Table 4 presents the mean daily values of paleo-based stage and flow for P33, CP, SRS, and TSB (Fig. 2, steps 5 and 6) compared to observed values for the combined calibration and verification period (see Table 1). For stations P33 and CP, mean paleo-based values for stage were 0.55 and 0.60 m higher than the observed mean value of stage for the period of comparison. For SRS, the mean value for the paleo-based flow is increased by 73.4 m^{3}s^{-1}, while at TSB, the mean value for the paleo-based flow is increased by 6.7 m^{3}s^{-1}. The ratio of the paleo-based average flow to the observed average flow also is presented in Table 4. The paleo-based average flow at SRS was 2.7 times the observed flow for the period of comparison, while the TSB paleo-based flow is almost four times the observed flow.

When the daily flows are averaged to monthly values and compared, the seasonal differences between the current hydrologic conditions and the hydrologic regime in the absence of drainage disturbances can be seen. Figure 9 (top) presents the paleo-based mean monthly flow volumes (m^3 × 10^6) for Shark River Slough compared to the observed volumes. Paleo-based mean monthly flow volumes for Shark River Slough range from about 250 to 465 m^3 × 10^6 with the observed volumes ranging from 45 to 215 m^3 × 10^6. For Taylor Slough (Fig. 9, middle), mean monthly paleo-based flow volumes average between 18.5 and 38 m^3 × 10^6, while observed volumes are between 0.75 and 13.5 m^3 × 10^6. The average monthly flows into north Shark River Slough for the paleo-based regime are between three and eight times the observed flows over the year (Fig. 9, top). For Taylor Slough, the range for the paleo-based regime is three to 24 times greater than the observed flow (Fig. 9, middle). During the months of July, August, September, and October (wet season), the paleo-based

Table 3 Output from step 4A and 4B (Fig. 2)

Station	Observed				Simulated		
	Number	Mean	Standard deviation	% Error of mean	Number	Mean	Standard deviation
SRS (flow)	4,052	42.39	40.15	5.02	4,036	44.63	39.25
TSB (flow)	3,645	2.22	2.86	13.62	4,778	2.57	3.04
CP (stage)	4,497	0.39	0.17	−5.41	4,117	0.37	0.32
P33 (stage)	4,601	1.93	0.21	1.03	4,117	1.95	0.27

Mean, standard deviation, and number of values represent flow and stage simulations using the suite of models with observed Whipray Basin salinity as initial input. Percent error of the mean compares observed and stimulated stage and flow data. Flow values are in cm^3/s. Stage values (m) are relative to the NGVD29 datum.

Table 4 Output from steps 5 and 6 (Fig. 2)

Station	Observed		Paleo-based		Difference (paleo − observed)	Paleo: observed
	Number	Mean	Number	Mean		
P33 (stage)	4,581	1.93	3,920	2.48	0.55	1.28
CP (stage)	4,477	0.39	3,922	0.99	0.60	2.54
SRS (flow)	4,052	42.40	4,036	115.80	73.40	2.73
TSB (flow)	3,627	2.23	4,760	8.90	6.67	3.99

Comparison of observed and simulated paleo-based stage and flow. Flow values are in cm^3/s. Stage values (m) are relative to the NGVD29 datum.

flows are about three times the observed flows for both sloughs. However, during the dry season, there is a larger deficit, and later in the dry season, the flow deficit in Taylor Slough is much greater than the flow deficit in Shark River Slough. Figure 9 (bottom) presents the ratio of the monthly average simulated paleo-based flow to the monthly average observed flow for SRS and for TSB, illustrating the differences between the two flow regimes.

The paleo-based average annual hydroperiod durations for selected CERP Indicator Regions also were calculated (Fig. 2, step 7). Table 5 compares the paleo-based hydroperiod estimates with the observed hydroperiod and the CERP targets (U. S. Army Corps of Engineers 2006). For all stations examined, the paleo-based hydroperiods are longer than the observed hydroperiods by amounts ranging from 267 to 300 days or 34 to 43 weeks. Station TSH in Taylor Slough is located in a freshwater marsh area and should be wet most of the time, yet currently averages only 77 days.

The paleo-based salinity regime at other stations in Florida Bay was also simulated (Fig. 2, step 8). Table 6 presents a comparison of the observed salinity data and the simulated paleo-based salinity. The differences in the average salinity values for the shown periods of comparison were between 5.3 and 20.1, with the largest differences at the inner embayments and the smallest differences at the western-most stations. For the existing situation, the average value of salinity at seven stations exceeds 30. For the paleo-based regime, only one station has an average salinity value for the period of comparison greater than 30.

Discussion

One of the primary goals of Everglades restoration is to “get the water right,” which means restoring a more natural flow pattern through the system (Sklar et al. 2005; US Army Corps of Engineers 1999). In order to accomplish these goals, an understanding of the historic conditions in the Everglades is necessary, along with the ability to quantify linkages between ecology and water depths, hydroperiods, and flow (Sklar et al. 2005). The restoration of the upstream hydrology (stage and flow) in the freshwater Everglades is a major step toward the restoration of the freshwater ecology and is expected to restore the

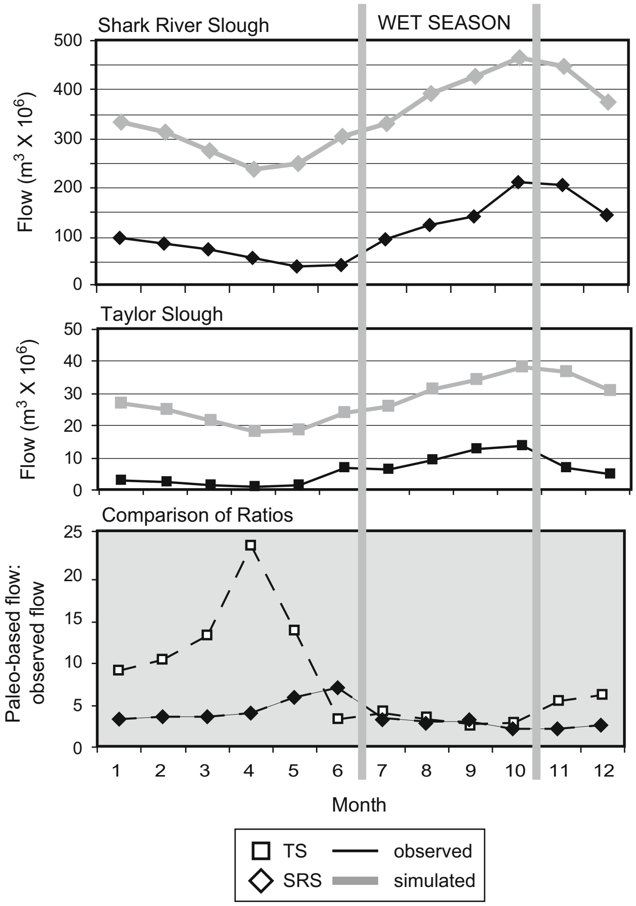

Fig. 9 Comparison of paleo-based flow (output from step 6, Fig. 2) to observed flow on a mean monthly basis for Shark River Slough (*SRS*) and Taylor Slough (*TS*); paleo-based values were computed from daily simulations over the 1965–2000 periods using regression models based on salinity regime determined from the paleoecological data in sediment core from Whipray Basin. *Top*—paleo-based vs. observed flow for SRS. *Middle*—paleo-based vs. observed flow for TS. *Bottom*—ratio of paleo-based to observed salinity for SRS and TS. Note different *y*-axis scales

Table 5 Output from step 7 (Fig. 2)

Indicator Region	Name	Station	Paleosalinity regime		Observed		Difference (paleo − observed)		RECOVER target
			days	weeks	days	weeks	days	weeks	
147	Rocky Glades East	G3273	316	45	16	2	300	43	~24 weeks average
148	Rocky Glades West	NP206	325	46	86	12	239	34	32–34 weeks average
133	Taylor Slough	TSH	344	50	77	11	267	39	Natural System Model

Average hydroperiod in days and weeks for the paleo-based salinity regime and the observed values. For this study, hydroperiod is defined as the period of time that stage is greater than 15 cm above ground surface. Paleo-based hydroperiod is the average over 36 years of simulation. Target values provided are from RECOVER Greater Everglades performance measures (U. S. Army Corps of Engineers 2006). Location data on stations in Table 1

downstream estuarine environments within Florida Bay. Because of the connectivity and continuity between the freshwater and estuarine hydrology and biota, a return to a more natural salinity condition in Florida Bay cannot be accomplished on a regional scale without returning the upstream freshwater and transition zone ecosystems to the pre-drainage hydrologic environments (rocky glades, ridge/slough/tree island, mangrove zone), which includes restoring stage and flow. In addition, it has been suggested that maintaining the freshwater head on the salt/fresh interface zone is the most effective measure in adapting naturally to the projected rise in sea level for the twenty-first century (Nicholls et al. 2007).

The suite of hydrologic regression models that have been developed link an estuarine hydrology indicator (salinity) and a freshwater hydrology indicator (stage) with a forcing factor (flow) that is a primary hydrologic component. Even though flow is controlled, the link between stage in the Everglades and salinity in Florida Bay is primarily a link between two uncontrolled response variables to flow inputs. For example, once the flow has been delivered to ENP across Tamiami Trail, the predominately natural physical conditions of Shark River Slough will determine the level of water stored in the slough (hydroperiod for the marshes) and the resulting downstream salinity in the west coast mangrove estuaries. A similar situation exists for Taylor Slough—once the freshwater flows past Taylor Slough Bridge, there are only minor anthropogenic influences. Therefore, determining the flow required at these two locations is essential to Everglades and Florida Bay restoration, and this study suggests that it can be derived from paleo-based salinity and stage targets.

As with all linear regression models based on real data, there are embedded errors that have to be taken into account. Residual analysis showed that the basic assumptions of normality have not been seriously violated by any of the models, but there is a seasonal pattern to the model errors. The models do not estimate the highest values of wet season daily flow as well as they do the daily flows in the low to middle range, as can be seen in the plots of observed and simulated values for calibration and verification periods (Fig. 7).

Plots of observed and simulated data and model statistics for P33 and CP stations for the calibration and verification periods show that the model output traces the observed daily salinity data well for normal rainfall and wet years, but not as well in dry times (Fig. 6). Even so, when the models are used in the inverse calibration mode with observed salinity used to estimate stage, the errors in the simulated P33 and CP mean values for the calibration/verification period were only about 1% and 5%. When daily flow is then estimated using these P33 and CP simulated daily values, the error of the mean for the two-model simulations of SRS and TSB increases to 5% and 14%, respectively. So the coupling of models also introduces uncertainty but not to a high level.

Table 6 Output from step 8 (Fig. 2)

Florida Bay Station	Observed salinity average	Paleo-based salinity average	Salinity difference (observed − paleo)
Bob Allen	33.2	21.1	12.1
Buoy Key	32.8	22.2	10.6
Butternut Key	31.3	17.7	13.6
Duck Key	29.0	16.8	12.2
Garfield Bight	28.9	10.3	18.6
Joe Bay	15.4	2.7	12.6
Johnson Key	35.3	27.0	8.3
Little Madeira Bay	23.8	8.2	15.6
Little Rabbit	34.4	27.3	7.1
Murray Key	33.0	24.8	8.2
Peterson Key	35.8	30.5	5.3
Terrapin Bay	23.6	3.5	20.1

Comparison of observed salinity data and simulated paleo-based salinity data at various locations in Florida Bay, Everglades National Park, including the difference. Daily average calculated over the period of measurement for the observed and over the period of simulation for the paleo-based data. The period of comparison for each station extends from the "date data begins" (Table 1) through December 31, 2000

In addition to the uncertainty in the models, there also is uncertainty in the paleo-based salinity regime used as input to the models. The interpretation of the paleoecological data to start the process for this analysis is somewhat qualitative (cluster analyses were used to establish the assemblage/paleosalinity zones) and the necessary assumption is made that the organisms have not changed their salinity tolerances as measured in the modern environment. Errors associated with age models for the core could lead to selecting the wrong paleo-based salinity regime for input; however, as discussed above, for the Whipray Basin core, the polyhaline assemblage spans a period of decades that incorporates 1800s to mid-1900s within the range of error of the age model.

By utilizing the method developed here of coupling paleoecologic data with regression models based on observed data, some of the issues of uncertainty with the models (Sklar et al. 2005) are overcome, while also overcoming problems associated with temporal scales of paleosalinity data. Given errors within the age range of core samples and the sedimentary process of time-averaging, typically the best resolution achieved on early twentieth century samples is approximately a decade. In order to develop realistic salinity targets for restoration, short-term salinity variations need to be understood. By generating a daily time series that simulates a typical minimum and maximum salinity regime over a period that includes a wide range of actual climatic and hydrologic conditions, the problems of temporal scale with paleosalinity interpretations and the problems of realistic historical data for the models are both overcome.

To manage uncertainty in hydrology and salinity, a daily time step was used for the basic model simulations and then averaged to monthly and annual mean values before interpreting. In this manner, a large number of daily values ($N=13{,}149$) from 36-year simulations were averaged and inferences were made using the monthly or annual mean values. An analysis of the monthly mean data shows that the error that is apparent in simulations of high daily flow values has been minimized by averaging. This means that the model output can best be used to estimate average flow conditions. Overall, annual, and monthly mean simulations are robust when they have been computed from daily estimates over a period that includes a variety of wet, dry, and average rainfall years as is included in the 36-year record of daily values used for this study. Mean daily values translate easily to mean annual flows for wet, dry, and normal rainfall periods. Mean annual values can be used with monthly mean values to evaluate annual and seasonal needs, including flows for the water management structures that supply freshwater to Shark River Slough and Taylor Slough.

An evaluation of stage values in both Shark River Slough and Taylor Slough shows that freshwater levels in the Everglades are about 0.15 m lower on average now than during the pre-drainage period. Kelble et al. (2007) postulate that water levels in Shark River Slough may have been high enough before drainage disturbances that freshwater frequently overtopped the Buttonwood Embankment, which rarely happens today. If true, the freshwater supply to the central part of Florida Bay has been reduced, contributing to the onset of hypersalinity.

The simulated overall mean flow values are useful for interpretive purposes as an indicator of the overall hydrologic conditions in the system. The overall mean values produced by the regression models indicate that pre-drainage freshwater flow into ENP was about 2.5 to four times higher than the observed flows. This compares favorably to the findings of Smith et al. (1989) who estimated flow to northeast Florida Bay has been reduced by about half compared to historical conditions on the basis of coral skeleton analyses.

When comparisons between existing flows and paleo-based flows are made on a monthly average basis (Fig. 9), there is a large flow deficit in both Shark River and Taylor Sloughs in the dry season. However, the deficit in Taylor Slough in the dry season is much greater than the Shark River Slough deficit during the same period. During extended drought periods, the large deficit during the dry season likely contributes significantly to the establishment of hypersaline conditions at Whipray Basin.

This difference between the deficits in Shark River and Taylor Sloughs may be caused, in part, by the impact of C-111 Canal drainage of freshwater flow from the eastern portion of the Everglades into the ENP eastern panhandle area (Knight and Kotun 2001; Knight 2001). In addition, the difference may reflect the fact that the stored water levels in Shark River Slough currently are not high enough during the wet season so that freshwater can spill over the Rocky Glades into Taylor Slough, which is thought to be the pre-drainage condition. Taylor Slough also may be impacted by reductions in the freshwater contribution from groundwater compared to pre-drainage times, or by increases in saline groundwater contributions due to saltwater intrusion. It appears that the capacitive ability of the system to store freshwater during normal and wet periods over multiple years may be compromised by the release of large volumes of water for flood protection and the consumptive uses of a growing population.

When average mean hydroperiods are compared, it appears that the hydroperiod in both sloughs has been reduced significantly by water management. The Taylor Slough hydroperiod has been reduced more than the Shark River Slough hydroperiod. The hydroperiod information reinforces the findings of the flow analysis—water management appears to have impacted Taylor Slough more severely compared to Shark River Slough. The hydroperiod estimates also corroborate the findings of Willard et al. (2006) that indicate that the Rocky Glades areas of Shark River Slough, both east and west, were much wetter before drainage disturbances than once thought.

When the Whipray Basin paleo-based salinity regime is used to simulate the salinity regime at other locations within Florida Bay, the pattern of salinity that is produced is more estuarine than the current system. While the average paleo-based salinity regime at locations in the western and southern Bay remained in the polyhaline range (18–30), the paleo-based salinity regime at the near-shore embayments became oligohaline (0.5–5), with the mid-Bay stations in the mesohaline range (5–18). Results of this study suggest that hypersaline events occur in Whipray Basin naturally (see Fig. 5). However, comparing the paleo-based salinity to the observed data indicates that water management practices appear to have exacerbated the situation resulting in additional hypersaline episodes that many not have occurred in a natural regime.

The paleo-based flows and stages produced by the models are an estimate of how the current system could be operated to achieve the paleo-based salinity target at Whipray Basin and hydroperiod targets in Shark River Slough and Taylor Slough. Mean monthly flow values for wet, dry, and normal rainfall years can be sampled from the 36-year paleo-based salinity runs and used as a starting point for operational restoration targets. From a seasonal frame of reference, the greatest improvement in hydrology toward restoration of the southern Everglades would be the provision of additional flows to Shark River Slough and Taylor Slough to extend wet conditions in the sloughs further into the dry season. This change in hydrology would improve Florida's southern estuaries by keeping salinities at more desirable lower levels for longer periods. Managing upstream freshwater levels to mimic paleo-based stages would greatly serve to restore the ecosystem. The results of this study provide a scientific basis for setting restoration targets to pre-drainage conditions. These targets may not be achievable, however, due to future climate change, economics, and/or political decisions, but understanding past conditions is an essential part of understanding future conditions.

The coupling of paleoecological information with regression models based on observed data represents an important step forward in the establishment of relevant, scientifically based hydrologic and salinity targets for Everglades and Florida Bay restoration. The paleoecologic data provide long-term historic information on ecosystem conditions while the regression models provide seasonal and annual variations absent in the paleoecologic data. The regression models provide a link between salinity targets in the estuary and upstream freshwater stage, hydropatterns, and flow targets because they are physically based. The addition of paleo-based estimates of hydrology and salinity based on sediment core analyses from other locations in the estuaries of South Florida, when available, will serve to corroborate or modify the findings of this study and the inferred salinity regime.

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References

Appleby, P.G., and F. Olfield. 1978. The calculation of ^{210}Pb dates assuming a constant rate of supply of unsupported ^{210}Pb to the sediment. *Catena* 5: 1–8. doi:10.1016/S0341-8162(78)80002-2.

Appleby, P.G. 1997. Sediment records of fallout radionuclides and their application to studies of sediment–water interactions. *Water, Air and Soil Pollution* 99: 573–586.

Basso, R., R. Schultz. 2003. *Long-term variation in rainfall and its effect on Peace River flow in West-Central Florida*. Brooksville, Florida: Hydrologic Evaluation Section, Southwest Florida Water Management District.

Boyer, J.N., J.W. Fourqurean, and R.D. Jones. 1999. Seasonal and long-term trends in the water quality of Florida Bay (1989–1997). *Estuaries* 22: 417–430. doi:10.2307/1353208.

Brewster-Wingard, G.L., and S.E. Ishman. 1999. Historical trends in salinity and substrate in central and northern Florida Bay: a paleoecological reconstruction using modern analogue data. *Estuaries* 22: 369–383. doi:10.2307/1353205.

Brewster-Wingard, G.L., J.R. Stone, and C.W. Holmes. 2001. Molluscan faunal distribution in Florida Bay, past and present: an integration of down-core and modern data. *Bulletins of American Paleontology* 361: 199–231. [Available at: http://sofia.usgs.gov/publications/papers/mollusc_distribution/index.html].

Browder, J., Z. Zein-Eldin, M. Criales, M. Robblee, S. Wong, T. Jackson, and D. Johnson. 2002. Dynamics of pink shrimp (*Farfantepenaeus duorarum*) recruitment potential in relation to salinity and temperature in Florida Bay. *Estuaries* 256B: 1355–1371. doi:10.1007/BF02692230.

Brush, G.S., and W.B. Hilgartner. 2000. Paleoecology of submerged macrophytes in the upper Chesapeake Bay. *Ecological Monographs* 704: 645–667.

Cole, K.L., and E. Wahl. 2000. A late Holocene paleoecological record from Torrey Pines State Reserve, California. *Quaternary Research* 533: 341–351. doi:10.1006/qres.1999.2121.

Cosby, B.J. 1993. *An examination of the relationships of stage, discharges and meteorology in the panhandle and Taylor Slough areas of Everglades National Park to salinity in upper Florida Bay. Volumes 1–5*. Charlottesville, Virginia: University of Virginia.

Cronin, T.M., C.W. Holmes, G.L. Brewster-Wingard, S.E. Ishman, H. J. Dowsett, D. Keyser, and N. Waibel. 2001. Historical trends in epiphytal ostracodes from Florida Bay: implications for seagrass and macro-benthic algal variability. *Bulletins of American Paleontology* 361: 159–197.

Davis, S.M., and J.C. Ogden. 1994. Introduction. In *Everglades: The ecosystem and its restoration*, eds. S.M. Davis, and J.C. OgdenDelray Beach, Florida: St. Lucie.

Davis, S.M., L.H. Gunderson, W.A. Park, J.R. Richardson, and J.E. Mattson. 1994. Landscape dimension, composition, and function in a changing Everglades ecosystem. In *Everglades: The ecosystem and its restoration*, eds. S.M. Davis, and J.C. OgdenDelray Beach, Florida: St. Lucie.

Davis, S.M., D.L. Childers, J.L. Lorenz, H.L. Wanless, and T.A. Hopkins. 2005. A conceptual model of ecological interactions in the mangrove estuaries of the Florida Everglades. *Wetlands* 25: 832–842. doi:10.1672/0277-5212(2005)025[0832:ACMOEI]2.0.CO;2.

Douglas, M.S. 1947. *The Everglades: River of grass, 60th anniversary addition*. Sarasota, Florida: Pineapple.

Ducat, D.A., and S.A. Kuehl. 1995. Non-steady state ^{210}Pb flux and the use of 228Ra/226Ra as a geochronometer on the Amazon continental shelf. *Marine Geology* 125: 329–350. doi:10.1016/0025-3227(95)00018-T.

Enfield, D.B., A.M. Mestas-Nunez, and P.J. Trimble. 2001. The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U. S. *Geophysical Research Letters* 2810: 2077–2080. doi:10.1029/2000GL012745.

Fourqurean, J.W., and M.B. Robblee. 1999. Florida Bay: a history of recent ecological changes. *Estuaries* 22: 345–357. doi:10.2307/1353203.

Helsell, D.R. and R.M. Hirsch. 1991. Statistical methods in water resources. In *Techniques of Water Resource Investigations of the United States Geological Survey*, Book 4 Hydrologic Analysis and Interpretation, Chapter A3. U. S. Reston, Virginia: Geologic Survey.

Hutson, W.H. 1979. The Agulhas Current during the Pleistocene: analysis of modern faunal analogs. *Science* 2074426: 64–66. doi:10.1126/science.207.4426.64.

Imbrie, J., and N.G. Kipp. 1971. A new micropaleontological method for quantitative paleoclimatology: application to a Late Pleistocene Caribbean core. In *The Late Cenozoic Glacial Ages*, ed. K. K. TurekianNew Haven, CT: Yale Univ. Press.

Ishman, S.E., T.M. Cronin, G.L. Brewster-Wingard, D.A. Willard, and D.J. Verardo. 1998. A record of ecosystem change, Manatee Bay, Barnes Sound, Florida. proceedings of the international coastal symposium (ICS98). *Journal of Coastal Research, Special Issue* 26: 125–138.

Kashigan, S.K. 1991. *Multivariate statistical analysis*. New York: Radius.

Kelble, C.R., E.M. Johns, W.K. Nuttle, T.N. Lee, R.Y. Smith, and P.B. Ortner. 2007. Salinity patterns of Florida Bay. *Estuarine, Coastal and Shelf Science* 71: 318–334. doi:10.1016/j.ecss.2006.08.006.

Knight, E. 2001. *The status of hydrologic conditions in Everglades National Park June 2000 to May 2001*. Homestead, Florida: South Florida Natural Resources Center, Everglades National Park.

Knight, E., and K. Kotun. 2001. *The status of hydrologic conditions in Everglades National Park June 1999 to May 2000*. Homestead, Florida: South Florida Natural Resources Center, Everglades National Park.

Marshall III, F.E., D. Smith, and D. Nickerson. 2004. *Using statistical models to simulate salinity variation and other physical parameters in north Florida Bay*. New Smyrna Beach, Florida: Cetacean Logic Foundation, Inc[Available at http://sofia.usgs.gov/publications/reports/salinity_variation/index.html].

Marshall III, F.E. 2005. *RECOVER Southern Estuaries performance measures: identification of hydrology–salinity relationships for coastal estuaries and analysis of interim CERP update scenarios*. New Smyrna Beach, Florida: Environmental Consulting & Technology, Inc.[Available at http://sofia.usgs.gov/publications/reports/hydrosal_relation/ index.html].

Marshall, F.E. 2008. *Task 3—Development of additional multivariate linear regression salinity models for Florida Bay and the southwest Gulf coast, Everglades National Park. Critical Ecosystems Studies Initiative Task Report to Everglades National Park*. New Smyrna Beach, Florida: Cetacean Logic Foundation, Inc[Available at http://sofia.usgs.gov/publications/reports/mlr_sal_models/ index.html].

Marshall, F.E., and W.K. Nuttle. 2008. *Task 7—Simulating and forecasting salinity in Florida Bay: a review of models. Critical Ecosystems Studies Initiative Project Task Report for Everglades National Park*. New Smyrna Beach, Florida: Cetacean Logic Foundation, Inc[Available at http://sofia.usgs.gov/publications/reports/salinity_flbay/ index.html].

McPherson, B.F., R. Halley. 1996. *The South Florida environment—a region under stress. U. S. Geological Survey, Circular 1134*. Washington, DC: United States Government Printing Office.

Montague, C.L., and J.A. Ley. 1993. A possible effect of salinity fluctuation on abundance of benthic vegetation and associated fauna in northeastern Florida Bay. *Estuaries* 16: 703–717. doi:10.2307/1352429.

Neter, J., W. Wasserman, and M.H. Kutner. 1990. *Applied linear statistical models*. Boston, Massachusetts: Irwin.

Nicholls, R.J., P.P. Wong, V.R. Burkett, J.O. Codignotto, J.E. Hay, R.F. McLean, S. Ragoonaden, and C.D. Woodroffe. 2007. Coastal systems and low-lying areas. In *Climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, eds. M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson, 315–356. Cambridge, United Kingdom: Cambridge University Press.

Nuttle, W.K. 1997. *Central and Southern Florida Project Restudy: Salinity transfer functions for Florida Bay and west coast estuaries. Volume 1: Main Report*. Miami, Florida: Southeast Environmental Research Program, Florida International University.

Ogden, J.C., S.M. Davis, K.J. Jacobs, T. Barnes, and H.E. Fling. 2005. The use of conceptual ecological models to guide ecosystem restoration in South Florida. *Wetlands* 25: 795–809. doi:10.1672/0277-5212(2005)025[0795:TUOCEM]2.0.CO;2.

Oswald, W.W., L.B. Brubaker, F.S. Hu, and G.W. Kling. 2003. Holocene pollen records from the central Arctic Foothills, northern Alaska: testing the role of substrate in the response of tundra to climate change. *Journal of Ecology* 91: 1034–1048. doi:10.1046/j.1365-2745.2003.00833.x.

Parker, G.G., G.E. Ferguson, S.K. Love, et al. 1955. *Water resources of southeastern Florida with special reference to the geology and ground water of the Miami area. Water Supply Paper 1255*. Washington, DC: U. S. Geological Survey.

Parsons, M.L., Q. Dortch, R.E. Turner, and N.N. Rabalais. 1999. Salinity history of coastal marshes reconstructed from diatom remains. *Estuaries* 22: 1078–1089. doi:10.2307/1353085.

Pitts, P., D. Hallac, D. Deis, and J. Browder. 2005. *Establishing targets for salinity in Florida's Southern Estuaries. Southern Estuaries Sub-team of RECOVER, U. S.* Jacksonville, Florida: Army Corps of Engineers.

Renken, R.A., J. Dixon, J. Koehnstedt, A.C. Lietz, S. Ishman, R.L. Marella, P. Telis, J. Rogers, and S. Memberg. 2005. *Impact of anthropogenic development on coastal ground-water hydrology in southeastern Florida, 1900–2000. Circular 1275*. Reston, Virginia: United States Geological Survey.

Robbins, J.S., C.W. Holmes, R. Halley, M. Bothner, E. Shinn, J. Graney, G. Keeler, M. ten Brink, K.A. Orlandini, and D. Rudnick. 2000. Time-averaged fluxes of lead and fallout radionuclides to sediments in Florida Bay. *Journal of Geophysical Research* 105: 28,805–28,821. doi:10.1029/1999JC000271.

Rudnick, D.T., P.B. Ortner, J.A. Browder, and S.M. Davis. 2005. A conceptual model of Florida Bay. *Wetlands* 25: 870–883. doi:10.1672/0277-5212(2005)025[0870:ACEMOF]2.0.CO;2.

Schaffranek, R.W., T.J. Smith, and C.W. Holmes. 2001. *An investigation of the interrelation of Everglades hydrology and Florida Bay dynamics to ecosystem processes in South Florida. Fact Sheet FS-49-01*. Reston, Virginia: U. S. Department of Interior, U. S. Geological Survey.

Sklar, F.H., M.J. Chimney, S. Newman, P. McCormick, D. Gawlik, S. Miao, C. McVoy, W. Said, J. Newman, C. Coronado, G. Crozier, M. Korvela, and K. Rutchey. 2005. The ecological–societal underpinnings of everglades restoration. *Frontiers in Ecology and the Environment* 33: 161–169.

Smith, T.J., J.H. Hudson, M.B. Robblee, G.V.N. Powell, and P.J. Isdale. 1989. Freshwater flows from the Everglades to Florida Bay: a historical reconstruction based on fluorescent banding in the coral *Solenastrea bournoni*. *Bulletin of Marine Science* 44: 274–282.

South Florida Water Management District and Interagency Modeling Center. 2005. *Documentation of the South Florida Water Management Model*. West Palm Beach, Florida: South Florida Water Management District.

Symposium on the Classification of Brackish Waters. 1958 [1959]. Final resolution: the Venice system for the classification of marine waters according to salinity. *Archivo di Oceanografia e Limnologia* 11supp.: 243–245.

Swart, P.K., G. Healy, L. Greer, M. Lutz, A. Saied, D. Anderegg, R.E. Dodge, and D. Rudnick. 1999. The use of proxy chemical records in coral skeletons to ascertain past environmental conditions in Florida Bay. *Estuaries* 22: 384–397. doi:10.2307/1353206.

Tabb, D.C. 1967. *Prediction of estuarine salinities in Everglades National Park, Florida, by the use of ground water records*. Ph. D. Dissertation, University of Miami, Miami, Florida.

Trappe, C.A., and G.L. Brewster-Wingard. 2001. Molluscan fauna from Core 25B, Whipray Basin, Central Florida Bay, Everglades National Park. Open-File Report 01–143. U. S. Geological Survey, Reston, VA. [Available at http://sofia.usgs.gov/publications/ofr/01-143/index.html]

UNESCO. 1985. The international system of units (SI) in oceanography, UNESCO Technical Papers No. 45, IAPSO Pub. Sci. No. 32, Paris, France.

U. S. Army Corps of Engineers. 1999. Central and southern Florida comprehensive review study, final integrated feasibility report and programmatic environmental impact statement. Jacksonville, Florida. [Available at http://www.evergladesplan.org/]

U. S. Army Corps of Engineers. 2006. Comprehensive Everglades restoration plan system-wide performance measures, RECOVER Leadership Group draft.

Walling, D.E. 2003. Using environmental radionuclides as tracers in sediment budget investigations, erosion, and sediment transport measurement in rivers, p. 57–78. *In Technological and methodological advances, Proceedings of the Oslo Workshop on Erosion and Sediment Transport in Rivers*, June 2002.

Willard, D.A., C.E. Bernhardt, C.W. Holmes, B. Landacre, and M. Marot. 2006. Response of Everglades tree islands to environmental change. *Ecological Monographs* 764: 565–583. doi:10.1890/0012-9615(2006)076[0565:ROETIT]2.0.CO;2.

Wingard, G.L., T.M. Cronin and W. Orem. 2007a. Ecosystem history, p. 9–29. In *Florida Bay Science Program: A synthesis of research on Florida Bay*, eds. W. Nuttle, and J. Hunt. Florida Fish and Wildlife Research Institute Technical Report, TR-11. [Available at http://research.myfwc.com/engine/download_redirection_process.asp?file = tr11%5F2211%2Epdf&objid = 52697&dltype = publication]

Wingard, G.L., J.W. Hudley, C.W., Holmes, D.A. Willard, and M. Marot. 2007b. Synthesis of age data and chronology for Florida Bay and Biscayne Bay Cores collected for the Ecosystem History of South Florida's Estuaries Projects. U. S. Geological Survey, Open File Report 2007-1203. Reston, Virginia. [Available at http://sofia.usgs.gov/ publications/ofr/2007-1203/index.html]

Wingard, G.L., J.R. Stone, C.A. Trappe, and C. Budet. 2007c. Ecosystem history of South Florida estuaries database. [Available at http://sofia.usgs.gov/exchange/flaecohist/]

Wingard, G.L. and J.W. Hudley. 2008. Verification of a molluscan dataset for paleosalinity estimation using modern analogues: a tool for restoration of South Florida's estuaries. Proceedings, 2008 Florida Bay and Adjacent Marine Systems Science Conference.