Estuaries and Coasts (2012) 35:262–280
DOI 10.1007/s12237-011-9441-3

Application of a Weighted-Averaging Method for Determining Paleosalinity: A Tool for Restoration of South Florida's Estuaries

G. Lynn Wingard · Joel W. Hudley

Received: 8 February 2011 / Revised: 10 June 2011 / Accepted: 29 August 2011 / Published online: 13 September 2011

Abstract A molluscan analogue dataset is presented in conjunction with a weighted-averaging technique as a tool for estimating past salinity patterns in south Florida's estuaries and developing targets for restoration based on these reconstructions. The method, here referred to as cumulative weighted percent (CWP), was tested using modern surficial samples collected in Florida Bay from sites located near fixed water monitoring stations that record salinity. The results were calibrated using species weighting factors derived from examining species occurrence patterns. A comparison of the resulting calibrated species-weighted CWP (SW-CWP) to the observed salinity at the water monitoring stations averaged over a 3-year time period indicates, on average, the SW-CWP comes within less than two salinity units of estimating the observed salinity. The SW-CWP reconstructions were conducted on a core from near the mouth of Taylor Slough to illustrate the application of the method.

Keywords South Florida restoration · Salinity reconstructions · Mollusks · Weighted averaging · Florida Bay · Everglades National Park

Electronic supplementary material The online version of this article (doi:10.1007/s12237-011-9441-3) contains supplementary material, which is available to authorized users.

G. L. Wingard (✉)
U.S. Geological Survey, MS 926A National Center,
Reston, VA 20192, USA
e-mail: lwingard@usgs.gov

J. W. Hudley
Department of Geological Sciences, University of North Carolina,
Chapel Hill, NC 27599, USA

Introduction

Paleoecologic analyses of biotic assemblages are currently being applied to a number of societal issues, including global change, land use, and ecosystem restoration (for example see, Brush and Hilgartner 2000; Byrne et al. 2001; Cronin et al. 2005; Dowsett 2007; Oswald et al. 2003; Vandergoes and Fitzsimons 2003; Willard et al. 2005; Willard and Cronin 2007). The common element in these studies is the application of a modern analogue dataset to the interpretation of fossil biotic assemblages preserved in sediment cores, using either the analytical transfer function (Imbrie and Kipp 1971) or the modern analogue method (Hutson 1979). These studies generally use pollen or microfossil assemblages because the broad geographic distribution of these groups is consistent with examining large-scale environmental changes. For smaller-scale ecosystem or watershed-based studies, however, macrofossils can play a significant role in paleoecologic interpretations.

Mollusks can be particularly useful environmental indicators since they are found in terrestrial, freshwater, estuarine, and marine ecosystems, and they represent several levels of heterotrophic consumers (grazers, deposit feeders, suspension feeders, and carnivores). Generalized environmental determinations have been made using mollusks since Lamarck investigated the Paris Basin (Lamarck 1802) and Conrad explored the Atlantic Coastal Plain (Conrad 1838) in the early 1800s. Detailed paleoecologic analyses of mollusks have been conducted using qualitative comparisons to living fauna, for example to determine paleo-depths (Brett et al. 1993), marine cycles (Dominici and Kowalke 2007; Kauffman 1969), marine environments (Allmon 1993; Fürsich and Kauffman 1983), and salinity (Hudson 1963). It is rare, however, to see the statistical application of analogue datasets to molluscan paleoecologic analyses. Rousseau's (1991) development of a climatic transfer function for terrestrial mollusks is an exception. A more common application of mollusks to environmental studies is the analyses of stable isotopes of carbon and oxygen in the shells to determine water temperature and salinity (for example, Andreasson et al. 1999; Arthur et al. 1983; Byrne et al. 2001; Cornu et al. 1993; Jones and Allmon 1995; Krantz 1990; Surge et al. 2001). Stanton and Dodd (1970) demonstrated a close correspondence between salinity derived from molluscan assemblage analysis and from oxygen isotopic methods.

A primary goal of the Comprehensive Everglades Restoration Plan (CERP) is to restore the flow of freshwater through the terrestrial ecosystem and into the estuaries to a more natural state (U. S. Army Corps of Engineers 1999). By setting performance measures and target salinities for the estuaries that reflect the natural pre-anthropogenic system, restoration managers hope to achieve that goal. A number of previous studies have examined the salinity history of Florida Bay using paleoecologic assemblages (for example, Alvarez Zarikian et al. 2001; Brewster-Wingard et al. 2001; Nelsen et al. 2002), stable isotopes of corals (for example, Swart et al. 1996, 1999), elemental analyses of ostracode shells (Dwyer and Cronin 2001), and stable isotopes of mollusks (Halley and Roulier 1999). These previous studies are summarized in Wingard et al. (2007a); however, the CERP groups responsible for setting restoration target salinities for the estuaries prefer historical salinity data that are amenable to modeling and statistical analysis (Browder et al. 2008).

A number of cores have been collected by the USGS in Biscayne Bay, Florida Bay, and the southwest coastal area of south Florida to establish pre-1900 temporal and spatial salinity patterns within the estuaries. The purpose of this paper is to determine the reliability of molluscan assemblage data from sediment cores in the reconstruction of historical salinities. We use a simplified version of the modern analogue technique (Hutson 1979), closely allied to weighted-averaging techniques (ter Braak and Juggins 1993; ter Braak and Looman 1986; ter Braak and van Dam 1989; Yuan 2005); all of these methods utilize data on living organisms to quantify biotic changes in terms of some ecologic variable of interest, in this case salinity. Like all paleoecologic studies, we are operating under the assumption that the "present is the key to the past" and that the species we are studying have the same ecological requirements today that they did in the past. In addition, we use assemblages rather than individual or selected species, in order to address the issue of multiple variables controlling the distribution and/or changes in environmental preferences of the fauna that may have occurred over time. As Bosence and Allison (1995, p. 1) explain in a discussion on the importance of using assemblages in paleoenvironmental analyses, "it is unlikely that all [species] will have changed their ecological requirements synchronously." We also discuss where the data and methods need to be improved to provide higher precision of the paleosalinity record. We believe these methods can provide data that are applicable to the management goals of CERP.

Before applying a modern analogue weighted-averaging method to the interpretation of faunal assemblages from core samples, however, we wanted to test the method using a modern dataset collected under known environmental conditions. We are making the assumption that if the method works reasonably well at estimating current conditions, than it will work reasonably well in cores collected from the same estuary and containing extant species. Testing the modern dataset allows us to answer the following questions. How good is the modern analogue dataset at predicting the known salinity? What temporal resolution—days, months, or years? What combination of the data subsets and what statistical measures (mean vs. median) provide the best correlation to the known salinity? Answering these questions will allow for more accurate interpretation of the historical salinity record preserved in the cores, and thus, will provide restoration managers with the ability to set performance measures and targets that accurately reflect the natural system. An example of the application of the cumulative weighted percent (CWP) method to one core, collected in the Northern Transition zone of Florida Bay is provided.

Methods

Molluscan Analogue Dataset

The first step in building the modern analogue dataset was to assemble records on molluscan species currently living in south Florida estuaries; these data on living mollusks provide the basic information for interpreting the past assemblages. Initial field surveys began in September 1994, and beginning in 1995, specific survey sites were established in Everglades National Park and Biscayne National Park. One hundred and twenty-seven different locations in Biscayne Bay, Florida Bay, and the southwest coastal region were sampled, assembling 481 individual field records from September 1994 through July 2007[1] (Figs. 1 and 2). Over one hundred molluscan taxa were observed alive at the various sites and significantly more fauna were represented in the death assemblages. Corresponding information on the water conditions (salinity, temperature, pH, specific con-

[1] All modern data are available at http://sofia.usgs.gov/exchange/flaecohist/. See Appendix 1 in the ESM available in the online version of this article.

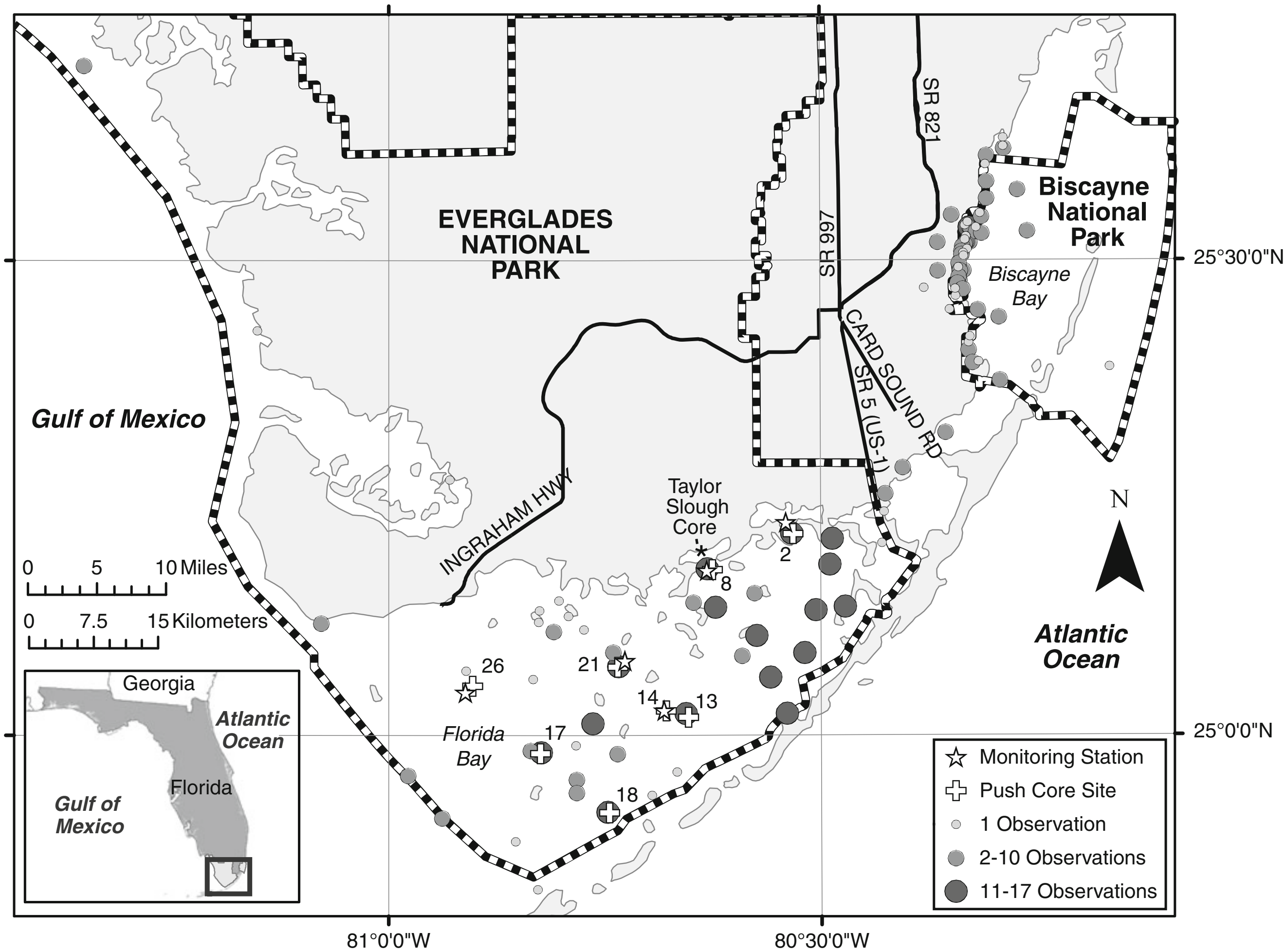


Fig. 1 Map showing location of modern observation sites, push-cores, water monitoring stations and piston core from mouth of Taylor Slough (*asterisk*). Frequency of observations at a particular site is indicated by the size and shading of the *circle*. *Small numbers* correspond to site numbers listed in Tables 2 and 6 and shown on Fig. 4. Data on specific locations are available at http://sofia.usgs.gov/exchange/flaecohist/

ductivity, etc.) and descriptive habitat information at each site were recorded at the time of observation using a portable water measuring device (YSI or Hydrolab). (Note, this paper utilizes the UNESCO (1985) salinity guidelines and the Practical Salinity Scale, therefore, values of salinity reported herein have no units.) Taxonomy was based on Turgeon et al. (1998); more recent work done by Bieler and Mikkelsen (2002) and Mikkelsen and Bieler (2008) was not included so these data would be taxonomically consistent with our previously published reports. For the purposes of this study, these data were recorded as presence/absence of live and dead molluscan species (or larger taxonomic groups) in the database.

The next step was to compile and standardize the list of all living mollusks recorded in our surveys and the associated salinity data at the time of collection/observation (see footnote 1). Histograms and box plots of the abundant species were produced to check for normal distribution relative to salinity; ter Braak and Looman (1986) discuss the importance of using species with normal distributions over the environmental variable being measured. Descriptive statistics on salinity values for each taxonomic group were calculated (mean, median, mode, deviation, count, error, etc.; partial list in Table 1; full list in Appendix 1 in the Electronic Supplementary Material (ESM). The faunal groups with no associated salinity data were removed and the resulting modern analogue dataset contains 412 records and 66 molluscan faunal groups. The construction of box plots provided information on the highest frequency of occurrence for each species and may indicate salinity preferences. Extreme salinity outliers were removed (data below the tenth percentile and above the 90th percentile) from the data before analysis.

The 66 taxa were separated into two categories for the analyses, in order to understand the importance of repeated observations and confidence levels: the confident dataset (CONFID) and the full dataset (FULL). CONFID includes the 36 taxonomic groups with ten or more observations and

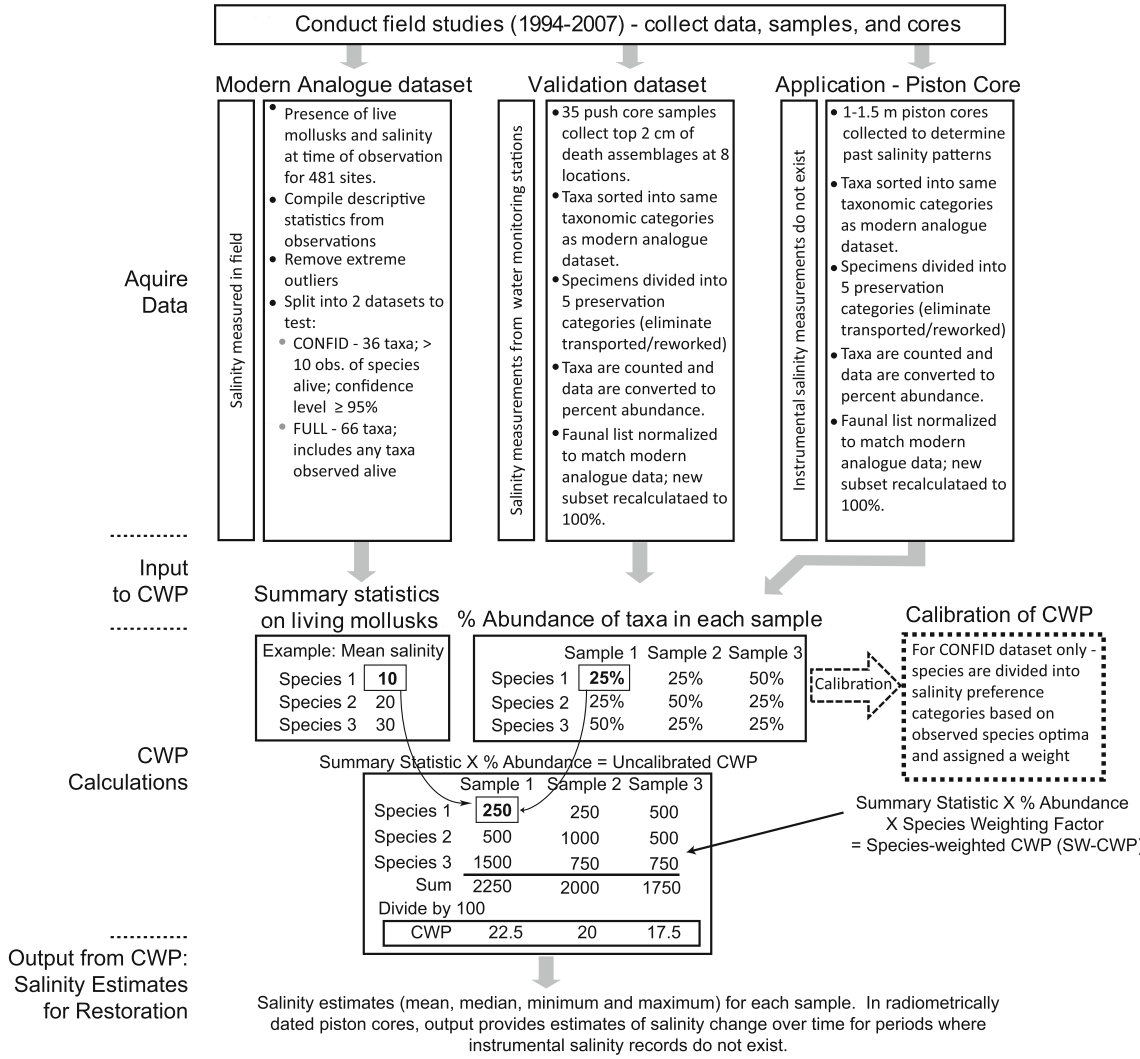


Fig. 2 Flow chart illustrating the components of the analyses discussed in the text. A simplified example of cumulative weighted percent (*CWP*) calculations for mean salinity estimates is provided

a confidence interval of <5±the mean at a 95% confidence level (Table 1). FULL includes the 36 taxa from the CONFID plus an additional 30 taxa for which we had any associated salinity data (Appendix 1 in the ESM).

Modern Test Dataset

For our test dataset, we selected 35 10-cm push-core samples collected between 1998 and 2001 from eight locations in Florida Bay (Figs. 1 and 2). These sites had relatively complete records of salinity and other data recorded at nearby fixed water monitoring stations (Table 2). Only the molluscan count data from the top two centimeters of each push-core were included in the analysis (Appendix 2 in the ESM). One to 2-meter piston cores collected throughout south Florida's estuaries by the USGS have typically been sliced into 2-cm sample increments; thus, the results from this test with the upper 2 cm of the push-cores are directly applicable to the analysis of piston cores collected for ecosystem history purposes.

The molluscan fauna (>850 μm) from the push-cores were identified using the same taxonomic groupings as the modern analogue dataset. The individual shells were divided into four preservation categories for adults and juveniles, plus fragments, as follows:

- Pristine (shells intact and still have luster and/or color);
- Whole (shells intact but luster and/or color all or mostly gone);
- Broken (>50% of shell present—has luster and/or color);
- Worn (shells show obvious signs of wear—may or may not be intact);
- Fragments (<50% of shell present—any degree of surface condition).

Table 1 Descriptive statistics on observed salinities for molluscan taxonomic groups in the “confident” data set (CONFID)

	Mean salinity	1st quartile	Median salinity	3rd quartile	Sample standard deviation	Salinity range	Minimum salinity	Maximum salinity	Number of observations	Confidence interval (at 95.0%)±the mean	Salinity preference category
Anomalocardia auberiana	22.94	15.19	25.43	30.22	10.82	41.28	0.94	42.22	61	2.71	Ubiquitous
Arcopsis adamsi	24.41	19.22	22.79	26.83	6.90	23.11	15.75	38.86	16	3.38	Euryhaline
Argopecten irradians	31.99	29.25	32.22	36.09	6.14	27.81	16.83	44.63	57	1.59	Euryhaline
Batillaria minima	25.41	19.40	26.73	31.19	8.02	38.96	1.61	40.57	42	2.42	Ubiquitous
Bittiolum varium	25.61	19.14	26.47	31.24	7.22	32.80	8.15	40.95	53	1.94	Euryhaline
Brachidontes exustus	26.48	19.85	28.40	33.23	9.07	39.99	2.23	42.22	217	1.21	Ubiquitous
Bulla striata	28.76	22.92	31.16	33.94	7.97	32.37	9.85	42.22	47	2.28	Euryhaline
Busycotypus spp.[a]	34.58	32.20	35.20	36.69	7.28	31.70	16.83	48.53	17	3.46	Poly-euhaline
Carditamera floridana	31.58	28.65	31.70	35.68	6.38	29.89	15.65	45.54	41	1.95	Euryhaline
Cerithidea costata	18.43	10.15	16.33	29.18	10.68	38.79	3.27	42.06	40	3.31	Ubiquitous
Cerithium muscarum	29.12	25.08	30.88	34.86	8.68	44.52	4.01	48.53	98	1.72	Ubiquitous
Cerithium spp.[b]	34.40	32.59	34.90	36.52	4.88	34.08	14.45	48.53	43	1.46	Poly-euhaline
Chione cancellata	33.78	30.22	35.31	38.32	6.78	43.11	0.22	43.33	53	1.83	Ubiquitous
Columbella spp.[c]	32.73	29.85	33.40	36.43	5.84	28.33	16.30	44.63	59	1.49	Euryhaline
Columbellidae (undifferentiated)	34.78	32.86	35.52	36.64	2.96	12.30	28.65	40.95	18	1.37	Poly-euhaline
Crepidula spp.[d]	29.26	23.85	30.16	35.15	7.99	34.44	7.78	42.22	84	1.71	Euryhaline
Fasciolaria spp.[e]	32.55	29.19	33.54	36.18	5.51	31.83	11.50	43.33	60	1.40	Euryhaline
Fissurellidae[f]	32.35	29.56	32.55	35.90	4.90	18.32	20.55	38.87	23	2.00	Euryhaline
Freshwater Gastropods[g]	6.42	0.34	4.61	9.64	7.06	26.21	0.24	26.45	15	3.57	Fresh
Hydrobiidae	22.24	15.70	18.33	30.97	8.02	18.53	14.45	32.98	10	4.97	Fresh
Laevicardium mortoni	28.26	24.21	28.14	31.24	6.44	23.37	17.20	40.57	21	2.75	Euryhaline
Melanoides tuberculatus	13.18	3.71	13.79	19.52	10.03	32.74	0.24	32.98	32	3.48	Fresh
Melongena spp.[h]	24.15	17.23	26.45	31.20	9.62	35.96	4.61	40.57	39	3.02	Ubiquitous
Mitrella spp.[i]	33.37	30.17	34.76	37.69	5.21	14.79	24.08	38.87	10	3.23	Euryhaline
Modulus modulus	31.18	28.60	33.05	35.69	7.48	40.81	4.01	44.82	107	1.42	Ubiquitous
Muricidae (undifferentiated)	33.31	30.55	34.43	35.96	3.51	11.10	25.65	36.74	14	1.84	Poly-euhaline
Nassarius spp.[j]	31.00	25.57	31.65	36.93	7.39	20.49	19.92	40.41	11	4.37	Euryhaline
Naticidae (limited)[k]	31.66	27.79	32.58	37.35	6.85	20.49	19.92	40.41	14	3.59	Euryhaline
Ostreidae[l]	22.12	15.00	19.85	29.50	10.11	36.35	2.65	39.00	35	3.35	–
Pinnidae[m]	34.80	34.26	35.74	37.13	3.43	11.48	26.66	38.14	10	2.12	Poly-euhaline
Prunum spp.[n]	28.13	23.87	29.33	33.15	7.70	38.68	9.85	48.53	95	1.55	Euryhaline
Pteria longisquamosa	30.18	26.20	30.70	35.13	7.11	35.63	9.00	44.63	129	1.23	Euryhaline
Tegula fasciata	33.63	31.56	33.76	35.52	3.26	13.14	25.73	38.87	39	1.02	Poly-euhaline
Tellinidae (undifferentiated)	22.70	14.15	25.46	32.30	10.48	37.99	0.94	38.93	31	3.69	–

Table 1 (continued)

	Mean salinity	1st quartile	Median salinity	3rd quartile	Sample standard deviation	Salinity range	Minimum salinity	Maximum salinity	Number of observations	Confidence interval (at 95.0%)±the mean	Salinity preference category
Turbinidae (limited)[o]	35.21	33.16	36.10	37.69	3.12	10.29	28.65	38.94	14	1.63	Poly-euhaline
Turbo castanea	33.41	31.65	33.91	35.61	4.54	27.78	16.85	44.63	53	1.22	Poly-euhaline

These species also are included in the FULL data set. (The FULL data set and all associated statistics are available in Appendix 1 in the ESM) Data are derived from a compilation of all presence/absence field observations between 1995 and 2007. Data are not weighted based on how many individuals of a given taxonomic group were observed at a location. Criteria for inclusion in the "confident" data set were greater than ten observations and a confidence interval of <5±the mean salinity at a probability of 0.05 or 95% confidence level. Statistics are based on all observations unless otherwise noted. Salinity preference categories indicate the categories used for the species weighting during the calibration step. Two taxa (Ostreidae and Tellinidae) were too broad to be categorized. Taxonomy consistent with Turgeon et al. (1998)

[a] Includes *Busycotypus canaliculatus* and *Busycotypus spiratus*

[b] Includes *Cerithium lutosum* and *Cerithium* sp. cf. *Cerithium eburneum* and/or *Cerithium* sp. cf. *Cerithium litteratum*

[c] Includes *Columbella rusticoides* and *Columbella mercatoria*

[d] Includes *Crepidula convexa*, *Crepidula fornicata*, and *Crepidula plana*

[e] Includes *Fasciolaria hunteria* and *Fasciolaria tulipa*

[f] Includes *Diodora cayenensis*, *Diodora listeri*, and *Lucapina sowerbii*

[g] Includes Physidae and *Planorbella* sp.

[h] *Melongena corona* and *Melongena bicolor* not distinguished

[i] Includes *Mitrella dichroa* and *Mitrella ocellata*

[j] Includes *Nassarius albus* and *Nassarius vibex*

[k] *Naticarius canrena* and undifferentiated naticid egg cases

[l] Includes *Crassostrea virginica* and *Ostreola equestris*

[m] Includes *Atrina rigida*, *Atrina serrata*, and *Pinna carnea*

[n] Primarily *Prunum apicinum* and some *Prunum* indeterminant juveniles

[o] Includes *Astralium phoebium*, *Lithopoma americanum*, and *Lithopoma caelatum*

Table 2 Measured salinity data from fixed-location hydrologic stations in Florida Bay

Push-core sample information			Hydrologic station data averaged over different time periods										36-month station data		
Sample identification number	Site number	Date collected	1 day	1 week	1 month	3 months	6 months	12 months	18 months	24 months	30 months	36 months	Average all data for a 36-month time period	Number of daily measurements	Standard deviation
GLW0299 FB02B	2	2/17/1999	28.18	19.86	21.32	17.16	13.72	15.26	13.08	14.34	13.62	*13.92*	13.92	1,072	9.25
GLW0799 FB02B	2	7/7/1999	12.31	15.77	28.75	32.93	28.51	21.31	18.80	15.87	17.01	15.56	15.56	1,096	10.70
GLW0200 FB02B	2	2/17/2000	–	–	*14.92*	8.90	8.18	18.71	16.94	16.91	15.23	15.72	15.72	1,073	10.82
GLW0700 FB02B	2	7/6/2000	25.30	26.80	23.87	–	–	12.56	19.45	17.88	16.90	15.04	15.04	970	10.65
GLW0801 FB02B	2	8/17/2001	4.51	6.41	20.51	30.41	–	–	*26.24*	17.97	21.41	19.42	19.42	719	12.17
GLW0798 FB08A	8	7/8/1998	24.14	24.14	22.85	19.62	16.73	15.40	17.59	*16.77*	17.17	16.23	16.23	1,069	4.95
GLW0299 FB08B	8	2/16/1999	20.63	20.31	20.80	18.52	*19.18*	19.24	17.69	18.40	*17.83*	17.94	17.94	1,041	4.97
GLW0799 FB08B	8	7/6/1999	29.65	28.75	30.97	30.41	26.70	*23.92*	21.36	19.45	19.99	*19.07*	19.07	1,040	6.17
GLW0200 FB08B	8	2/18/2000	14.21	15.35	15.53	14.17	17.27	22.62	*21.58*	21.02	19.75	19.85	19.85	1,068	6.32
GLW0700 FB08B	8	7/7/2000	25.21	25.30	24.85	23.50	19.43	19.71	22.04	*21.73*	20.69	19.54	19.54	1,066	6.11
GLW0299 FB13B	13	2/19/1999	35.35	35.37	34.65	32.26	32.46	33.88	*32.25*	–	–	–	32.25	529	4.63
GLW0799 FB13B	13	7/9/1999	39.20	39.92	38.75	38.29	37.36	35.58	34.56	*33.51*	–	–	33.51	669	4.83
GLW0200 FB13B	13	2/18/2000	38.06	37.21	37.63	34.55	30.11	33.99	33.49	33.92	*32.96*	–	32.96	893	5.26
GLW0798 FB13C	13	7/9/1998	40.05	39.97	40.13	36.56	32.54	*31.04*	–	–	–	–	31.04	304	4.36
GLW0798 FB14B	14	7/9/1998	40.05	39.97	40.13	36.56	32.54	*31.04*	–	–	–	–	31.04	304	4.36
GLW0299 FB14B	14	2/19/1999	35.35	35.37	34.65	32.26	32.46	33.88	*32.25*	–	–	–	32.25	529	4.63
GLW0799 FB14B	14	7/9/1999	39.20	39.92	38.75	38.29	37.36	35.58	34.56	*33.51*	–	–	33.51	669	4.83
GLW0200 FB14B	14	2/18/2000	38.06	37.21	37.63	34.55	30.11	33.99	33.49	33.92	*32.96*	–	32.96	893	5.26
GLW0700 FB14B	14	7/10/2000	38.70	39.60	39.12	35.87	36.30	33.10	34.52	34.33	33.98	*33.37*	33.37	1,036	5.12
GLW0798 FB17	17	7/13/1998	34.18	34.33	33.88	34.37	33.57	*33.88*	–	–	–	–	33.88	306	1.67
GLW0299 FB17	17	2/19/1999	33.13	34.03	32.91	33.76	34.89	34.44	*34.24*	–	–	–	34.24	486	1.69
GLW0799 FB17	17	7/8/1999	34.09	33.89	35.04	35.46	34.41	*34.81*	34.34	*34.36*	–	–	34.36	625	1.66
GLW0700 FB17	17	7/12/2000	37.55	37.44	38.09	37.35	34.50	32.76	33.31	*33.73*	33.69	*33.77*	33.77	995	3.03
GLW0798 FB18B	18	7/13/1998	34.96	36.40	35.96	36.02	*34.07*	*34.30*	*34.78*	*34.68*	*34.51*	*34.10*	34.10	802	2.57
GLW0299 FB18B	18	2/20/1999	34.96	34.82	34.56	–	–	34.85	*34.32*	*35.11*	*34.71*	34.73	34.73	726	2.26
GLW0799 FB18B	18	7/9/1999	36.44	36.46	37.29	36.71	35.64	–	34.98	*34.90*	*35.07*	*34.98*	34.98	731	2.19
GLW0200 FB18B	18	2/16/2000	30.70	30.84	30.19	29.09	31.67	33.82	–	34.14	*34.05*	*34.51*	34.51	799	2.92
GLW0700 FB18B	18	7/12/2000	37.07	37.03	37.06	37.45	34.53	33.74	34.35	–	34.36	*34.40*	34.40	840	2.89
GLW0299 FB21	21	2/20/1999	29.96	30.22	30.51	26.75	28.00	32.95	34.12	33.12	32.57	32.31	32.31	1,097	5.05
GLW0799 FB21	21	7/8/1999	42.61	42.28	41.46	40.22	35.59	32.89	34.21	34.57	33.50	33.01	33.01	1,096	5.34
GLW0700 FB21	21	7/10/2000	48.10	48.05	48.18	45.34	41.80	40.69	39.05	36.80	36.82	36.63	36.63	1,097	5.97

Table 2 (continued)

Push-core sample information			Hydrologic station data averaged over different time periods										36-month station data		
Sample identification number	Site number	Date collected	1day	1week	1month	3months	6months	12months	18months	24months	30months	36months	Average all data for a 36-month time period	Number of daily measurements	Standard deviation
GLW0798 FB26	26	7/10/1998	34.12	34.25	35.60	35.61	34.70	33.76	34.40	*34.53*	*34.41*	*33.77*	33.77	755	3.20
GLW0299 FB26	26	2/21/1999	31.25	32.15	31.81	–	*33.64*	*34.65*	33.96	34.46	*34.35*	*34.37*	34.37	748	2.73
GLW0799 FB26	26	7/12/1999	34.16	32.58	32.62	34.71	33.70	*34.12*	*34.36*	33.93	34.31	*34.41*	34.41	816	2.65
GLW0700 FB26	26	7/12/2000	38.16	37.03	38.39	38.14	34.87	32.91	33.16	33.39	*33.65*	33.52	33.52	909	3.38

Data are averaged over different time periods working backwards from the date of sample collection. Florida Bay hydrologic station data are available from Everglades National Park (EVER_data_request@nps.gov). Note: sites 13 and 14 are in relatively close proximity and share the same station data from site 14. Entries set in italics indicate portion of data in that time increment which are missing; dashes indicate all data are missing

Since the push-cores constitute a death assemblage, we made the assumption that worn shells and fragments may indicate transport and/or time averaging and thus may not represent the environment of deposition. The worn and fragmented shells were excluded from all analyses.

CWP Salinity Estimate

The next step was to calculate a single estimated salinity value for each sample in the push-core test set. We refer to this value as the CWP salinity estimate. To calculate the CWP, push-core samples are normalized to the modern analogue dataset by re-calculating the percentages in each sample based on only the taxonomic groups present in the analogue dataset. The normalized percentage becomes the weight of a species in the sample, which is then multiplied by the mean salinity for that species (Fig. 2). Finally, the values for all taxonomic groups in each sample are summed and divided by 100. This number becomes the CWP mean salinity estimate for a sample. This process is repeated to calculate the CWP median salinity.

CWP estimates were calculated on different combinations of the assemblage data from the push-core test dataset and the modern analogue dataset, for a total of four trials, to determine which combination of the data provide the best correlation to the observed salinity values. The FULL and CONFID modern analogue datasets each were tested using two combinations of preservation categories: (1) pristine+broken+whole and (2) pristine+broken. The mean and median CWP values for each of the four combinations were calculated, providing a total of eight CWP values to be evaluated.

Calibration of the CWP Values

Based on the results of a comparison of the initial CWP salinity estimates from the push-core test dataset to the measured salinity at the fixed water monitoring stations, one subset of the data was selected for the calibration step. The goal of calibrating the data was to minimize the absolute value of the difference between the estimated CWP salinity and the instrumentally measured salinity (Table 2) averaged over a 36-month period. Four species weighting factors (Table 3) were established for each salinity preference category listed in Table 1. The factors were selected by trial and error, starting with an examination of the descriptive statistics and field observations. For example, we know that the presence of freshwater gastropods is always indicative of the presence of freshwater, despite the fact that those species may be carried out into more saline water, so the species weight for the freshwater category needed to reduce the estimated CWP salinity. The large salinity range for the ubiquitous category (typically

Table 3 Species weighting factors derived in calibration step

Salinity preference category	Nearshore sites	Basin sites
Freshwater	0.30	0.30
Poly-euhaline	1.50	1.50
Euryhaline	1.25	1.25
Ubiquitous	0.24	1.18

Table 1 lists the species included in each category

greater than 35) required that two separate correction factors be developed for the nearshore and basin or open-water sites; these corrections allow for the fact that in the nearshore, the ubiquitous species can thrive in low salinities and in basins they can be found in mesohaline to hypersaline salinities.

The species weighting factors shown in Table 3 were selected after experimenting with values that minimize the difference between estimated and observed salinity while maintaining a relationship to the observed field distribution of the taxa. The factors selected have a difference between the grand mean of the observed and the grand mean of the estimated salinity of 1.04 for the nearshore samples (sites 2, 8) and 0.87 for the basin (sites 13, 14, and 21) and open-water samples (sites 17, 18, and 26). The output from this calibration step is the species-weighted CWP (SW-CWP), which is the mean observed salinity for each species multiplied by the weighting factor and the percent abundance of each species in each sample (Fig. 2).

Application to Piston Core Dataset

Following our testing and calibration of the CWP method, we conducted the SW-CWP analyses on a core collected in 1994 by USGS researchers from near the mouth of Taylor Slough (core FB594 24/T24) (Fig. 1) to illustrate application of the CWP method to ecosystem restoration. The 86-cm long core was cut into 2-cm samples, and all molluscan faunal remains >850 μm were identified, categorized, counted, and converted to percent abundance data as described above for the push-core test set (Fig. 2). Worn and fragmented shells were excluded from the counts for each sample, because we assume these may not be representative of the depositional environment. The traditional qualitative molluscan faunal paleoecologic analysis for the Taylor Slough core has been previously presented and discussed (Brewster-Wingard et al. 1998, 2001), and the age model, based on lead-210, a pollen biomarker, and a carbon-14 date, is discussed in Wingard et al. (2007b). The SW-CWP analysis was conducted on the subset of core taxa that are included in the CONFID modern analogue dataset, normalized to equal 100%. The nearshore species weighting factors were used, because the core is located near the outflow of Taylor Slough in the northern transition zone of Florida Bay, close to modern site 8.

Results

Distribution of the Molluscan Analogue Dataset

The 481 site observations recorded between 1994 and 2007 cover a range of water temperatures and salinities as indicated in Fig. 3 and Table 4. The wet seasons (typically mid-May through mid-October) during the sampling period were characterized by water temperatures ranging from 26°C to 35°C. The dry season (typically mid-late October through early May) temperatures ranged from 17°C to 31°C during the study period. Water temperature measurements reflect the seasonality of the sampling (Fig. 3), with the 30–35°C category indicating the typical summer/wet season temperatures (median, 31°C), and the 20–25°C category indicating the typical winter/dry season water temperatures (median, 23°C).

Salinity covered a wide spectrum from nearly zero to nearly 50 during the study period, but the majority of the observations (82%) were grouped between salinities of 15 and 40. All salinity measurements below 10, and most below 15, are from sampling sites in canals, or near the mouths of creeks and canals along the shoreline of Biscayne Bay and Florida Bay. The hypersaline (>40) measurements were recorded in Florida Bay during the summer, mostly in isolated shallow basins where water exchange is limited and evaporation rates are high. Wet season salinities showed a greater range (0–49) and higher standard deviation (12.01; Table 4) than dry season salinities (range, 0–39; standard deviation, 7.22).

Salinity data were compiled for 66 molluscan taxa. Descriptive statistics for the 36 taxa selected for the CONFID analogue dataset are shown in Table 1. Eight taxonomic groups in the CONFID dataset have inner quartile salinity ranges of less than six. Excluding outliers, the salinity range is less than 14 and the minimum salinity is greater than 25. These taxa are placed in the poly-euhaline salinity preference category (Table 1). The taxa in this category generally have lower standard deviations and are typically considered to be more open marine stenohaline fauna (e.g., *Astralium* and *Lithopoma* in the Turbinidae group, Pinnidae, and *Tegula*).

Three categories of gastropods typically classified as freshwater are included in the analyses; however, the salinity range observed in the field for these groups is 0–33 (including outliers). Despite their measured salinity ranges, all three of these categories indicate proximity to freshwater influx. Hydrobiids, one of the categories, are frequently rafted out into the estuaries on currents from creeks and canals (personal observation). It is unknown

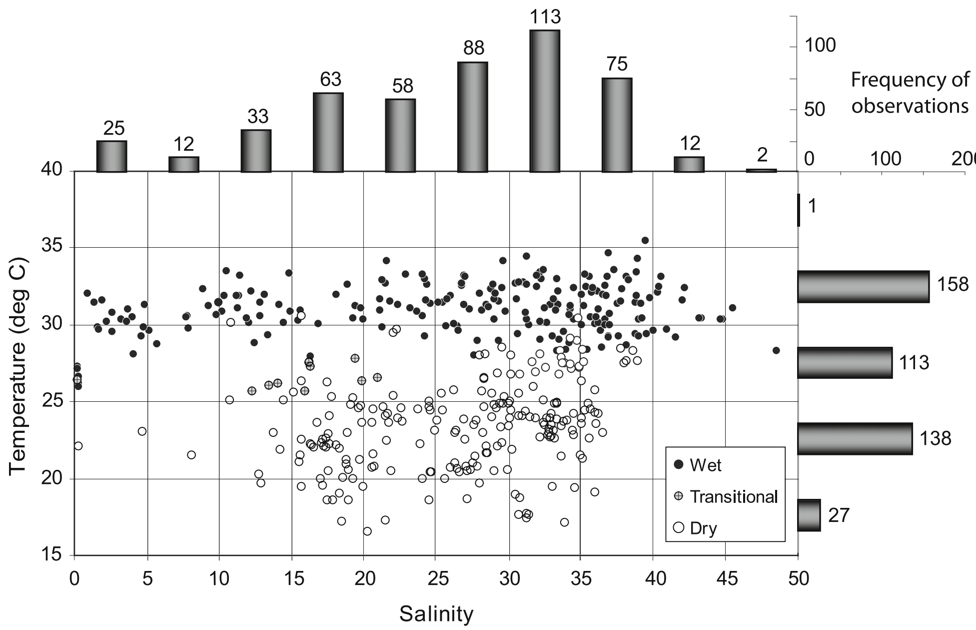


Fig. 3 Comparison of temperature (in °C) and salinity (in PSU) for observations included in the modern analogue dataset. Histograms on *x*- and *y*-axis show frequency distribution of observations

how long freshwater hydrobiids can survive in more saline waters, but some species are adapted to low salinities. In order to distinguish hydrobiid species, however, examination of soft-tissue is necessary and this process was not undertaken because it is not applicable to death assemblages. *Melanoides tuberculatus*, another group typically considered to be freshwater gastropods, have been introduced to south Florida and are adapting to higher salinities (Wingard et al. 2008; Murray et al. 2010). While the hydrobiids and *Melanoides* are not exclusively freshwater species, they are indicative of the presence of freshwater influx and therefore are categorized as such for these analyses. The third group, "freshwater gastropods" includes all other freshwater taxa that are carried out into the estuaries on the currents (e.g., *Physa* and *Planorbella*).

The remaining taxonomic groups have inner quartile salinity ranges of greater than six. Excluding outliers, the salinity range is greater than 14 and the minimum salinity is less than 25. These fauna are split into two salinity preference categories: ubiquitous and euryhaline. The eight ubiquitous species have been found in salinities less than five; typically, these species have salinity ranges greater than 35 and higher standard deviations. The ubiquitous species can be found in most locations and most salinity regimes in Florida Bay and includes species such as *Brachidontes exustus, Cerithidea costata*, *Cerithium muscarum*, and *Chione cancellata*. The euryhaline salinity category includes species with minimum salinities above five and generally the salinity ranges are less than 35. *Bittiolum varium*, *Bulla striata*, and *Modulus modulus* are in the euryhaline category and these species are relatively common at many sites in Florida Bay.

Table 4 Summary statistics on environmental conditions in which modern analogue data were collected

	Wet season	Dry season	Overall[a]
Salinity			
Minimum	0.22	0.30	0.22
Maximum	48.53	38.94	48.53
Mean	25.81	26.50	25.92
Median	28.88	28.01	28.00
Standard deviation	12.01	7.22	9.97
No. of observations[a]	236	235	481
Temperature			
Minimum	25.93	16.55	16.55
Maximum	35.48	30.55	35.48
Mean	31.04	23.40	27.07
Median	31.10	23.54	27.81
Standard deviation	1.61	2.89	4.44
No. of observations[a]	206	221	437

[a] Number of total observations for temperature and salinity, and for wet season, dry season, and overall are not the same for the following reasons: (1) first year of sampling only salinity was measured, and in subsequent years if primary multisensor devices malfunctioned, year 1 backup method was used to record salinity only; (2) ten samples were collected during transitions between wet and dry seasons in October, 2004, so these were not included in either category but did contribute to the overall dataset

Correlation of CWP to Instrumental Data

A summary of the fixed water monitoring station data obtained for each push-core location is included in Table 2. The stations fall into two general categories: (1) stations with 3-year mean salinity ≤25 and standard deviations >9.0;

and (2) stations with 3-year mean salinity >30 and standard deviations <7. The lower salinities and higher standard deviations are recorded at Little Madeira Bay (site 8) and Trout Creek (site 2) water monitoring stations in the northern margin of Florida Bay, where freshwater outflow typically lowers salinity, and the pulses of freshwater influx cause significant fluctuations. Higher 3-year mean salinities and intermediate standard deviations are recorded for the isolated basins near the Bob Allen mudbank and Bob Allen Keys (sites 13 and 14) and Whipray Basin (site 21). The more open areas of western Florida Bay and the Atlantic transition zone (sites 17, 18, and 26) have the lowest standard deviations and slightly higher mean salinities on average.

The correlation coefficients between the calculated salinity (CWP) for the modern push-core test samples and the averaged salinity measured from the fixed water monitoring stations are shown in Table 5. Across all time intervals greater than 1 month, the CONFID dataset that included the pristine, broken and whole shells has the highest correlation coefficients, with little difference between the mean and median values. Across all eight trials, the highest correlation values (r>0.83) are recorded for the 24 to 36 month time periods. The lowest correlation coefficients for the eight trials were recorded for 3-month time period.

Figure 4 illustrates the relationship between the uncalibrated CWP estimated salinities for the FULL and CONFID and the observed salinities for 36-month time period (values in Table 6). The mean CWP salinity estimate for all sites is approximately 26, with a value of 24 for the nearshore sites, and 27 for the basin sites. There are few differences between the CONFID and FULL datasets. The close proximity of the values is expected because the CWP estimate is a measure of the central tendencies of the data. The measured salinities illustrate a bimodal aspect, with the lower salinities (13–19) occurring at the two nearshore transitional zone sites (Site 2, Trout Creek and Site 8, Little Madeira Bay), and the higher salinities (31–36) at the central and western bay sites.

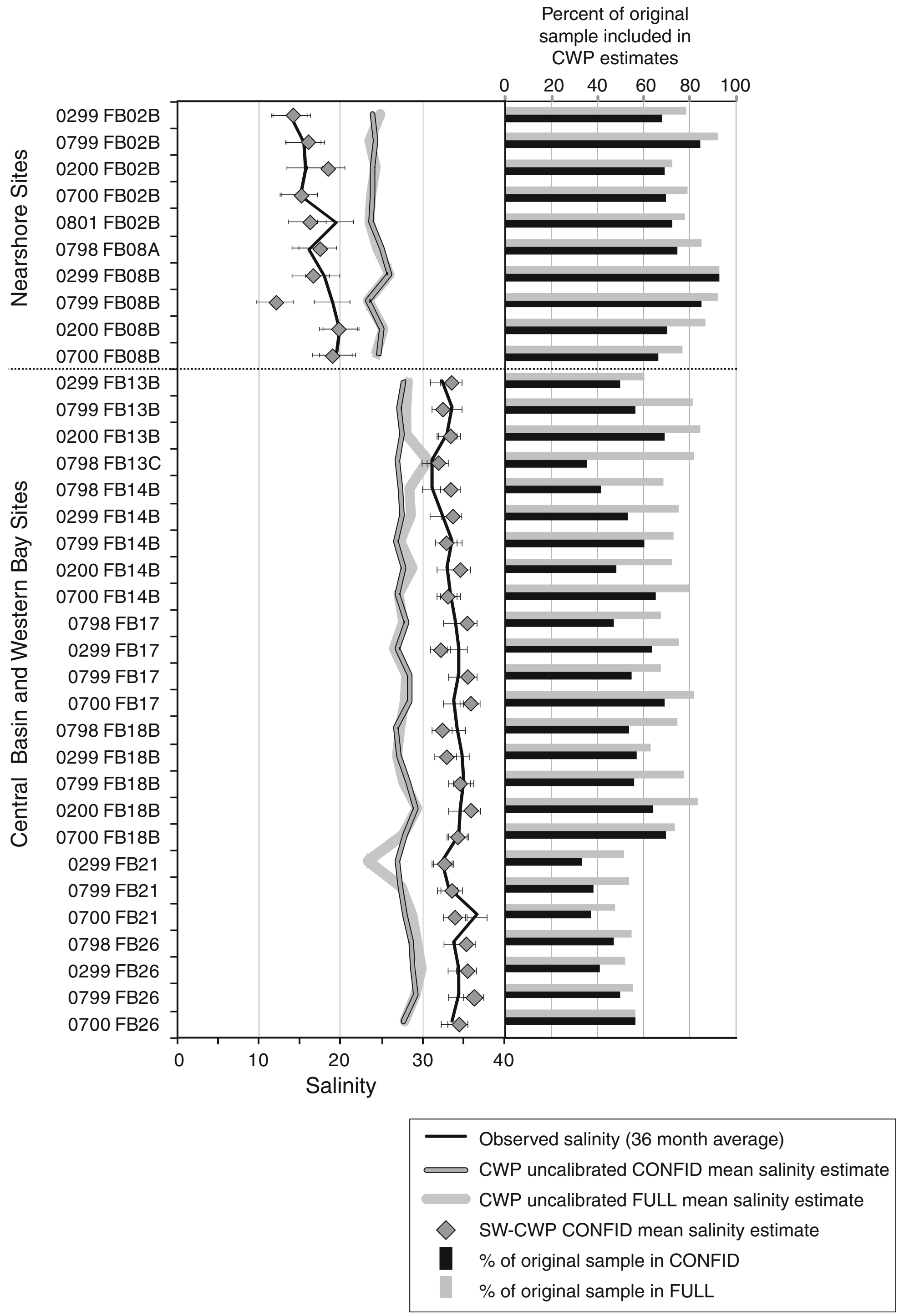
Calibration of CWP to Observed

The CONFID dataset provided the best initial estimate of the salinity at each site, so this dataset (pristine, broken and whole shells included) was selected for the calibration step. Figure 4 compares the SW-CWP to the observed and to the uncalibrated CWP (no species weightings). The SW-CWP estimates fall within the standard deviation of observed salinity for all samples except GLW0799 FB08B. Differences between the observed and the estimated salinities and confidence intervals are shown on Table 6. The mean SW-CWP for all sites equals the observed salinity for all sites

Table 5 Correlation coefficient (r) comparing hydrologic station data averaged over different time periods (Table 2) to the results of the uncalibrated cumulative weighted percent (CWP) analysis

CWP analyses			Correlation coefficient (r) between average hydrologic station salinity and CWP calculated salinity									
Statistical measure	Calibration data set	Preservation categories	1 day	1 week	1 month	3 months	6 months	12 months	18 months	24 months	30 months	36 months
Mean	FULL	Pr+Br	0.6630	0.6878	0.6434	0.5523	0.6439	0.7971	0.8108	0.8664	0.8553	0.8717
Mean	CONFID	Pr+Br	0.5973	0.6385	0.5985	0.5349	0.6617	0.8011	0.8200	0.8574	0.8563	0.8727
Mean	FULL	Pr+Br+Wh	0.7137	0.7310	0.6952	0.6140	0.6826	0.7808	0.7995	0.8637	0.8447	0.8570
Mean	CONFID	Pr+Br+Wh	0.6755	0.7062	0.6756	0.6093	0.7254	0.8408	0.8602	0.9082	0.8999	0.9107
Median	FULL	Pr+Br	0.6623	0.6935	0.6275	0.5211	0.6192	0.7832	0.8060	0.8634	0.8431	0.8584
Median	CONFID	Pr+Br	0.6068	0.6535	0.5890	0.5095	0.6357	0.7845	0.8011	0.8441	0.8333	0.8483
Median	FULL	Pr+Br+Wh	0.7143	0.7367	0.6916	0.5999	0.6788	0.7784	0.8037	0.8658	0.8432	0.8556
Median	CONFID	Pr+Br+Wh	0.6764	0.7102	0.6674	0.5879	0.7073	0.8266	0.8495	0.8991	0.8851	0.8955

Fig. 4 Comparison of the observed water monitoring station data averaged over 36 months (Table 2) to the uncalibrated cumulative weighted percent (*CWP*) salinity estimates (in PSU) for the CONFID and FULL subsets and to the calibrated species-weighted CWP (*SW-CWP*) salinity estimates (in PSU). Data plotted include the subset of the pristine, whole, and broken shells. *Error bars* are standard deviations for SW-CWP and observed salinity. Histogram on the *right* shows the percent of the original sample fauna included in the CONFID and FULL datasets. Table 6 displays the values plotted here



(28.92). The mean difference for all sites is 1.37, for the nearshore 1.69, and for the basin 1.24. This indicates the SW-CWP method on average comes within less than 2 salinity units of estimating the average observed salinity over a 3-year time period for sites within Florida Bay. The confidence intervals for the estimated salinities are only slightly higher (0.15) than the confidence intervals for the observed salinities.

Application of SW-CWP to Ecosystem History Analyses

The results of the SW-CWP analyses of a piston core from the mouth of Taylor Slough are shown on Fig. 5, alongside plots of the abundance of key molluscan salinity indicators in the core. The SW-CWP salinity estimates agree with the salinity estimates derived from qualitative paleoecologic analyses of faunal assemblages (Fig. 5;

Table 6 Comparison of uncalibrated cumulative weighted percent (CWP) for FULL and CONFID data subsets, calibrated species-weighted CWP (SW-CWP), and observed instrumental data, averaged over a 36-month period preceding sample collection (Table 2)

	Sample identification	Site number	Date collected	Uncalibrated CWP mean salinity estimates (Pr+Br+Wh)		Calibrated SW-CWP mean salinity estimates (Pr+Br+Wh)	Observed 36-month average instrumental salinity	Difference (calibrated–observed)
				FULL	CONFID	CONFID		
Nearshore sites	GLW0299 FB02B	2	2/17/1999	24.83	23.93	14.05	13.92	0.13
	GLW0799 FB02B	2	7/7/1999	23.55	24.26	15.91	15.56	0.35
	GLW0200 FB02B	2	2/17/2000	24.38	23.99	18.33	15.72	2.61
	GLW0700 FB02B	2	7/6/2000	23.74	23.92	15.05	15.04	0.01
	GLW0801 FB02B	2	8/17/2001	23.64	23.73	16.13	19.42	3.30
	GLW0798 FB08A	8	7/8/1998	24.43	25.13	17.35	16.23	1.12
	GLW0299 FB08B	8	2/16/1999	26.02	26.02	16.50	17.94	1.44
	GLW0799 FB08B	8	7/6/1999	23.45	23.44	11.97	19.07	7.09
	GLW0200 FB08B	8	2/18/2000	25.31	25.06	19.63	19.85	0.22
	GLW0700 FB08B	8	7/7/2000	24.43	24.72	18.87	19.54	0.68
Basin/Central Bay sites	GLW0299 FB13B	13	2/19/1999	28.21	27.58	33.47	32.25	1.22
	GLW0799 FB13B	13	7/9/1999	27.96	27.09	32.40	33.51	1.12
	GLW0200 FB13B	13	2/18/2000	28.03	27.45	33.34	32.96	0.39
	GLW0798 FB13C	13	7/9/1998	30.60	26.94	31.87	31.04	0.82
	GLW0798 FB14B	14	7/9/1998	28.46	27.28	33.37	31.04	2.33
	GLW0299 FB14B	14	2/19/1999	28.51	27.40	33.63	32.25	1.38
	GLW0799 FB14B	14	7/9/1999	27.22	26.77	32.84	33.51	0.68
	GLW0200 FB14B	14	2/18/2000	28.80	27.69	34.54	32.96	1.58
	GLW0700 FB14B	14	7/10/2000	27.05	26.87	33.02	33.37	0.35
	GLW0798 FB17	17	7/13/1998	27.71	28.11	35.39	33.88	1.52
	GLW0299 FB17	17	2/19/1999	26.47	26.91	32.15	34.24	2.09
	GLW0799 FB17	17	7/8/1999	28.06	28.46	35.45	34.36	1.09
	GLW0700 FB17	17	7/12/2000	27.94	28.36	35.83	33.77	2.06
	GLW0798 FB18B	18	7/13/1998	27.21	26.81	32.34	34.10	1.76
	GLW0299 FB18B	18	2/20/1999	26.88	27.08	32.87	34.73	1.86
	GLW0799 FB18B	18	7/9/1999	27.61	28.25	34.50	34.98	0.48
	GLW0200 FB18B	18	2/16/2000	29.36	29.15	35.85	34.51	1.34
	GLW0700 FB18B	18	7/12/2000	27.59	27.82	34.23	34.40	0.17
	GLW0299 FB21	21	2/20/1999	23.32	26.83	32.59	32.31	0.29
	GLW0799 FB21	21	7/8/1999	27.55	27.23	33.52	33.01	0.50
	GLW0700 FB21	21	7/10/2000	28.85	27.80	33.88	36.63	2.75
	GLW0798 FB26	26	7/10/1998	29.36	28.64	35.27	33.77	1.50
	GLW0299 FB26	26	2/21/1999	29.97	28.82	35.43	34.37	1.06
	GLW0799 FB26	26	7/12/1999	29.06	29.24	36.26	34.41	1.85
	GLW0700 FB26	26	7/12/2000	27.81	27.74	34.40	33.52	0.88
Mean			All sites	26.95	26.76	28.92	28.92	1.37
			Nearshore	24.38	24.42	16.38	17.23	1.69
			Basin	27.98	27.69	33.94	33.60	1.24
Standard deviation			All sites			8.21	7.59	
			Nearshore			2.32	2.18	
			Basin			1.30	1.23	
Confidence interval (95%)			All sites			28.92±2.82	28.92±2.67	
			Nearshore			16.38±1.66	17.23±1.64	
			Basin			33.94±0.54	33.60±0.52	

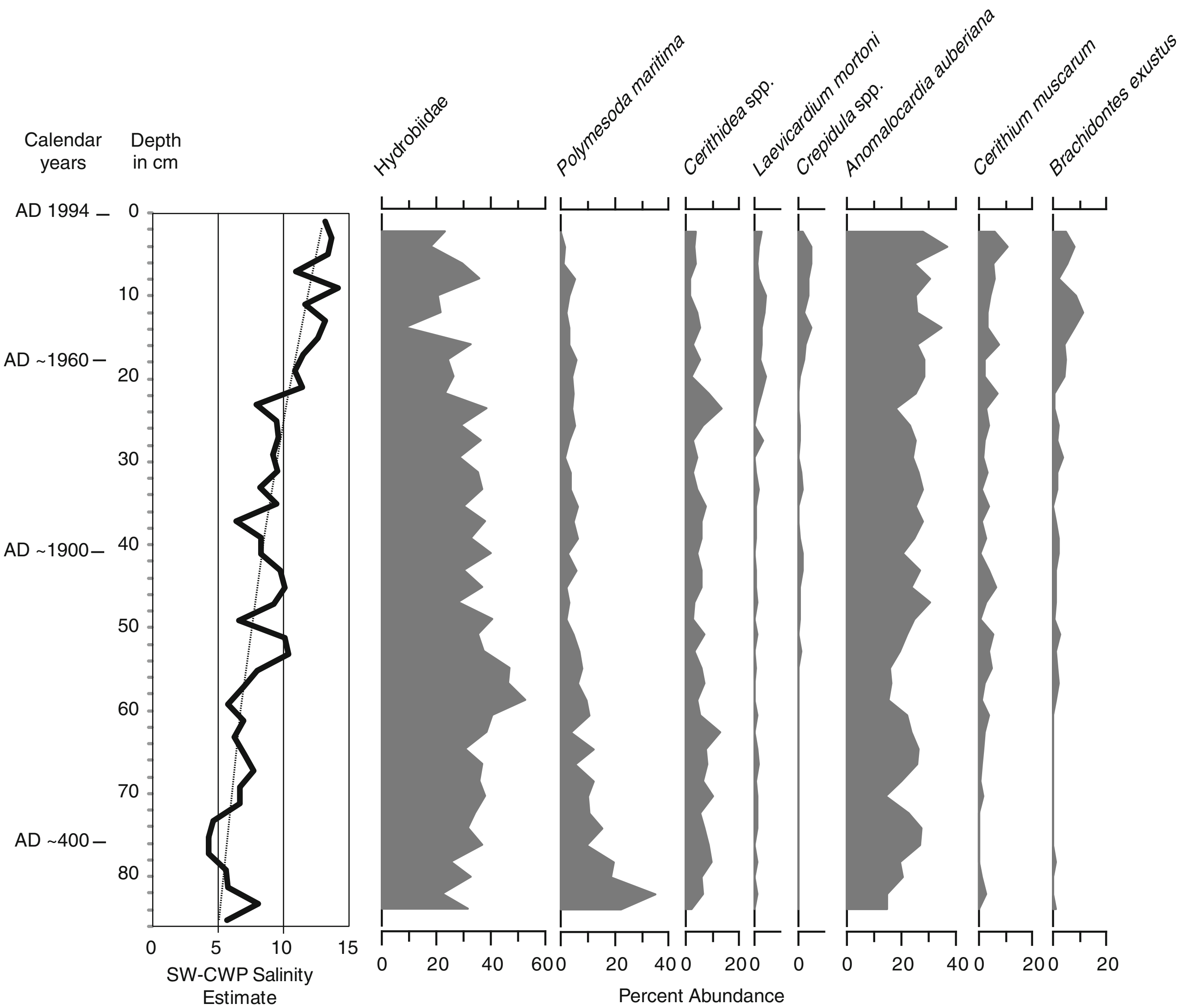


Fig. 5 Plot of species-weighted CWP (*SW-CWP*) mean salinity estimates (in PSU) for core from the mouth of Taylor Slough (FB594 24/T24) plotted against depth in centimeters on the *y*-axis. Calendar years AD located on the *left-hand side* are derived from lead-210, carbon-14, and pollen biostratigraphy (Wingard et al. 2007b). Trend line for SW-CWP is plotted. *Right-hand side* shows the percent abundance of key indicator molluscan fauna in the core (data originally published in Brewster-Wingard et al. 2001)

Brewster-Wingard et al. 1998, 2001). Salinity estimates for the lower portion of the core (approximately 86–56 cm) fluctuate between four and eight. Between 58 and 24 cm, estimated salinity increases to between six and ten, consistent with the gradual decline in hydrobiids. Above 24 cm, estimated salinity increases to ten to 14. The upper portion of the core corresponds to deposition in the second half of the twentieth century, and the fauna illustrate significant declines in hydrobiids, loss of *Polymesoda maritima* (a reported mesohaline species), and increases in the ubiquitous species *Anomalocardia auberiana*, *C. muscarum*, and *B. exustus* during this time period.

Discussion

Calibration of the CWP

The uncalibrated CWP (Fig. 4) illustrates a problem inherent in all weighted-averaging techniques—it emphasizes the central tendencies of the data. Thus, the nearshore lower salinity sites are overestimated and the central and western basin higher salinity sites are underestimated. Yuan (2005) and Marchetto (1994) identify this overestimation in the low end of the sampled range and underestimation in the upper end as being a typical result of weighted-averaging techniques, and suggest "deshrinking" as a means to correct for this emphasis on the central tendencies of the data (see also, Birks et al. 1990).

We explored the idea of developing a deshrinking function, which would use a linear equation based on the current environmental conditions to drive the CWP estimates toward the instrumental measurements. We rejected this method, however, because it relies solely on the current salinity conditions to correct the estimates. Instead, we opted to use species weighting factors to calibrate the CWP estimates to the instrumental data because these factors are derived from both the current salinity regime and knowledge of the species salinity optima. We acknowledge that this is not ideal because a component of the correction is still based on an anthropogenically altered salinity regime; however, at the present we believe the SW-CWP offers the best method available to estimate the pre-anthropogenic conditions of south Florida's estuaries in order to develop salinity targets and performance measurements for restoration.

Using the knowledge of the species salinity optima as one component of the CWP calibration process requires the assumption that the fauna living in Florida Bay today have the same general tolerances, salinity range, and species optima as the same species did over the last few centuries to millennium. It also assumes that other factors, such as changing pH, rainfall, or nutrient levels have not had compounding influences on the osmoregulation process of the fauna. We believe these assumptions are valid; however, the use of assemblage data decreases the impact on our calculations if these assumptions might be false for a few species (Bosence and Allison 1995). The weightings are based on over a decade of data on molluscan occurrence and salinity preferences and were only applied to the CONFID dataset where we have enough data to believe we have adequately captured the species optima. The application of two different weighting factors (Table 3) for ubiquitous species in the nearshore sites versus the central and western bay sites solved the problem of averaging data for species that can range from salinities of less than ten to greater than 40. We know from observations and measurements that these species do equally well in the low salinity nearshore environments and the higher salinity basin environments, so the 0.24 weighting factor for nearshore sites emphasizes the lower end of the species range and the 1.18 weighting factor for basin and open-water sites emphasizes the higher range. The presence of any freshwater species in a sample is highly significant and indicates a shift toward lower salinities, which is emphasized by the 0.30 factor. The presence of the more stenohaline species (the poly-euhaline category) also is significant (weighting factor, 1.50) because it emphasizes a more open-water environment. The application of these species weighting factors calibrates the CWP and provides salinity estimates that on average come within less than two salinity units of the observed salinity (Table 6).

Application of CWP Method

The results of the test and calibration of the CWP method (Fig. 4; Table 6) indicate that this method can be applied to molluscan down-core assemblages to provide estimates of historical salinity patterns in the absence of instrumental data. This is highly significant for the purposes of the CERP. If the estuaries of the south Florida ecosystem are to be restored, it is essential to understand the impact of changes in freshwater delivery to the estuaries. Historical instrumental salinity data are spotty at best, and few records prior to 1950 exist (Robblee et al. 1989; Nuttle et al. 2000). Marshall et al. (2009) developed a method of coupling paleoecologic data with linear regression models to estimate historical hydrologic patterns in south Florida, based on qualitative paleoecologic interpretations of the down-core assemblages. The CWP method illustrated here, combined with the analogue dataset, provides a quantitative tool for application to the linear regression models of Marshall et al. (2009).

The initial CWP trials (Table 5) indicated which combinations of data yield the best results, enabling us to determine which subsets should be used for the calibration step and for analyses of data from piston cores collected for paleoecologic studies. The similarity of results between the mean and the median trials suggests that the samples are close to normal distributions, and that either value could be used for output; however, the r values for the mean are slightly higher, so we used the mean for calibration. In general, the combination of the pristine, broken and whole individuals provided higher r values than the combination of pristine and broken specimens, most likely because more taxa from the modern analogue dataset were included allowing for more accurate calculations of the salinity.

The comparison of the correlation coefficients across the different time periods provided a means to estimate temporal resolution of the CWP method in piston cores (Table 5). The highest correlation coefficients across all trials are in the 24- to 36-month time periods, and the lowest correlation coefficients are for the 3-month time periods. The high correlations for 24 to 36 months are not unexpected because generally the more data you are averaging, the more likely you will smooth out anomalies, such as El Niño years or drought years. The 2–3-year time period is significant for analysis of Florida Bay sediment cores. Holmes et al. (2001) have demonstrated that the average sedimentation rate for Florida Bay mudbanks is ~1.3-cm per year. Two-centimeter thick surface samples were utilized for this test of the CWP method, so the samples represent an approximately 2–3-year average period of deposition and correspond to the same thickness used in analysis of sediment cores in south Florida's estuaries by USGS researchers (for example, Brewster-Wingard et al. 1998, 2001; Cronin et al. 2001; Wingard et al. 2003, 2004). The results indicate the CWP salinity estimates used for interpretation of sediment cores from Florida Bay represent an average of 2–3 years (based on typical sedimentation rates), and therefore can be used to reconstruct sub-decadal scale changes in salinity patterns. Variations in sedimentation rates with depth will vary the temporal resolution of the CWP salinity estimates, but it will not introduce error into the calculation of the estimates themselves.

The SW-CWP salinity estimates for the Taylor Slough core provide an example of how the method will be applied to additional cores from the estuaries in the south Florida ecosystem. The strength of this method is that the initial CWP is built from the assemblage of species present in the core, applying the average salinity values recorded in the modern environment. While species patterns of dominance may have changed over the last 100–500 years, we assume their salinity preferences have not and that other environmental factors have not altered their osmoregulatory responses; thus, we can interpret salinity patterns in areas that have undergone change, as long as we have data on the species from the modern environment. For example, the low salinity regime seen in the lower portion of the Taylor Slough core does not exist in our push-core test set, but we do have data on the individual species preferences, which allows us to estimate the salinity for this assemblage. Traditional qualitative paleoecologic faunal analyses serve as a check for the SW-CWP results as they have in this example from Taylor Slough (Fig. 5); however, when primarily euryhaline fauna are present, faunal assemblages can be difficult to interpret. The CWP method also has the advantage of summarizing the fluctuations of multiple species abundance patterns into single points that represent changes in the mean salinity estimates over sub-decadal time spans, thus highlighting shifts in the general salinity pattern not revealed by traditional faunal assemblage plots.

Sources of Error in the Modern Analogue Dataset

Understanding the potential sources and distribution of error is essential in order to apply the CWP method to the determination of targets for salinity, freshwater flow and other critical restoration performance measures. In any modern analogue method, the ideal condition is for the sampled environmental range to encompass the true species range and for the analogue dataset to include the same species and environmental conditions as the validation test dataset (Hutson 1977; ter Braak and Looman 1986; Yuan 2005). As stated above, we are assuming the species included in the analogue dataset have not altered their salinity preferences or their osmoregulation in response to other environmental changes over the time periods being studied in the cores. Yuan (2005) discusses the role of the analogue data in introducing bias when using weighted averages to infer environmental variables. He states that the two primary sources of error in a weighted average environmental inference are (1) the error caused by inferring environmental conditions from a finite range of species optima and (2) the error in the estimates of those optima, with the second being the primary source of error (Yuan 2005). The test of our analogue dataset was designed to reduce the sources of error primarily to the modern analogue dataset itself—the estimates of the "species optima". Bigler and Hall (2003) discuss the circular reasoning involved when the validation data and the calibration data come from the same initial dataset. In our initial uncalibrated CWP, we tested the analogue dataset and method against an independent validation dataset (the push-cores) and to instrumentally measured (not inferred) salinity data. Any errors associated with the count data from the push-cores and the salinity data from the monitoring stations are nominal. In addition, our analogue data and push-core test data are from the same location, increasing the likelihood of similar taxa and environmental conditions.

The risk of bias increased, however, when we added the calibration step, because the push-core test set is used to adjust the species weighting factors to drive the CWP toward the instrumental readings. As stated above, south Florida's estuaries are altered systems, so our correction factors contain some bias. The current Florida Bay ecosystem does not contain the same range of oligohaline to euhaline environments that existed in the past, based on qualitative assemblage analyses. For example, mesohaline fauna are rare in Florida Bay today and the majority of the species are euryhaline, with wide ranges of salinity tolerances that emphasize central tendencies when averaged. In addition, the modern analogue dataset contains few observations made under more extreme salinity conditions (salinities, <10 and > 40) (Fig. 3). Yuan (2005, p. 245) shows that biases are dependent "upon the range of conditions sampled in the calibration dataset and the true optima and niche breadths of the species observed in the calibration dataset." If the initial analogue dataset does not cover the full spectrum of possible conditions it increases the likelihood of a bias (ter Braak and Looman 1986). Salinity extremes are particularly important in the analysis of historical salinity patterns in south Florida's estuaries and can be related to regional climate patterns. Within our modern analogue dataset, 11 of the 37 observations of salinities less than ten occurred immediately following Hurricane Dennis in July 2005. Eight of the 14 highest salinity observations (>40) occurred in the summer of 2001, following one of the driest periods recorded in state history.[2]

[2] Statewide precipitation data collected between 1895 and 2005 ranks the period from January 2000 through February 2001 as the fifth driest period on record for the state (http://climvis.ncdc.noaa.gov).

Improvements to CWP Method

One of the primary sources of error in the CWP calculation is the compiled salinity data for each species, so increasing the number of observations included in the analogue dataset would increase the reliability of the data (up to a certain limit). More observations also would allow us to move species from the FULL to the CONFID dataset, thus reducing the number of species present in the initial samples, but excluded from the SW-CWP calculations. The histogram on Fig. 4 compares the percent of taxa included in the calculations from the FULL and CONFID datasets compared with the full assemblage in the original sample. Particular gaps in the modern analogue dataset are the following: (1) species that live under the more extreme salinity (<10 and >40) conditions, (2) stenohaline species (current dataset is predominantly euryhaline species), and (3) more infaunal taxa (current dataset is predominantly epifaunal). Additionally, information is being lost in the process of lumping individual species into larger taxonomic groups (see notes on Table 1); for example, different species of Tellinidae or Collumbellidae have different salinity preferences. Continuing sampling efforts since July 2007 are filling in some of these data gaps (all data are available at http://sofia.usgs.gov/exchange/flaecohist/). Another possible source of error is bias introduced by deriving the species weights for the calibration step from the initial CWP push-core test set. One of the next steps will be to test the calibration against an independent modern sample set.

The possibility of using counts of species abundance for the modern analogue dataset instead of the current presence/absence observations of living mollusks will be explored. Counts of the abundance of species may provide us with a better estimate of the true salinity optima for any given taxon, thus reducing the error in the calculation. In Yuan's (2005, p. 252) comparison of presence/absence data to relative abundance data, however, he noted that the data "exhibited approximately the same behavior." In contrast, Gasse and Tekaia (1983) point out the species preference is more important than species tolerance; abundance data would give us a better indication of species salinity preferences. Species counts are time and labor intensive, so for now we have utilized the presence/absence method, but future work will consider how the salinity estimates might be improved by incorporating abundance data.

Conclusions

The CWP method was developed as a means to provide modelers and those responsible for restoration of south Florida's estuaries with a salinity estimate for core samples that predates instrumental data records. The CWP contains several advantages over traditional qualitative paleoecologic assemblage analyses: (1) it is a single value that can be used in statistical models; (2) it is based upon empirical data and the sources of error are mostly understood; (3) standard deviations and confidence intervals provide a means for assessing the reliability of the estimates. The initial trials of the uncalibrated CWP indicated which subsets of the modern analogue data set and of the samples provided the best input to the analyses. In general, the modern analogue CONFID subset (observations, ≥10; confidence interval, <5±the mean at a 95% confidence level) with the pristine, whole, and broken shells included provided the best correlations to the actual data. This subset was utilized in the calibration data step, and the results indicate that the SW-CWP method utilizing our current analogue dataset can estimate observed salinity within an average of less than two salinity units. The differences between the nearshore observed and estimated values are greater than the basin sites, but this is to be expected given the higher standard deviation in actual salinity at these locations. Basin locations have better correspondence between observed and estimated, and lower standard deviations for the instrumental measurements.

The test of the modern analogue dataset and the CWP method has demonstrated that these techniques can supply reliable estimates of paleosalinity for south Florida's estuaries with measurable levels of confidence and associated errors. These estimates are sub-decadal salinity values that can be used in linear regression models to estimate historical freshwater flow and stage in the Everglades using the methods outlined in Marshall et al. (2009). The results will allow CERP restoration teams to establish performance measures and targets for the greater Everglades ecosystem restoration that incorporate an understanding of the pre-anthropogenic system.

Acknowledgments We would like to thank Thomas M. Cronin and Harry J. Dowsett, U.S. Geological Survey (USGS) for their early reviews of the manuscript, and two anonymous reviewers whose thorough comments have improved the final version. The statistical components of this research have benefited greatly from discussions with Frank Marshall (Cetacean Logic Foundation), Harry Dowsett (USGS), and Lucy Edwards (USGS). Patrick Pitts (U.S. Fish & Wildlife) has provided valuable insights and kept us on track in our goal to develop a method applicable to restoration issues. Emily Philips (formerly USGS) and Bethany Stackhouse (USGS) prepared the map, and B. Stackhouse assisted in the final proofing of the data. This research was funded by the U.S. Geological Survey Priority Ecosystems South Florida Study Unit (coordinated by G. Ronnie Best, USGS). Everglades National Park and Biscayne National Park facilitated our field work; research was conducted under NPS study numbers EVER-00141 and BISC-02027. Numerous people have assisted with the field and lab work that contributed to development of the modern analogue dataset. We would especially like to thank James Murray and Rob Stamm (USGS); Jeffery Stone (University of Nebraska, Lincoln); Sara Schwede-Thomas, Carleigh Trappe, Carlos Budet, and Ruth Ortiz (former USGS contractors); and Thomas Scott (retired, Florida Geological Survey) and G. Harley Means (Florida Geological Survey). The staff at Keys Marine Lab, Layton, Florida provided boats and facilities over the years.

Conflict of Interest Notification Page This work was funded entirely by the U.S. Geological Survey, for whom I work, and no conflict of interest exists because we are a science agency and do not have a regulatory mission. As a federal government agency, all data are part of the public domain, and can be provided in any format necessary if requested.

References

Allmon, W.D. 1993. Environment and mode of deposition of the densely fossiliferous Pinecrest Sand (Pliocene of Florida): Implications for the Role of Biological Productivity in Shell Bed Formation. *Palaios* 8: 183–201.

Alvarez Zarikian, C.A., P.K. Swart, T. Hood, P.L. Blackwelder, T.A. Nelsen, and C. Featherstone. 2001. A century of variability in Oyster Bay using ostracode ecological and isotopic data as paleoenvironmental tools. *Bulletins of American Paleontology* 361: 133–143.

Andreasson, F.P., B. Schmitz, and E. Jönsson. 1999. Surface-water seasonality from stable isotope profiles *Littorina littorea* shells: implications for paleoenvironmental reconstructions of coastal areas. *Palaios* 14: 273–281.

Arthur, M.A., D.F. Williams, and D.S. Jones. 1983. Seasonal temperature-salinity changes and thermocline development in the mid-Atlantic Bight as recorded by the isotopic composition of bivalves. *Geology* 11: 655–659.

Bieler, R., and P. Mikkelsen. 2002. Bivalve Studies in the Florida Keys: Proceedings from the International Bivalve Workshop, Long Key, Florida, July 2002. *Malacologia* 46: 1–677.

Bigler, C., and R.I. Hall. 2003. Diatoms as quantitative indicators of July temperature: a validation attempt at a century-scale with meteorological data from northern Sweden. *Palaeogeography, Palaeoclimatology, Palaeoecology* 189: 147–160.

Birks, H.J.B., J.M. Line, S. Juggins, A.C. Stevenson, and C.J.F. ter Braak. 1990. Diatoms and pH reconstruction. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* 327: 263–278.

Bosence, D.W.J. and P.A. Allison. 1995. A review of marine paleoenvironmental analysis from fossils. In Marine palaeoenvironmental analysis from fossils, eds. D.W.J. Bosence and P.A. Allison, 1–5. London, U.K., Geological Society of London, special publication 83.

Brett, C.E., A.J. Boucot, and B. Jones. 1993. Absolute depths of Silurian benthic assemblages. *Lethaia* 26: 25–40.

Brewster-Wingard, G.L., S.E. Ishman, and C.W. Holmes. 1998. Environmental impacts on the southern Florida coastal waters: A history of change in Florida Bay. *Journal of Coastal Research* 26: 162–172.

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.

Browder, J., J. Serafy, C. Buckingham, S. Blair, S. Markley, D. Smith, D. Rudnick, T. Schmidt, P. Pitts, D. Deis, C. Kelble, F. Marshall. 2008. Southern estuaries – salinity documentation sheet. CERP System-wide performance measure. http://www.evergladesplan.org/pm/recover/recover_docs/perf_measures/090108_se_salinity.pdf. Accessed 2 June 2011.

Brush, G.S., and W.B. Hilgartner. 2000. Paleoecology of submerged macrophytes in the upper Chesapeake Bay. *Ecological Monographs* 70: 645–667.

Byrne, R.B.L., S.S. Ingram, and F. Malamud-Roam. 2001. Carbon-isotope, diatom, and pollen evidence for Late Holocene salinity change in a brackish marsh in San Francisco estuary. *Quaternary Research* 55: 66–76.

Conrad, T.A. 1838. *Fossils of the Medial Tertiary*. Philadelphia: Judah Dobson.

Cornu, S., J. Pätzold, E. Bard, J. Meco, and J. Cuerda-Barcelo. 1993. Paleotemperature of the last interglacial period based on $\delta^{18}O$ of *Strombus bubonius* from the western Mediterranean Sea. *Palaeogeography, Palaeoclimatology, Palaeoecology* 103: 1–20.

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.

Cronin, T.M., R. Thunell, G.S. Dwyer, C. Saenger, M.E. Mann, C. Vann, and R.R. Seal Jr. 2005. Multiproxy evidence of Holocene climate variability from estuarine sediments, eastern North America. *Paleoceanography*. doi:10.1029/2005PA001145.

Dominici, S., and T. Kowalke. 2007. Depositional dynamics and the record of ecosystem stability: early Eocene faunal gradients in the Pyrenean foreland, Spain. *Palaios* 22: 268–284.

Dowsett, H.J. 2007. The PRISM palaeoclimate reconstruction and Pliocene sea-surface temperature. In *Deep-time perspectives on climate change: marrying the signal from computer models and biological proxies*, ed. M. Williams, A.M. Haywood, J. Gregory, and D.N. Schmidt, 459–480. London: Micropalaeontological Society, Geological Society of London.

Dwyer, G.S., and T.M. Cronin. 2001. Ostracode shell chemistry as a paleosalinity proxy in Florida Bay. *Bulletins of American Paleontology* 361: 249–276.

Fürsich, F.T., and E.G. Kauffman. 1983. Paleoecology of marginal marine sedimentary cycles in the Albian Bear River Formation of south-western Wyoming. *Palaeontology* 27: 501–536.

Gasse, F., and F. Tekaia. 1983. Transfer functions for estimating paleoecological conditions (pH) from East African diatoms. *Hydrobiologia* 103: 85–90.

Halley, R.B., and L.M. Roulier. 1999. Reconstructing the history of eastern and central Florida Bay using mollusk-shell isotope records. *Estuaries* 22: 358–368.

Holmes, C.W., J. Robbins, R. Halley, M. Bothner, M. ter Brink, and M. Marot. 2001. Sediment dynamics of Florida Bay mud banks on a decadal time scale. *Bulletins of American Paleontology* 361: 31–40.

Hudson, J.D. 1963. The recognition of salinity-controlled mollusk assemblages in the Great Estuarine Series (Middle Jurassic) of the Inner Hebrides. *Palaeontology* 6: 318–326.

Hutson, W.H. 1977. Transfer functions under no-analog conditions: experiments with Indian Ocean planktonic Foraminifera. *Quaternary Research* 8: 355–367.

Hutson, W.H. 1979. The Agulhas current during the Late Pleistocene: analysis of modern faunal analogs. *Science* 207: 64–66.

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. Turekian, 71–181. New Haven: Yale Univ. Press.

Jones, D.S., and W.D. Allmon. 1995. Records of upwelling, seasonality and growth in stable-isotope profiles from Pliocene mollusk shells from Florida. *Lethaia* 28: 61–74.

Kauffman, E.G. 1969. Cretaceous marine cycles of the Western Interior. *The Mountain Geologist* 6: 227–245.

Krantz, D. 1990. Mollusk-isotope records of Plio-Pleistocene marine paleoclimate, U.S. Middle Atlantic Coastal Plain. *Palaios* 5: 317–335.

Lamarck, J.B. 1802. Memoires sur les fossils des environs de Paris, comprenant la détermination des espèces qui appartiennent aux animaux marins sans vertèbres, et dont la plupart sont figurés dans la collection des vélins du Muséum. *Annales du Muséum National d'Histoire Naturelle* 1: 299–312.

Marchetto, A. 1994. Rescaling species optima estimated by weighted averaging. *Journal of Paleolimnology* 12: 155–162.

Marshall, F.E., G.L. Wingard, and P.A. Pitts. 2009. A Simulation of Historic Hydrology and Salinity in Everglades National Park: Coupling Paleoecologic Assemblage Data with Regression Models. *Estuaries and Coasts* 32: 37–53.

Mikkelsen, P.M., and R. Bieler. 2008. *Seashells of southern Florida: Bivalves*. Princeton: Princeton University Press.

Murray, J.B., G.L. Wingard, and E.C. Philips. 2010. Distribution of the non-native gastropod *Melanoides tuberculatus* in Biscayne National Park, Florida. U.S. Geological Survey Open-File Report 2010–1125. http://sofia.usgs.gov/publications/ofr/2010-1126/index.html. Accessed 18 January 2011.

Nelsen, T.A., G. Garte, C. Featherstone, H.R. Wanless, J.H. Trefry, W. J. Kang, S. Metz, C. Alvarez-Zarikian, T. Hood, P. Swart, G. Ellis, P. Blackwelder, L. Tedesco, C. Slouch, J.F. Pachut, and M. O'Neal. 2002. Linkages between the South Florida peninsula and coastal zone: a sediment-based history of natural and anthropogenic influences. In *Everglades, Florida Bay and coral reefs of the Florida Keys: an ecosystem sourcebook*, ed. J.W. Porter and K.G. Porter, 415–449. Boca Raton: CRC Press.

Nuttle, W.K., J.W. Fourqurean, B.J. Cosby, J.C. Zieman, and M.B. Robblee. 2000. Influence of net freshwater supply on salinity in Florida Bay. *Water Resources Research* 36: 1805–1822.

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.

Robblee, M.B., J.T. Tilmant, and J. Emerson. 1989. Quantitative observations on salinity. *Bulletin of Marine Science* 44: 523.

Rousseau, D.D. 1991. Climatic transfer function from Quaternary molluscs in European loess deposits. *Quaternary Research* 36: 195–209.

Stanton, R.J., and J.R. Dodd. 1970. Paleoecologic techniques—comparison of faunal and geochemical analyses of Pliocene paleoenvironments, Kettleman Hills, California. *Journal of Paleontology* 44: 1092–1121.

Surge, D., K.C. Lohmann, and D.L. Dettman. 2001. Controls on isotopic chemistry of the American oyster, *Crassostrea virginica*: implications for growth patterns. *Palaeogeography, Palaeoclimatology, Palaeoecology* 172: 283–296.

Swart, P.K., G.F. Healy, R.E. Dodge, P. Kramer, J.H. Hudson, R.B. Halley, and M.B. Robblee. 1996. The stable oxygen and carbon isotopic record from a coral growing in Florida Bay: a 160 year record of climatic and anthropogenic influence. *Palaeogeography, Palaeoclimatology, Palaeoecology* 123: 219–237.

Swart, P.K., G.F. 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.

ter Braak, C.J.F., and S. Juggins. 1993. Weighted averaging partial least squares regression (WA-PLS): an improved method for reconstructing environmental variables from species assemblages. *Hydrobiologia* 269(270): 485–502.

ter Braak, C.J.F., and C.W.N. Looman. 1986. Weighted averaging, logistic regression and the Gaussian response model. *Vegetatio* 65: 3–11.

ter Braak, C.J.F., and H. van Dam. 1989. Inferring pH from diatoms: a comparison of old and new calibration methods. *Hydrobiologia* 178: 209–223.

Turgeon, D.D., J.F. Quinn Jr., A.E. Bogan, E.V. Coan, F.G. Hochberg, W.G. Lyons, P.M. Mikkelsen, R.J. Neves, C.F.E. Roper, G. Rosenberg, B. Roth, A. Scheltema, F.G. Thompson, M. Vecchione, and J.D. Williams. 1998. *Common and scientific names of aquatic invertebrates from the United States and Canada: mollusks*, 2nd ed. Bethesda: American Fisheries Society. special publication 26.

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. http://www.evergladesplan.org/. Accessed 18 January 2011.

Vandergoes, M.J., and S.J. Fitzsimons. 2003. The last glacial-interglacial transition (LGIT) in south Westland, New Zealand: paleoecological insight into mid-latitude southern Hemisphere climate change. *Quaternary Science Reviews* 22: 1461–1476.

Willard, D.A., C.E. Bernhardt, D.A. Korejwo, and S.R. Meyers. 2005. Impact of millennial-scale Holocene climate variability of eastern North American terrestrial ecosystems: pollen-based climatic reconstruction. *Global and Planetary Change* 47: 17–35.

Willard, D.A., and T.M. Cronin. 2007. Paleoecology and ecosystem restoration: Case studies from Chesapeake Bay and the Florida Everglades. *Frontiers in Ecology and the Environment* 5: 491–498.

Wingard, G.L., T.M. Cronin, G.S. Dwyer, S.E. Ishman, D.A. Willard, C.W. Holmes, C.E. Bernhardt, C.P. Williams, M.E. Marot, J.B. Murray, R.G. Stamm, J.H. Murray, and C. Budet. 2003. Ecosystem History of Southern and Central Biscayne Bay: Summary Report on Sediment Core Analyses. U.S. Geological Survey, OFR 03–375. http://sofia.usgs.gov/publications/ofr/03-375/. Accessed 18 January 2011.

Wingard, G.L., T.M. Cronin, C.W. Holmes, D.A. Willard, G.S. Dwyer, S.E. Ishman, W. Orem, C.P. Williams, J. Albeitz, C.E. Bernhardt, C. Budet, B. Landacre, T. Lerch, M.E. Marot, and R. Ortiz. 2004. Ecosystem History of Southern and Central Biscayne Bay: Summary Report on Sediment Core Analyses—Year Two. U.S. Geological Survey, OFR 2004–1312. http://sofia.usgs.gov/publications/ofr/2004-1312/. Accessed 18 January 2011.

Wingard, G.L., T.M. Cronin, and W. Orem. 2007a. Ecosystem History. In *Florida Bay Science Program: a synthesis of research on Florida Bay*, ed. J.H. Hunt and W. Nuttle, 9–29. St. Petersburg: Fish and Wildlife Research Institute Report TR-11.

Wingard, G.L., J.W. Hudley, C.W. Holmes, D.A. Willard, and M. Marot. 2007. Synthesis of Age Data and Chronology for Florida Bay and Biscayne Bay Cores Collected for Ecosystem History of South Florida's Estuaries Projects. U.S. Geological Survey OFR 2007–1203. http://sofia.usgs.gov/publications/ofr/2007-1203/index.html. Accessed 18 January 2011.

Wingard, G.L., J.B. Murray, W.B. Schill, and E.C. Phillips. 2008. Red-Rimmed Melania (*Melanoides tuberculatus*)—A Snail in Biscayne National Park, Florida—Harmful Invader or Just a Nuisance?: U.S. Geological Survey Fact Sheet 2008–3006. http://pubs.usgs.gov/fs/2008/3006/. Accessed 18 January 2011.

Yuan, L.L. 2005. Sources of bias in weighted average inferences of environmental conditions. *Journal of Paleolimnology* 34: 245–255.