Methods of Historical Shoreline Analysis

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1) This paper was published in Coastal Zone '89, the Proceedings of the Sixth Symposium on Coastal and Ocean Management, 1989, Vol. 5, pp. 4434-4448, published by the American Society of Civil Engineers, N.Y., USA. Permission to place this copy on the FDEP/BBCS WEB site was granted by ASCE in January 1997. Table 1 has been slightly revised.

2) The agency name is now the Florida Department of Environmental Protection, Office of Beaches and Coastal Systems. The author's e-mail address is as follows : Emmett.Foster@dep.state.fl.us (as of jan. 2000).

3) The opinions expressed in this paper are those of the authors and do not necessarily reflect those of the FDEP. The methods described in this paper remain very much in use but have since been advanced. The essential change is

greater reliance on the results of general case longshore numerical modeling to better understand the coastal processes and to select time periods for rate calculations.

4) The figures and appendix for the ASCII text version have been enclosed in the zipped total file as separate bitmap files, which can be viewed and printed via many software products, e.g., Wordperfect, Adobe, etc. The intent was to produce a document for general informational purposes which can be read independent of any particular software.

Abstract

A large data base of digitized historic coastal map data and Department of Natural Resources (DNR) profile surveys is being constructed to assist in growth management and regulatory programs. Several methods have been developed to analyze this information. The first step is to plot the data so as to be able to view the patterns of shoreline change both spatially and temporally. Using the computer- generated map overlays, supplemental aerial photography, the storm

records, and basic knowledge of coastal processes, the pattern of shoreline change can be resolved. Average shoreline change rates at each DNR profile location are then determined for time segments in which the pattern of change has been relatively constant. A rate calculation method has been developed which chooses and averages "long- term" rates out of all possible combinations of rates within a selected time segment. Comparison of the results with those of other calculation methods, such as least- squares fitting and simple end-point rates, is used to verify the relative magnitude of the average rates, and determine the sensitivity of the results to the method of calculation. Ideally, if the time pattern is correctly determined, the results will be relatively insensitive to the method of calculation, although the uneven clustering of data points and mix of data types can result in significant differences. Further averaging of rates along several adjacent profiles is used to minimize random profile variability. The number of profiles to be averaged is dependent on local shoreline conditions, such as inlet effects, armored areas, and rock outcroppings.

Introduction

The objective of this article is to describe the data base of historic shoreline data for Florida and to present several techniques which have been developed to analyze that data. Results obtained by the use of these methods can be found in two case studies reported in these proceedings: Foster and Savage (1989), Savage and Foster (1989).

Description of the Data Base

All coastal topographic maps of Florida by the U.S. Coast and Geodetic Survey (USC&GS), National Ocean Survey (NOS), and U.S. Geologic Survey (USGS), have been carefully digitized by researchers at Florida State University (FSU) for seventeen coastal counties, and at the University of Florida (UF) for seven counties, under contract with the Florida Department of Natural Resources (DNR). The locations of DNR coastal monuments and beach profiles were superimposed as a shoreline sampling pattern. The digitized historic shoreline locations along each profile bearing were then tabulated in a standardized format. Composite maps were produced showing all the digitized historic shorelines on standardized scale and coordinate systems. An example of such a map is shown as Figure 1.

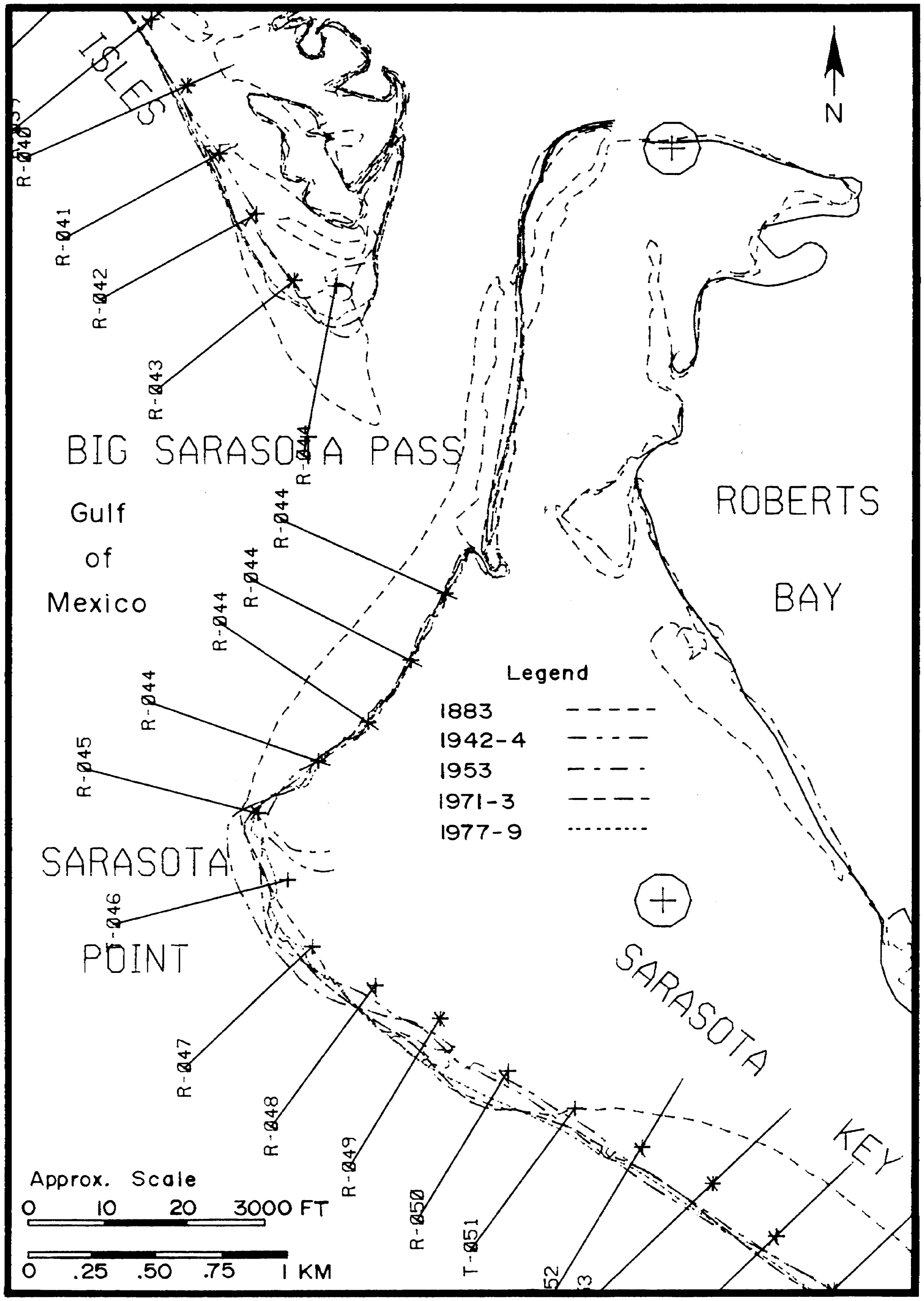

Figure 1. Map Example

The DNR coastal monument and beach profile system physically consists of a maintained set of concrete survey monuments spaced approximately at 1000 feet (300 meter) intervals along Florida's sandy beaches. Profile bearings from the monuments are established in directions which are approximately shore-normal. Beach profile surveys are performed by the Division of Beaches and Shores for monitoring and regulatory purposes. The DNR survey data acquisition program has been described by Sensabaugh, Balsillie, and Bean (1977).

The authors have proceeded to check and verify the DNR profile survey data in areas selected for analysis. The distance locations from the monuments of the approximate Mean High Water (MHW) and zero National Geodetic Vertical Datum (NGVD) elevations were extracted and added to the tables of map survey data to complete the historic data files. The combined data sets provide a quantitative record of shoreline changes from the mid to late 1800's to the present. An example of a tabulated data set is shown as Table 1.

Since all the map data is relative to the approximate MHW contour, the analysis of historic changes is also relative to that contour. The zero NGVD contour changes in the DNR data

TABLE 1
HISTORICAL SHORELINE DATA FOR EXAMPLE COUNTY

ID	SURVEY DATE(S) YEAR	MONTH	STATE PLANE COORDINATES FOR DNR MONUMENT NORTHING (FEET)	EASTING (FEET)	AZIMUTH (DEGREE)	SHORELINE DISTANCE FROM DNR MONUMENT (FEET)	DATUM	SHORELINE NORTHING (FEET)	SHORELINE EASTING (FEET)	SOURCE SCALE	SOURCE
R- 1	1883-1885		949541.100	378090.440	240	169.68	MHW	949455.125	377944.156	20000	U.S.C. & G.S.
R- 1	1939-1944		949541.100	378090.440	240	163.91	MHW	949457.625	377949.376	10000	U.S.C. & G.S.
R- 1	1953	12	949541.100	378090.440	240	144.24	MHW	949467.625	377966.313	10000	U.S.C. & G.S.
R- 1	1956-1957		949541.100	378090.440	240	206.90	MHW	949436.000	377912.219	24000	U.S.G.S.
R- 1	1974	5	949541.100	378090.440	240	118.87	MHW	0.000	0.000	EL1.2	DNR, B&S
C R- 1	1974	5	949541.100	378090.440	240	132.12	NGVD	0.000	0.000		DNR, B&S
R- 1	1978-1979	11,3	949541.100	378090.440	240	151.42	MHW	949464.250	377959.969	20000	N.O.S.
R- 1	1982	12	949541.100	378090.440	240	87.57	MHW	0.000	0.000	EL1.2	DNR, B&S
C R- 1	1982	12	949541.100	378090.440	240	96.14	NGVD	0.000	0.000		DNR, B&S
R- 1	1983	9	949541.100	378090.440	240	72.28	MHW	0.000	0.000	EL1.2	DNR, B&S
C R- 1	1983	9	949541.100	378090.440	240	83.01	NGVD	0.000	0.000		DNR, B&S
R- 2-A	1883-1885		948688.270	378526.770	245	159.06	MHW	948619.375	378383.407	20000	U.S.C. & G.S.
R- 2-A	1939-1944		948688.270	378526.770	245	149.05	MHW	948623.563	378392.500	10000	U.S.C. & G.S.
R- 2-A	1953	12	948688.270	378526.770	245	149.53	MHW	948623.563	378391.969	10000	U.S.C. & G.S.
R- 2-A	1956-1957		948688.270	378526.770	245	200.16	MHW	948601.875	378346.219	24000	U.S.G.S.
C R- 2	1974	5	948673.899	378515.253	245	104.88	MHW	0.000	0.000	EL1.2	DNR, B&S
C R- 2	1974	5	948673.899	378515.253	245	120.71	NGVD	0.000	0.000		DNR, B&S
R- 2-A	1974	5	948688.270	378526.770	245	121.39	MHW	0.000	0.000	EL1.2	DNR, B&S
C R- 2-A	1974	5	948688.270	378526.770	245	137.22	NGVD	0.000	0.000	SL008	DNR, B&S
R- 2-A	1978-1979	11,3	948688.270	378526.770	245	143.09	MHW	948626.063	378397.906	20000	N.O.S.
R- 2-A	1982	12	948688.270	378526.770	245	67.42	MHW	0.000	0.000	EL1.2	DNR, B&S
C R- 2-A	1982	12	948688.270	378526.770	245	76.25	NGVD	0.000	0.000		DNR, B&S
R- 3	1883-1885		947768.500	378959.000	240	117.97	MHW	947708.438	378857.469	20000	U.S.C. & G.S.
R- 3	1939-1944		947768.500	378959.000	240	115.09	MHW	947710.125	378859.813	10000	U.S.C. & G.S.
R- 3	1953	12	947768.500	378959.000	240	77.06	MHW	947729.250	378892.688	10000	U.S.C. & G.S.
R- 3	1956-1957		947768.500	378959.000	240	176.23	MHW	947679.375	378806.969	24000	U.S.G.S.
R- 3	1974	5	947768.500	378959.000	240	91.59	MHW	0.000	0.000	EL1.2	DNR, B&S
C R- 3	1974	5	947768.500	378959.000	240	106.44	NGVD	0.000	0.000		DNR, B&S
R- 3	1978-1979	11,3	947768.500	378959.000	240	115.60	MHW	947710.125	378859.219	20000	N.O.S.
R- 3	1982	12	947768.500	378959.000	240	95.81	MHW	0.000	0.000	EL1.2	DNR, B&S
C R- 3	1982	12	947768.500	378959.000	240	105.37	NGVD	0.000	0.000		DNR, B&S
R- 3	1983	9	947768.500	378959.000	240	85.40	MHW	0.000	0.000	EL1.2	DNR, B&S
C R- 3	1983	9	947768.500	378959.000	240	95.19	NGVD	0.000	0.000		DNR, B&S

FORMAT EXPLANATION: THE DATA COLUMN HEADINGS ARE SHOWN AT THE TOP OF THE FIRST PAGE OF EACH DATA SET. THE FILE IS 132 COLUMNS WIDE. - NOTE THAT MONUMENT R-2-A HAD A DIFFERENT COORDINATE LOCATION IN 1974 AND WAS CALLED "R-2". THE R-2 LINES FOR MHW AND NGVD ARE COMMENTED OUT WITH A "C" IN COLUMN 2. ALL COMMENTED LINES ARE NOT USED IN THE RATE CALCULATIONS FOR THIS STUDY. THE MATHMATICALLY ADJUSTED RESULTS ARE GIVEN AS "R-2-A" IN 1974. THE ADJUSTED 1974 MHW LINE IS NOT COMMENTED. ALL NGVD LINES ARE COMMENTED, INCLUDING THE ADJUSTED NUMBER. - THE "SOURCE SCALE" COLUMNS CONTAIN THE SOURCE MAP SCALES (E.G. "20000" WOULD BE 1:20000 SCALE). FOR DNR SURVEY MHW LINES, THEY CONTAIN THE VERTICAL CONTOUR ELEVATION IN FEET OF THE APPROX. MHW ("EL1.2"). THE ADJUSTED 1974 NGVD LINE CONTAINS THE CHARACTERS "SL008" IN THOSE COLUMNS. THE PROFILES R-2 AND R-2-A ARE SEPARATED ("S") BY A DISTANCE PERPENDICULAR TO THE PROFILE AZIMUTH OF EIGHT FEET ("OO8"). THE ADJUSTED PROFILE R-2-A IS TO THE LEFT ("L") OF R-2 WHEN VIEWING FROM THE SEA. - THE PROFILE AZIMUTHS ARE IN DEGREES CLOCKWISE FROM NORTH. - DISTANCES FROM THE DNR MONUMENT ARE SIGNIFICANT ONLY TO THE NEAREST FOOT; TWO DECIMAL PLACES ARE SHOWN FOR EASE IN TRACKING DATA SET REVISIONS.

can be calculated and compared to the MHW changes to determine what sensitivity, if any, the results have to the choice of contour in the upper tidal zone.

The use of coastal topographic maps as a tool for historic shoreline analysis has been generally discussed by several researchers. Shalowitz (1962) and Swanson (1949) discussed coastal mapping by USC&GS (the predecessor of NOS). Collins (1978) reported on NOS maps. Banks and Lenart (1978) discussed joint efforts by NOS and USGS. Brownsworth (1978) discussed the USGS method of photo- determination of shorelines in the post-1947 era. These and others have reported that in general this information should prove both useful and accurate for this purpose. Our experience is that this is very good data provided sufficient care is taken in the digitizing process, and that maps with apparent horizontal control problems are identified for qualitative use only. Strict quality control is necessary in the assembly of any data base if confidence is to be had in the results. In studies where direct date comparisons are possible, the level of agreement between map data and DNR profile survey data has been very good to excellent.

Historic bathymetric survey maps from the same sources were also digitized under the contracts. However, there is usually much less comparative bathymetric data available than shoreline data, and reference datums vary. There can also be considerable subjectivity in the digitizing and sampling of complex bathymetry, such as shoal systems and reef formations. For these reasons, the bathymetric data has been used only for qualitative purposes at this time. In addition, soundings from DNR offshore profile surveys were used to investigate profile shapes and bottom features within 3000 feet (900 meters) of the beach.

It is noted that nearly all the modern survey maps (post 1920's) were compiled using controlled aerial photography, generally followed by field editing. Aerial photography sets were not digitized (with few exceptions) in this project due to costs and the problems of photo rectification, horizontal control, and MHW location. Some photography was digitized on the lower east coast, but with mixed results. However, all sets of historic aerial photography available at DNR and the Florida Department of Transportation have been collected for the study areas. The photographs are used for qualitative verification of the conditions shown in the survey maps, as well as for the study of wave refraction, shoal, dune ridge, vegetation and overwash patterns. In addition, they are very helpful in locating nearshore and offshore rock and reef formations, and man-made coastal structures.

Geographic and Temporal Analysis

The shoreline can be divided into geographic sections according to the location of inlets and areas where the coastal processes can be described as a system. The computer-generated composite maps are very useful in defining geographic sections and quickly recognizing areas where major changes have occurred over time.

A special graphic format, called a "stack plot", has been developed to clearly display the quantified pattern of shoreline change over long sections of shoreline, such as an entire island. The distance versus time plots for eight adjacent profiles are graphed in sequence ("stacked") on a single page. Several pages can then be placed end to end (e.g. taped together) to show the pattern of how, when, and where the distance/time plots systematically change along the entire reach. This capability is the main purpose of the graphic format, with the pages generally included as an appendix in an area report. An example stack plot is shown as Figure 2.

It is readily observed in the data sets that shoreline change often does not occur at a constant rate, and that the various types of coastal processes affecting a site can change in relative significance over time. Shorelines tend to evolve to orientations dependent on the sand supply, initial conditions, extreme events or a series of events, prevailing directional wave energy patterns, and underlying or nearshore geologic features.

The next step is to select time segments along the total time record and in a consistent manner alongshore, such that an average shoreline change rate in each segment is usefully descriptive of the coastal processes occurring at the site. A correct time segment selection will be consistent with all the available reference information and on-site observations. The selected recent trend will generally be used to project future changes, which in turn will be tested (and probably revised) by future survey data.

The selection of time segments can be accomplished by working backwards in time, comparing recent DNR data trends with successively longer segments. Breaks in time segments should

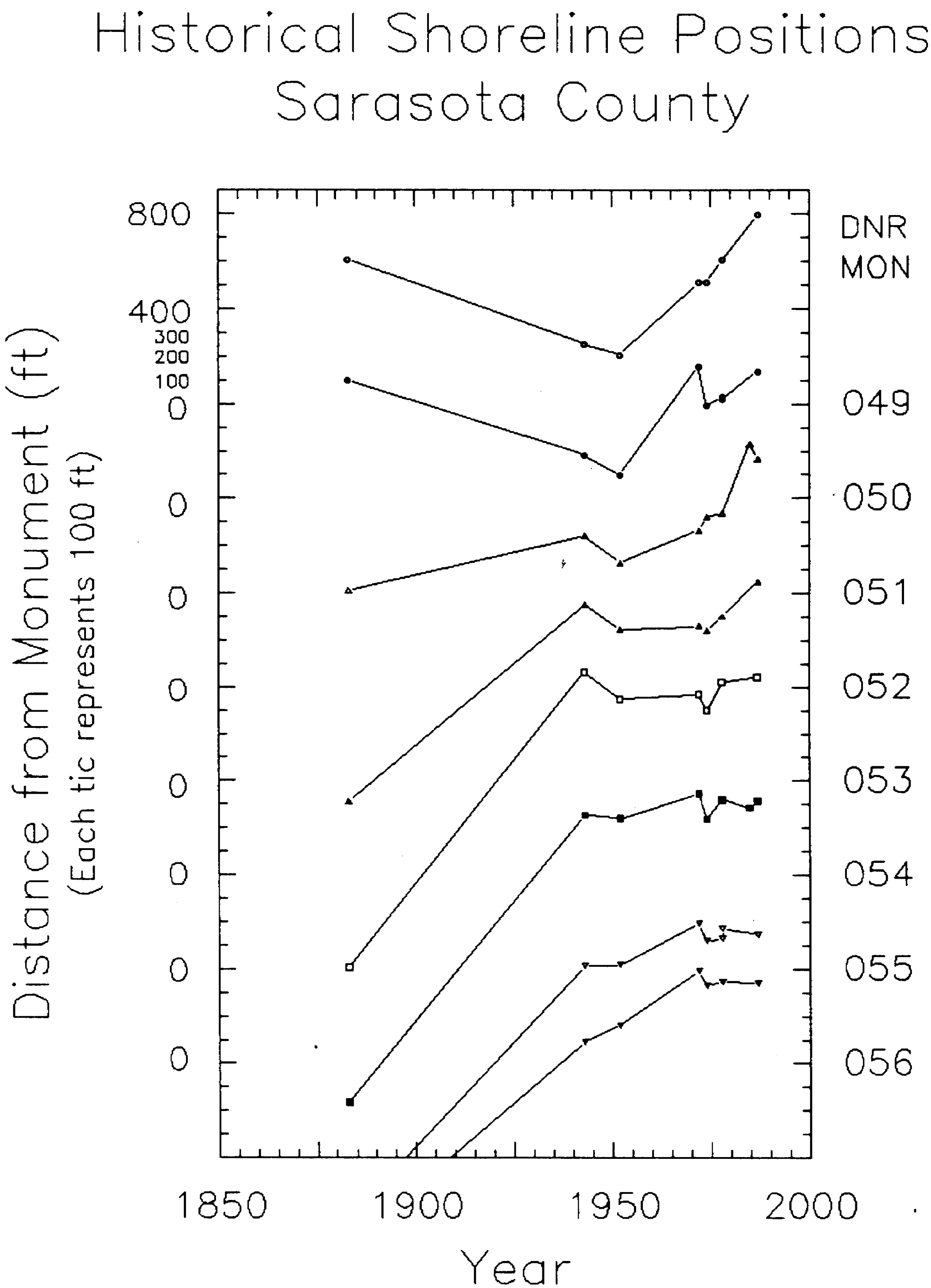

Figure 2. Stack Plot Example

generally be limited to major changes in shoreline orientation or coastal processes. However, it is occasionally necessary to use time segments to linearize sections of a non-linear response.

Rate Calculations

There are several possible methods for calculating an average rate of change within a selected time segment having more than two measurement points. One strategy is to compare the results of three different rate calculations, to observe the reasons for any significant differences in results, and to recommend what is determined to be the best estimate of the rate. The rationale is simply that the rate results should not be highly method- dependent without a reason. The three calculations are the following:

1.) The slope of the least-squares fit (Y on X) to the distance/time data points within the time segment.
2.) The "end-point" rate, i.e. the first to last net difference in distance divided by the net time for the segment.
3.) The arithmetic average of all "long-term" rates

within a time segment.

It is observed that the shoreline measurements are unevenly and randomly spaced in time, that earlier data is probably less accurate than more recent data, and that digitized map data is less accurate than DNR beach profile data in locating a shoreline position at some point in time. The spacing and measurement accuracy of the data can have important effects on the rate calculation. There are usually more points in the later years of the time line, and clusters of points including mixed data types in the most recent time period (1970-1988).

The least-squares fit can be very sensitive to uneven point distribution and point clusters. The effect can be to yield a rate which is a balance between the location of point clusters and the end-point rate. It is also noted that the least-squares method assumes equal variability in the points and therefore no consideration is given to the difference in data types. In the case where the time segment is short and the number of points small (e.g. three) and of mixed type, it may be unnecessary or misleading to use the least squares rate.

The simple end-point rate can be used for comparison with other rate calculations as a checking device, and in those situations where any other rate is meaningless. One example is in those ares adjacent to inlets where shorelines are subject to random, large scale changes dependent on shoal movements and storms. Another common case is where measurements randomly span several beach renourishments. A linearized average of several random measurements in these situations is meaningless. The end- point rate in these cases can be considered only to represent a net effect of some series of events, regardless of path.

An interesting end-point calculation is the first to last net effective change over the total time record, regardless of the path inbetween. This may or may not be meaningful, and can be very misleading, depending on that path.

The third method is newly developed, and consequently some explanation is required on how it works. The intent was to develop a way to arithmetically average rates within a time segment with consideration of the difference in data types. It is observed that all the measurements were randomly taken in time. The random timing of any measurement within a selected time segment means that any combination of two shoreline distance measurements was as likely to occur as any other. Each combination therefore represents a potential rate to be used in a calculation of an average rate for that segment. However, only "long- term" rates, relative to the magnitude of the end-point rate and levels of assumed measurement error in the data points, are to be averaged.

In defining "long-term", the basic concept is that it should take a longer time between observations to detect a significant shoreline change at, for example, a 2 ft/yr level than at a 15 ft/yr level, and that the measurement accuracy is relevant to whether or not there is an actual change or merely a possible measurement error.

As a simple example, suppose there are three measurements of shoreline location at a site over a ten year period, but two of the three measurements were taken only one year apart. Of the three possible rate combinations (1, 9, and 10 year rates), logic would say to average no more than the two longest term rates. The one year is simply too short of a time period to measure any longer-term trend. The long-term rate averaging method objectively makes that decision, for any number of points, and for the more complex situation of some measurements being significantly less accurate than others.

Specifically, for the end-point rate level, minimum times between different data types are calculated. Any rate combination having a time period less than its' respective data-type minimum would be excluded from the average rate calculation. The result is the average of the relative "long-term" rates within a time segment. The equations used in these calculations are given in the Appendix at the end of this article.

The averaging of as many long-term rates as possible is beneficial to reducing the effects of other potential sources of variability in the data, such as any seasonal beach width variability. Regardless of the calculation method used, the further averaging of a number of adjacent alongshore rates is useful in reducing any random profile variability.

The rate averaging method requires the assumption of reasonable levels of measurement error in the data types. The objective is to maximize the number of long-term rates in order to average out other sources of variability, i.e. to minimize the total error. Conservative choices for data error ranges would be a relatively low but reasonable estimate for the map data, and a relatively high but reasonable estimate for the DNR survey data. The choices should also be reasonable in terms of relative magnitude, e.g. one type may be approximately three times more accurate than the other. Rate comparison tests, sensitivity tests, and digitizing variability tests were performed. The result is that a useful and reasonable estimate of measurement error in the modern map data is +/- 30 feet (9.1 meters), and for DNR profile data +/- 10 feet (3 meters). For the map data, +/- 30 ft represents the lowest reasonable estimate, rounded to the nearest 10 ft. Less than this number is unrealistic, since the maps are estimated to be +/- 0.5 mm (or +/- 33 ft for 1:20000 and +/- 40 ft for 1:24000 scale maps), as noted in Shalowitz (1962), Swanson (1949), Collins (1978), and Everts, Battley, and Gibson (1983). Repeated digitizing variability tests using triple setup and greater than 40 points have consistently yielded +/- 15 feet (approx. 4 meters) as a mean plus two standard deviations for FSU data, and as a mean for UF data. The combined map and digitizing error could therefore be estimated to be on the order of +/- 40 to 50 feet (12-15 meters). The use of +/- 40 feet (12 meters) or greater tends to significantly reduce the number of rates for averaging, and consequently to increase the total error estimate, while not significantly affecting the magnitude of the result.

The oldest map surveys, from the 1850's to the 1930's and constructed by planetable methods, possibly have more measurement error than modern maps. Shalowitz (1962) suggested +/- 10 meters at measured locations, and possibly greater where the shoreline was interpolated between points. However, he also stated that the accuracy of some maps may be considerably greater. Our experience has ranged from apparently very accurate to unreliable, based on comparative locations of stable landmarks and other control points. In recognition of this situation, it is recommended that consideration be given to selecting one time segment as "old data" to first "modern data", which makes the error assumption unimportant. Maps known to be unreliable, whatever the date, should not be used in calculations.

The +/- 10 ft estimate for DNR survey data is probably on the high side as rounded to the nearest 10 feet. Errors can exist in horizontal and vertical control, and due to interpolation along a profile.

It is noted that data with significantly lower assumed ranges, such as the DNR profile data, more readily pass the long-term selection process and have a greater influence on the magnitude of the average rate. Therefore, the average will often be a balance between the longest term map data and the longest term, more accurate, DNR data where both are included within the time segment.

Consideration must be given to the following logical and practical restraints on the long-term averaging method. In cases where the end-point rate, and generally the entire sequence of data, yields a very small (near zero) rate, the minimum time period becomes very large. The result is a default to the end-point rate as the only "long-term" rate. The end-point rate in such a situation is not logically a bad estimate. However, comparisons with lesser (or greater) time period rates and least squares results should be used to confirm the magnitude and sign of the result. In the opposite case of the end-point rate being very large in magnitude, the minimum time period becomes very short. Short-term effects in such cases must be searched out and possibly excluded from the calculation of the average. A search based on the standard deviation of the rates has been successfully used, but the results should be individually checked. Sometimes this is an indication that the time segmenting is incorrect or that an end-point rate is more meaningful.

"Seasonal variation", for the purpose of this discussion and consistent with our observations to date, can be defined as follows:

- beach width changes due to the development and maintenance of a persistent longshore bar system in many shoreline areas during a high wave energy season, typically winter;
- accumulations and deficits of sand on opposite sides of longshore structural, geologic, or other barriers, or within pocket beaches in response to seasonal net wave energy directional changes; and
- the observed passage of large masses or slugs of sand through some shoreline areas in directions and under conditions dependent on seasonal wave climate.

These situations do not necessarily present major problems with time segmenting or rate calculations. With experience and the amount of data in hand, areas susceptible to each can be observed in the data plots, aerial photography, and in the field. Time segmenting and interpretation of the results should be made with these known processes in mind. In our opinion, shoreline change numbers should be accompanied by an explanation (or theory) of the major physical process occurring at the site.

In summary, the spacing and mix of data types has resulted in the strategy of analyzing the data using more than one method of rate calculation in a comparative process. All the methods yield a result of some value to the analyst. No single method works best all the time. Generally the method of "long-term" rate averaging within selected time segments yields the result which is recommended as the best estimate of the average rate of shoreline change.

Longshore Averaging

For the purpose of projecting future changes, or as a means of comparing consecutive time period changes, it is beneficial to average rates along some number of adjacent profiles. This minimizes any random single profile variability. It is not generally useful to average over very large distances: this tends to obscure local conditions and the relationships between areas. If the analysis is reasonably correct, it will be observed that the rates among adjacent profiles will already appear relatively smooth in longshore transition. The question of how many adjacent rates to average is largely dependent on the specific local conditions, such as inlet effects, armored areas, and nearshore rock outcroppings. Since it is convenient and consistent to determine average longshore rates at each monument, some obvious choices are 7, 5, and 3 point running averages. These would encompass 3, 2, and 1 adjacent monument(s) on each side, respectively.

It is possible to mathematically identify site specific situations by observing where the running longshore average exceeds the calculated error bounds on the individual profile rates. Such locations should be examined for something unusual in the local conditions which may reduce the number of points to be averaged.

Where a boundary such as an inlet is reached, a simple method is to reduce the number of points averaged from 7 to 5 to 3 points on approach to the boundary.

Projections of Future Shoreline Changes

Projections are used by DNR for regulatory and planning purposes. All projections should be based on specific assumptions about the future conditions. Generally what is believed to be the present trend of change is used as the future projection. However, it is very possible in many if not most areas that a future sequence of storms will significantly change the assumed conditions. The effects are especially unpredictable near inlet areas. The data near inlets are generally records of large shoreline fluctuations, losses and gains, in response to storms and changes in the offshore shoals. The future would logically be an expectation of the same.

Another concern is that in many areas with presently high erosion or accretion rates, these levels of change may not be expected to continue indefinitely. Instead, the shoreline should gradually reach an orientation over some time period that is a balance between the directional prevailing wave energy and the available sand supply. In such cases a judgment can be made based on the feasibility of the projected location of the shoreline at the present high rate, and a choice of assumptions. It is also possible to develop and calibrate longshore erosion models for such areas, but this has not yet been attempted for these projects.

There are other problems with making projections for armored areas, beach renourishments, and areas with several combined influences. Experience and judgment are called for in all cases.

Conclusions

Historic shoreline changes in Florida can be studied using a large data base of historic coastal map data and DNR beach profile survey data, supplemented with aerial photography and other reference information. The changes can be analyzed geographically and temporally in developing a basic understanding of the major coastal processes occurring at the local and regional level. Shoreline change rates can be calculated in a comparative methodology to yield results which are not highly method-dependent. Projections of future changes will test the level of understanding. A knowledge of historic changes and projections of future changes can be useful tools in the management and regulation of coastal areas.

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Appendix

The minimum time in years (TMIN) between any two shoreline measurements, used to select relative "long-term" rates:

(EQN 1) $TMIN = (E1^2+E2^2)^{0.5} / R1$

Where:
- E1 = Assumed +/- error range in distance measurement number 1 in feet (e.g. +/- 30).
- E2 = Assumed +/- error range in distance measurement number 2 in feet (e.g. +/- 10 or +/- 30).
- R1 = End-point rate for the selected time segment in feet/year.

The average (ARATE) in feet/year of the "long-term" rates:

(EQN 2) $ARATE = Sum((D2 - D1) / DATE_{2-1})_i / N$

Estimates of the error in the average rate, in feet/year:

(EQN 3) $ER1 = +/- Sum((E2 + E1) / DATE_{2-1})_i / N$

(EQN 4) $ER2 = +/- (Sum((E2^2 + E1^2) / DATE^2_{2-1})_i)^{0.5} / N$

Where:
- Sum = Summation function, from i = 1 to N.
- D2 = 2nd distance in a two-point "long-term" rate calculation, in feet.
- D1 = 1st distance in a two point "long-term" rate calculation, in feet.
- $DATE_{2-1}$ = Difference in time relative to distances D2 and D1, in years.
- N = Number of "long-term" rates in a time segment.
- ER1 = Estimate #1 of the error in ARATE. This estimate can be considered the mean or average variation in ARATE assuming that each error occurs at the maximum of its' respective assumed range.
- ER2 = Estimate #2 of the error in ARATE. This estimate can be considered the mean or average variation in ARATE assuming it is unlikely each error will occur at the maximum of the respective assumed range.