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HISTORICAL SHORELINE RESPONSE TO INLET MODIFICATIONS AND SEA LEVEL RISE

by

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Thesis

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This thesis examines the historical shoreline response to inlet modifications and sea level rise. Inlet modifications are considered to be the geographic stabilization and training (through the use of structures) of natural inlets and the creation and further modification of artificial inlets. Shoreline response to natural and artificial processes must be understood in order to predict the performance of the coastline. The tendency for creating and modifying inlets increases as industry and population growth demands. Sea level rise is a natural process which cannot be controlled at this time. Current theoretical approaches to predicting shoreline response indicate that sea level rise and inlet modifications can cause substantial shoreline impact. Florida, with roughly a century of shoreline position and relative sea level data, provides a basis for examining past trends and comparing them with theory.

The shoreline of Florida was found to be accreting with the greatest accretion along the east coast. Shoreline responses within the boundaries of the erosional influence of inlets due to their creation and/or modification were examined for 19 inlets around the coast of Florida. The differences in the shoreline response before and after the initial modification of each inlet show the erosional strain that inlets apply on the nearby shoreline. The effect on shoreline response due to the human intervention (unnatural processes) of modifying inlets was isolated and examined. The shoreline response due to this "human intervention" was erosional, thereby showing the negative impact that modified inlets have on shorelines. This induced erosion is responsible for the loss of roughly 21.6 million cubic yards of sand from the shoreline that is within the erosional influence of Florida's east coast inlets. Combining the shoreline changes due only to natural processes with sea level rise data allows for comparison with the commonly accepted Bruun Rule for shoreline response as a result of a changing sea level. This comparison and the effects of including a lag time between a rise in sea level and a change in shoreline along the east coast of Florida during the last century show no agreement with the Bruun Rule and no correlation with a specific lag time.

CHAPTER 1
INTRODUCTION

1.1 Purpose of this Study

The present development of our coastlines and the predictions of their future performance are only as good as the available background information and the validity of the prediction techniques. The long term erosion rates and the influence that sea level rise and human intervention (coastal development) have on these erosion rates are of primary importance.

Florida, due to its mild climate and abundant natural resources (specifically, sandy white beaches and sparkling water), has experienced a rapidly growing population (fourth largest in the nation) and an industry almost entirely dependent upon tourism. In 1989 tourism provided $8 billion in beach related sales, $500 million in beach related sales tax collections and generated 320,000 beach related jobs with a payroll of $1.9 billion (Task Force for Beach Management Funding, 1990). These figures all increase if one considers the expenditures and employment generated by construction of condominiums and summer/retirement houses. Oceanfront property (land alone) in Florida ranges from $1000 to $12000 per lineal foot for residential lots with commercial lots running as high as $61000 per lineal foot (Wang, 1985). This thin belt of developable land therefore represents a multi-billion dollar asset. However, considering Florida's predominately low elevations, the enormous storm damage potential and effects of sea level rise overshadow the coastlines value if not properly protected and managed.

Nourishment is becoming the method of choice for coastal erosion control and storm protection in Florida and is being utilized throughout the state. In addition, many of Florida's inlets and waterways are being modified to better handle the increased commercial and recreational traffic as well as to correct some of the inherent problems which have occurred from the original modifications undertaken without a thorough knowledge of consequences.

This thesis analyzes existing historical shoreline position data and sea level data in an attempt to examine the effects of human intervention and sea level rise on shoreline impacts. For this study, the human intervention examined is the creation of artificial inlets and the geographic stabilization and modification of natural inlets. Beach nourishment projects have been removed from the data sets since the effects of nourishment are better known for the state of Florida. In order to isolate the effects of inlets, the length of shoreline predominately affected by each inlet is determined. This allows for an historical examination of the coast of Florida with and without the presence of inlets. From this analysis, the effects of human intervention are found. The removal of the shorelines influenced by inlets provides a shoreline affected only by natural processes. The natural changes in shoreline position with respect to time are examined with corresponding sea level changes in order to determine if a correlation exists as is predicted by the Bruun Rule.

1.2 Scope

The open coastline of Florida can be considered in three segments. The east coast of Florida extends approximately 330 miles from the Florida-Georgia border south to Key Biscayne. It encompasses 12 coastal counties and 19 inlets. Six of these are constructed inlets and were cut for navigational and/or water quality purposes. Of these 19 total, all but two have been modified. Fourteen of these inlets have been selected for detailed study, extending from St. Augustine Inlet at the north through Bakers Haulover at the southernmost end. Figure 1.1 presents the locations of these inlets selected for study along the coastline of Florida.

The west coast of Florida can be separated into two segments of sandy beaches on either side of a length of rocky and mud coast located in the geographical "Big Bend." The lower segment extends from Collier County north through Pinellas County encompassing six coastal counties and 170 miles of shoreline. Due to the fairly weak and variable longshore sediment transport, and the milder wave energy, only the shoreline changes have been analyzed without a through examination of inlet effects. Venice Inlet is the only inlet examined within this segment. The upper segment of the west coast extends from Franklin County west to Escambia County, a length of 133 miles. This shoreline includes nine inlets, six of which have been modified and four of which are studied here.

The major focus is placed on the east coast inlets due to the greater longshore sediment transport and resulting interaction with modified inlets. This coast has a longshore transport rate of approximately twice that of the upper west coast and six times that of the lower west coast as shown by Figure 1.3. This increased wave energy places the east coast inlets in a more demanding zone as far as maintenance and design are concerned as well as accentuating the effects of the human influence from construction and modification.

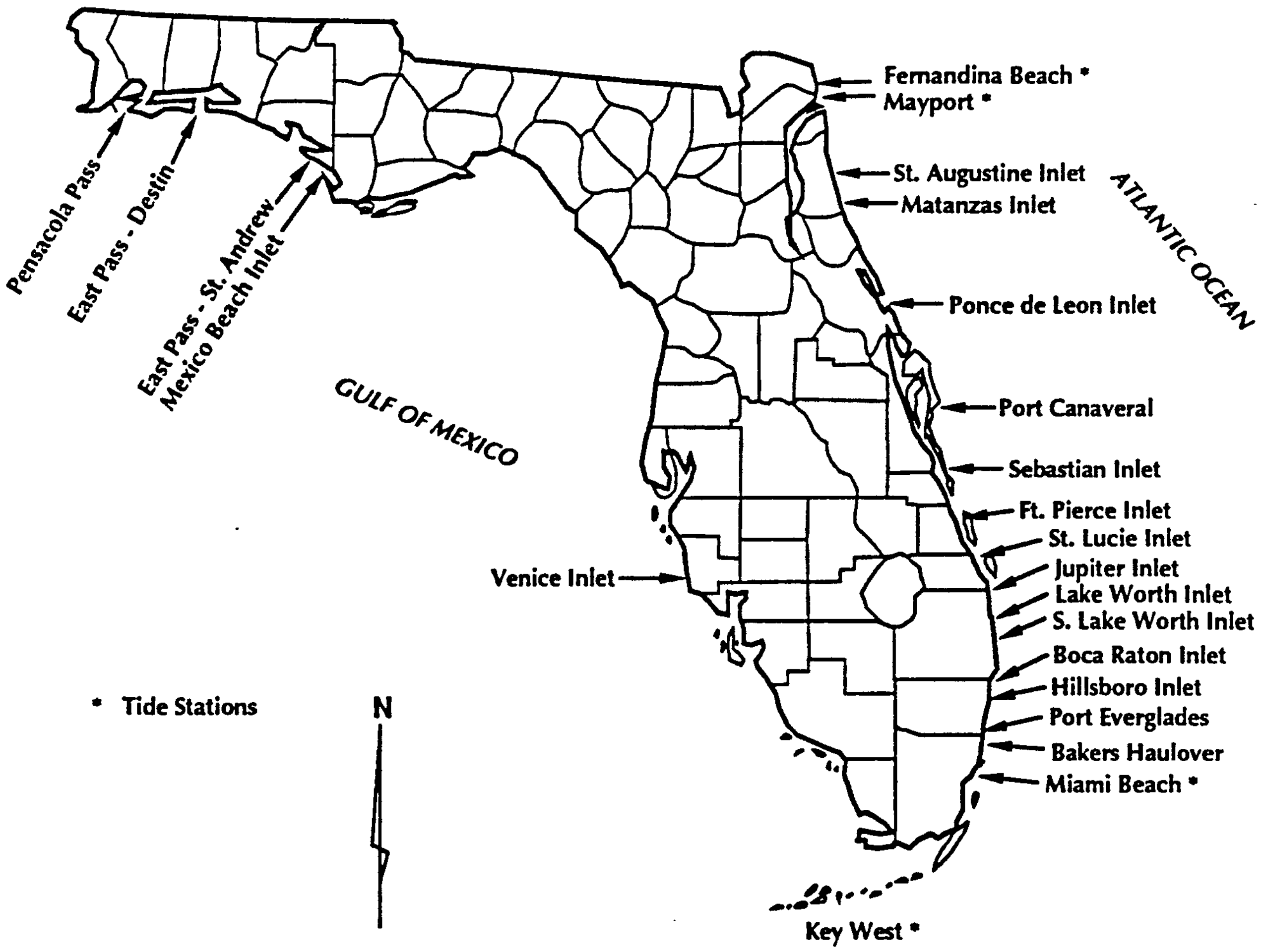


Figure 1.1: Location of inlets along the coast of Florida covered in this thesis including the location of tide gauges from which the sea level data were obtained.

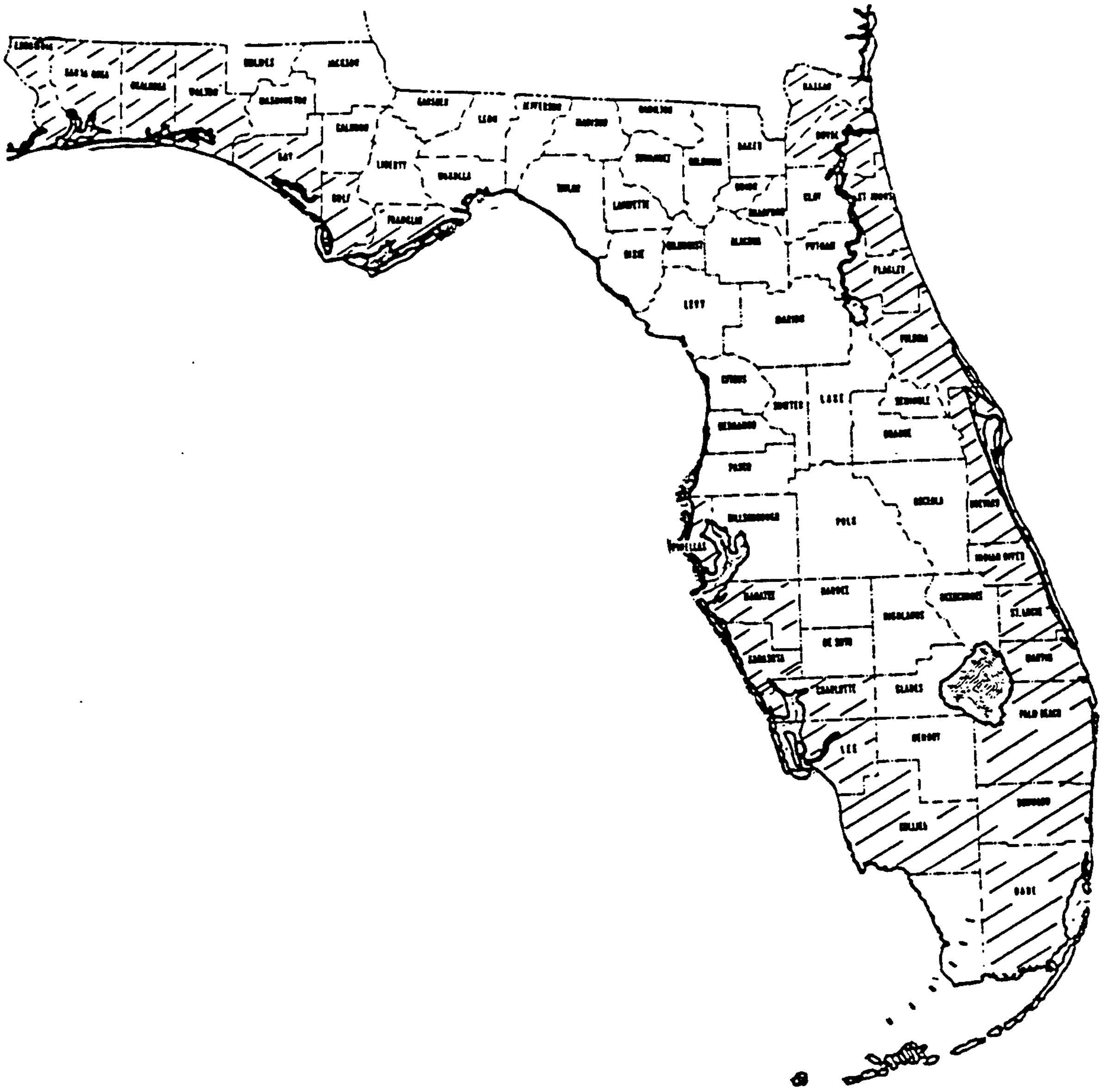


Figure 1.2: Location of counties examined in this thesis for shoreline change.

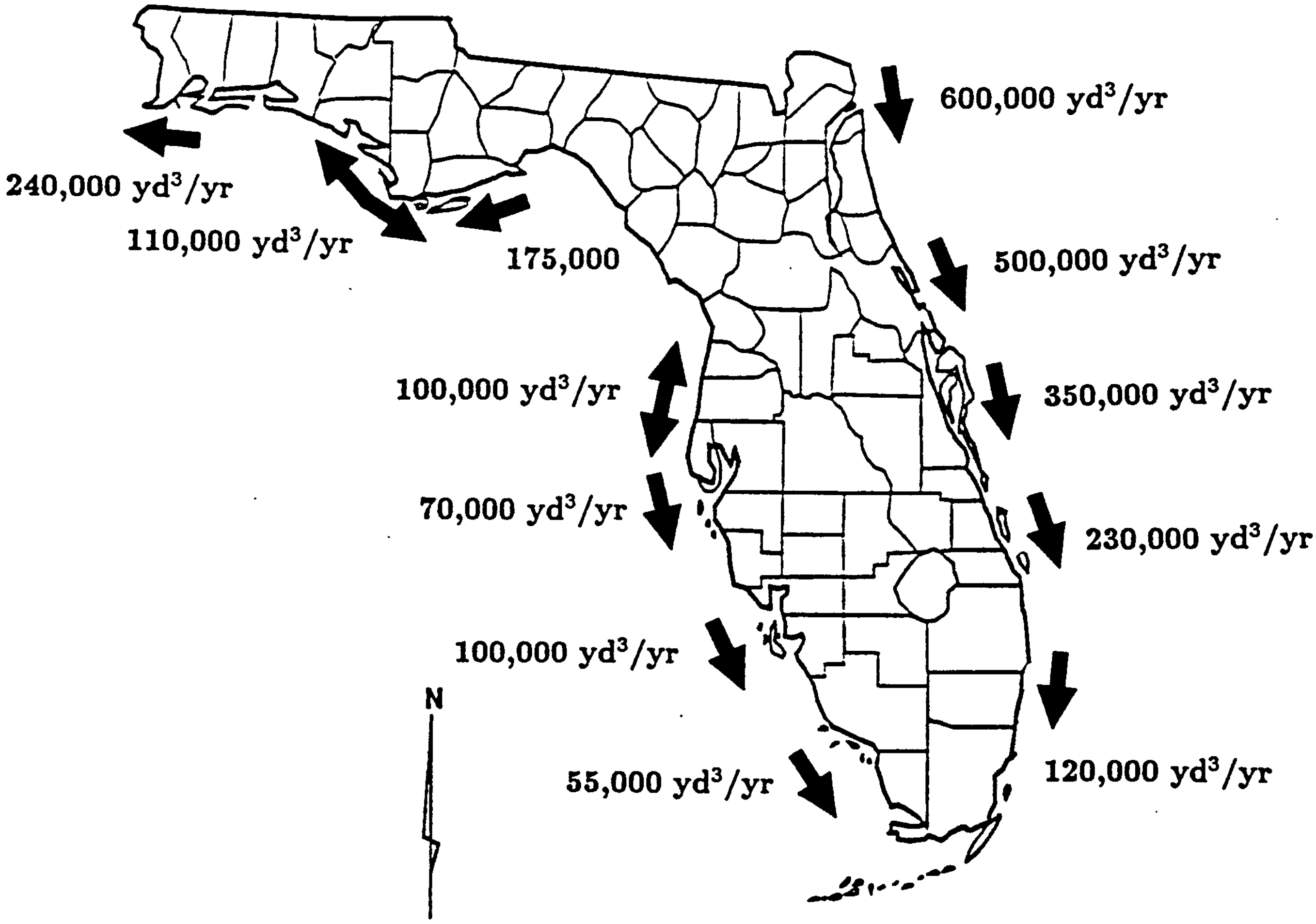


Figure 1.3: Approximate longshore sediment transport along the coast of Florida.

CHAPTER 2
APPROACH

2.1 Review of Available Data

Historical shoreline positions have been digitized and compiled by the Florida Department of Natural Resources (FDNR) for much of the coast of Florida. This information has been organized and combined from aerial photographs, maps and charts, and hydrographic and beach surveys. The data are referenced to permanent FDNR monuments and further to State Plane Coordinates. The Division of Beaches and Shores (DBS) of the FDNR maintains these monuments along counties with predominantly sandy shorelines. They were placed starting in 1971 and all surveys since have used them as a reference. All surveys that pre-date 1971 have been digitized from their respective sources and combined to yield shoreline positions referenced to the DNR monuments. There are a total of 3,587 monuments, each spaced approximately 1000 feet apart, along approximately 682 miles of ocean-fronting beach (DNR, 1989). As an example, Figure 2.1 shows St. Johns County with the locations of the DNR monuments. The earliest shoreline position data available are from the mid to late 1800s with accuracy depending upon the data sources. The bulk of this comes from the U.S. Coastal and Geodetic Survey (USC&GS) T-sheet map series which are the earliest reliable maps for quantitative analysis. These supply the great majority of data from the mid 1800s through the mid 1900s (Wang and Wang, 1987). Unfortunately, they are only as accurate as the maps themselves and this is further reduced by the digitizing of these maps to quantify shoreline changes. Therefore these data are used only after verifying them as carefully as possible.

The more recent (mid 1960s and on) information comes from two sources. The first of

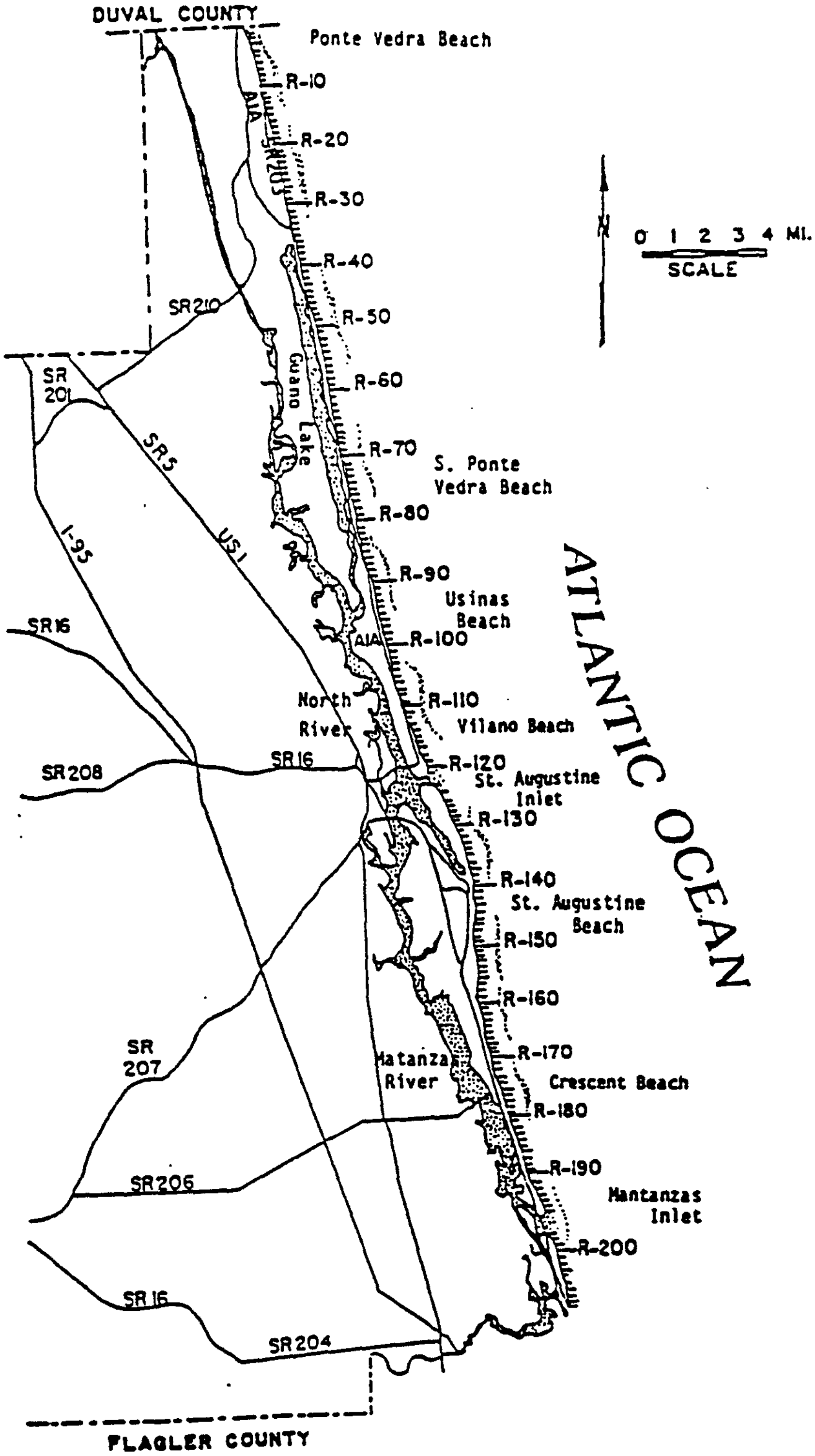


Figure 2.1: DNR monuments located in St. Johns County.

these is aerial photographs taken by the Division of Beaches and Shores of FDNR. These are produced to a large scale (1:1200 and 1:2400) and offer much better resolution than the earlier maps. The final and most recent source is ground survey data furnished by FDNR. This is the most accurate, as the profiles are referenced directly to the monuments and the high water shorelines are interpolated from current tidal datums for the corresponding region.

Shoreline fluctuations due to seasonal variations and storm events can be significant, up to as much as 70 feet. In order to remove as much of the noise and scatter as possible, every data set that is considered reliable and accurate is used when constructing long term erosion rates. This is not always possible with some of the shorter term rates and therefore a certain variance must be recognized.

2.2 Erosion at Inlets

Inlets, when left in their natural state will achieve a near equilibrium with the natural sand supply and processes. This will not be a constant state, but one that is always shifting in order to remain in equilibrium as seasonal variations change the shore and bar formations. Large shifts due to storm activity are also common as well as the natural opening and closing of inlets. Natural or untrained inlets tend to migrate in the direction of longshore sediment transport (see Figure 2.2). Sediment is deposited on the updrift shoulder of the inlet mouth which causes a reduction in cross sectional area. This results in an increase in the water velocity in the inlet and thus erosion at the mouth. Since sediment is building up on the updrift bank, the downdrift bank will erode as the inlet attempts to return to its former size. The resulting cycle will cause an inlet to migrate along the shoreline without any large changes in the normal direction of the shoreline with some loss of sediment to the trailing flood tidal shoals.

The formation of a tidal inlet tends to create an ebb tidal shoal. An ebb tidal shoal is characteristically a crescent shaped formation located offshore of the mouth of an inlet that consists of sediment removed from the littoral drift. Typically, this shoal will grow in size until a balance is reached at which point the shoal becomes, in effect, a sand bridge bypassing sand from the updrift to the downdrift shore. In a natural inlet, the sand entering the inlet is jetted out to the ebb shoal by the ebb tidal currents and then driven back to shore (downdrift) by the incident waves as shown by Figure 2.3. This natural bypassing and migration reduce sediment losses around an inlet. As noted previously, sediment deposited in the flood tidal shoal by a migrating inlet represents a loss to the outer coast. The human influence comes into play as inlets are modified to maintain a deepened, constant and consistent channel in which the natural variations are prevented or limited.

2.2.1 Erosion at Modified Inlets

The migration and relatively shallow depths of natural inlets pose a serious navigation hazard. Most of Florida's inlets have been modified (or trained) to create a safely navigable waterway as well as for water quality purposes. These modifications include the construction of jetties, deepening of entrance channels and dredging in an attempt to stabilize the inlet location and produce a channel of constant depth and orientation. However, when inlet locations are stabilized and the inlets trained by jetties, changes normal to the shoreline are induced. This is because the quasi-equilibrium reached by the inlet in its natural state is disrupted and becomes unattainable without artificial means. The greatest cause of the induced shoreline changes is due to the construction of jetties (usually necessary to create a navigable waterway). The resulting shoreline erosion can be better understood by considering a littoral barrier extending perpendicularly from an initially straight and uniform shoreline. Waves arriving at an angle to the shoreline cause a longshore sediment transport. At the littoral barrier the transport is zero (assuming an impermeable barrier), impounding all sediment on the updrift side of the barrier until the shoreline reaches the tip of the barrier, at which time bypassing of sediment around the barrier commences. This requires that the local shoreline at the barrier be oriented parallel to the incoming wave crests. Meanwhile, if the effects of diffraction are neglected at this idealized level, erosion on the downdrift side occurs in an anti-symmetric fashion (see Figure 2.4). The total volume

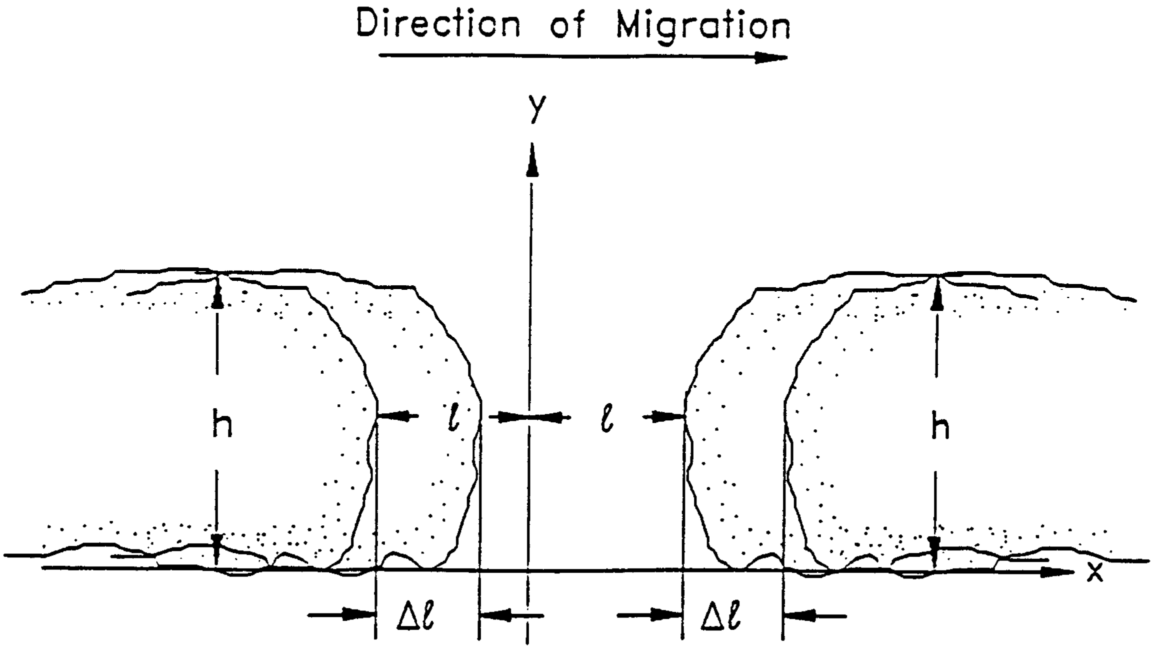


Figure 2.2: Longshore migration of a natural inlet.

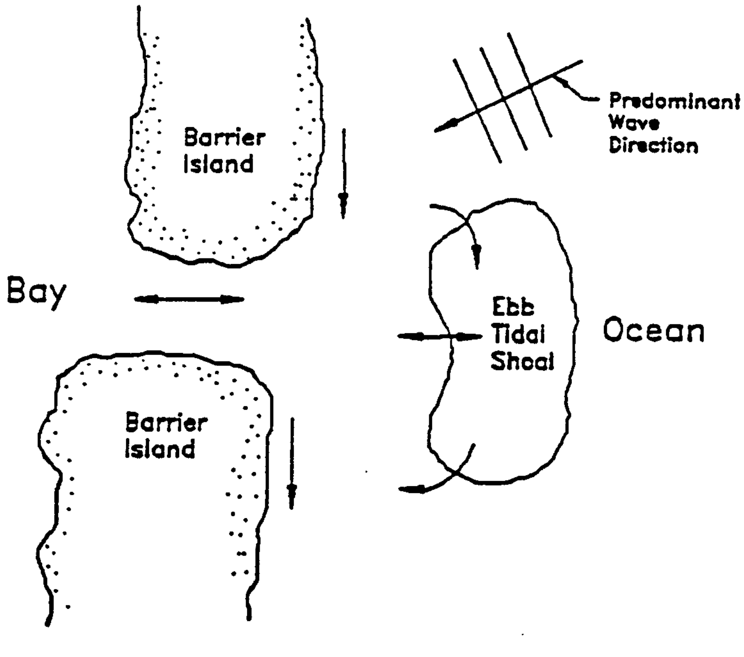


Figure 2.3: Basic transfer process of sand at a natural inlet.

trapped is equal to the total volume eroded regardless of diffraction effects as can be seen by considering transport at large distances updrift and downdrift of the structure. At these locations, the shorelines are unaffected by the barrier.

A trained inlet may be thought of as a littoral barrier split down the center and separated. The same updrift accretion and downdrift erosion occur. However, there can also be an added downdrift erosion due to the jettied inlet so that there now exists a greater volume of sand eroded than the volume trapped as shown in Figure 2.5. This arises when the flow out of the inlet, amplified by the jetties, transfers sediment past and through the natural offshore bar (or ebb tidal shoal). The jetties at inlets are ideally designed to a length that is capable of maintaining a navigable channel out to the desired depth. This depth is often deeper than that of the offshore bar. The offshore bar acts as a sand bridge and allows sediment transport to flow across the inlet mouth when it is in its natural state. The inlet system, trying to return to its natural state, will attempt to fill the deepened channel and to restore the offshore bar thereby removing sand from the longshore transport system (sand that would normally be bypassed along the shoal from the updrift beach to the downdrift beach). Equilibrium will not be recovered until the offshore bar has returned to its original depth, at which point in time, natural sediment bypassing will resume. However, to maintain the navigable channel, the jetties must be capable of self-cleaning the channel of sediment deposited by the inlet system in the inlets attempt to return to equilibrium. This battle usually results in the seaward displacement of all sediment accumulated in the channel area. Olsen (1977) has determined that the St. Mary's Entrance jetties, constructed in the late 1800s and early 1900s, have caused the seaward displacement from the nearshore zone, of 120 million cu. yds. of sand an additional two miles offshore. This sand deficit from the sand sharing system is compensated for by an increased erosion from the adjacent nearshore system. The dredging of channels during and after construction (creation of artificial inlets and deepening of natural inlets in Florida) has resulted in large losses of sediment. Most of the original dredge spoil from the inlets was dumped offshore or used

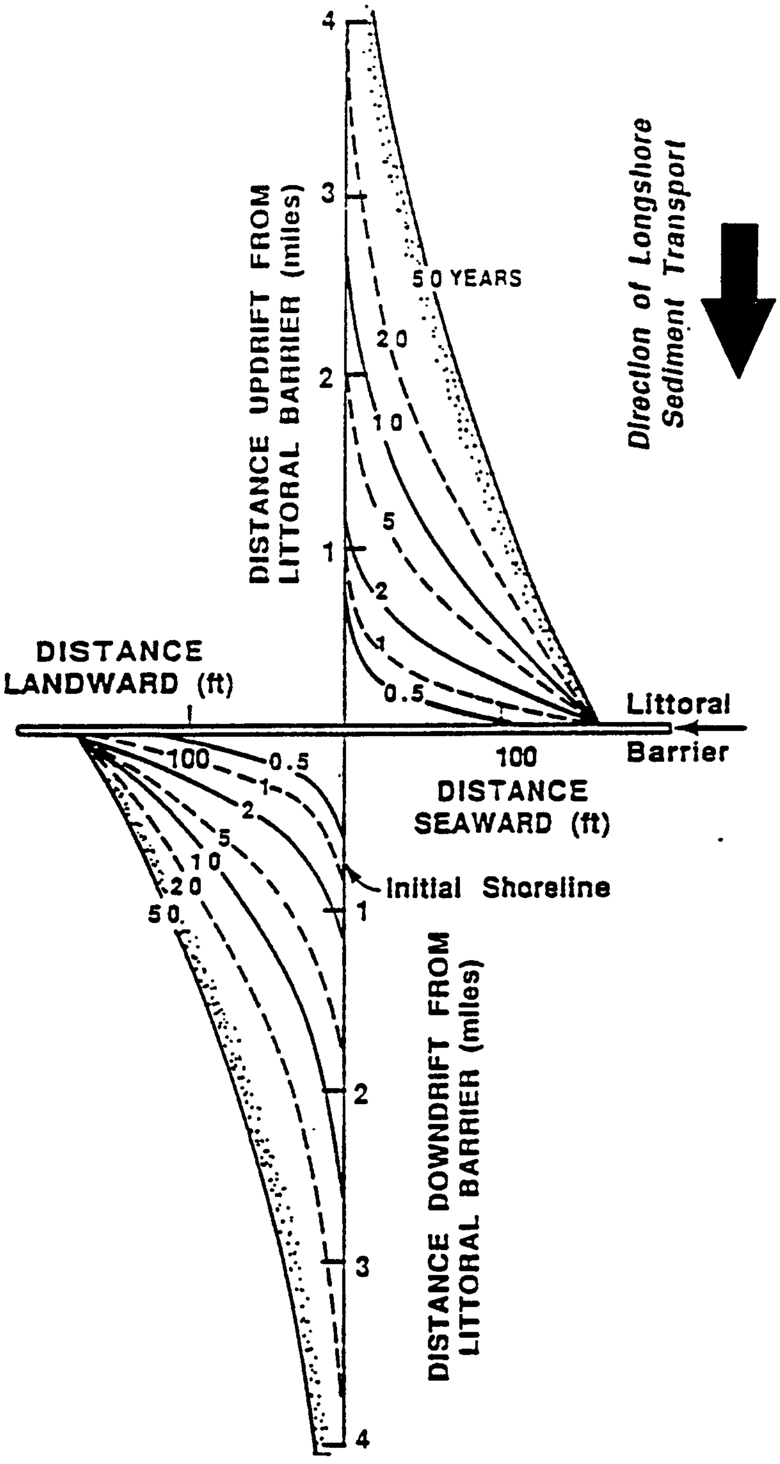


Figure 2.4: Shoreline changes due to placement of a shore normal littoral barrier.

elsewhere. For artificial inlets which had no ebb tidal shoal, the removal of sediment out of the sand sharing system is disastrous since all of the updrift sediment not impounded goes directly to the creation of an offshore bar. This places an enormous erosional strain on the downdrift beach which now has no inflow of sediment to balance its outflow of sediment until the offshore bar is established. This leads to large shoreline offsets within a few years after construction as can be seen in Figure 4.13 of St. Lucie Inlet. Table 2.1 presents approximate offsets for the trained east coast inlets. These offsets show a substantial departure from the initial straight shorelines which existed before the inlets were cut and modified. The material resulting from the ensuing maintenance dredging which is necessary to maintain the navigable inlet should be placed on the downdrift beach. This downdrift placement does not always occur, and for most inlets, this further erodes the downdrift shoreline as any sediment removed from the inlet (assuming a constant direction of longshore sediment transport) is sand removed from the downdrift shoreline. So there are now two components (natural and human induced) to the erosion of the shoreline influenced by the presence of modified inlets. The downdrift beach (with respect to direction of transport, which is south for the east coast of Florida) will experience the greatest negative affect.

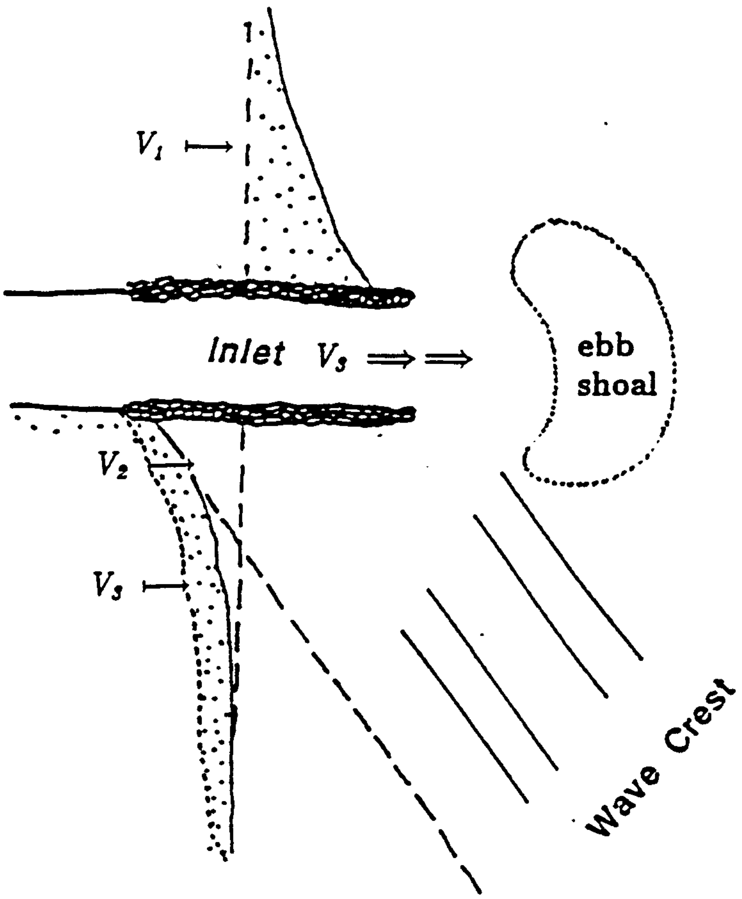
2.2.2 The Updrift and Downdrift Extent of the Influence of Inlets

Douglas (1989) and Work and Dean (1990) have used a numerical shoreline change model to evaluate inlet effects. The use of this model demonstrates the anti symmetric shoreline changes which occur for the idealized case of placing a littoral barrier on a shoreline. This model will be described briefly below. The shoreline change is computed through the use of a one-line finite-difference model in which the nearshore wave climate is developed by a two-dimensional finite-difference wave propagation routine. This allows for spatial and temporal variability in the nearshore wave climate. The governing equation and boundary conditions are taken from a method proposed by Pelnard-Considère (1956). A sediment continuity equation and a dynamic transport equation are combined and linearized to show

Table 2.1: Approximate Offsets at East Coast Inlets and the Year of the Shoreline Measured. A Positive Offset Indicates an Updrift Accretion and a Downdrift Erosion.

INLET	OFFSET *feet*	YEAR MEASURED
St. Augustine	-1200	1985
Matanzas	*	*
Ponce de Leon	-800	1986
Port Canaveral	1000	1986
Sebastian	600	1974
Ft. Pierce	750	1970
St. Lucie	2500	1970
Jupiter	350	1969
Lake Worth	1400	1955
South Lake Worth	350	1986
Boca Raton	400	1956
Hillsboro	700	1961
Port Everglades	750	1962
Bakers Haulover	100	1962

* The offset at Matanzas Inlet was not measured since the inlet has no training structures.



$V_1 = V_2$

V_3 = **losses from inlet (offshore)**

Figure 2.5: Shoreline changes as a result of placing jetties at an inlet.

that the governing equation is the diffusion equation (Pelnard-Considère, 1956):

$$\frac{\partial y}{\partial t} = G\frac{\partial^2 y}{\partial x^2} \tag{2.1}$$

where G is a diffusivity parameter given by:

$$G = \frac{KH_b^{5/2}\sqrt{\frac{g}{\kappa}}}{8(s-1)(1-p)(h_* + B)} \tag{2.2}$$

where

- K = Dimensionless transport coefficient of order 1
- H_b = Wave height at breaking
- g = Acceleration of gravity
- $\kappa = \frac{H_b}{h_b}$ (Spilling breaker assumption)
- h_b = Water depth at breaking
- s = Sediment specific gravity
- p = Sediment porosity
- h_* = Maximum depth of sediment motion (depth of closure)
- B = Berm height

G has the dimensions of length squared per unit time, and expresses the time scale of shoreline change. For a value of $h_* + B = 27$ feet, G has a value of 0.0214 $H_b^{5/2}$ ft^2/sec.

The initial condition is taken as an infinitely long, straight shoreline:

$$y(x,0) = 0, \qquad |\, x \,| < \infty \tag{2.3}$$

and a boundary condition stating that there is no change in the far field:

$$y(\pm\infty, t) = 0, \qquad \text{for all } t \tag{2.4}$$

At the barrier, a boundary condition that is dependent upon the time of bypassing exists:

$$\frac{\partial y}{\partial x}\Big|_{x=0} = \tan\theta_b \qquad 0 < t < t_{bp} \tag{2.5}$$

$$y(0,t) = \pm l \qquad t \geq t_{bp} \tag{2.6}$$

This boundary condition assumes an impermeable littoral barrier at $x = 0$, where θ_b is the angle (measured counter-clockwise) between the shore-normal and the wave ray at breaking (Figure 2.6). Equation 2.5 states that the shoreline at the structure will orient itself to match the direction of the incoming waves, yielding zero longshore sediment transport at the structure until the time of bypassing, t_{bp}. Once bypassing of sediment around the barrier has commenced, Equation 2.6 becomes valid, where l is the length of the littoral barrier. The time of bypassing, t_{bp}, is expressed as:

$$t_{bp} = \frac{\pi}{4}\frac{l^2}{G\tan^2\theta_b} \tag{2.7}$$

The solution to Equation 2.3 for the above stated boundary and initial equations (Pelnard-Considère, 1956) is anti-symmetric (ie. $y(-x,t) = -y(x,t)$) about the y-axis and is presented here only for $x > 0$.

$$y(x,t) = \frac{-\tan\theta_b}{\sqrt{\pi}}\left[\sqrt{4Gt}\exp\left(-\frac{x^2}{4Gt}\right) - x\sqrt{\pi}erfc\left(\frac{x}{\sqrt{4Gt}}\right)\right] \quad \text{for } t < t_{bp} \tag{2.8}$$

$$y(x,t) = -l\,erfc\left(\frac{x}{\sqrt{4Gt}}\right) sign(x) \quad \text{for } t \geq t_{bp} \tag{2.9}$$

where $sign(x)$ denotes the sign of the x value and *erfc* denotes the complementary error function:

$$erfc = 1 - erf \tag{2.10}$$

$$erf(z) = \frac{2}{\sqrt{\pi}}\int_0^z \exp(-u^2)du \tag{2.11}$$

Figure 2.4 shows the evolution of a shoreline with time as defined by Equations 2.8 and 2.9, after a littoral barrier has been placed normal to the shore. The solution for $t \rightarrow \infty$ is an asymptotic limit where a uniform shoreline, with a net offset $2\,l$ at all locations, is reached and the structure no longer affects the longshore transport. Figure 2.4 presents the solution to the Pelnard-Considère method. This clearly shows the anti-symmetry produced from the placement of a littoral barrier on the shoreline.

The anti-symmetric shoreline change indicates an odd pattern for the erosion at inlets. An odd pattern is anti-symmetric about its midpoint, and at points equidistant from its center has the same magnitude but opposite signs. The shoreline change, $Y_n(x)$, can be divided into two components; one even and one odd as was done by Berek and Dean (1982), Dean and Pope (1987) and Douglas (1989). The solutions for these two components are given as follows:

$$y_e(x) = \frac{Y_n(x) + Y_n(-x)}{2} \tag{2.12}$$

$$y_o(x) = \frac{Y_n(x) - Y_n(-x)}{2} \tag{2.13}$$

The boundaries of the erosional influence of the inlet are then obtained from the even and odd functions and the shoreline change function (Work and Dean, 1990). The odd component, which can be considered as relating directly to the interruption of longshore sediment transport, gives the updrift and downdrift distances at which the inlet still affects the shoreline. The integral of the square of the amplitude of the even and odd function provides a measure of the relative effects of the even and odd function versus distance from the inlet. These integrals are approximated by:

$$I_e(x_n) = \sum_{i=1}^{n} [y_e(x_i)]^2 (x_i - x_{i-1}) \tag{2.14}$$

$$I_o(x_n) = \sum_{i=1}^{n} [y_o(x_i)]^2 (x_i - x_{i-1}) \tag{2.15}$$

where $x_0 = 0$.

By plotting these integrals versus distance from the inlet, it is possible to identify the limit of inlet influence. The erosional boundaries for all the east coast inlets of Florida to be analyzed here have been approximated in this manner and are presented in Table 2.2.

2.3 Sea Level Rise

Relative sea level rise is considered to be a dominant cause of shoreline change (Mehta et al., 1987). A change in sea level causes the shoreline to be out of equilibrium with the

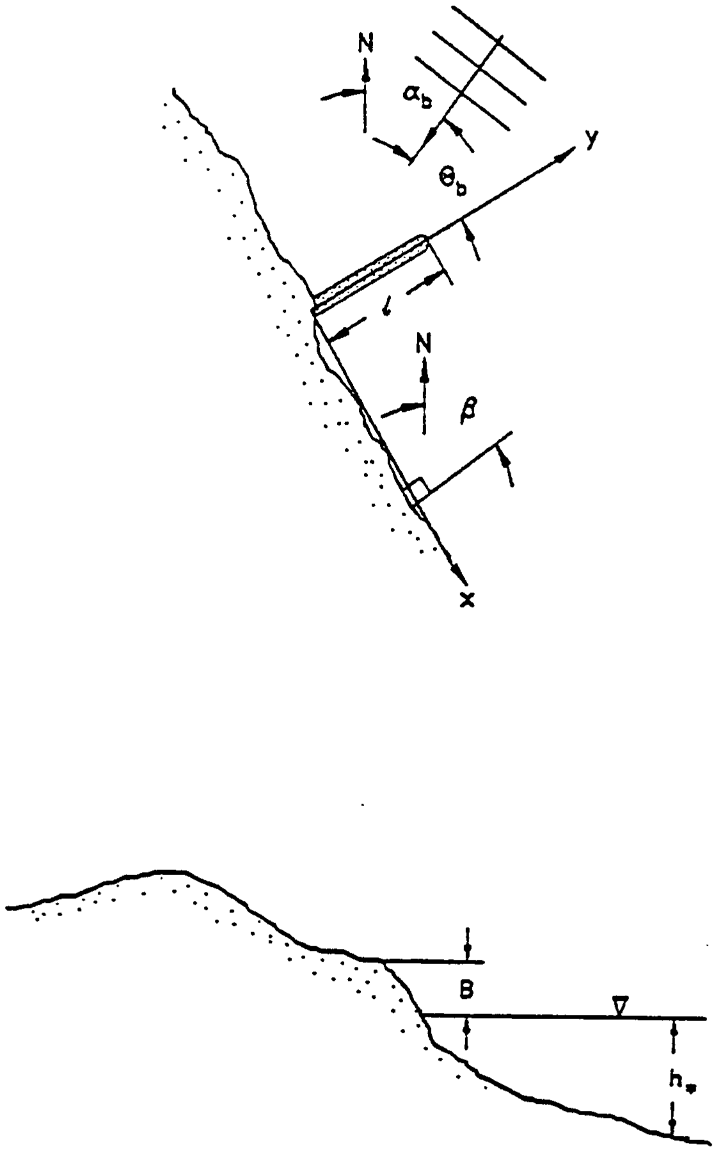


Figure 2.6: Definitions of the variables θ_b, B, h_* and l.

Table 2.2: Shoreline Distances Away From Inlet, Within Which the Inlets Exert Erosional Influence. For the East Coast of Florida (Work and Dean, 1990).

INLET	UPDRIFT *feet*	DOWNDRIFT *feet*	TOTAL SHORELINE *feet*
St. Augustine	15,000	26,000	41,000
Matanzas	13,000	13,000	26,000
Ponce de Leon	9,000	9,000	18,000
Port Canaveral	19,000	19,000	38,000
Sebastian	31,000	30,000	61,000
Ft. Pierce	21,000	21,000	42,000
St. Lucie	22,000	23,000	45,000
Jupiter	12,000	14,000	26,000
Lake Worth	10,000	10,000	20,000
South Lake Worth	25,000	25,000	50,000
Boca Raton	21,000	20,000	41,000
Hillsboro	19,000	19,000	38,000
Port Everglades	25,000	25,000	50,000
Bakers Haulover	9,000	9,000	18,000

'new' higher sea level and therefore changes occur as the shoreline attempts to return to equilibrium. These changes result in either an advance or retreat of the existing shoreline. The future trend of sea level change is impossible to predict with high accuracy. Therefore it is imperative that the present and past sea level changes are understood in order to better prepare for the future.

The trends of sea level rise over the last 20,000 years have been based on Carbon 14 dates in relatively stable areas (Shepard, 1963). Essentially, the sea level rose rapidly (roughly 2.6 feet/century) from 20,000 years before present to about 6,000 years before present. Over the last 6,000 years, sea level has risen at a reduced rate of 0.4 feet/century which is more consistent with present trends which will be discussed later.

The dominant engineering approach to predicting shoreline response to sea level rise is the Bruun Rule which considers only cross-shore transport (Dean, 1990). The Bruun Rule was initially presented by Bruun in 1962 and has since been improved by reconsiderations of Bruun's initial assumptions. However, the basic principal has been largely verified as reviewed by Dean and Maurmeyer (1983). This rule has two assumptions: *a)* that the active profile is always in equilibrium and that it retains its position relative to sea level, and *b)* that the active portion of the profile is limited by the 'depth of effective motion' seaward of which no sediment exchange occurs (Mehta et al., 1987). With these assumptions, a vertical rise, S, of the sea level causes the entire active profile to also rise by S.

This rise requires a volume of sand, V, per unit beach length:

$$V_{deposited} = S\,L \tag{2.16}$$

where L is the offshore length of active profile. This required that sand be provided by the retreat, R, of the profile over a vertical distance, $h_* + B$, as presented in Figure 2.6. The volume generated by this retreat is:

$$V_{eroded} = (h_* + B)\,R \tag{2.17}$$

Equating these two volumes ($V_{eroded} = V_{deposited}$) results in the Bruun Rule which presents a correlation between sea level rise and shoreline change (Dean, 1990).

$$R = S\,\frac{L}{(h_* + B)} \tag{2.18}$$

The Bruun Rule states simply that a rise in sea level will result in a shoreline retreat.

Sea level data, like shoreline change data, are limited to roughly the last century here in the United States. The National Ocean Service (NOS) (a division of the National Oceanic and Atmospheric Administration) maintains and operates tide gauges around the United States. The gauges, predominately mounted on piers, measure sea-level heights relative to the adjacent land. Each gauge is referenced to monuments located on land, therefore, in Florida shoreline change data and sea level data are relative to the same reference points. Hicks, Debaugh and Hickman (1983) present yearly sea level data for NOS tide gauges, four of which are located on the east coast of Florida. The yearly mean sea level is the arithmetic mean of a calendar year of hourly heights taken from each gauge.

CHAPTER 3
METHODOLOGY

3.1 Introduction

This chapter outlines briefly the methods employed in this study. Three main objectives were set. The first was to establish accurate shoreline change rates along the sandy coast of Florida. The second was to utilize these erosion and accretion rates to evaluate the effects of inlets, more specifically the effects of training or modifying inlets. Finally, shoreline changes were used along with sea level rise data to determine if a correlation exists between the rising sea level and shoreline changes along the Florida coast.

3.2 Shoreline Change Rates

All of the shoreline change data are referenced to FDNR monuments. These monuments thus provide a useful basis for referencing the shoreline change rates to be grouped later into areas for evaluating the influence of inlets. The initial shoreline position data were examined for any points which had obvious inconsistencies or errors. Twenty of the points (within the 515 monuments that comprise the east coast inlets) that couldn't be attributed to storms or historical accounts of construction and shoreline modifications were removed in order to create as accurate a data set as possible. In the roughly 130 years of data, there is no single year survey which encompass the entire coast of Florida. Most of the data are from surveys conducted within individual counties and around inlets, with each survey having been completed in various years. This does not allow for the erosion to be referenced to a common year since there are inconsistent time gaps from one monument to the next. For this reason, a least squares method was applied to the data at each monument to establish a shoreline change rate from the entire time series of available shoreline positions.

The shoreline variation between monuments was assumed to be linear since the length of shoreline between monuments is on the same order of magnitude as the long term shoreline changes. This assumption allows for shoreline change rates to be calculated for various geographic groupings of monuments.

3.2.1 Inlet Influenced Shoreline Segments

Inlet influenced segments are taken as the shoreline updrift and downdrift within the erosional influence of the inlet as quantified in Table 2.2. Average shoreline change rates are only calculated in specific cases for comparative purposes, since the combined updrift and downdrift shorelines tend to average out giving a value that is not representative of the shoreline changes at the inlet. Therefore, for each inlet the shoreline changes are referenced to the individual monuments. Each inlet is examined before and after any major modifications in order to evaluate the impact of the modifications. For many inlets it is difficult to acquire accurate shoreline change rates before modifications, since not enough data exist. In these cases, whenever possible, historical shorelines are presented to show the direction of shoreline motion. This is accurate in trend but not in magnitude.

3.2.2 The Coast of Florida

The majority of shoreline surveys are county specific, so accurate county wide average shoreline change rates are easily obtained. It should be noted that Cape Canaveral is listed as an individual county instead of being included in Volusia and Brevard Counties, where it is located. This is due to the military and Federal holdings within Cape Canaveral which has led to surveys and historical shorelines separate from Volusia and Brevard Counties.

Each county was examined before and after the 1930s; chosen as a somewhat arbitrary time roughly separating the data set in half with regard to temporal length. The shoreline influenced by each inlet is removed whenever possible to obtain erosion or accretion rates due predominantly to natural causes. Long term rates were calculated for each county as these are essentially unaffected by storm and seasonal fluctuations. The Appendix presents each county as long term shoreline change rates along the coast, and as a corresponding histogram providing the distribution of accretion and erosion rates within each county. The rates for all monuments were then averaged in order to find the changes on each coast and finally around Florida as a whole.

3.3 Sea Level Changes

According to the Bruun Rule (Equation 2.18), the rising sea level is affecting (increasing) shoreline erosion. Since the east coast of Florida has both sea and shoreline data from 1897 on, it is possible to test the Bruun Rule. Sea level rise data and shoreline change data for the same shoreline were organized separately and then combined in order to examine the correlation. Three tidal stations located at Fernandina Beach, Mayport and Miami Beach (see Figure 1.1) were used, supplying data which geographically encompassed the east coast counties studied. The data from all three stations follow the same trend with time but have different magnitudes as shown in Figure 3.1. Therefore it is possible to fill in gaps in the data by first establishing the correlation between stations, and secondly using existing data at one station to create a full record at another station resulting in three stations with sea level records covering 1897–1980. The result is a yearly mean sea level at each station for each year. Changes in sea level can then be determined to test for correlation with shoreline changes.

A shoreline change is obtained first since shoreline changes are dependent upon the years of the shoreline surveys. All of the counties from (and including) Flagler County south through Dade County (see Figure 1.2) were used in order to create as long a control area as possible. Nassau, Duval and St. Johns counties were excluded from the shoreline studied due to the highly influential inlets located within them. These inlets present a problem when trying to remove their effects from the surrounding shoreline due to the relatively short shoreline segments. Therefore, their exclusion resulted in a more accurate data set. Also, shorelines influenced by nourishment projects were removed from each data set, leaving shoreline change data which is 'ideally' a result of only natural processes and consisting of relatively straight shorelines. Since most surveys are county specific, the shoreline data set for each county was split into time segments which could produce an accurate shoreline change. In order to examine if a correlation exists, as many points as possible need to be generated. However, in order to maintain accuracy, the time segment must be long enough to reduce 'noise' generated by seasonal fluctuations and storm effects. The result of this was three to four time segments for each county.

This produced an average shoreline change, ΔY, for every time period (each roughly 15–30 years long) in each county. A corresponding change in sea level, ΔZ, was obtained for each time period (t_i). Each sea level change was taken from the tide station closest to that specific county. A least squares method was utilized to best find accurate ΔY and ΔZ values. A mean shoreline change and a mean sea level rise were found by averaging all the ΔY and ΔZ values. The mean values were subtracted in order to examine the changes from the trends. Equation 3.1 was used to find if any correlation exists between sea level rise and shoreline change. Since it is highly unlikely that a rise in sea level instantaneously affects the shoreline, each county was examined with a shoreline change which lagged sea level rise in yearly increments. The lag time, τ, was examined for up to 19 years with a correlation value found for each year. The shoreline change was kept constant, while the sea level change was recalculated with all sea level change values lagged by τ years.

$$r(\tau) = \frac{\sum \left[\Delta Y(t_i) - \overline{\Delta Y}\right] \left[\Delta Z(t_i - \tau) - \overline{\Delta Z}\right]}{\sqrt{\sum \left(\Delta Y(t_i) - \overline{\Delta Y}\right)^2 \sum \left(\Delta Z(t_i - \tau) - \overline{\Delta Z}\right)^2}} \tag{3.1}$$

where $\overline{\Delta Y}$ and $\overline{\Delta Z}$ are the mean values of their respective arrays. The mean value of sea level rise, $\overline{\Delta Z}$, has a weak dependency on τ. However, this has been neglected since it is calculated by summing ΔZ and is therefore a second order dependency. If a perfect linear relationship such as $\Delta Y = m\Delta Z + b$ is found between ΔY and ΔZ, Equation 3.1 will yield $r(\tau) = \pm 1$. If the Bruun Rule represents the shoreline change, $r(\tau) = -1$. By subtracting out the mean values the bounds of the equation are set at $0 \leq | r(\tau) | \leq 1$.

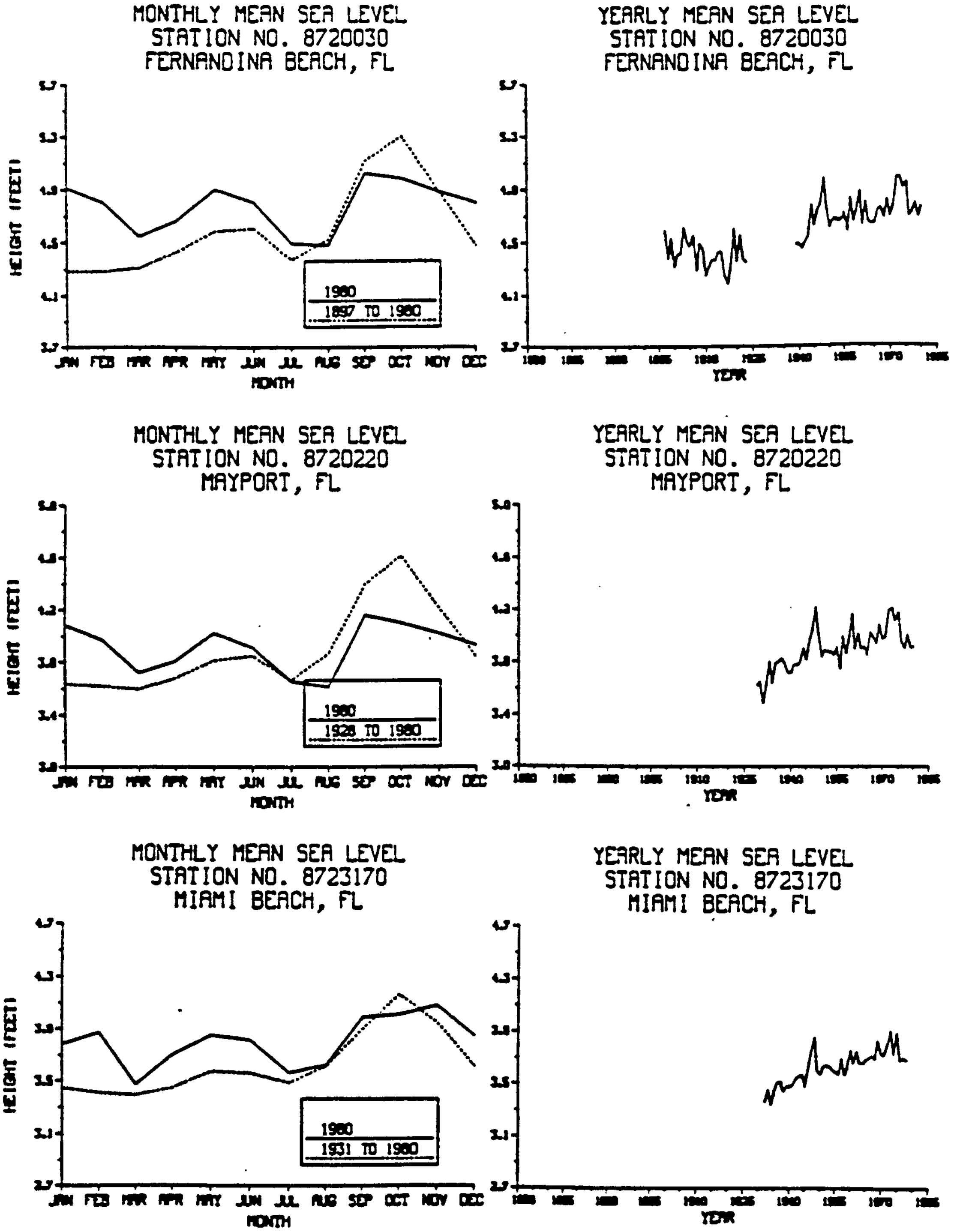


Figure 3.1: Monthly mean sea level variations and long-term sea level data at the three locations on the east coast of Florida used in this study. Based on tide gauge data (from Hicks et al., 1983).

CHAPTER 4
RESULTS

4.1 Introduction

This chapter will present the historical shoreline changes for various geographic regions and temporal extents. This allows for comparison of counties with and without their respective erosionally influenced areas due to inlets. It is then possible to reduce these to pre- and post-inlet training (where the data set allows) in an attempt to see if there are any consistent erosional effects due to human intervention with what were originally 'quasi-equilibrated' shorelines. A comparison of these shorelines is presented in an attempt to better understand inlet effects on Florida's changing coastline. A brief history is given of each inlet to offer reasons for the deviations from theory for the shoreline change associated with that area. Since a least-squares method was used to determine the change rate at each monument, the fact that the construction (with regard to training of inlets) dates vary from inlet to inlet does not pose a problem when comparing them.

4.2 East Coast Inlets

4.2.1 St. Augustine Inlet

St. Augustine Inlet is an artificial inlet which was cut and stabilized in 1941. Prior to this, it existed as a natural inlet that shifted naturally between two well-defined locations until the present inlet was cut at a location 2.5 miles to the north of the previous outlet (see Figure 4.1). The north jetty was constructed in 1941 and by 1946 the old inlet to the south was starting to shoal and close (Florida Coastal Engineers, 1976). In 1957 the south jetty was built. At this time, the old inlet was almost entirely closed and its ebb shoal had moved landward and formed what is now Conch Island as shown in Figure 4.1. The south jetty is almost two and a half times longer than the north and all but 120,000 cu. yds. of the 1.6 million cu. yds. of material dredged from the inlet since construction began has been placed on the beach or within the ebb shoal area (Marino and Mehta, 1986), from where it possibly could have moved ashore. The net longshore sediment transport is southerly with frequent reversals during the summer and is estimated at 380,000 cu. yds. per year (Walton, 1976). Figure 4.2 presents the before and after shoreline change rates with regard to the present St. Augustine Inlet's existence and stabilization. The rates along the updrift shoreline have varied little from before to after construction. This is a result of the high permeability of the north jetty which has allowed sediment to leak through the jetty instead of being impounded by it. This leakage has formed a large depositional sand spit (Porpoise Point) which extends southward into the channel (see Figure 4.1). Downdrift, the shoreline has experienced a large accretion after the cutting of the inlet. This is the landward movement of the old inlet's ebb shoal onto Conch Island. This area of accretion has survived since it is now in the lee of the present ebb tidal shoal which was estimated to be 110.4 million cu. yds. in 1979 by Marino and Mehta (1986). South of this, severe erosion is occurring on the downdrift shoreline as the protection of the original ebb tidal shoal no longer provides the same degree of sheltering. Prior to the existence of the present St. Augustine Inlet, the downdrift shoreline exhibited large fluctuations. As St. Augustine Inlet migrated, what had once been the channel now became land as the shoreline opened up in other places. Therefore, the accretion/erosion fluctuation seen in Figure 4.2 is due to the historic inlet migration. There has been a decrease in shoreline change rates both updrift and downdrift since the inlet was trained in 1941: $\Delta \frac{dy}{dt}_{up} = -1.28\ \mathrm{ft/yr}$ $\Delta \frac{dy}{dt}_{down} = -1.78\ \mathrm{ft/yr}$. The decrease downdrift is substantially less than it would be due to the large ebb shoal volume which moved ashore (estimated at 7.3 million cu. yds., Marino and Mehta, 1986) after construction. Without this material moving ashore, the severe downdrift erosion to the south would be concentrated along the northern portion of the downdrift shoreline.

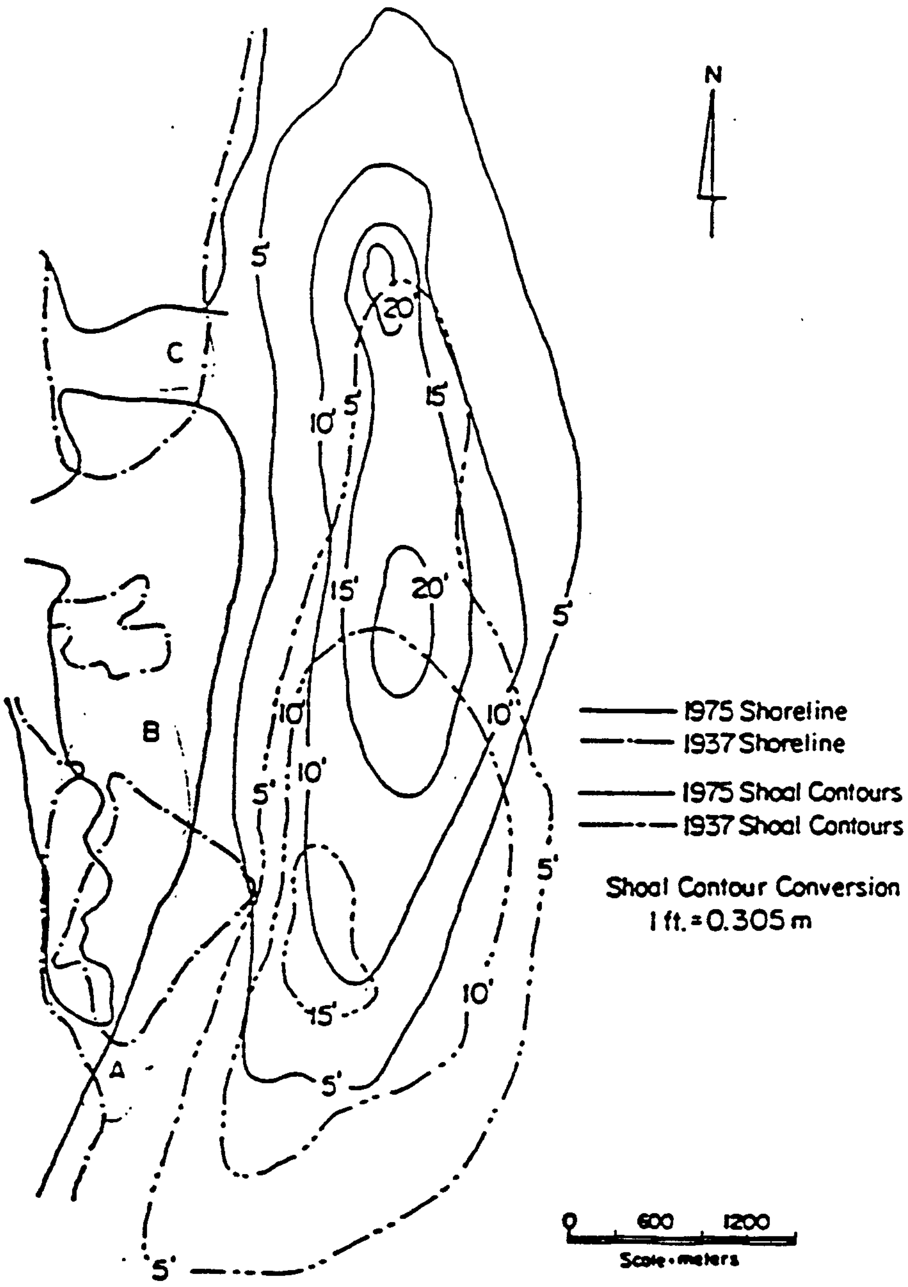


Figure 4.1: Historical shorelines for St. Augustine Inlet (from Marino, 1986).

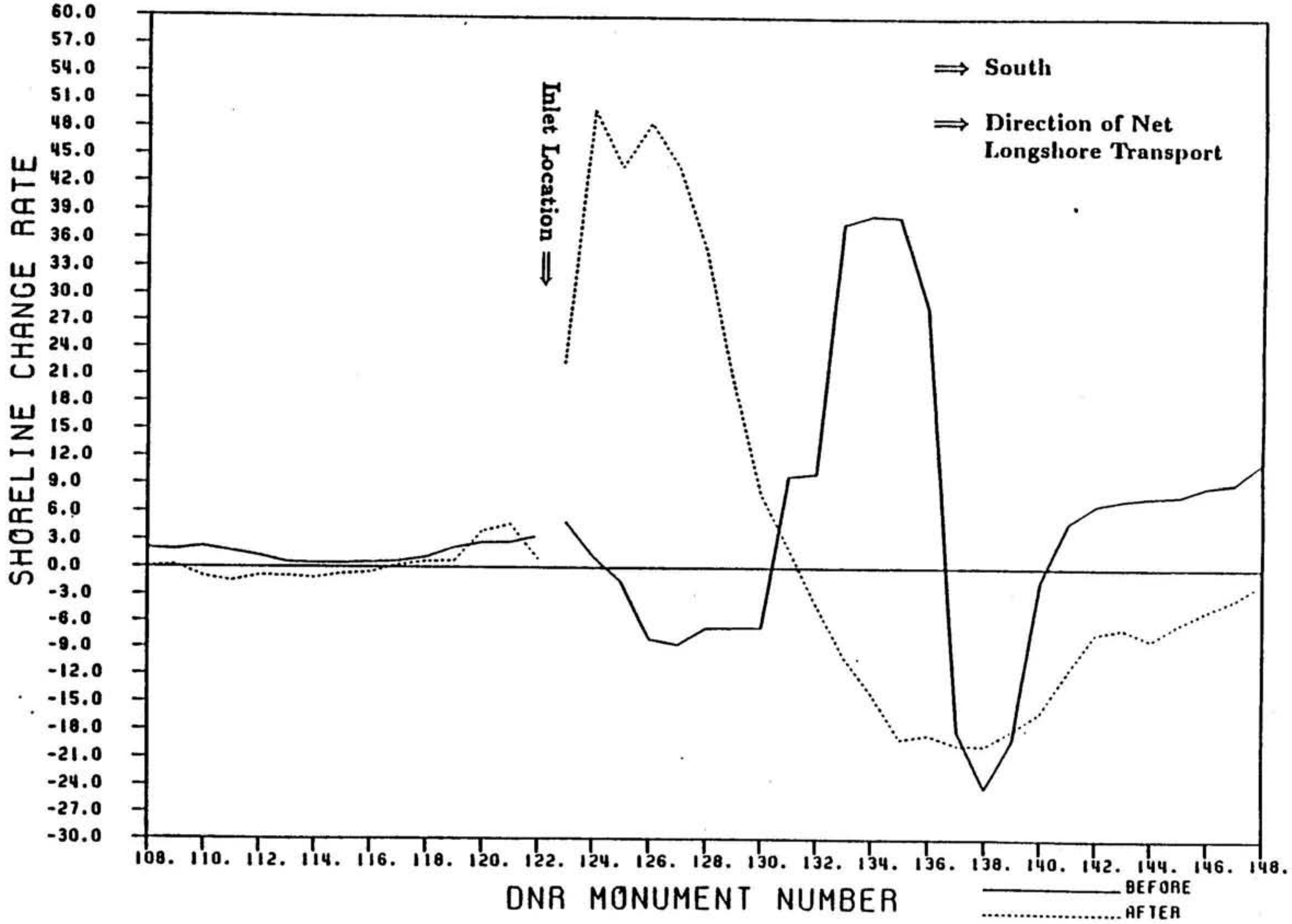


Figure 4.2: Shoreline change rates before (1858–1937) and after (1943–1986) training St. Augustine Inlet. Change rates in feet per year.

4.2.2 Matanzas Inlet

Matanzas Inlet is a natural inlet that is untrained by dredging or jetties. During the period 1872–1923, Matanzas Inlet is shown to have migrated 1100 feet south on historical charts presented by Mehta and Jones (1977). In 1925 a highway bridge (carrying route A1A) was constructed parallel to the shore in the region of the inlet's throat. It was replaced in 1956. A by-pass channel, Matanzas Relocation Cut, was dredged in 1932 through the marsh west of the inlet which had a significant effect on the inlet's flood shoals. In 1964, Hurricane Dora created a breakthrough in Rattlesnake Island, directly behind Matanzas Inlet (Mehta and Jones, 1977). By 1972 this breakthrough had widened to 230 feet, causing increased erosion along both sides of the inlet, until 1976 when a dike was constructed which closed the break. The concrete bridge abutments tend to keep the inlet location stable and prevent any migration to the south in the direction of longshore transport, but nothing has been done to stabilize the depth. The inlet is therefore considered non-navigable and has a large volume of sand trapped in the flood shoal, part of which is now attached to Rattlesnake Island. Figure 4.3 shows the shoreline change rates before and after the initial bridge construction. The evolution of the change rates into an offset planform is similar to that observed at most stabilized inlets although significantly smaller in magnitude. Much of this is due to the inadequate passing of sand across the ebb tidal shoal and the 71,000 cu. yds. of sand entering the inlet each year (Mehta and Jones, 1977). Since the bridge keeps the inlet from migrating and the inlet is unable to clear itself due to a wide shallow mouth, the resulting updrift accretion and downdrift erosion has resulted and increased since the construction of the Rt. A1A bridge.

4.2.3 Ponce de Leon Inlet

Ponce de Leon Inlet is a natural inlet that has been considered navigable since 1513 when early Spanish settlers sailed through the inlet (Mehta and Jones, 1978). It was first dredged in 1943 but left untrained at that time. Due to its natural stability, it was not until 1968 that construction was started on the north and south jetties. They were completed in 1971

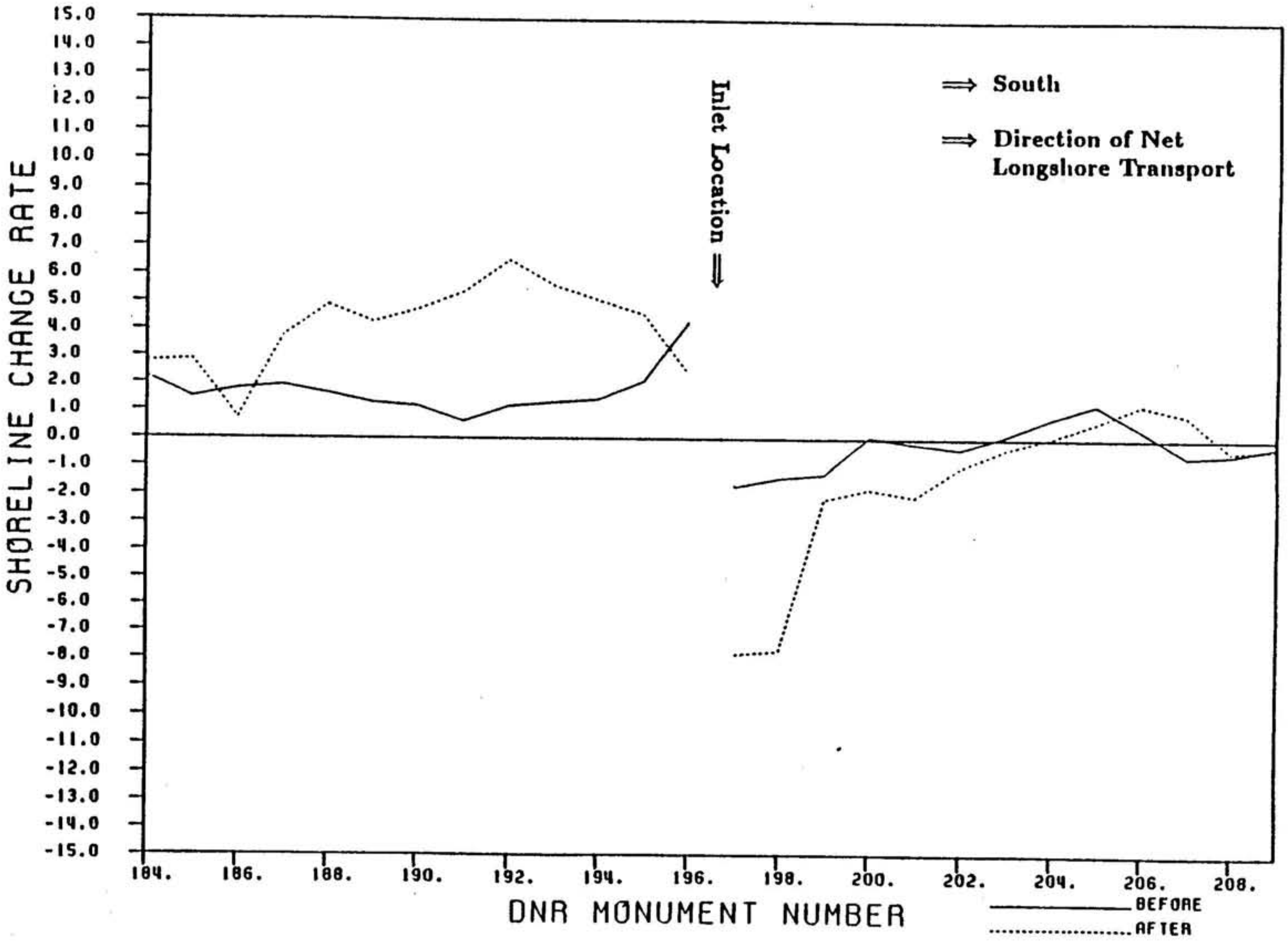


Figure 4.3: Shoreline change rates before (1858-1924) and after (1937-1986) construction of the Rt. A1A bridge over Matanzas Inlet. Change rates in feet per year.

with an 1800 foot long weir section in the north jetty. The construction sequence consisted of completing the rubble-mound portions of both jetties prior to the completion of the weir section. This caused considerable flow through the weir section which led to increased erosion north of the northern jetty (Mehta and Jones, 1978). The weir section allowed a portion of the flow (both ebb and flood) to pass over the section, thereby increasing scour from the impoundment basin in the inlet. Therefore in 1984 the weir section was closed. All of the 3.6 million cu. yds. of sand dredged from the channel has been placed on the north (updrift) beach. During the summer months, transport reversals (southerly transport is predominate) are common. Figure 4.4 shows the before and after training (construction of jetties) change rates of the inlet.

The addition of the jetties has developed a considerable updrift/downdrift offset. The updrift shoreline changes (specifically monuments #140–149) are not consistent with usual patterns due to the weir section included in the original north jetty. The weir elevation of 0.0 ft. MLW still allowed for sediment to pass over the north jetty instead of impounding all of it. The closing of the weir in 1984 by rock placement coupled with the placement of the sand on the updrift beach account for the increase in accretion close to the inlet. The erosion on the downdrift shoreline is expected, due to the construction of a jetty interacting with longshore transport; however, the accretion directly at the south jetty is not expected. This is primarily due to the orientation of the south jetty, Figure 4.5 (Work and Dean, 1990). The sheltered pocket formed by the jetty was partially filled with dredge spoil and has continued to fill during transport reversals. According to Purpura and Chiu (1977) this area is a convergent nodal zone, therefore the pocket formed by construction of the south jetty becomes self-maintaining and will continue to grow until the pocket is full. The average shoreline change rates for the updrift and downdrift shoreline have each been offset by roughly the same amount, with the downdrift offset slightly larger: $\Delta \frac{dy}{dt}_{up} = +4.55\,\mathrm{ft/yr} \qquad \Delta \frac{dy}{dt}_{down} = -5.58\,\mathrm{ft/yr}$.

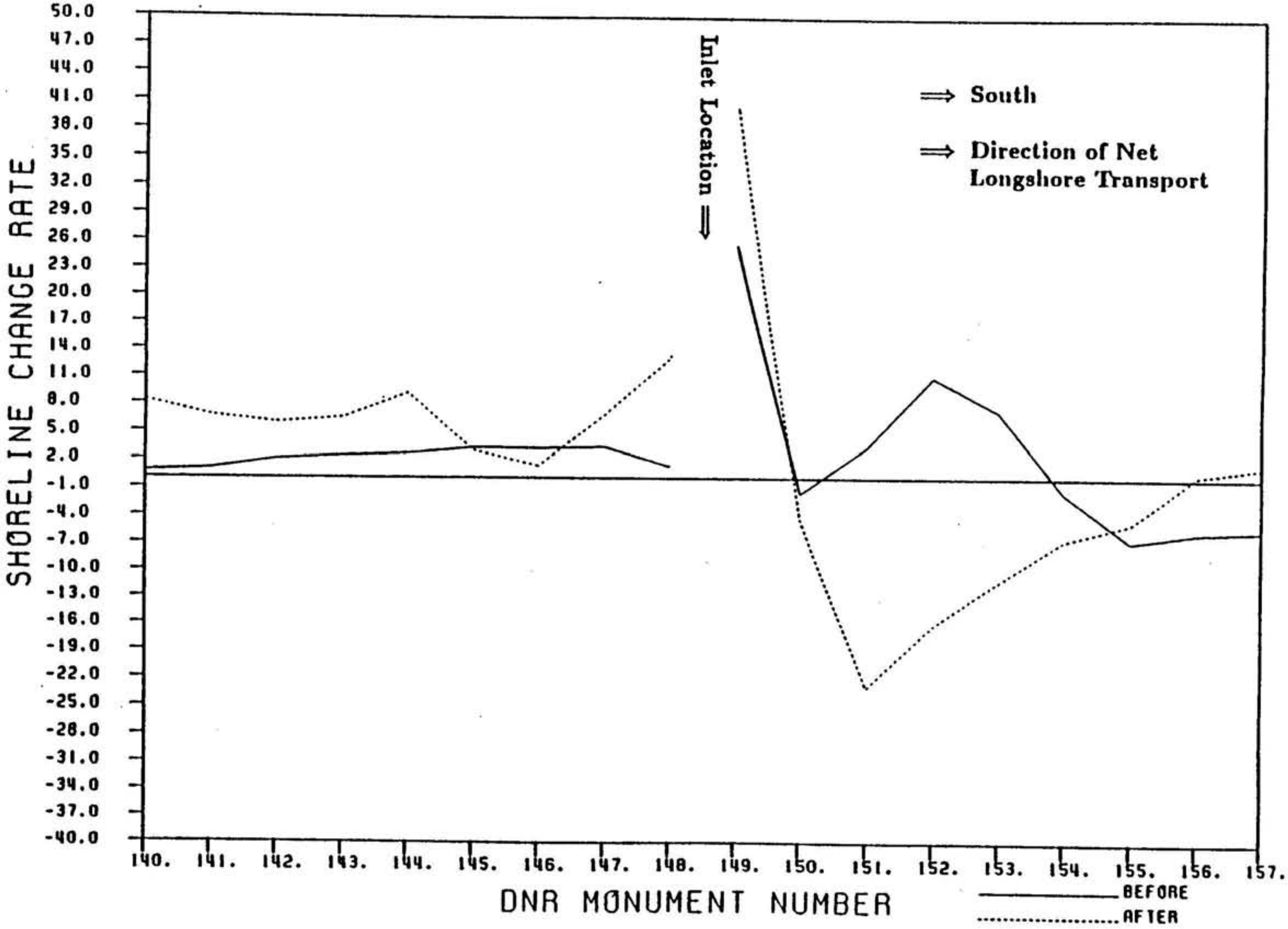


Figure 4.4: Shoreline change rates before (1873-1967) and after (1972-1989) training Ponce de Leon Inlet. Change rates in feet per year.

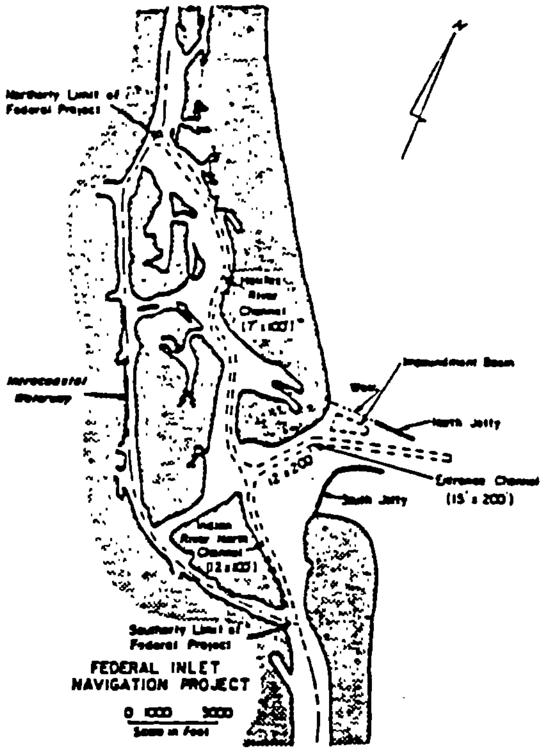


Figure 4.5: Ponce de Leon Inlet: South jetty alignment. Adapted from Jones and Mehta, 1978.

4.2.4 Port Canaveral Entrance

Port Canaveral Entrance is an artificial inlet that was cut in 1951. Equal length (1150 foot) jetties were constructed in 1953–1954. The original depth of the inlet was 24 feet, which was increased in 1956, in 1961 and again in 1974 to its present depth of 43 feet for the Trident submarines (Hunt, 1980). The 1974 dredge spoil was placed on the south beach as a beach nourishment project of 2.5 million cu. yds.. These dredgings of the channel have amounted to a total volume of 31.1 million cu. yds. removed, with only the 1974 dredging being placed on the beach (Dean and O'Brien, 1987a).

Port Canaveral's shoreline was remarkably stable with a consistent accretion prior to construction. Since 1951, the greatest differences have occurred downdrift. Figure 4.6 shows the shoreline change rates before and after inlet conception and jetty construction. Due to the short time span (37 years) since training, there is a substantial amount of noise due to storms and seasonal effects in the shoreline changes from monument to monument, but the trend can be considered reasonably accurate. Updrift there is an increase in accretion due to the impoundment of sediment by the north jetty, with the greatest increases occurring toward the inlet. The data for the downdrift beach are misleading unless the 1974 beach nourishment is considered. Figure 4.7 splits the post training shoreline change rates into pre and post nourishment. Note that these graphs are changes relative to the shoreline position at the beginning of the time period studied. Therefore, a nourished beach will have the largest erosion rates due to spreading out losses as the entire beach attempts to return to a straight, equilibrium planform. So the large erosion just downdrift of the jetty (post-nourishment) is related somewhat to the spreading out losses after adding the 2.5 million cu. yds. of sand. That combined with the accretion just south of the nourished area show this nourishment to be moving as a wave in the direction of southerly transport. This largely explains the lack of offset (with respect to updrift) in the downdrift shoreline change since inlet construction as shown in the previous figure.

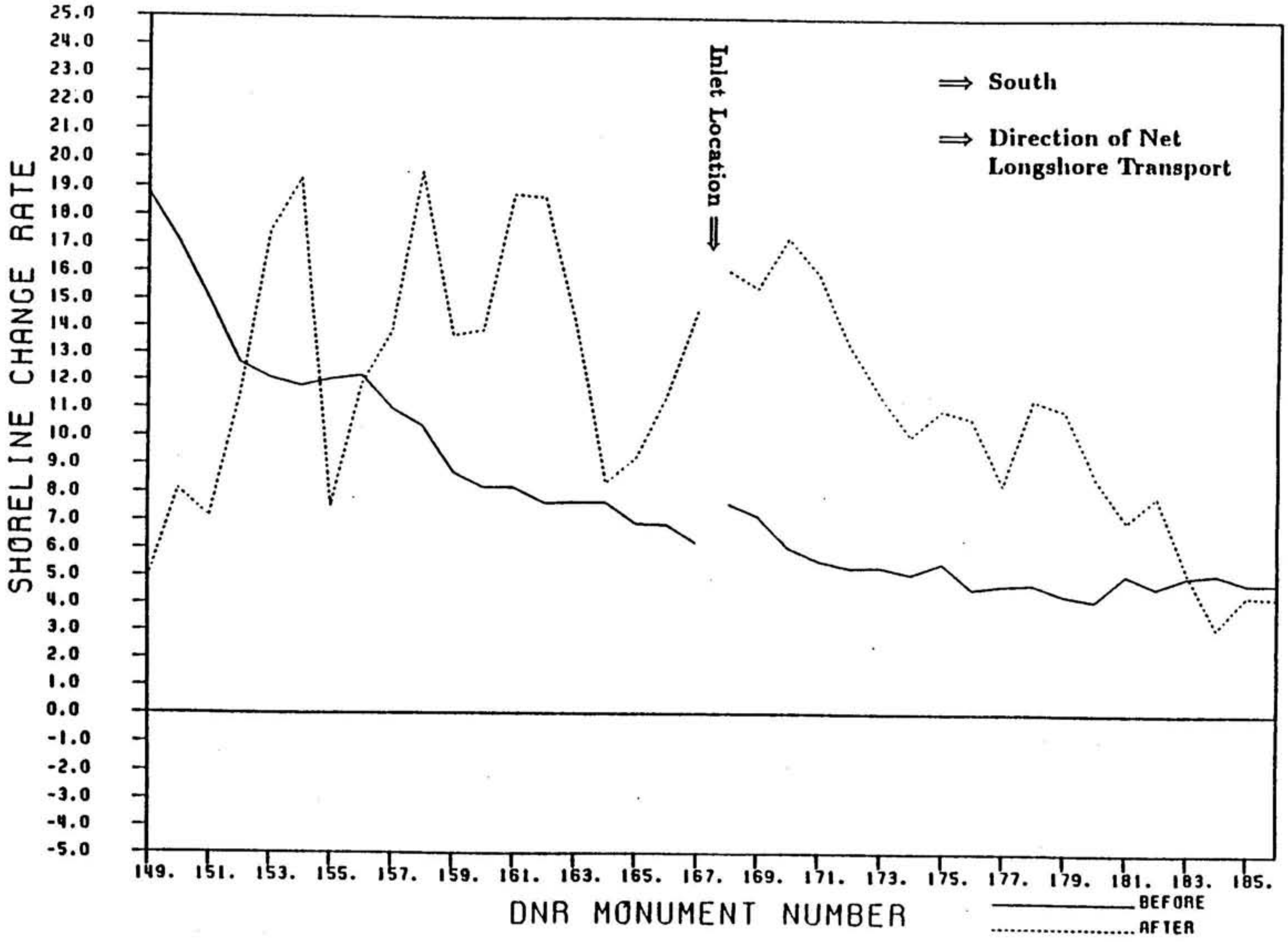


Figure 4.6: Shoreline change rates before (1874–1948) and after (1964–1986) training Port Canaveral. Change rates in feet per year.

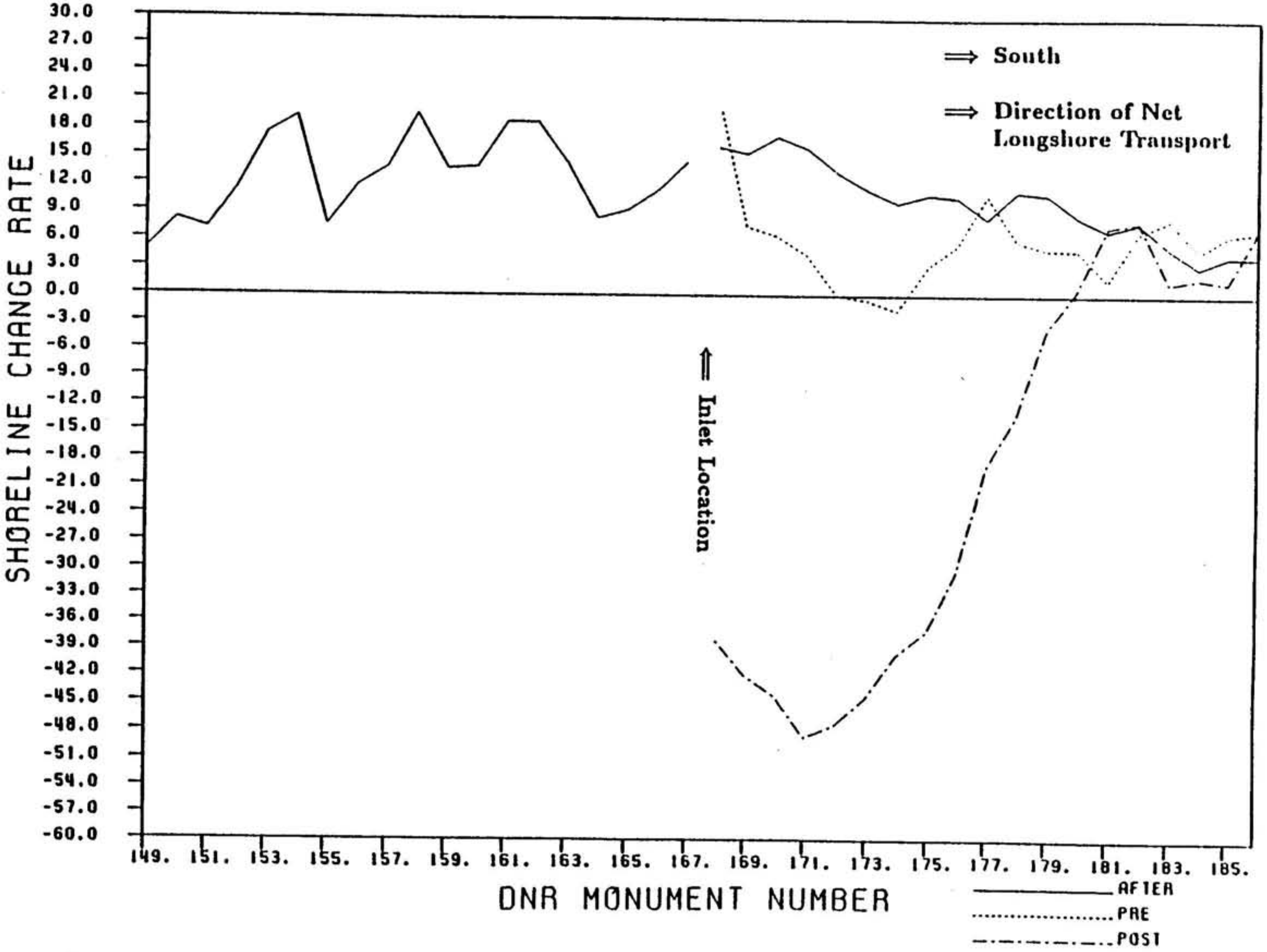


Figure 4.7: Shoreline change rates for pre- (1964-1974) and post-nourishment (1976-1986) of the south beach of Port Canaveral. The shoreline change rates for after training (see previous figure) are included for reference. Change rates in feet per year.

4.2.5 Sebastian Inlet

Many attempts were made to create an artificial inlet in the area of Sebastian Inlet during 1886–1948. In 1924 two jetties were constructed around an artificial inlet after two earlier (1886, 1895) inlets were closed by storms (Mehta et al., 1976). In 1929 the jetties were reinforced with rock, maintaining the inlet until the early 1940s when it was closed by a northeast storm (Mehta et al., 1976). Sebastian Inlet was reopened in 1947 and then again in 1948 at its present alignment. A new north jetty was constructed in 1952 and both jetties were extended during 1968–1970 (Mehta et al., 1976). The majority (1.8 million cu. yds.) of the sand dredged during construction was placed offshore, while present maintenance dredging places all beach quality sand downdrift. Two small nourishment projects have also been undertaken on the south beach. The first consisted of 22,000 cu. yds. in 1977–1979 while the second, in 1985–1986, was roughly the same volume (exact value unknown). Due to incomplete surveys and information quantifying inlet construction it is not possible to obtain good data for the pre-construction era. However, earlier charts show a shoreline (see Figure 4.8) accretion prior to 1948 with the greatest buildup to the north of the inlet (roughly 45 feet over 30 years). Since construction, the shoreline has responded with an updrift/downdrift offset as can be seen in Figure 4.9 (1948–1986). The signal is fairly noisy due to storm and seasonal influences over a 20 year period. The downdrift shoreline has worse erosion than is evident from this figure. The slight bulge shown from monuments #232–240 corresponds to the migrating and diminishing nourishment project of 1977–1979 with the accretion rates at the south jetty due to the latest (1985–1986) project. This gives a downdrift average erosion that is only half of the updrift accretion (in magnitude) instead of the expected greater magnitude of downdrift erosion due to sediment losses at the inlet. $\frac{dy}{dt}_{up} = +1.67\,\mathrm{ft/yr} \qquad \frac{dy}{dt}_{down} = -0.78\,\mathrm{ft/yr}$.

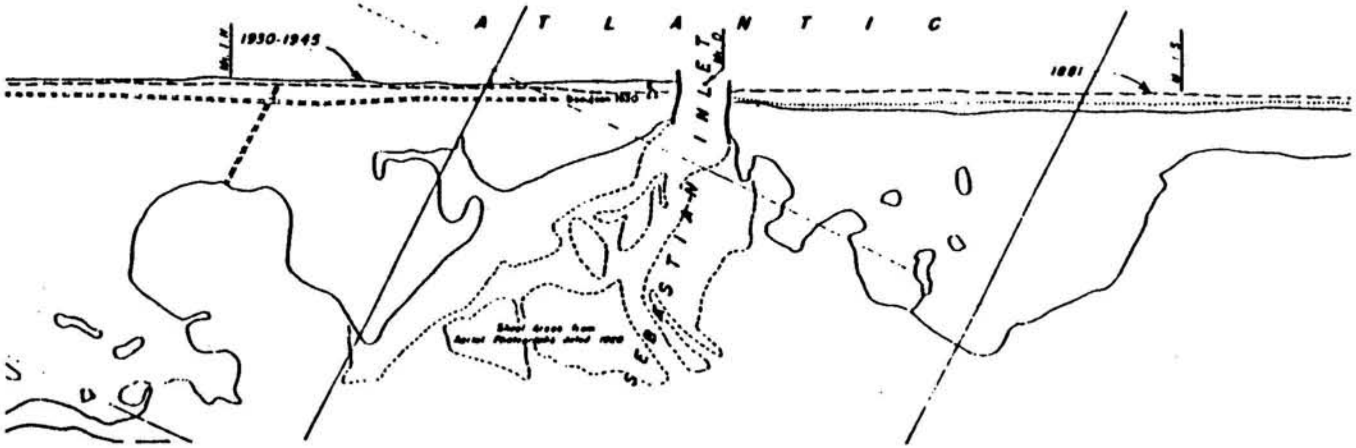


Figure 4.8: Historical shorelines for Sebastian Inlet.

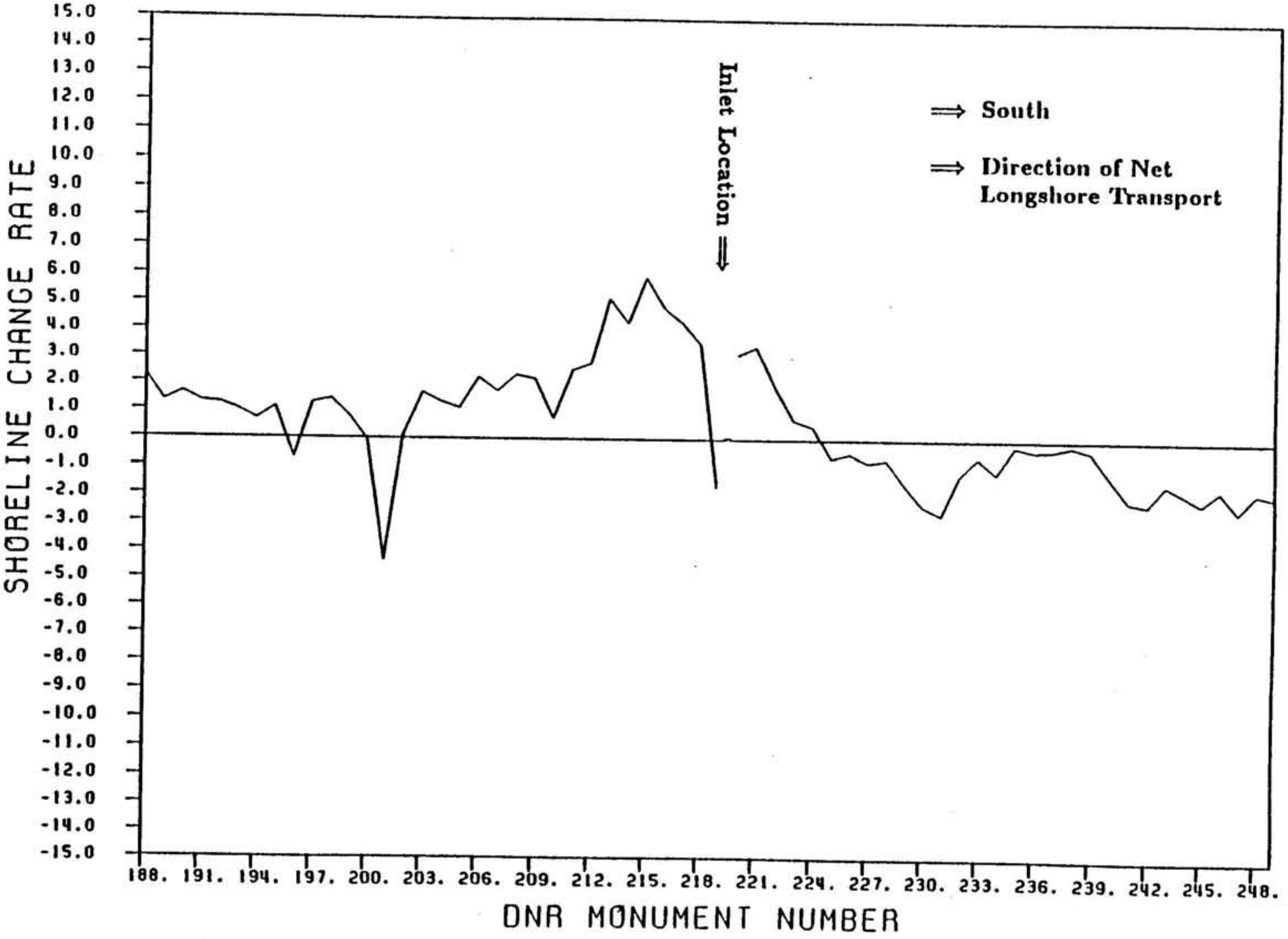


Figure 4.9: Shoreline change rates after training (1948-1986) Sebastian Inlet. Change rates in feet per year.

4.2.6 Ft. Pierce Inlet

A natural inlet connecting the Indian River and the Atlantic Ocean existed 2.6 miles north of the present Ft. Pierce Inlet during the 1800s. When St. Lucie Inlet, 23.4 miles to the south, was cut in 1892, the ensuing changes (hydraulic and morphologic) in the Indian River caused the natural inlet to close (Walton, 1974b). In 1920, due to the need for an inlet in that area, Ft. Pierce was constructed with north and south jetties that were too close and too short. During 1926 the north and south jetties were reconstructed, lengthened (1800 feet and 1200 feet respectively) and the inlet widened to 900 feet due to inlet damage sustained from a storm (Walton, 1974b). The channel was deepened by dredging in 1938 and maintenance dredging is utilized to maintain the 27 foot depth. Of the 3.2 million cu. yds. of material removed, none has been placed on the beaches, with 2.7 million pumped offshore, out of reach of the swash zone. In 1971 a beach nourishment project was completed consisting of 700,000 cu. yds. of material obtained from an offshore borrow area. According to Walton (1977), this project nourished the beach just south of the inlet for approximately one mile. This explains the lack of symmetry shown in Figure 4.11 for the post-construction shoreline change rates. The updrift accretion due to the northern jetty is consistent with expectations, while the downdrift erosion is reduced from monuments # 33–45 due to the nourishment. The nourished area has spread out past the original mile (roughly 5 monuments) which can also be seen in Figure 4.12. This figure which presents the rates for pre- and post-nourishment (1971) (both post-construction) shows the nourishment to have spread out over the entire influenced downdrift shoreline during the sixteen years since project completion. Prior to the inlet, early charts show the 1883 shoreline to be straight with an almost anti-symmetric offset occurring after the construction of the inlet (see Figure 4.10). The only reason this anti-symmetry occurs is due to the added 700,000 cu. yds. of sand. Without it, the influenced area of Ft. Pierce Inlet is definitely eroded due entirely to the construction of the inlet.

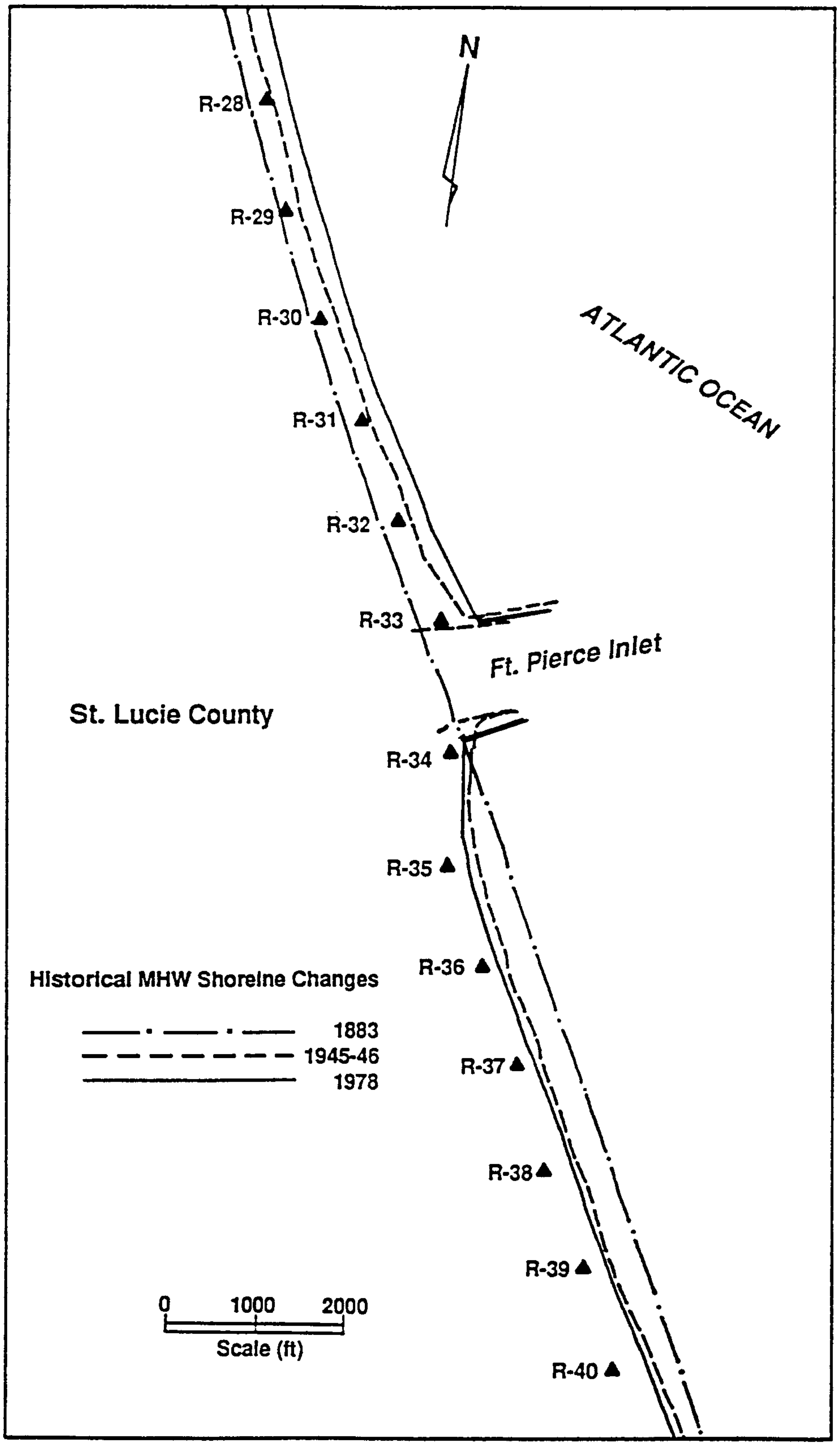


Figure 4.10: Historical shorelines for Ft. Pierce Inlet.

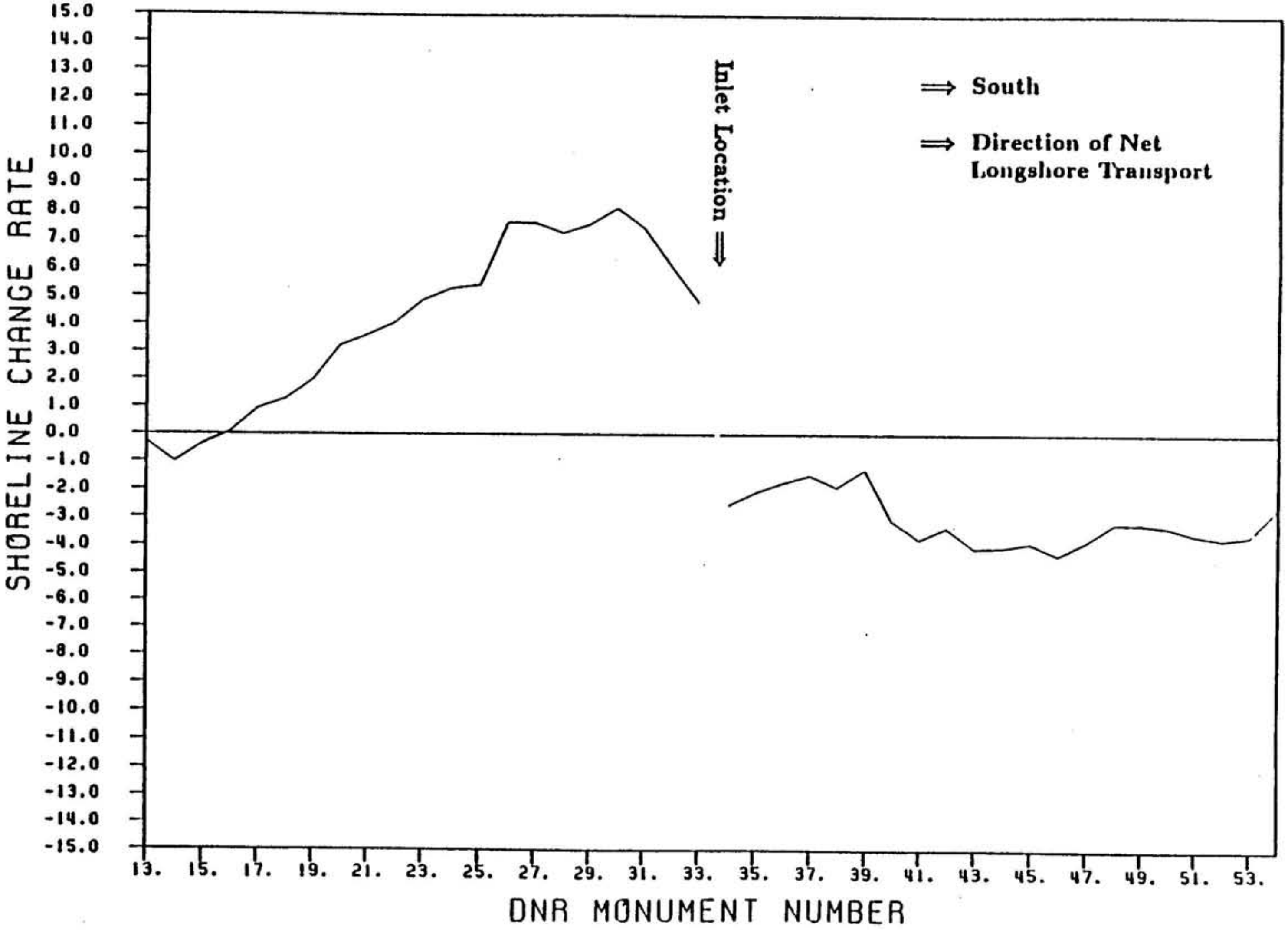


Figure 4.11: Shoreline change rates after training (1928–1987) Ft. Pierce Inlet. Change rates in feet per year.

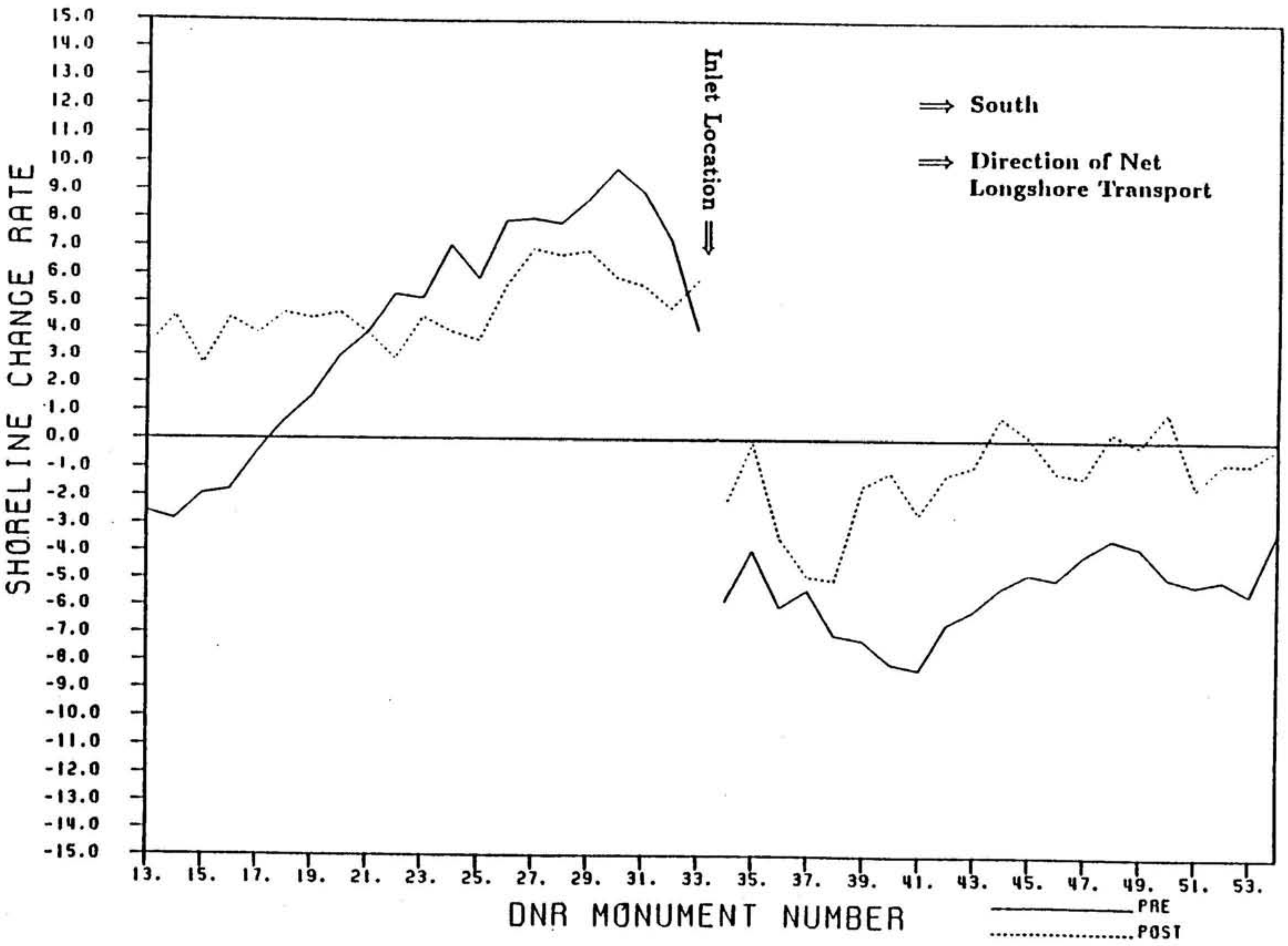


Figure 4.12: Shoreline change rates for pre- (1928–1970) and post-nourishment (1972–1987) of Ft. Pierce Inlet. Change rates in feet per year.

4.2.7 St. Lucie Inlet

St. Lucie Inlet is an artificial inlet cut in 1892 (Walton, 1974a). The original inlet was 27 feet wide and through natural processes the inlet widened until 1926, when it reached a width of 2400 feet. At that time a north jetty was constructed to a length of 3325 feet. Roughly four miles south of the inlet, a large storm in 1962 caused a breakthrough in the beach back to the Indian River. In the ensuing year, this breakthrough continued to widen thereby causing St. Lucie Inlet to shoal. Dredging work done between 1963–1965 closed the breakthrough and restored St. Lucie Inlet to a depth of six feet (Walton, 1974a). In 1981, the north jetty was extended with a dog-leg extension and a shorter (1500 feet long) south jetty was constructed. A detached breakwater was constructed south of the channel which acts as a training structure (see Figure 4.13). This created an 800 foot wide channel. A total of 3.0 million cubic yards of sand, the result of dredging, has been placed on the downdrift beach in the form of beach nourishment projects. The first in 1928, placed 1.1 million cu. yds. on the south beach (Walton, 1974a) with the remaining 1.9 million cu. yds. placed in the same area during the period during 1965–1985. The last two years (1984–1985) included a 400,000 cu. yd. project covering 3000 ft south of the inlet.

Since St. Lucie Inlet was constructed prior to any substantial shoreline data, accurate pre-construction shoreline change rates are unavailable. However, Figure 4.13 shows the relative position of the shorelines in 1883 (prior to inlet existence) and in 1970. There is an enormous difference in offset but not one that is anti-symmetric at the inlet. The shoreline retreat is close to 2500 feet downdrift of the inlet. Figure 4.14 presents the post-construction shoreline change rates which also lack anti-symmetry. Updrift of the inlet, the accretion due to the north jetty construction has allowed the north beach to return and surpass the 1883 shoreline. This has compensated for the significant erosion on the updrift side that Walton (1974a) indicates took place on both sides of the inlet immediately after it was cut. Downdrift erosion is enormous. The beach directly south of the inlet seems to be accreting however this is due to the 3.0 million cu. yds. of nourishment. Even with all of the added material, the average erosion rate of $\frac{dy}{dt} = -21.18$ ft/yr for the downdrift influenced shoreline is over seven times greater than that of any other inlet in Florida. This has caused the entire shoreline influenced by St. Lucie Inlet to have a net average $\frac{dy}{dt} = -9.03$ ft/yr due primarily to the cutting of the inlet (this value also includes all added nourishment). The inlet has accumulated roughly 25 million cu. yds. of sediment in ebb (21.7 million) and flood (3.0 million) shoals (Walton, 1974a) which accounts for much of the material lost from one side of the inlet to the other. The south jetty has been in place since 1981 which is only two years prior to the end of the data set. Therefore, the effects of this jetty which should reduce (slightly) the downdrift losses during summer transport reversals are not fully shown here. An aerial photograph presented by Dean and O'Brien (1987a) show that by April 1986 the south jetty was impounded to capacity.

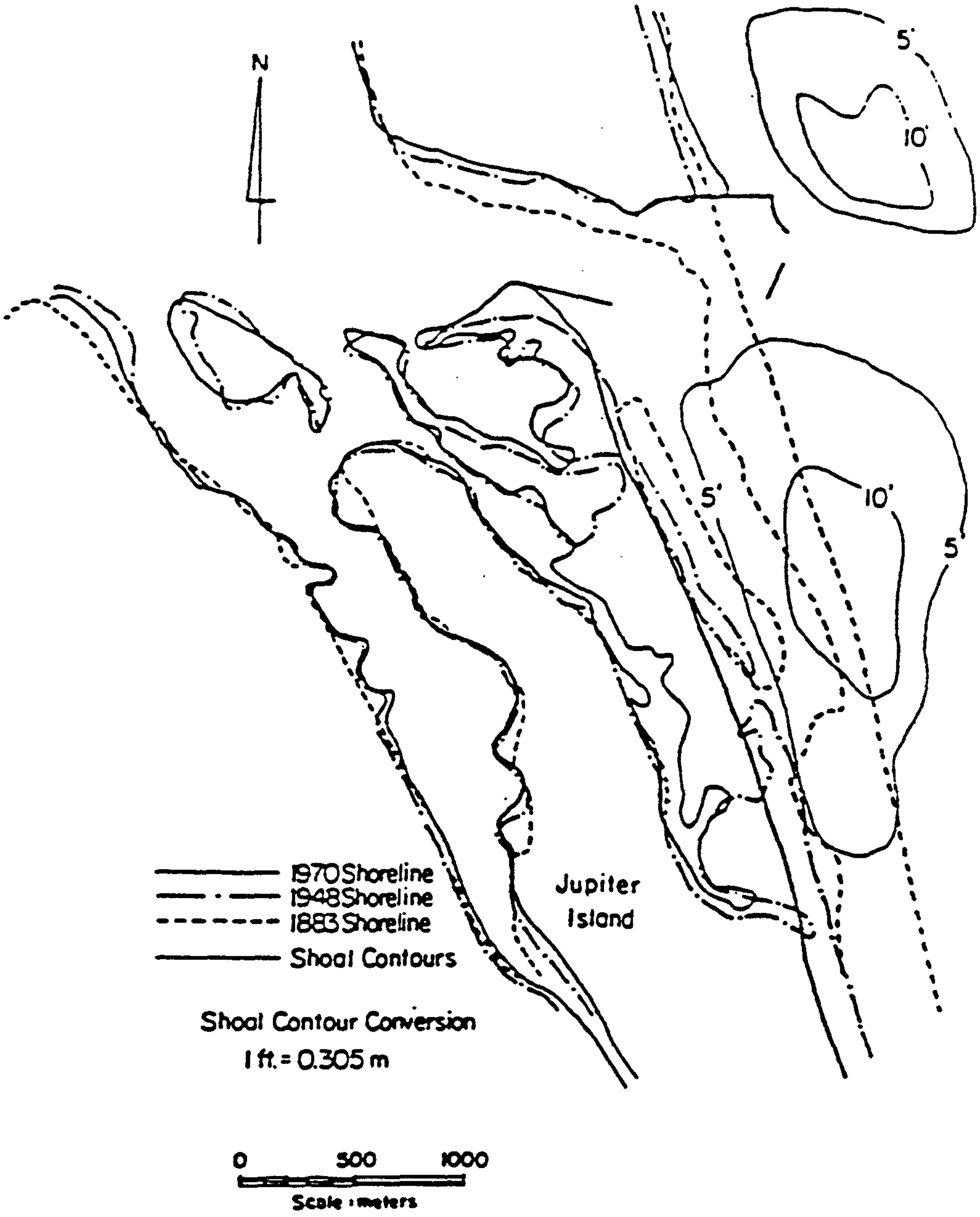


Figure 4.13: Historical shorelines for St. Lucie Inlet (from Marino, 1986).

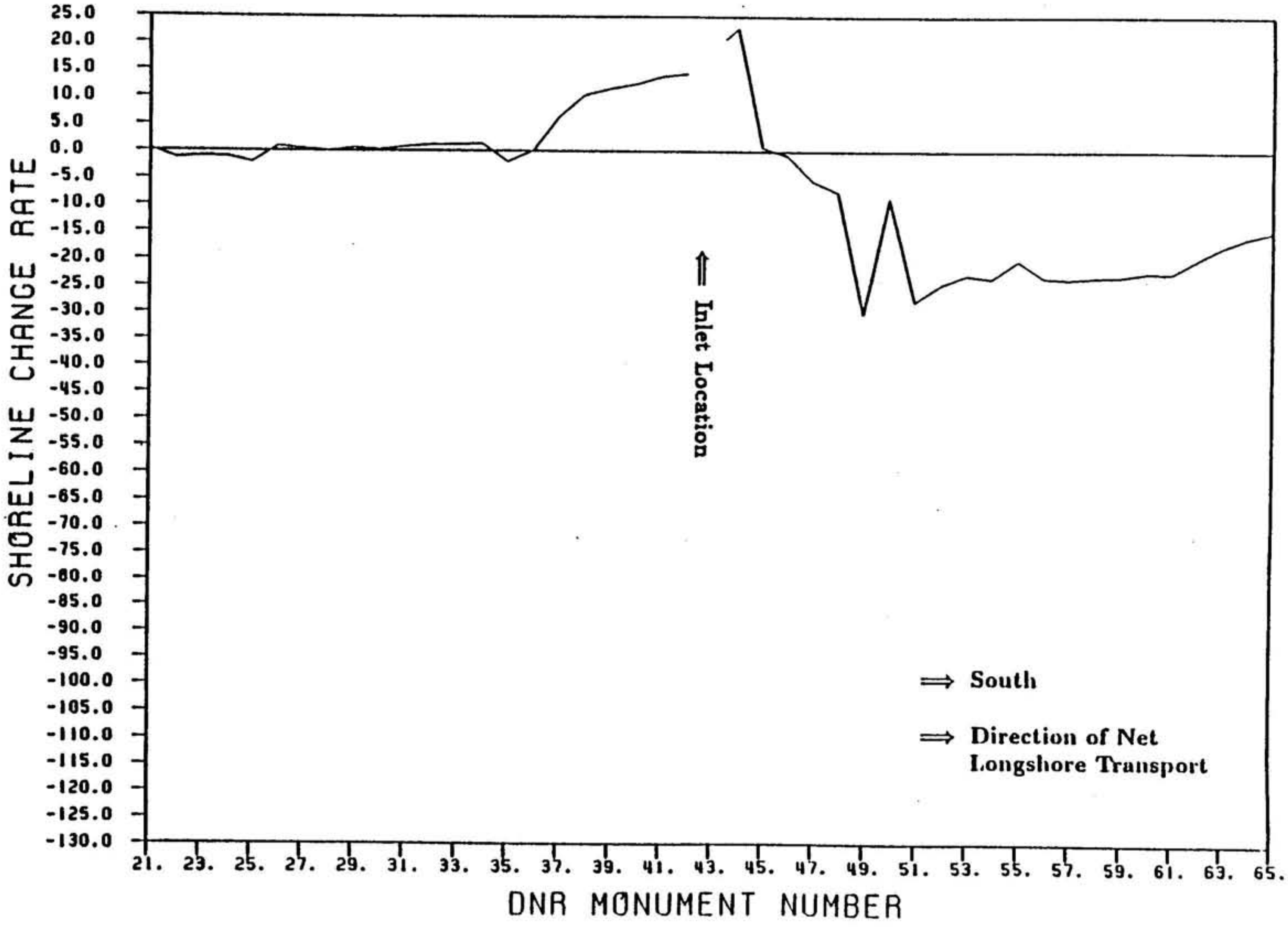


Figure 4.14: Shoreline change rates after training (1928–1984) St. Lucie Inlet. Change rates in feet per year.

4.2.8 Jupiter Inlet

Jupiter Inlet is a natural inlet that had opened and closed several times due to natural causes, primarily, the construction of St. Lucie Inlet to the north prior to training (COEL, 1969). From 1913–1922 the inlet migrated about 1200 feet north, at which time north and south jetties were built out of rock. These were extended to 600 feet and 375 feet respectively in 1929. In 1942 the inlet closed, and it wasn't until 1947 that Jupiter Inlet was reopened. A second north jetty was constructed 900 feet updrift of the existing north jetty in 1956 and then both jetties were lengthened at the shore in the late 1960s to prevent flanking (COEL, 1969). Maintenance dredging has been undertaken throughout the inlet's trained history to keep it open and navigable. There is a sand trap in the inlet's throat from which roughly 44,000 cu. yds. of sand is bypassed annually. Between 1952–1977 a total of 1.1 million cu. yds. of sand has been dredged from the Jupiter Inlet, all of which has been placed on the south beach (Marino and Mehta, 1986). The shoreline changes associated with Jupiter Inlet are within the range of over ±4 ft/yr. The effect of bypassing can be seen clearly in Figure 4.16. The updrift shore is accreting due to sediment impoundment while downdrift erosion is existent only in the southern half of the downdrift influenced area. This is due to bypassing which has effectively nourished the beach just south of the inlet (greater bypassing nourishes more of the downdrift beach) thereby reducing the erosion rate (due to the training of the inlet) to roughly one third that of the accretion rate: $\frac{dy}{dt}_{up} = +1.06\,\mathrm{ft/yr}$ $\quad \frac{dy}{dt}_{down} = -0.38\,\mathrm{ft/yr}$. Prior to training, the shoreline (1883) was straight on both sides of the inlet with the migration of the inlet reducing any accretion or erosion as shown in Figure 4.15.

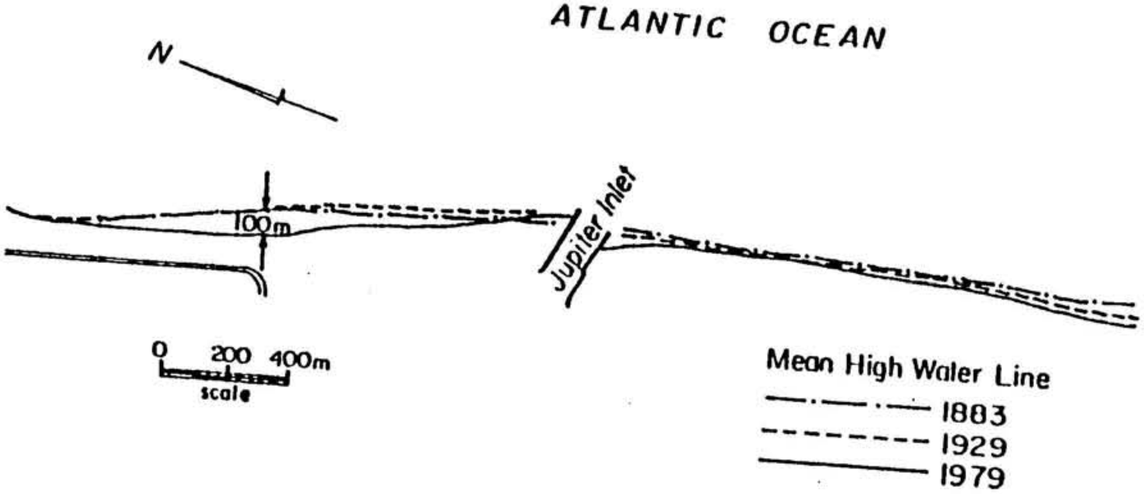


Figure 4.15: Historical shorelines for Jupiter Inlet.

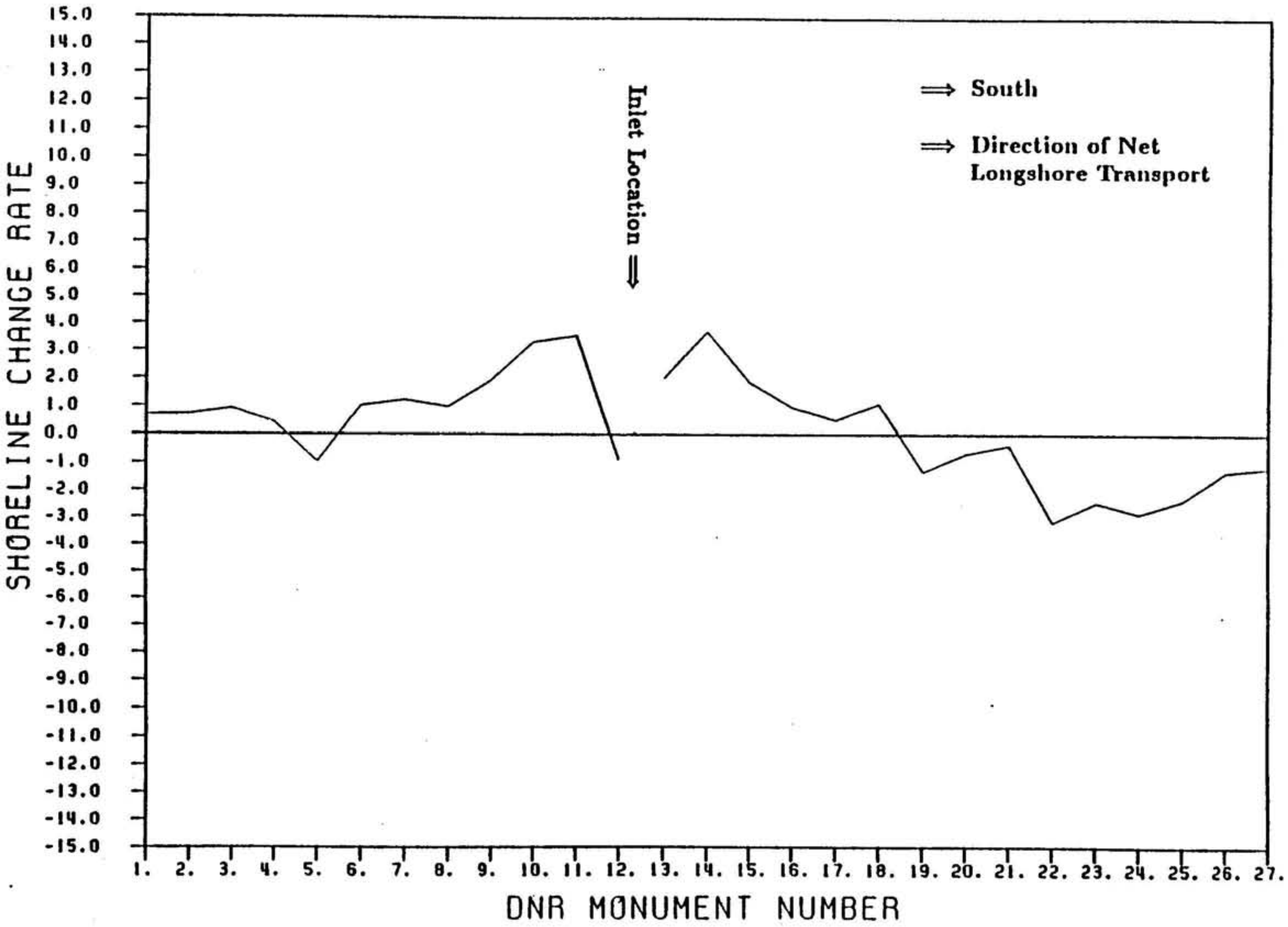


Figure 4.16: Shoreline change rates after training (1927–1980) Jupiter Inlet. Change rates in feet per year.

4.2.9 Lake Worth Inlet

The present Lake Worth Inlet is the third artificial inlet in this general area to connect the Atlantic Ocean with the north end of Lake Worth (Walker and Dunham, 1977). The first inlet was cut in 1876 (closed in 1886) and the second inlet was cut in 1887 (closed in 1924). Both of these were untrained inlets located north of the existing inlet. Lake Worth Inlet was cut in 1917 and two stone jetties were built between 1918 and 1925 (Walker and Dunham, 1977). The channel has been deepened three previous times until it reached its present depth of 35 feet in 1967. Of the 5.2 million cu. yds. of sand dredged since construction commenced, only 1.5 million has been placed on the south beach with 2.8 million cu. yds. used to build an exposed interior shoal (known as Peanut Island) (Walker and Dunham, 1977). Currently, a sand transfer plant installed in 1958 bypasses 70,000 cu. yds. per year of sand to the south (downdrift) beach. Prior to training (according to historical shoreline charts as presented in Figure 4.17), the shoreline had an erosion rate of roughly -6 ft/yr. The shoreline was straight and due to the migration of the inlet it stayed that way with a constant natural erosion. The north jetty has caused accretion updrift due to impoundment of sediment by the north jetty. The downdrift shoreline changes give a false impression of accretion due partly to the years for which data are available. After Lake Worth Inlet was cut in 1917, there was an initial drawback of the shoreline (Walker and Dunham, 1977). This recession was fairly severe since the jetties were not completed until 1925 at which time the shoreline began to partially recover. Therefore, the after training shoreline change rate, which starts in 1927, includes the effect of the downdrift shoreline recovering from this initially severely recessed position. If data were available for 1917, the positive shoreline change shown, would be balanced by the negative shoreline change which caused it. Thus, the indicated downdrift accretion is not a true measure of the effects of training this inlet.

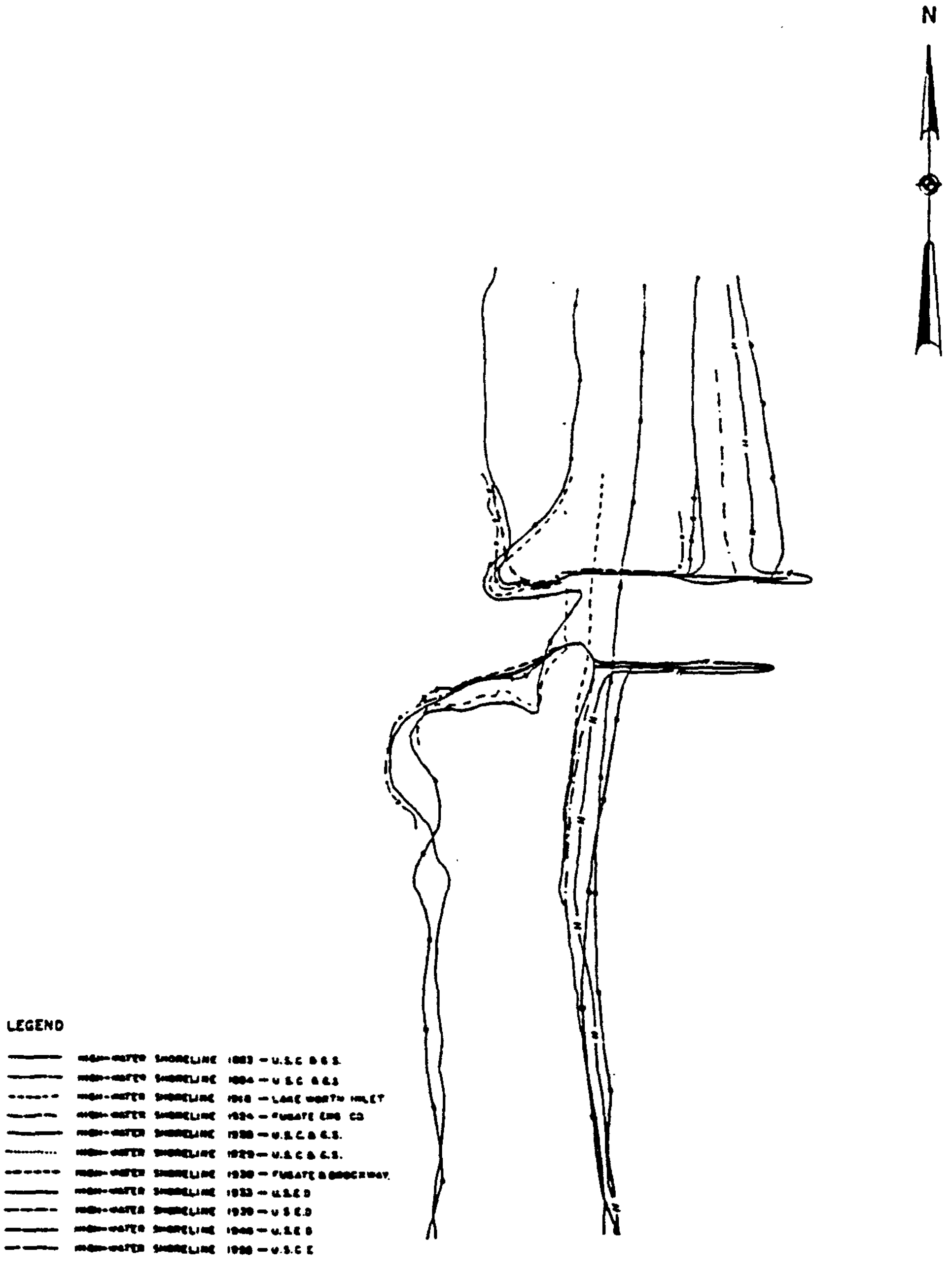


Figure 4.17: Historical shorelines for Lake Worth Inlet.

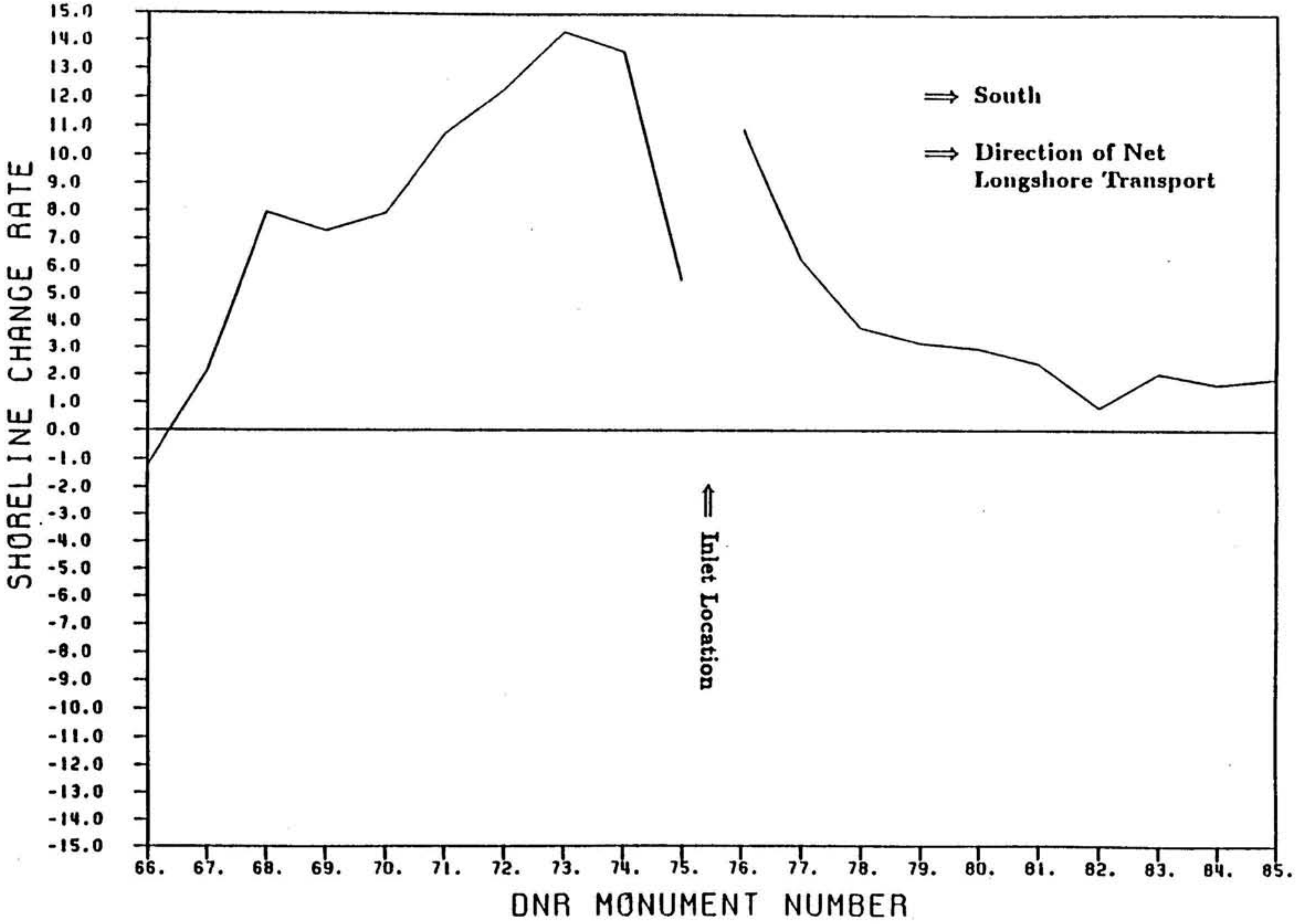


Figure 4.18: Shoreline change rates after training (1928–1980) Lake Worth Inlet. Change rates in feet per year. Note that indicated downdrift accretion is due to recovery following south jetty construction.

4.2.10 South Lake Worth Inlet

South Lake Worth Inlet is an artificial inlet at the south end of Lake Worth that was cut in 1927 both to enhance navigation and to improve the water quality of Lake Worth by increasing flushing. The north and south jetties were constructed in 1926 before the inlet was cut, and in 1967 the north jetty was extended with a curve to the southeast (Strock, 1983b). This inlet has a sand transfer plant that has been in operation since 1937 with a four year suspension of operations during World War II during which time the inlet shoaled badly and, on occasion, closed completely (COEL, 1965). Currently 60,000 cu. yds. per year of sand are bypassed by the present pumping facility. In 1964 a substantial nourishment project placed sand (exact amount unknown) dredged from the bay shoals, onto the south beach. This project survived well due to the presence of the groins that exist on the south beach as can be seen in Figure 4.19. This along with the maintenance dredging and the 'pre-inlet' (1928) data already including severe erosional effects explain the apparent accretion rate immediately to the south of the inlet, as shown in Figure 4.20, as well as the lower downdrift erosion rate as compared to the magnitude of the updrift accretion rate: $\frac{dy}{dt}_{up} = +1.22$ ft/yr $\frac{dy}{dt}_{down} = -0.20$ ft/yr. This inlet has affected the influenced shoreline less than other inlets. Prior to construction, the shoreline was eroding and after the initial sediment buildup along the north jetty the shoreline has returned (with the help of bypassing) to a more natural erosion. However, a downdrift erosional impact of the inlet system remains.

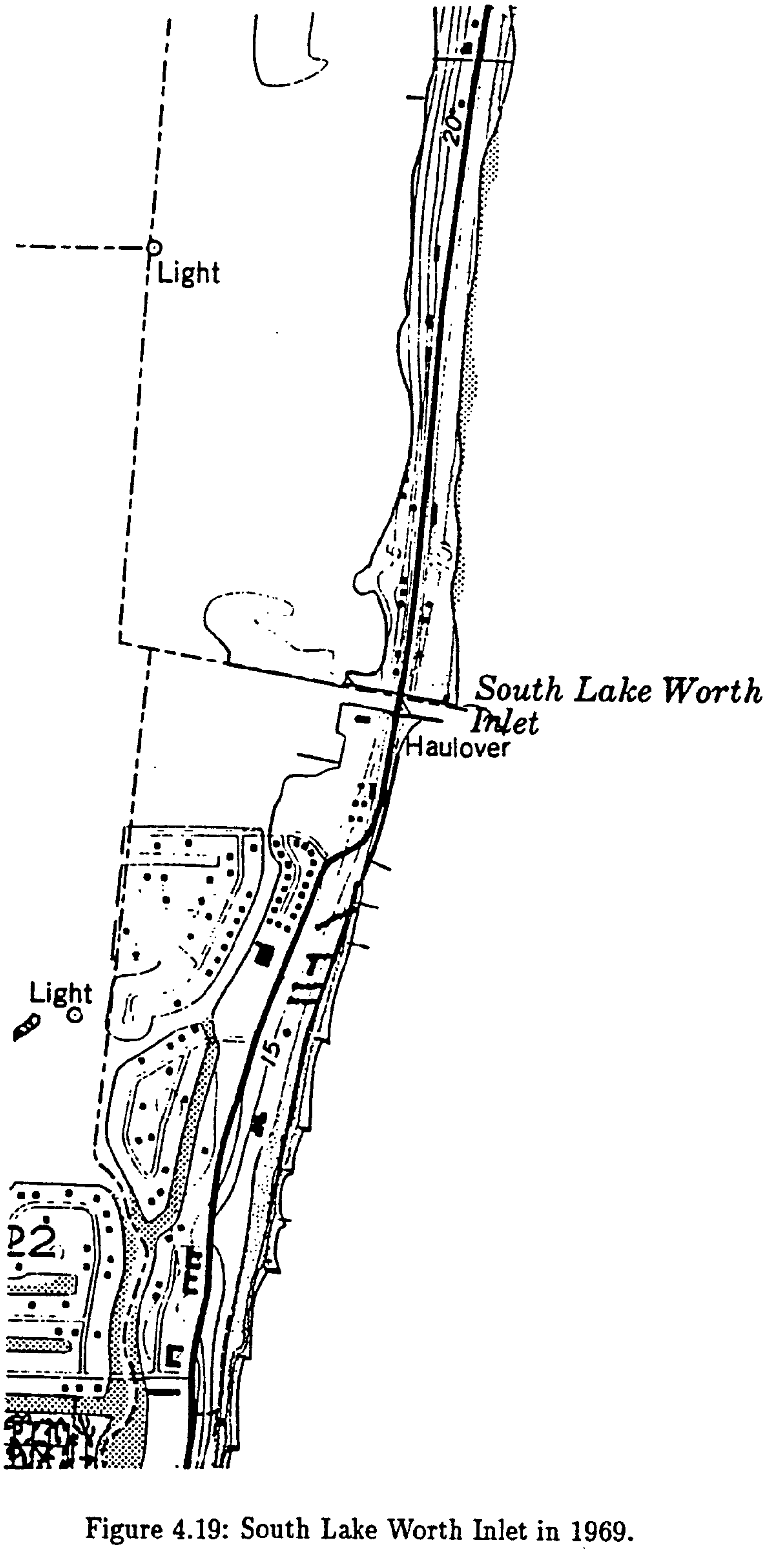


Figure 4.19: South Lake Worth Inlet in 1969.

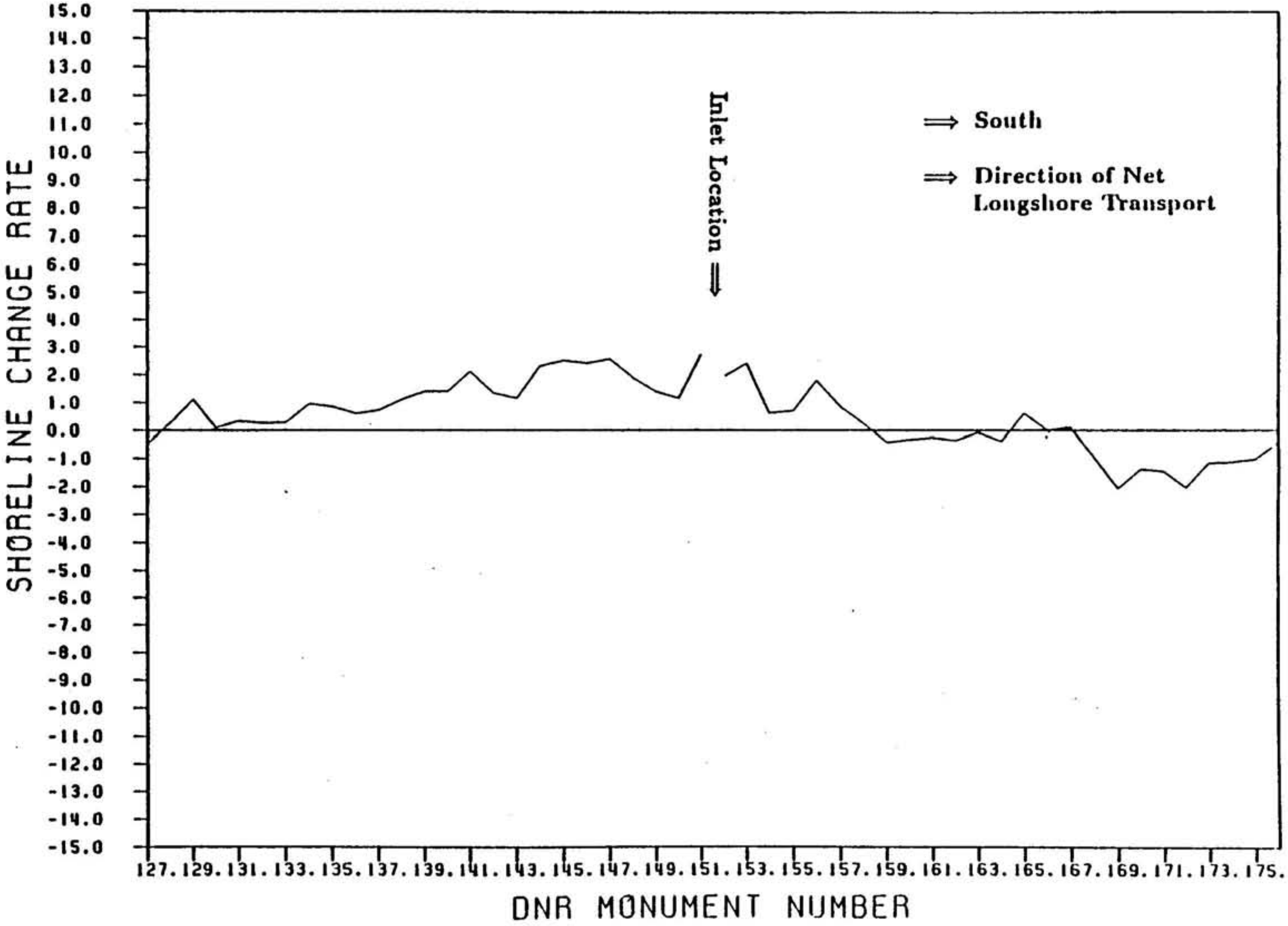


Figure 4.20: Shoreline change rates after training (1928–1980) South Lake Worth Inlet. Change rates in feet per year.

4.2.11 Boca Raton Inlet

Boca Raton Inlet is a natural inlet but was considered unstable as a navigable waterway due to very shallow depths until it was trained. In 1925 the inlet was initially dredged, but continued to shoal. Therefore, in 1930, two jetties were constructed and an offshore bar formed. Dredging continued through the 1940s maintaining the inlet until in 1967 Boca Raton Inlet again closed due to shoaling (Strock, 1983a). The City of Boca Raton then purchased and placed a small suction dredge into operation in 1972 and in 1975 the north jetty was extended and the south was reinforced. The resulting increase in the inlet's 'jetting' ability eliminated the offshore bar and reduced the internal shoaling tendency but it also caused severe erosion south of the south jetty. In 1980, a weir section was installed in the north jetty (Strock, 1983a). Since construction began, all of the 1.1 million cu. yds. of sand dredged has been placed on the downdrift beach. There has also been a beach nourishment project of 221,000 cu. yds. of sand which was dredged from the ebb tidal shoals. This was placed on the south beach in 1985 (CPE, 1991). Figure 4.22 presents shoreline change rates relative to 1942, at which point there was already an established offset. The dredge spoil placement on the south beach has reduced the erosion on the northern half of the downdrift beach by what appears to be over 50 %.

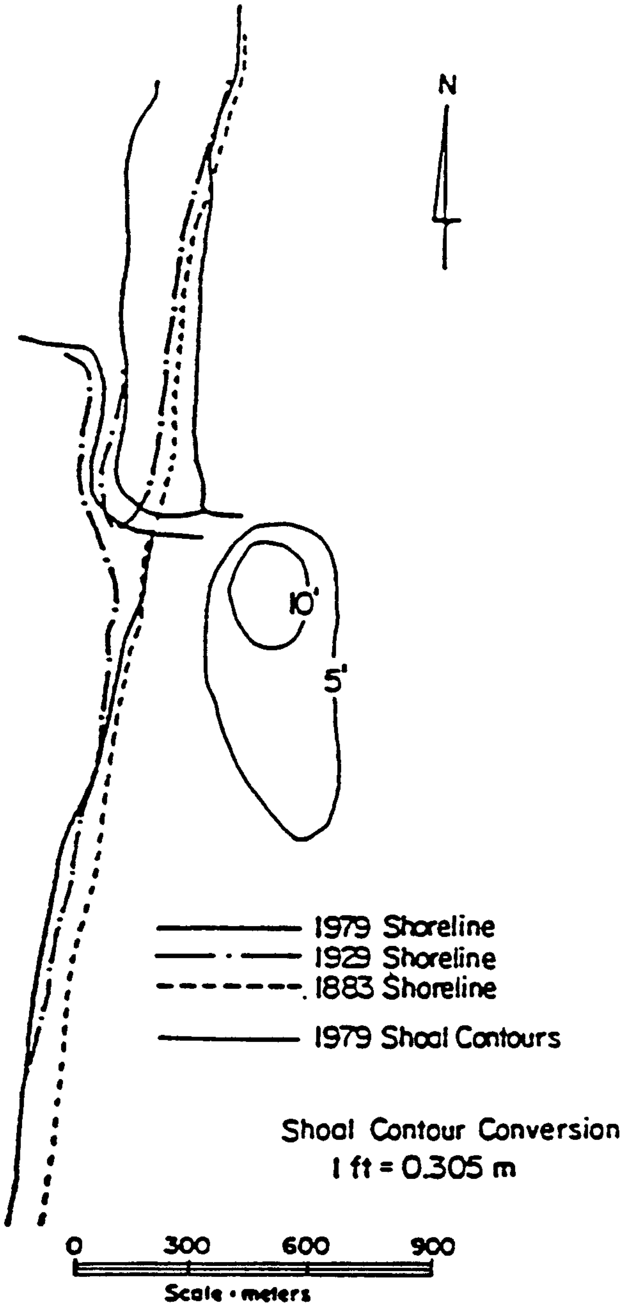


Figure 4.21: Historical shorelines for Boca Raton Inlet (from Marino, 1986).

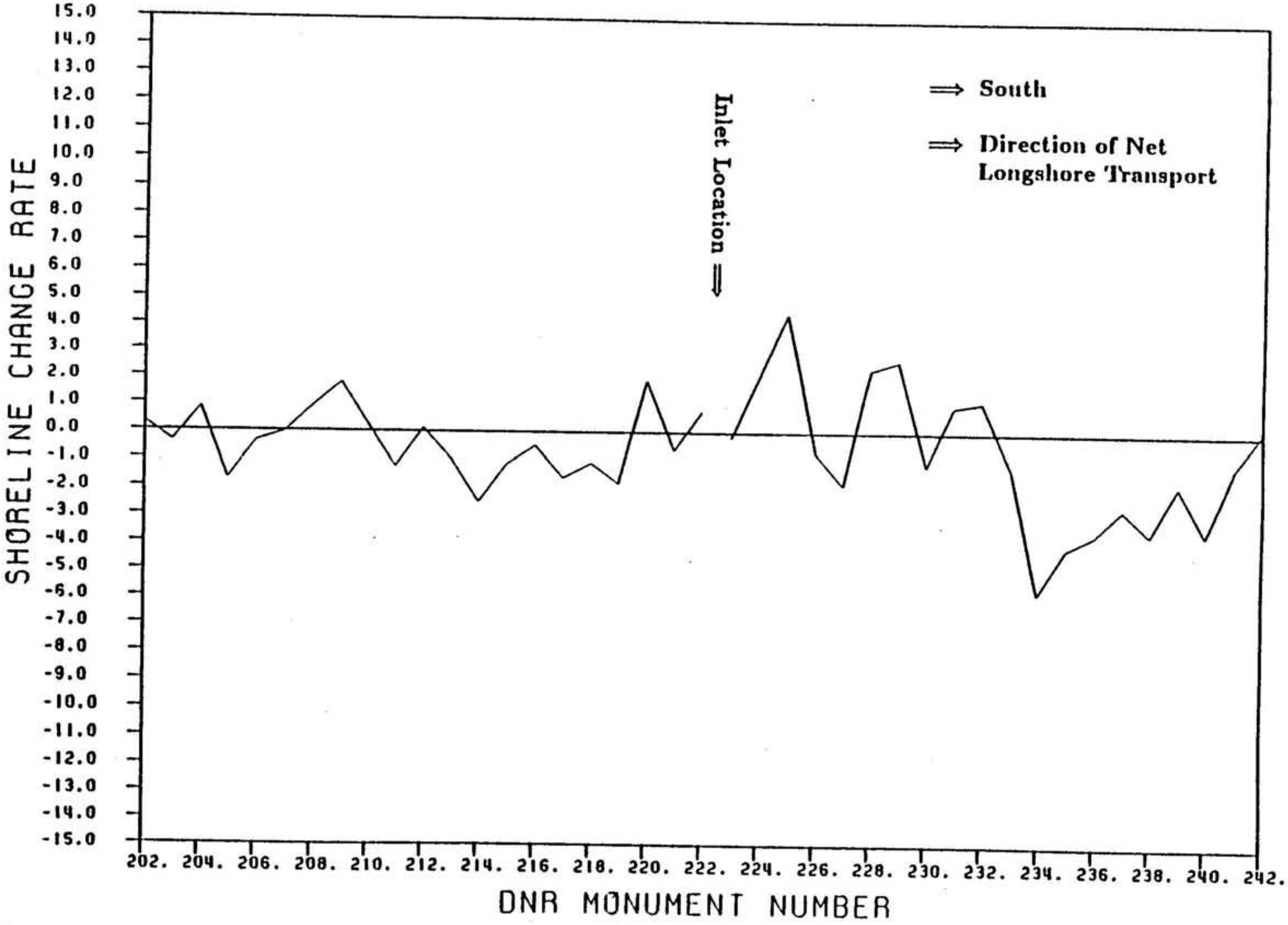


Figure 4.22: Shoreline change rates after training (1942-1980) Boca Raton Inlet. Change rates in feet per year.

4.2.12 Hillsboro Inlet

Hillsboro Inlet is a natural inlet which has natural northern protection provided by a rock reef running nearly shore-parallel, close to the shore (Marino, 1986). The reef acts as an offshore weir and submerged breakwater. It reduces wave induced transport by decreasing the wave energy and the reef restricts sediment transport. In 1930 a rock groin was built connecting the north beach with the reef in order to protect the lighthouse (Marino, 1986). A wood groin was built on the south side of the inlet in 1952 but lasted only twelve years before nature destroyed it. Two years later, in 1966, rock jetties were constructed with the north jetty built on the natural reef (see Figure 4.23). A pipeline dredge has been utilized since 1959 to bypass roughly 70,000 cu. yds. per year to the downdrift (south) beach (Marino and Mehta, 1986). In addition to the bypassing, 2.2 million cu. yds. of sand has been removed from Hillsboro Inlet, 70 % of which has been placed on the south beach. Figure 4.24 and Figure 4.25 need to be considered jointly due to the modifications undertaken between 1930–1966. The first (Figure 4.24) is the shoreline change rates before and after the construction of the existing jetties. There has been a very slight increase in accretion at the north jetty but this is minimal due to the already existing reef and rock groin on the north side. The downdrift beach has an increased erosion rate but this is balanced by the 1970 nourishment project and maintenance dredging already visible from monuments # 26–30. Since the jetties were not built until 1966, it is not possible to remove the 1970 nourishment project and still present the training effects of the jetties. Therefore it should be noted that the shoreline change rate of -0.04 ft/yr for the downdrift beach includes accretion due to nourishment. The other graph (Figure 4.25) indicates stability in the shoreline in the area of the rock reef but it was not until the jetty was constructed that the entire updrift beach began to benefit from the impounding of sediment. Downdrift, the beach eroded only just to the south due to the wooden groin built in 1952 and it wasn't until the south jetty was constructed that the erosion visible (if the nourishment is ignored) in the previous figure began to occur.

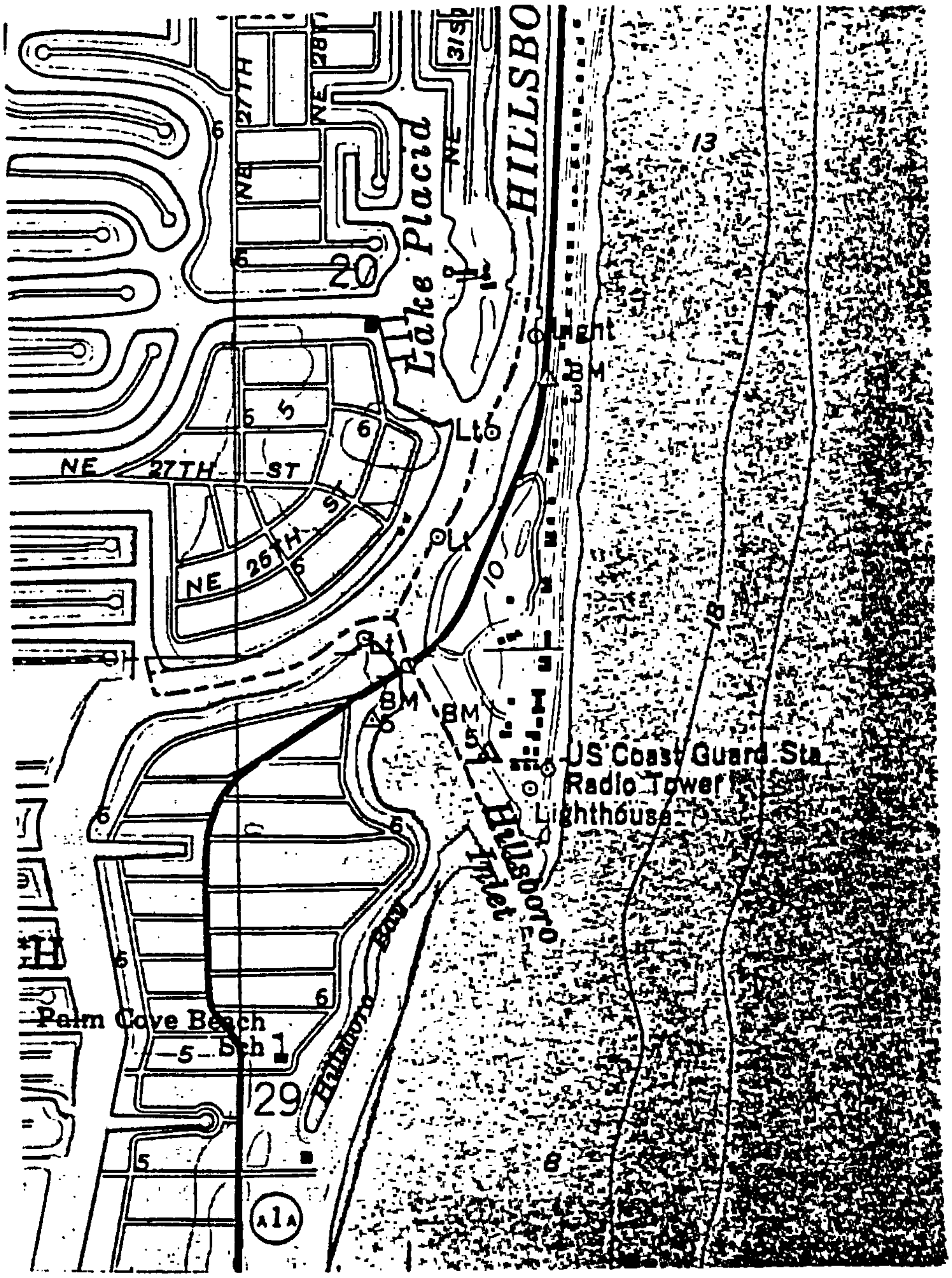


Figure 4.23: Hillsboro Inlet in 1967.

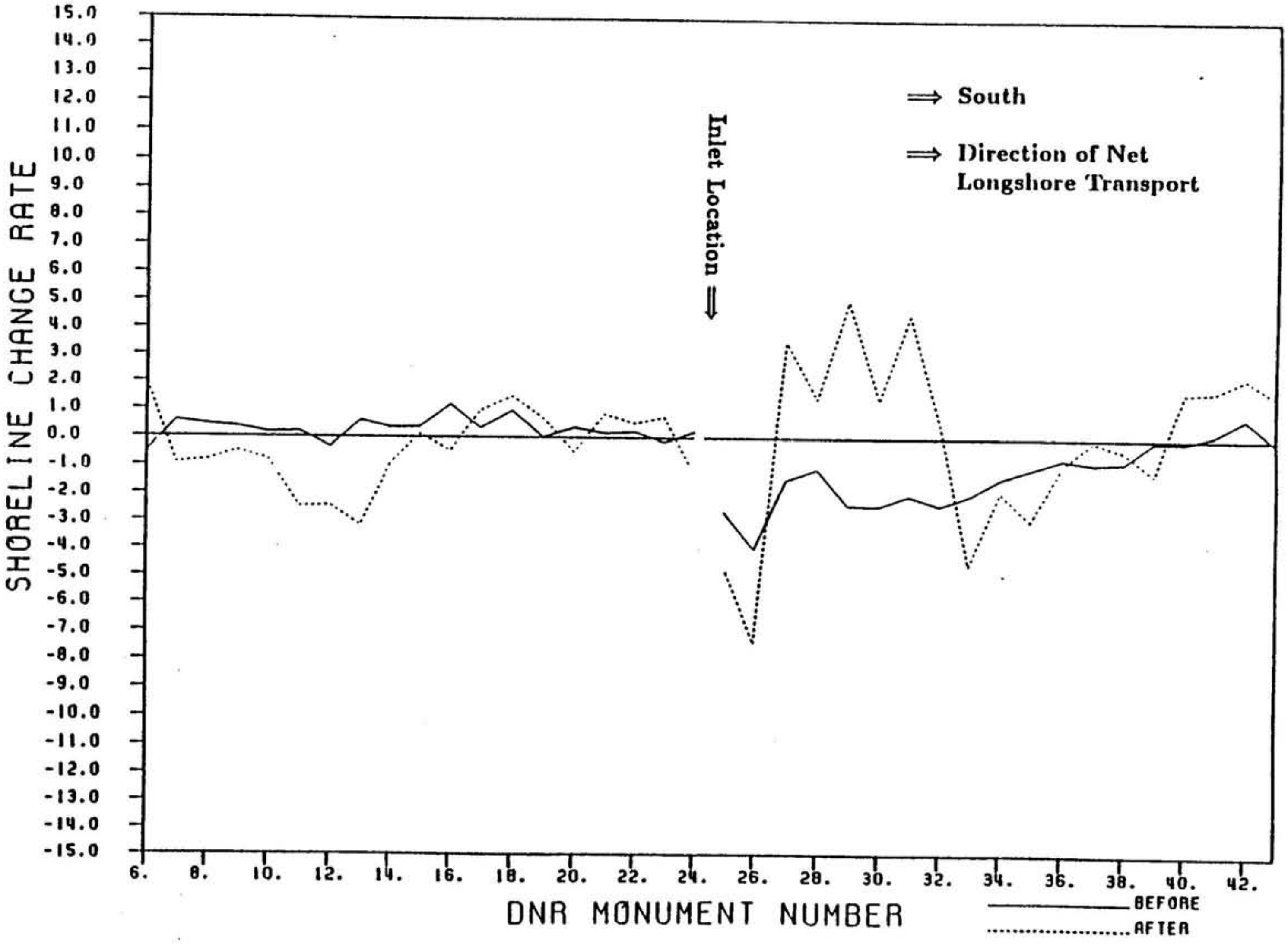


Figure 4.24: Shoreline change rates before (1883-1962) and after (1970-1985) jetty construction at Hillsboro Inlet. Change rates in feet per year.

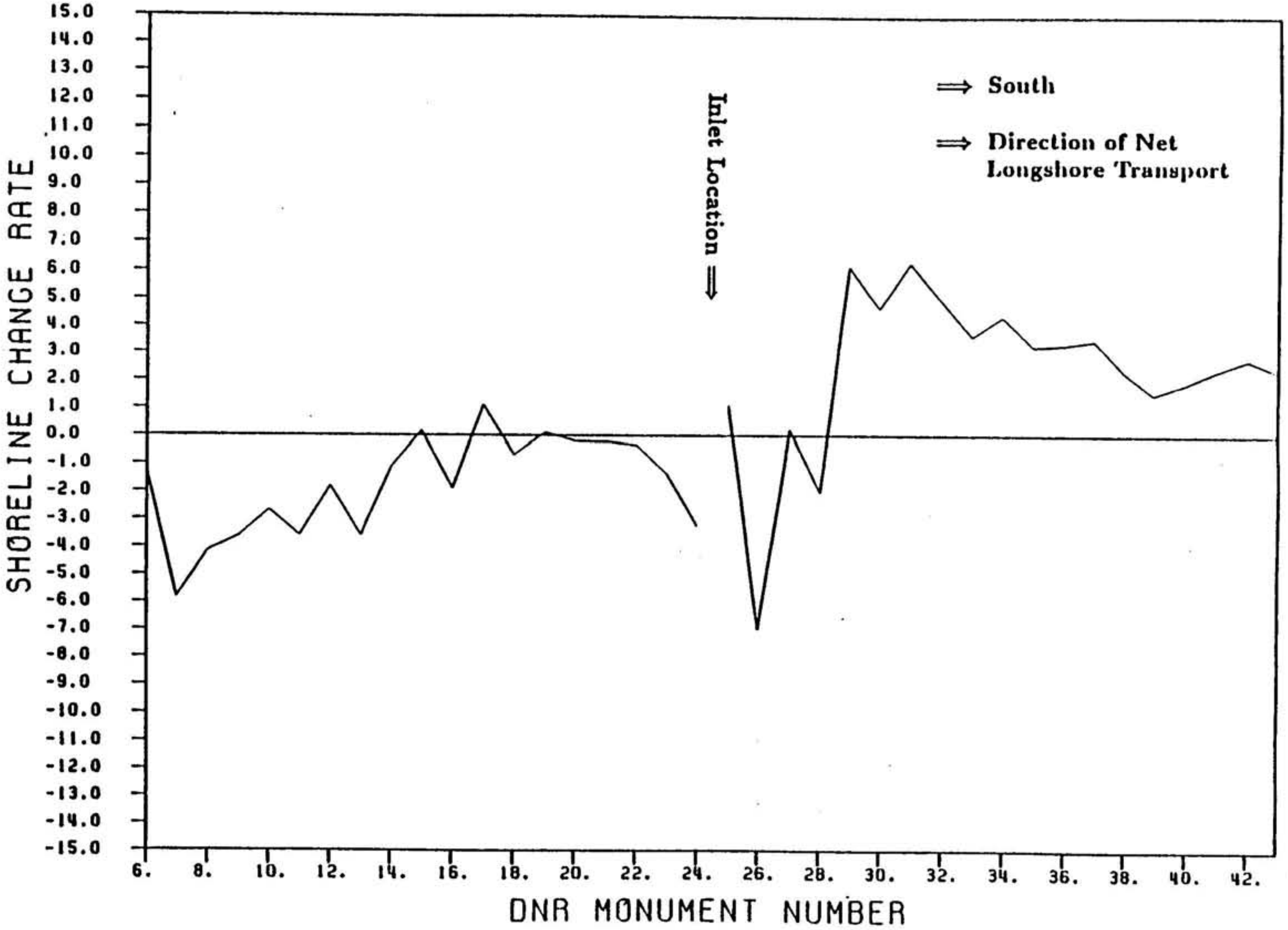


Figure 4.25: Shoreline change rates after construction (1935–1985) of initial training device (north rock groin) at Hillsboro Inlet. Change rates in feet per year.

4.2.13 Port Everglades Entrance

Port Everglades is an artificial inlet that was cut in 1928. At that time there were two natural inlets in the area; one 6200 feet to the north (New River Inlet) and one 10,000 feet to the south (Dania Inlet) (COE, 1968). Both of these inlets closed naturally in the late 1930s after construction was completed on Port Everglades Entrance. When Port Everglades was cut in 1928, two steel jetties were built along with five groins on the downdrift (south) beach. In 1931, two limestone jetties were constructed along with two submerged stone breakwaters; one on either side of the inlet (COE, 1968). The jetties were rebuilt with stone soon after and in 1978 the north jetty was shortened by 180 feet. Since construction commenced, 8.0 million cu. yds. of sand have been dredged, 3.2 million of which has been placed on the south beach (Marino and Mehta, 1986). Figure 4.26 presents the shoreline prior to construction and the resulting offset due to the cutting of Port Everglades. The erosion on the updrift beach prior to 1935 is due to the existence of New River Inlet and when New River Inlet closed, the updrift beach (with regard to Port Everglades) began to accrete (see Figure 4.27). Due to this previous erosion, the updrift shoreline has not accreted in an anticipated fashion (ie. greatest accretion at the jetty, gradually reducing to the north away from the jetty). Downdrift since 1935 (after the initial offset was established) the shoreline has continued to erode. The use of groins on the south beach along with nourishment has stabilized the shoreline erosion substantially as can be seen in the downdrift shoreline change rate.

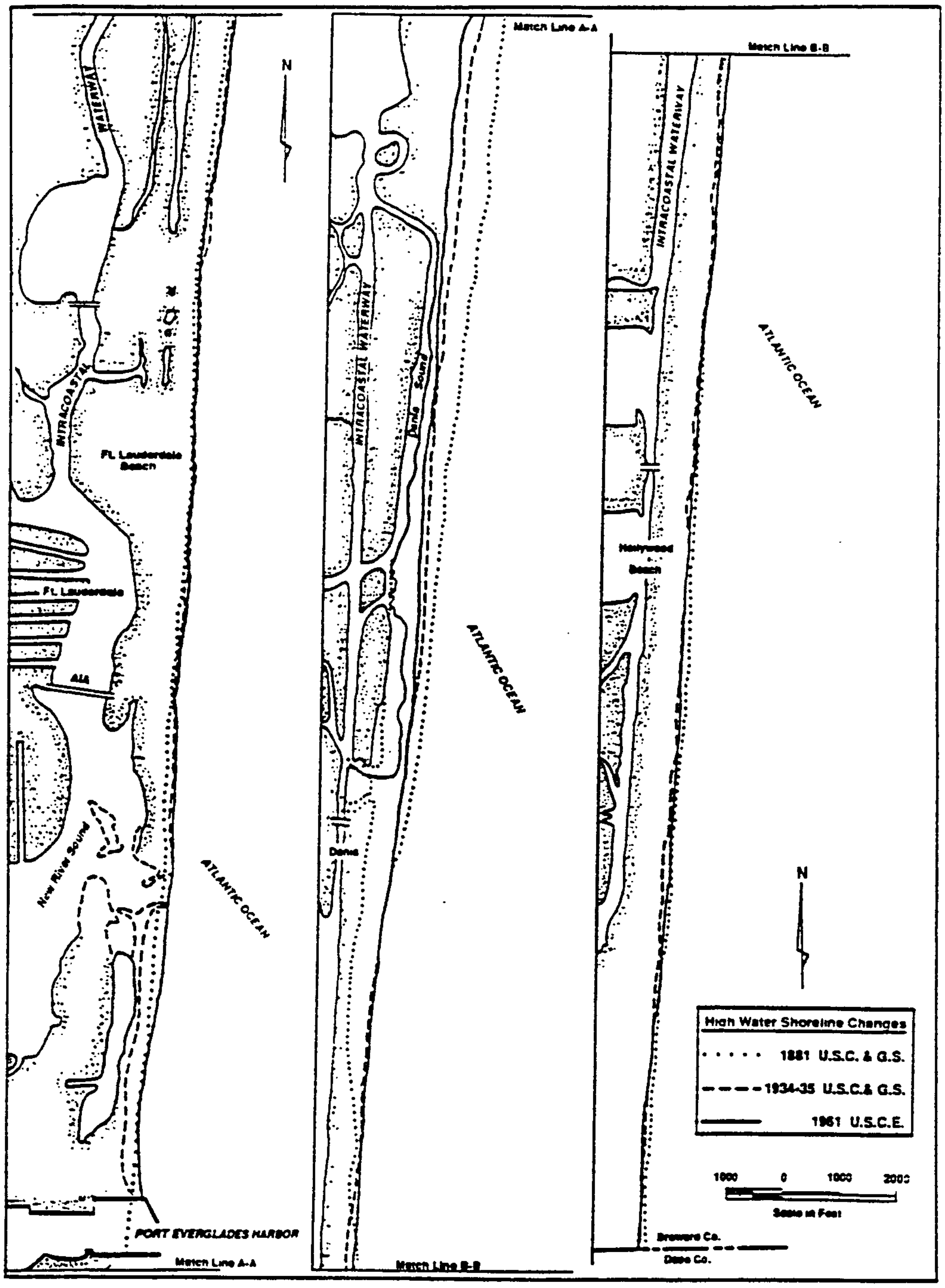


Figure 4.26: Historical shorelines for Port Everglades Entrance.

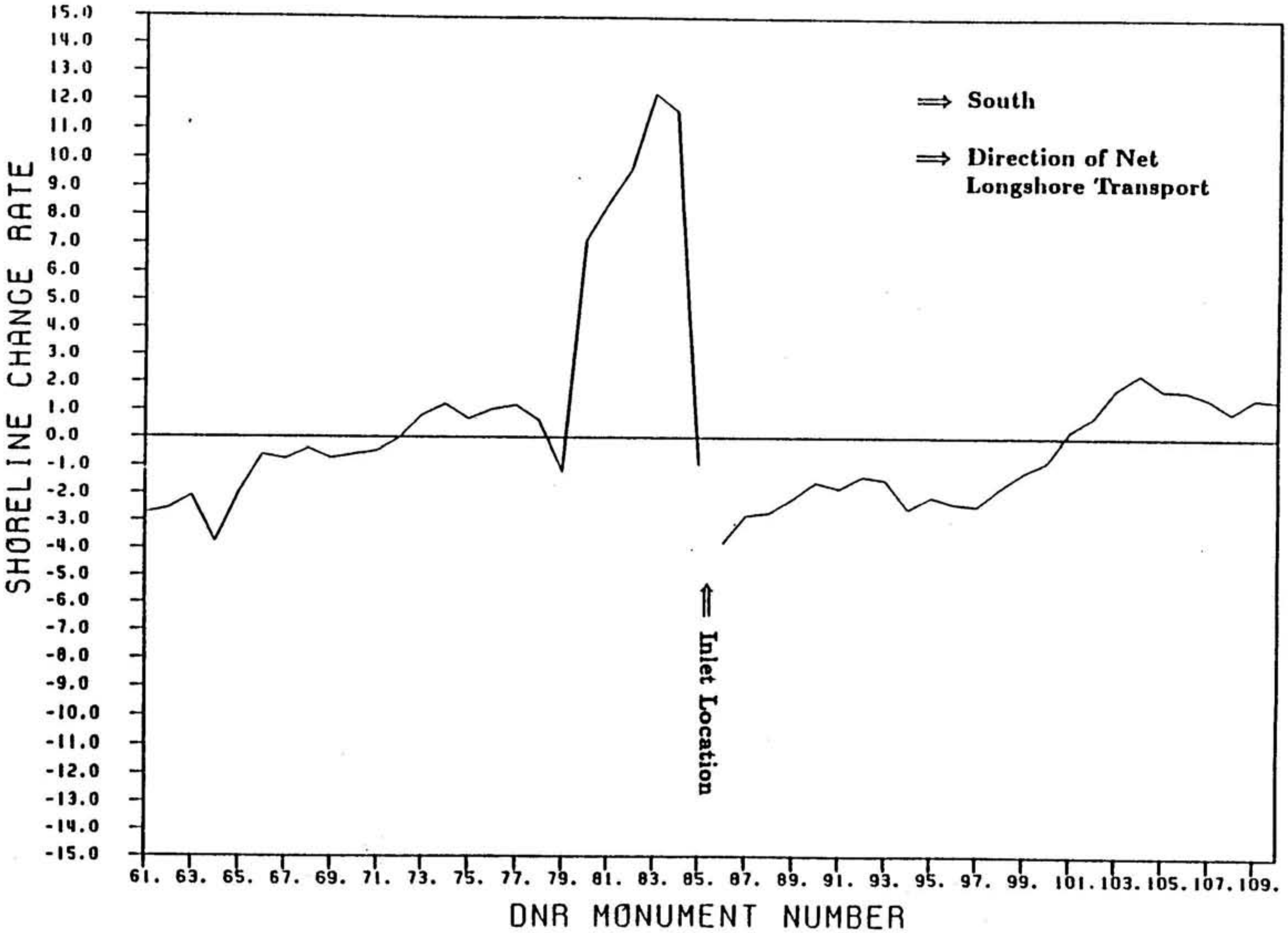


Figure 4.27: Shoreline change rates after training (1935–1985) of Port Everglades Entrance. Change rates in feet per year.

4.2.14 Bakers Haulover Inlet

Bakers Haulover Inlet is an artificial inlet cut in 1925, primarily to relieve pollution of Biscayne Bay (COE, 1969). Situated between north Biscayne Bay and the Atlantic Ocean, in was stabilized by two jetties in 1925. In 1926 both jetties were rebuilt after nearly being destroyed by a storm. Steel bulkheads were constructed parallel to the shoreline on either side of the inlet for roughly 600 feet (on each side) in 1928. Both jetties were reconstructed in 1964 using rubble-mound construction, including a concrete cap on the south jetty with the south jetty relocated 60 feet south to widen the inlet (COE, 1969). At the same time, a rubble mound groin was built on the south beach. In 1975 the south jetty was extended with a southward curve and five more groins were added on the downdrift (south) beach. Finally, in 1986, the north jetty was extended and a northern dog-leg extension included. Since construction, all of the 2.7 million cu. yds. of dredged sand has been placed on the adjacent beaches (Marino and Mehta, 1986). Figure 4.28 presents a stable updrift shoreline prior to construction with a downdrift shoreline that has accreted substantially. A survey of the updrift beach in 1851 is not available, thus it is not known whether this (substantial accretion) was a consistent trend or not. Since construction, the updrift beach has reached a rough equilibrium of $\frac{dy}{dt} = +3.58$ ft/yr while Figure 4.29 shows a reversed offset. This is caused by the downdrift beach receiving dredged sand and maintaining it through the use of groins. The south jetty seems to be very effective at trapping any sediment during summer transport reversals. Another major contributor to the positive shoreline change rate on the south beach is the Miami Beach Restoration project which was carried out in 1976. Figure 4.29 presents two sets of downdrift change rates, both after inlet construction. The first is for all years of data while the second is only up to 1974, prior to the nourishment project. The effects of the added sand are obvious at the south end of the influenced shoreline. The nourishing of Miami Beach has changed the shoreline change rate downdrift:

$$\left(\frac{dy}{dt}\right)_{1927--1974} = +0.27\,\mathrm{ft/yr} \quad \rightarrow \quad \left(\frac{dy}{dt}\right)_{1927--1986} = +3.03\,\mathrm{ft/yr}\,.$$

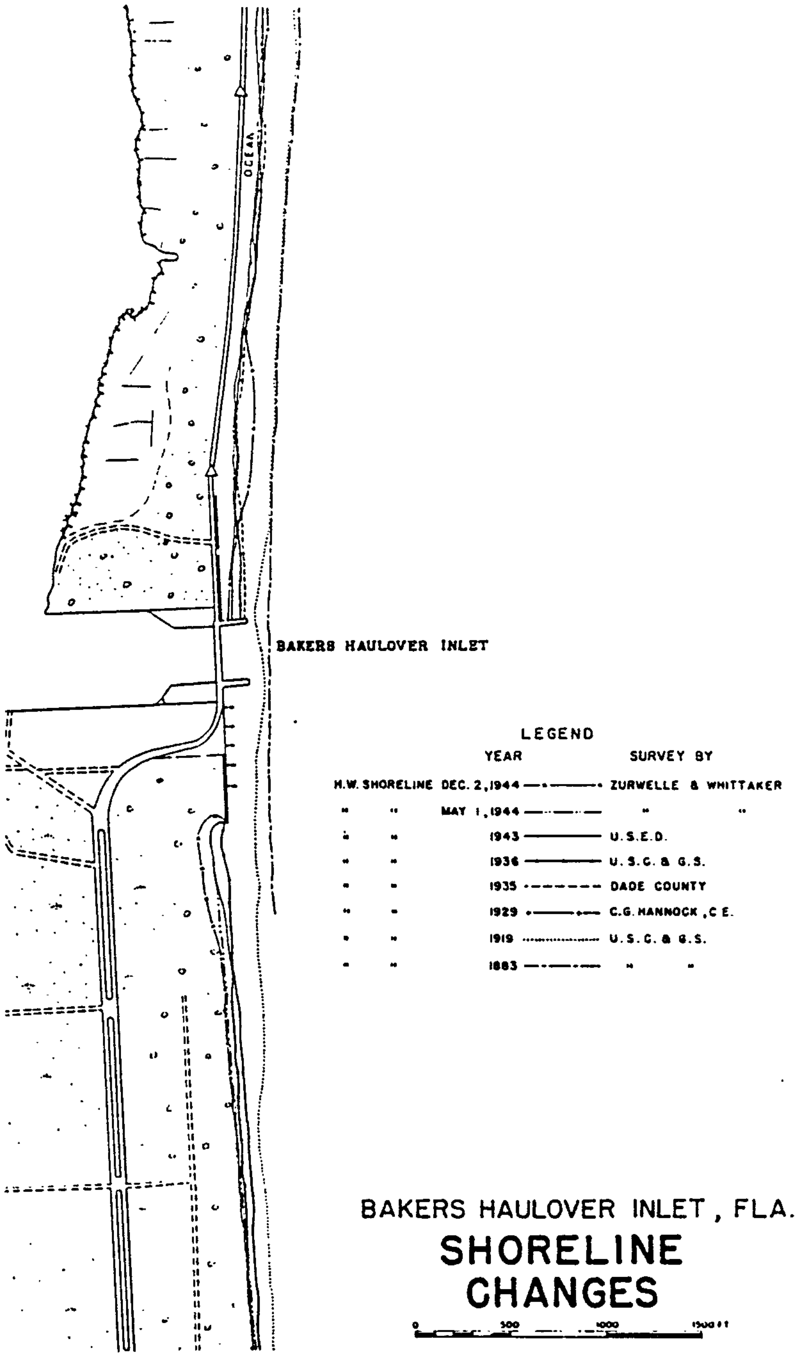


Figure 4.28: Historical shorelines for Bakers Haulover Inlet.

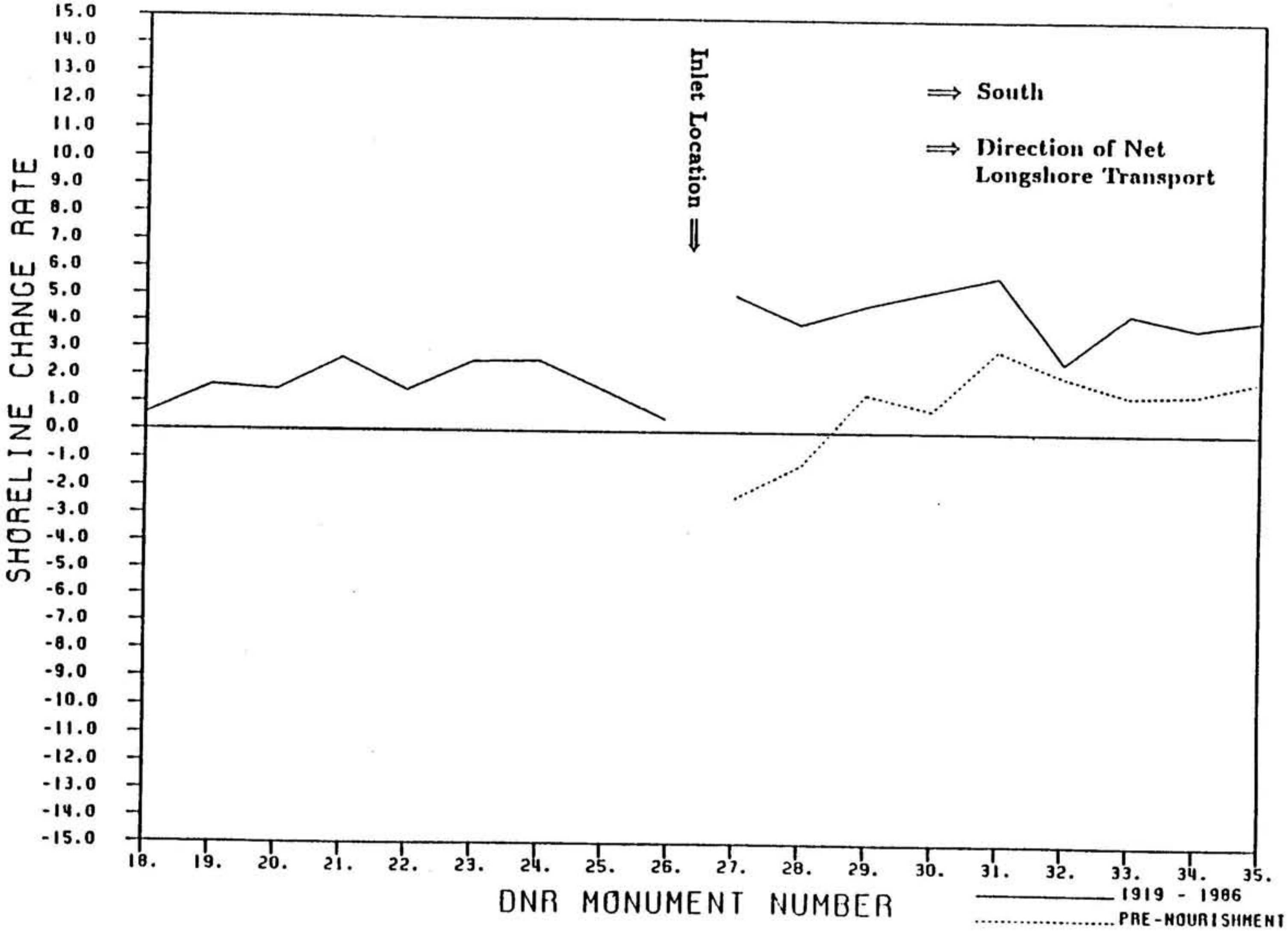


Figure 4.29: Shoreline change rates after training (1927 1986) of Bakers Haulover Inlet. Downdrift shoreline includes shoreline change rates prior to Miami Beach nourishment (1927 1974). Change rates in feet per year.

4.3 West Coast Inlets

4.3.1 Pensacola Pass

Pensacola Pass is a natural entrance connecting Pensacola Bay with the Gulf of Mexico. It has been a Federal Navigation project since 1881 and has two very short (roughly 300 feet) training structures built along the west shoreline of the inlet. The only substantial modification of Pensacola Pass has been construction and maintenance dredging projects. The original dredging of the channel was carried out in 1883 and the channel has been modified by a number of dredgings since. During the period 1883–1985, 35.6 million cu. yds. of sand have been dredged from the channel, of which 28.7 million have been dumped offshore out of the sand sharing system (Hine et al., 1986). The remaining 6.9 million cu. yds. have been placed on Santa Rosa Island and on Perdido Key in 1985. The inlet's location has been kept fairly stable through dredging to prevent migration. Figure 4.30 presents the long term shoreline change rates adjacent to Pensacola Pass. Long term rates are examined in this case since, apart from dredging, it is still a natural unmodified inlet.

The accretion to the east (updrift) is from the sand placed on Santa Rosa Island while the accretion just downdrift is the result of maintenance dredge spoil deposits during the last few years of the data set. The dredged channel through the pass is 37 feet deep (it has since been deepened to 48 feet) and 800 feet wide. This is basically an enormous sand trap which explains the dip in shoreline change rates at the mouth of the pass. It also is responsible for the erosion rates both updrift and downdrift. Since there are no substantial jetties to impound the longshore sediment transport and the ebb shoal has a dredged channel through it, the sand moving along the coast (to the west) will simply spill into the dredged channel. This is not obvious along the beach immediately updrift of the pass as a result of the 6.9 million cu. yds. of dredged sand placed there. Since only 19% of the dredged sand has been replaced on the beaches, the downdrift shoreline has been starved thereby causing the erosion shown.

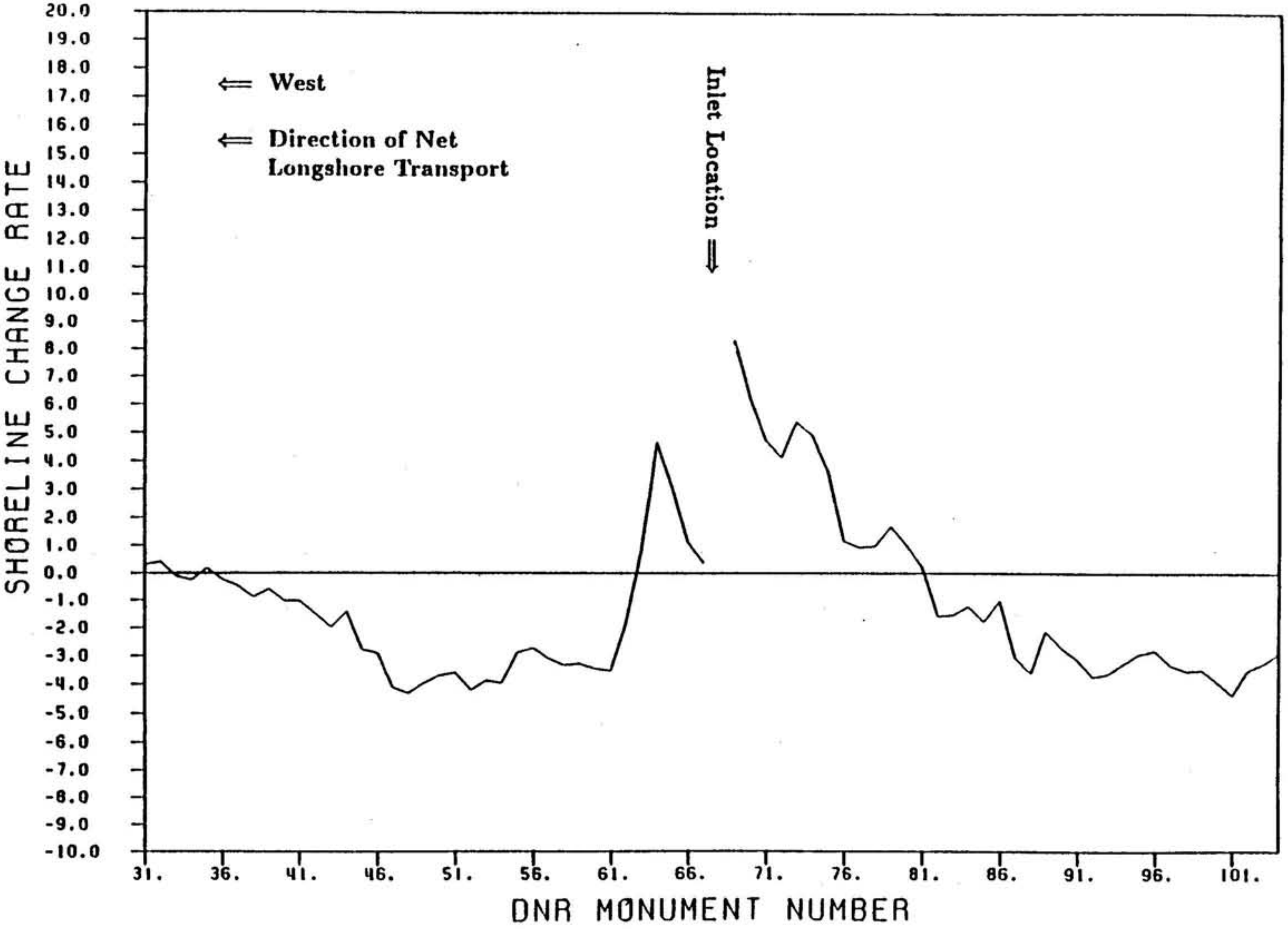


Figure 4.30: Long term (1856-1978) shoreline change rates adjacent to Pensacola Pass. Change rates in feet per year.

4.3.2 East Pass (Destin Harbor)

The original East Pass (Old East Pass) was migrating to the west in the direction of littoral transport at an average rate of 44 ft/yr during the period 1871–1929 according to the United States Engineering Office (1939). In 1928 a severe storm caused a breach through the eastern end of Santa Rosa Island roughly 8,000 feet west of Old East Pass (U.S. Army Corps of Engineers, 1975). Old East Pass began to shoal rapidly and by 1938 was completely closed. In 1969, twin jetties were constructed at the location of the 1928 breach to reduce shoaling and bar formation due to littoral drift. Since 1931, 4.4 million cu. yds. of material have been dredged from the pass of which 2.1 million cu. yds. were placed in the nearshore zone (Hine et al., 1986). The remaining 1.3 million cu. yds. were used to construct sand dikes at the base of both jetties to prevent flanking. Figure 4.31 shows the 1871 shoreline before the present East Pass existed. The erosion resulting from the breach is seen on both sides of the inlet with the updrift shoreline suffering the worst erosion due to the existence of Old East Pass. Figure 4.32 presents the shoreline change rates since 1934 which is after the shoaling of Old East Pass and after the new East Pass had initially stabilized. The increased accretion updrift of the inlet is due to the training of the inlet in 1969 and the final closing of Old East Pass with the subsequent shoreward movement of the ebb tidal shoal.

If the before and after training shoreline change rates are examined (see Figure 4.33), the presence of the updrift jetty (east) is seen. The erosion at the mouth of the inlet is due to the recession of the updrift beach after the inlet opened. After the jetties were constructed, the impoundment of sand against the updrift jetty has resulted in the accretion rates there. Not much has happened downdrift. There has been some erosion due to the anti-symmetry experienced at trained inlets, but due to the mild longshore transport of this area and the disposal of dredged sand on the beach, this erosion has not been severe.

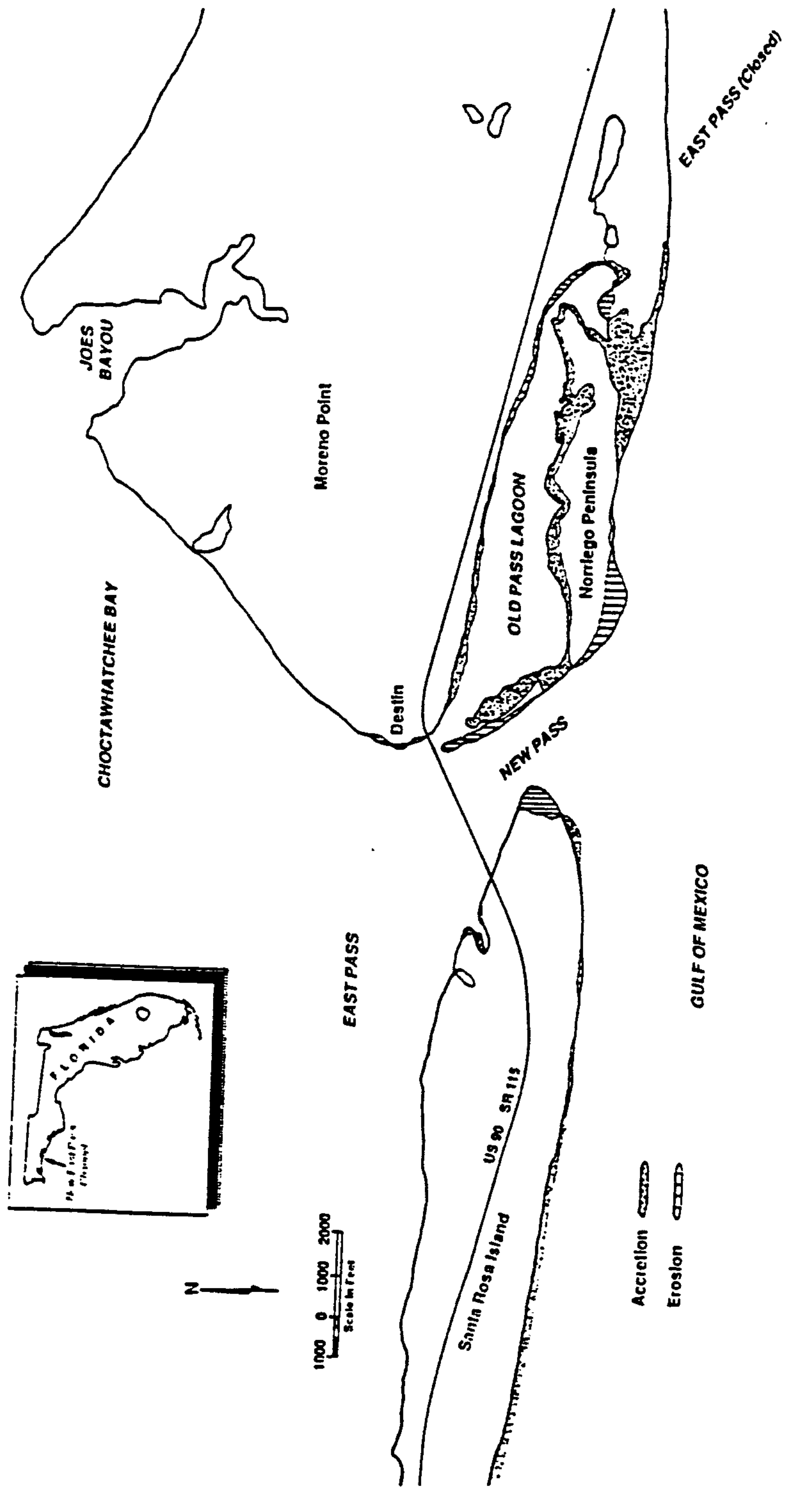


Figure 4.31: Historical shorelines for East Pass (Destin Harbor).

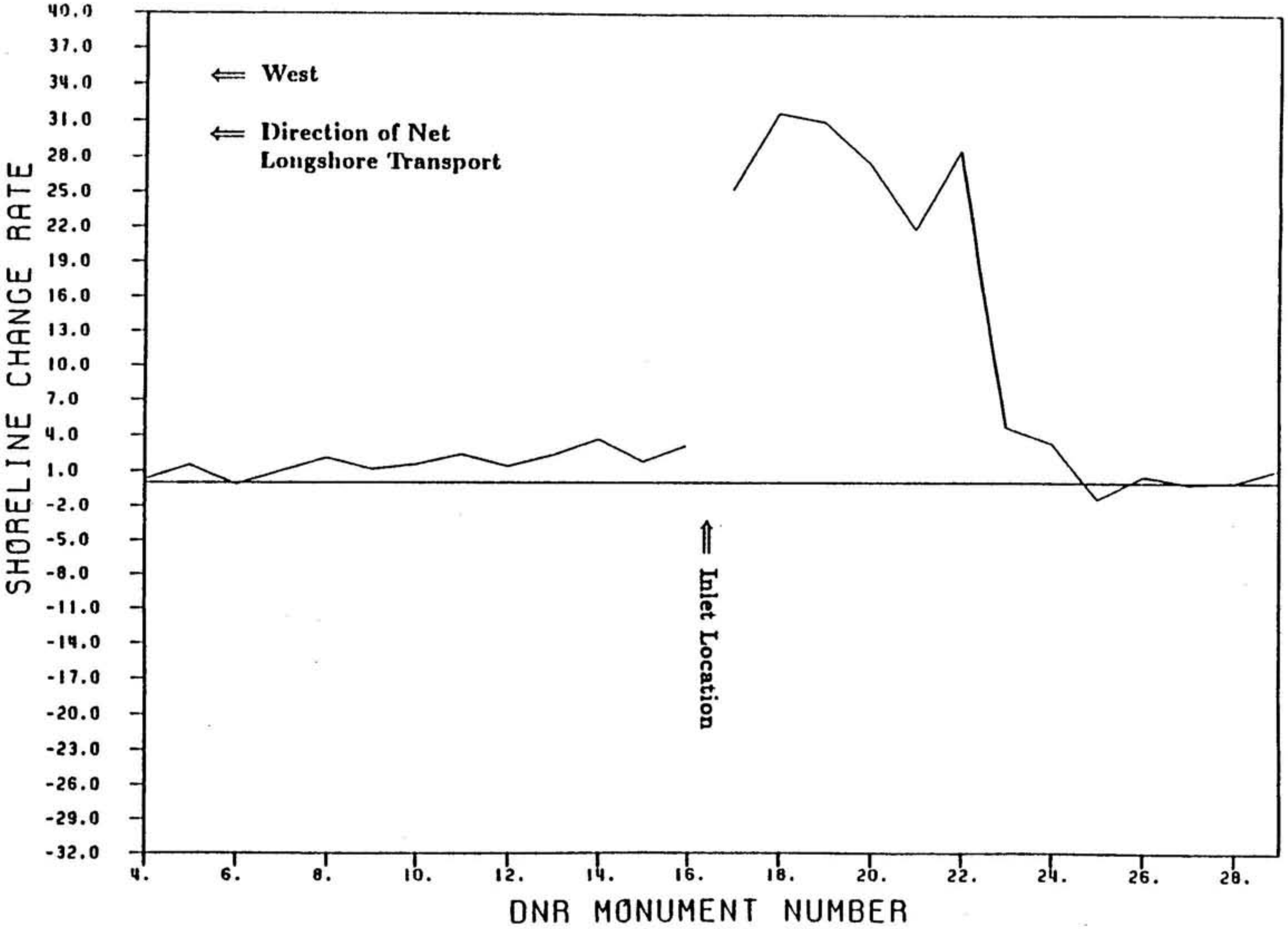


Figure 4.32: Shoreline change rates since the opening (1934–1987) of East Pass (Destin Harbor). Change rates in feet per year.

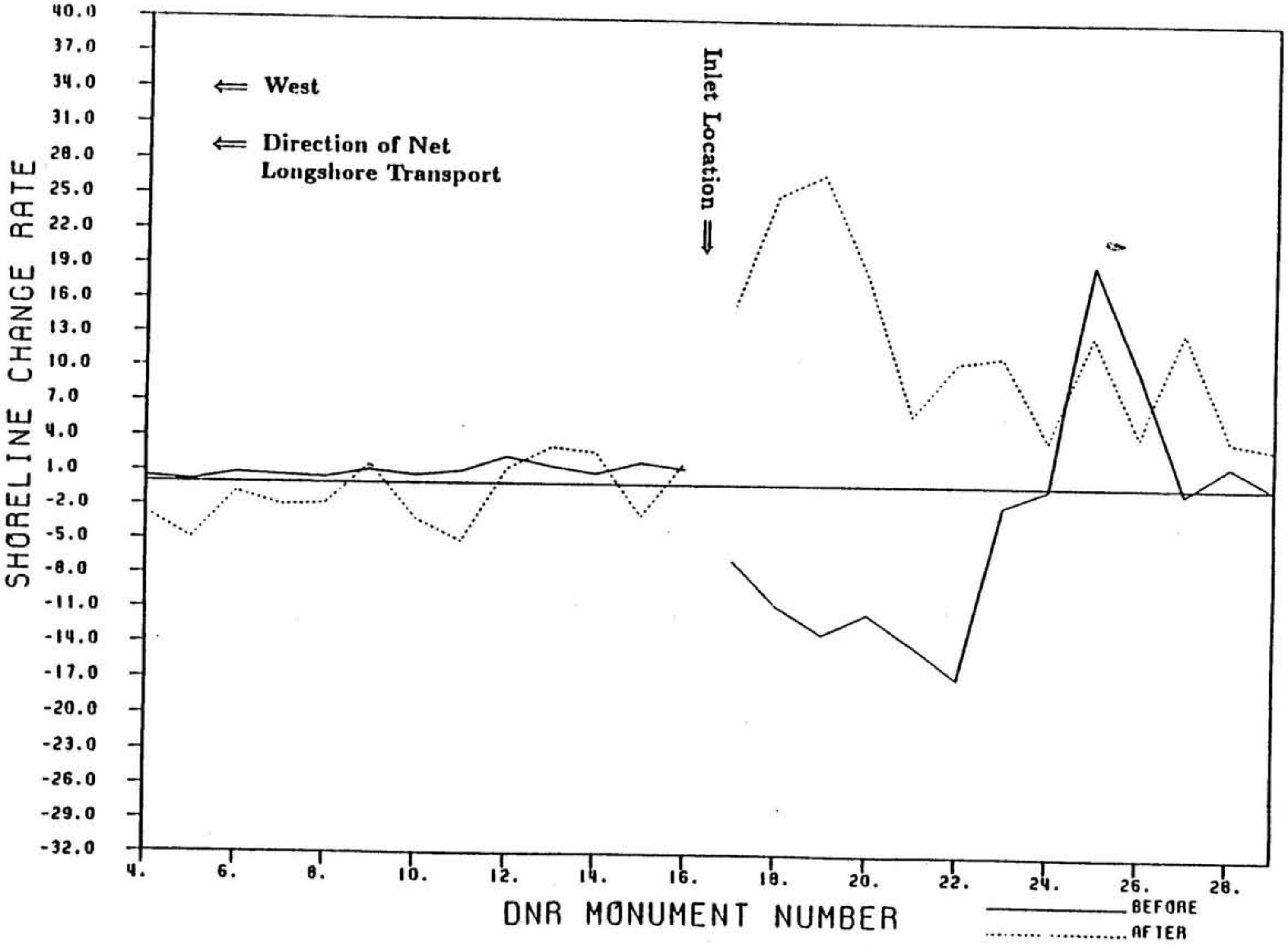


Figure 4.33: Shoreline change rates before (1871–1967) and after (1969–1987) training of East Pass (Destin Harbor). Change rates in feet per year.

4.3.3 St. Andrews Bay Entrance Channel (Panama City)

St. Andrews Bay Entrance is an artificial inlet connecting Panama City Harbor with the Gulf of Mexico. Four miles to the east is a natural inlet named East Pass (not the same as East Pass, Destin Harbor) which was abandoned when St. Andrews Bay Entrance was cut in 1934 (U.S. Army Corps of Engineers, 1948). The inlet was cut through a peninsula (see Figure 4.34) and a large channel was established; 1500 feet wide with a depth of 32 feet. Two jetties were constructed at the same time (1934), both of which had bulkheads and revetments added as jetty wings to counteract the erosion experienced by the new inlet. These wings had to be repaired and lengthened frequently as the shoreline continued to erode (U.S. Army Corps of Engineers, 1948). The predominate net longshore sediment transport is to the west. Since the entrance was constructed in 1934, roughly 13 million cu. yds. of material has been dredged for maintenance (Hine et al., 1986). Of this, 9 million cu. yds. has been placed offshore out of the sand sharing system. The remaining 3.8 million cu. yds. has been placed on the beaches, predominately the downdrift (west) beach. Figure 4.35 presents the shoreline change rates since construction. The downdrift erosion resulting from the west jetty is present with two 'bumps' (monuments #88–91 and #92–95) in the rates corresponding to previous maintenance dredge disposals.

Updrift (east) there is accretion associated with the impoundment of sediment at the east jetty but erosion is present beyond that. This could be due to transport nodal points, a possible 2 or 3 of which the U.S. Army Corps of Engineers (1971) say exist in Bay County. A nodal point may exist at the jettied entrance with drift to the east and west along the updrift shoreline. Another nodal point may exist in what is now the middle of the abandoned East Pass (Douglas, 1989). These two nodal points would explain the erosion and the accretion along the updrift shoreline. The major reason for the large difference in magnitude of updrift and downdrift shoreline change rates (147%) is the loss of the 9 million cu. yds. offshore, which has not been replaced downdrift even with the help of maintenance dredge spoil disposals. The 1855 shoreline (Figure 4.34) shows a straight shoreline across the present inlet that has eroded over 1000 feet back along Sand Island to the east. The increasing offset is shown by examining the 1855, 1934 and 1943 shorelines respectively.

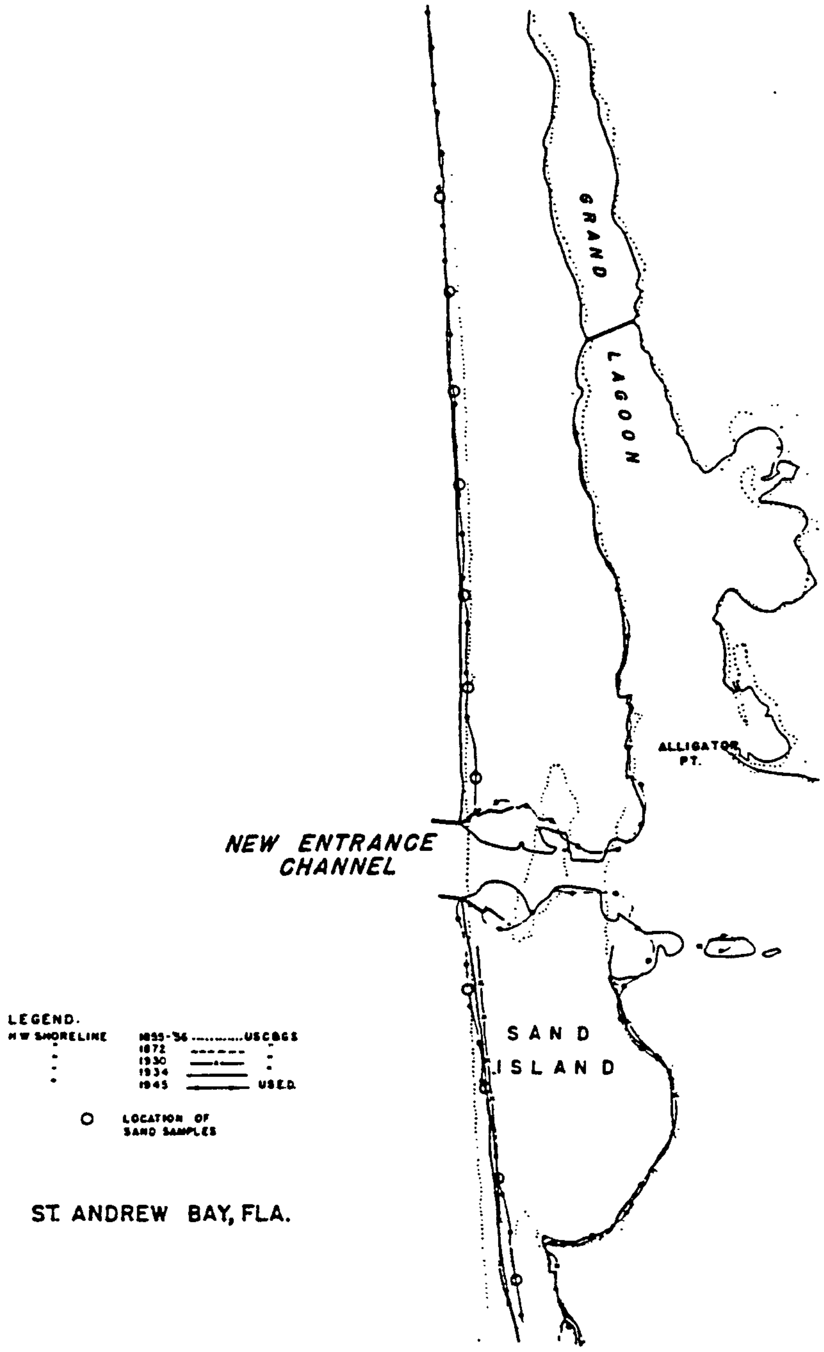


Figure 4.34: Historical shorelines for St. Andrews Bay Entrance Channel.

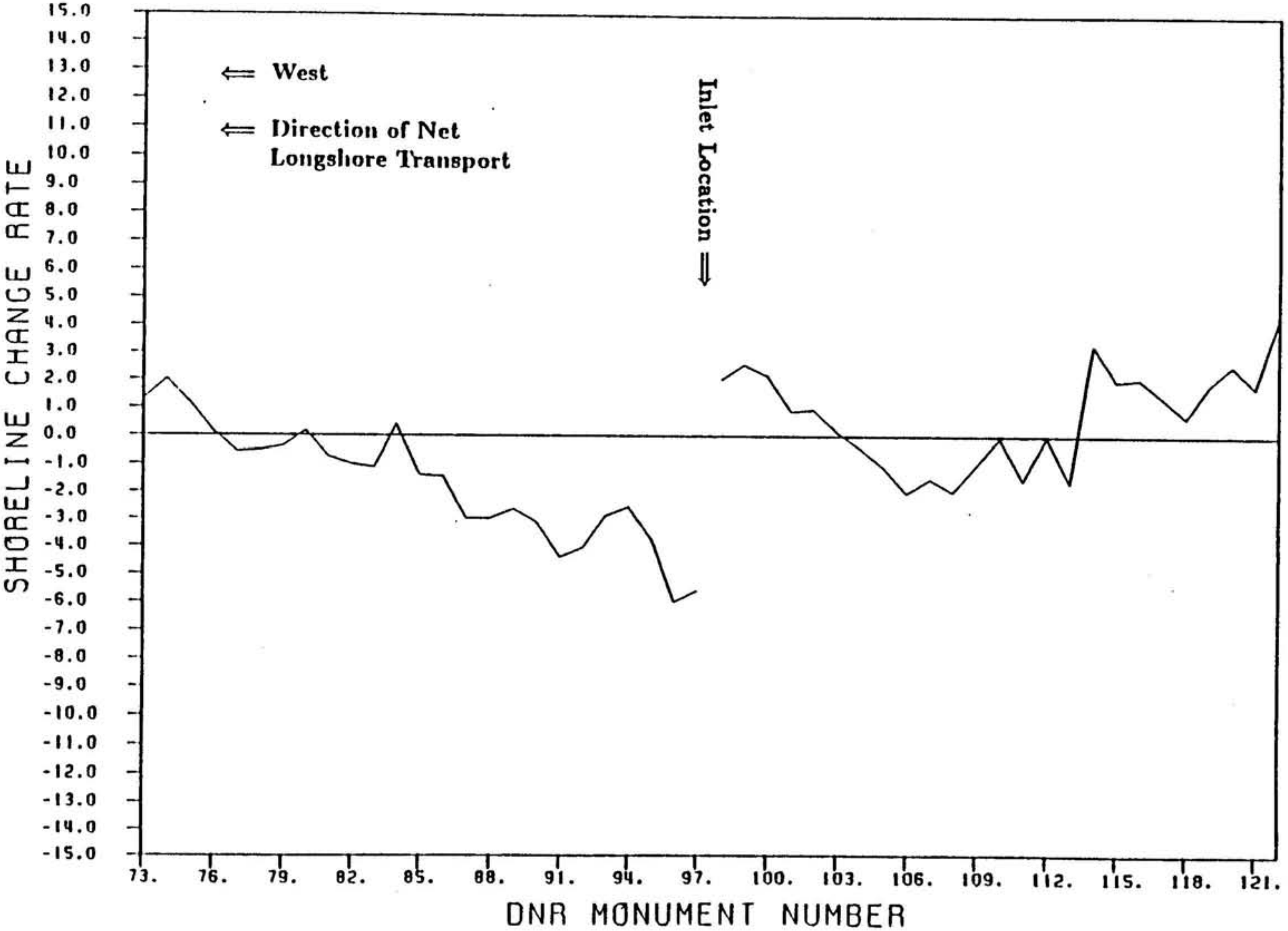


Figure 4.35: Shoreline change rates since the cutting and training (1943–1977) of St. Andrews Bay Entrance Channel. Change rates in feet per year.

4.3.4 Mexico Beach Inlet

Mexico Beach Inlet is a natural inlet that existed originally as a small creek draining a low marshy area (Dean and O'Brien, 1987b). In the 1940s, Mexico Beach Inlet was stabilized with two short jetties when the interior creek was converted into a canal system. The channel is only four feet deep and is not considered to be an important navigable waterway. Therefore, there is little information on dredge amounts or historical shoreline changes. There is an eastward littoral transport in this area which can clearly be seen in the shoreline change rates presented in Figure 4.36. The pre-modification rates show a constant erosion along the inlet with little variation due to the original creek. After the jetties were constructed, an offset occurred (although relatively minor) with an increase in accretion along the updrift shore and a decrease along the downdrift shore.

4.3.5 Venice Inlet

Venice Inlet is a natural inlet located on the lower west coast of Florida. The inlet connects Little Sarasota Bay and Roberts Bay with the Gulf of Mexico and was naturally migrating to the south until a nine feet deep channel was dredged in 1937 (U.S. Army Corps of Engineers, 1984). Longshore sediment transport is predominately southerly along this portion of the west coast of Florida (Dean and O'Brien, 1987b).

Between 1937–1938, two sheet-pile jetties were constructed which caused severe erosion, leading to the construction of flanking revetments in 1938–1940. In 1983 both of the jetties were repaired which has been the only work done on the inlet since construction. The initial dredging of the channel (70,000 cu. yds. of sand) was used as backfill for the revetments. The only other material dredged was 22,000 cu. yds. from the inlet in 1964, 19,000 cu. yds. of which was placed on Venice Beach (Dean and O'Brien, 1987b). According to the U.S. Army Corps of Engineers (1984), there has never been any maintenance dredging of Venice Inlet. Figure 4.38 presents the shoreline change rates for the post-construction era. This excludes the four years immediately after the jetties were built, so the severe erosion resulting from the construction of the jetties is not shown. However, most of this erosion

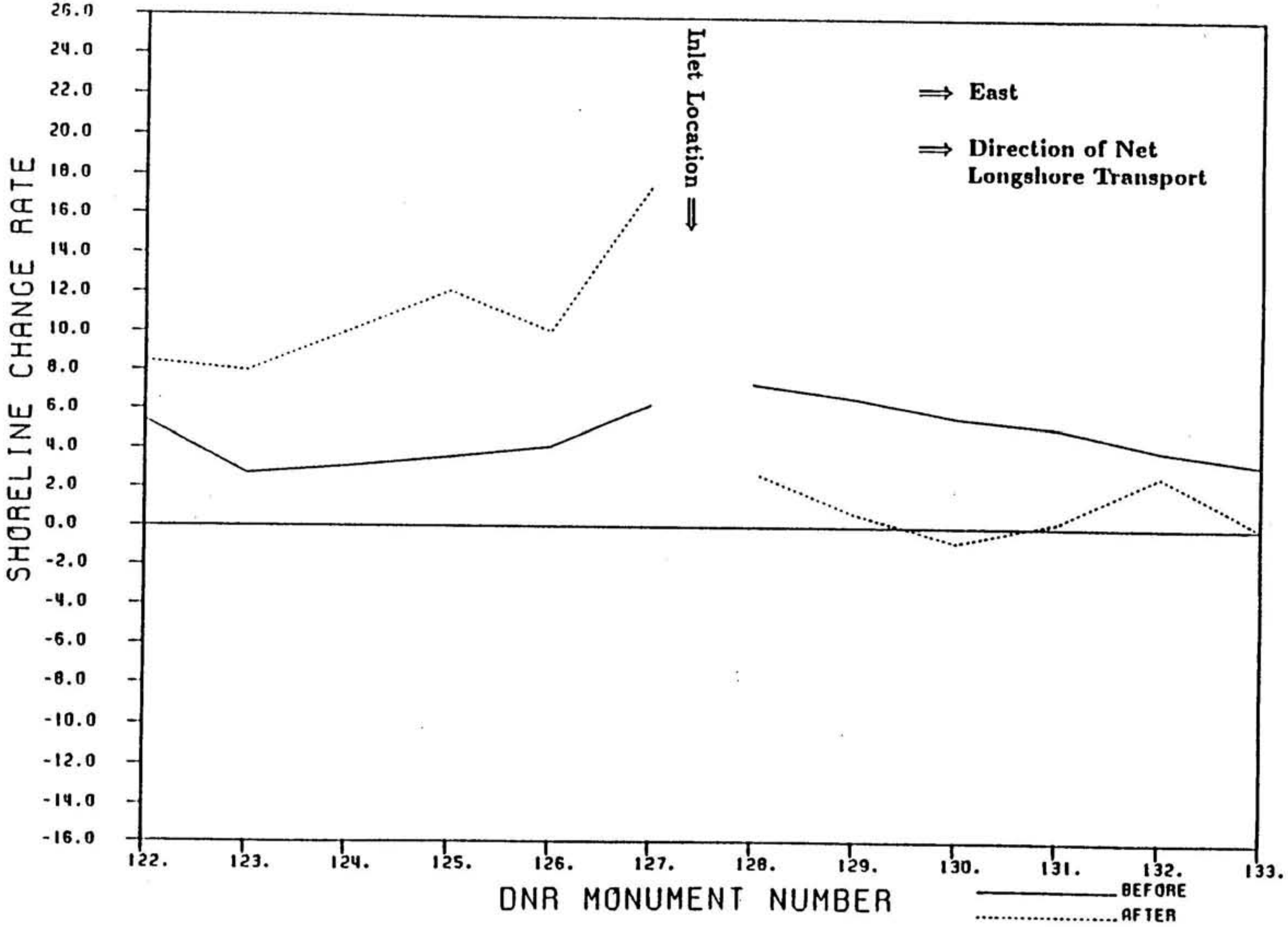


Figure 4.36: Shoreline change rates before (1855-1934) and after (1954 1977) training Mexico Beach Inlet. Change rates in feet per year.

was alleviated by the addition of the 70,000 cu. yds. of construction dredge spoil. The buildup along the updrift jetty is visible and the accretion along the entire updrift shoreline indicates relatively sand tight jetties. The accretion directly south of the inlet is the result of the 19,000 cu. yds. of sand placed on Venice Beach. This nourishment has not migrated as expected, due to a groin field 5,000 feet south of the inlet at the south end of Venice Beach. Beyond this groin field, the shoreline is experiencing erosion as the nourishment is not spreading out to reduce the erosional stress. Prior to the training of Venice Inlet, the 1883 shoreline shows a straight shoreline on either side of the inlet with a constant erosion that is slightly higher at the mouth of the inlet (see Figure 4.37). From 1942 on, the jetties have impounded a large amount of sediment without losing much of it to the inlet system. This has given (with the help of two dredge spoils) an overall $\frac{dy}{dt} = +1.42$ ft/yr.

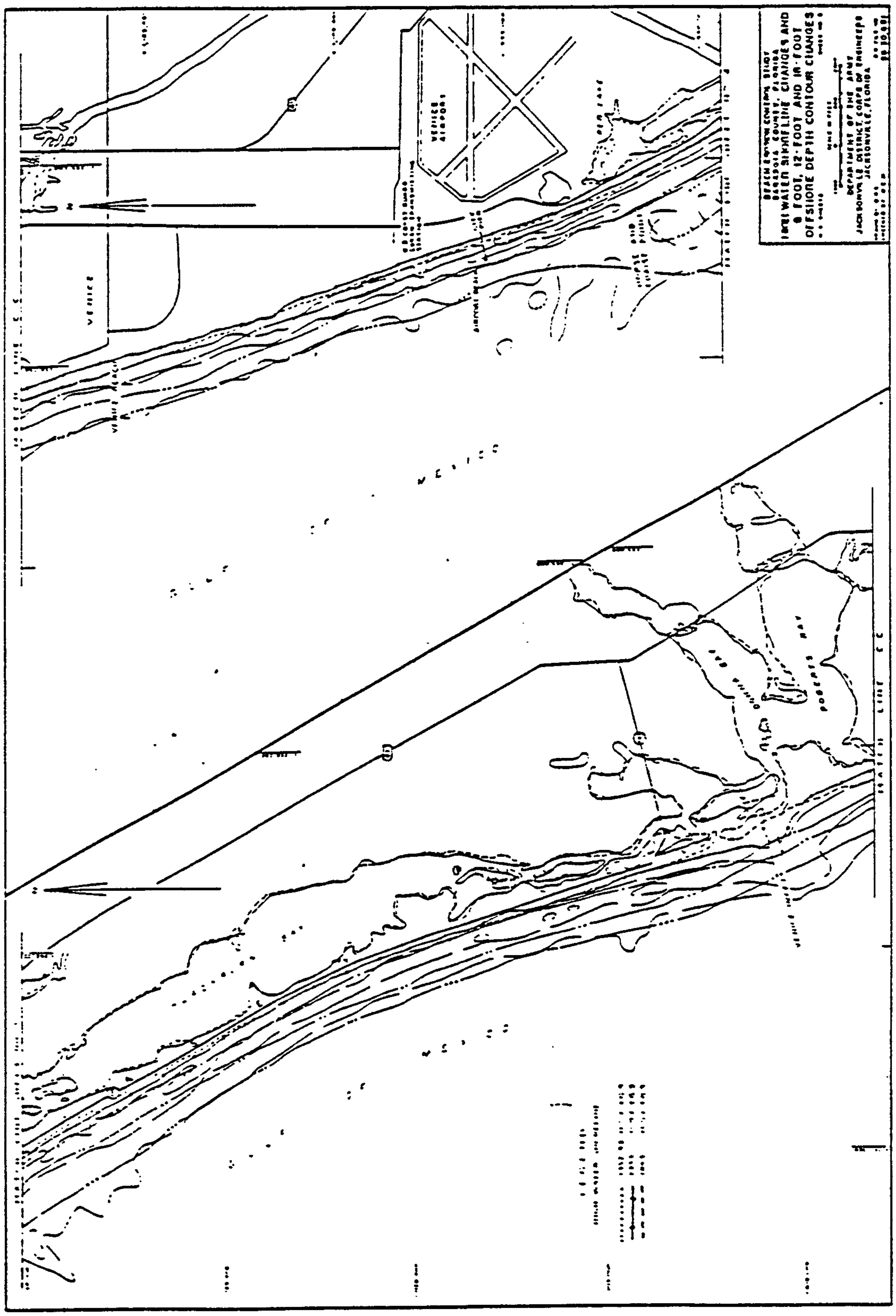


Figure 4.37: Historical shorelines for Venice Inlet.

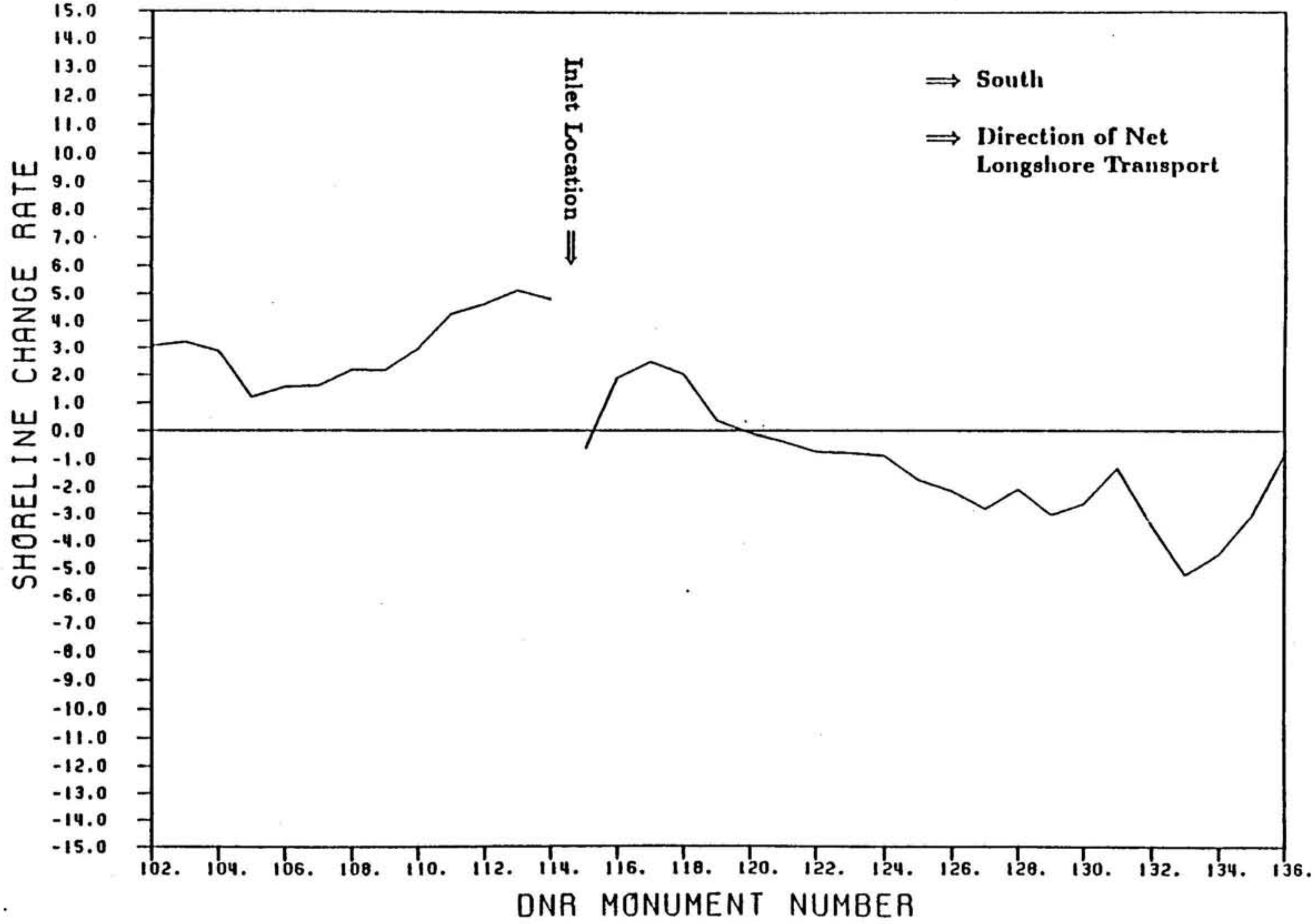


Figure 4.38: Shoreline change rates after training (1942 1987) Venice Inlet. Change rates in feet per year.

Table 4.1: Long Term Shoreline Change Rates For Florida's East Coast Counties and the Years of Survey Coverage. Shoreline Rates in Units of Feet per Year. Some of the Long Term Shoreline Change Rates are Influenced by Nourishment Projects.

COUNTY	NUMBER OF MONUMENTS	YEARS	SHORELINE CHANGE RATE *feet/year*
Nassau	82	1857–1980	+1.67
Duval	80	1853–1979	+1.86
St. Johns	209	1858-1986	+2.91
Flagler	100	1872–1979	−0.08
Volusia	234	1873–1989	+1.18
Cape Canaveral	167	1874–1976	+1.62
Brevard	219	1877–1986	+1.01*
Indian River	119	1882–1986	+0.34
St. Lucie	115	1883–1987	−0.38*
Martin	127	1883–1984	−5.00
Palm Beach	227	1883–1980	+0.04*
Broward	128	1883–1985	−1.14*
Dade	113	1851–1986	+0.89*

* Influenced substantially by nourishment projects.

4.4 Counties

4.4.1 East Coast

Analyzing historical data can provide interesting insight into possible future trends. Unfortunately, it also creates a large volume of calculated values. The following tables are the results of analyzing Florida's east coast counties with and without their respective inlets present. These will be discussed at the end of the section. Table 4.1 presents the shoreline change rates for each county encompassing all years of available historical data that are considered reliable. Also given are the number of monuments in each county that have been used for shoreline surveys. As noted previously, these monuments are roughly 1000 feet apart. These rates cover all available years of shoreline data and therefore have not had nourishment projects removed as has been done for all other shoreline change rates.

The advantage of examining long term rates is that the amount of noise due to large storms tends to be reduced. However it gives no indication of future trends. Therefore,

Table 4.2: Shoreline Change Rates for Florida's East Coast Counties up to the 1930s and from the 1930s to the Present. Shoreline Rates in Units of Feet per Year.

COUNTY	PRIOR TO THE 1930S *feet/year*	POST 1930S *feet/year*
Nassau	+2.05	+1.06
Duval	+0.91	+3.52
St. Johns	+3.04	+2.71
Flagler	+0.42	−1.55
Volusia	+1.05	+1.41
Cape Canaveral	+1.96	+0.73
Brevard	+1.25	−0.75
Indian River	+0.27	+0.46
St. Lucie	−0.53	−0.18
Martin	−4.93	−5.12
Palm Beach	−0.12	+0.30
Broward	−2.84	+0.62
Dade	−0.07	+0.36

Table 4.2 reduces the shoreline changes to pre- and post-1930s. This still allows for time periods large enough that they are not dominated by the effects of a single storm thus providing a better indication of erosional or accretional tendencies.

Tables 4.1 and 4.2 provide the means of obtaining long term shoreline change rates for the east coast of Florida as a whole. Combining all available shoreline change data, as shown in Table 4.1, results in a positive shoreline change rate of +0.51 ft/yr. Since this rate is based upon all shoreline surveys from 1851–1989 that are considered accurate, it includes some nourishment projects (predominately post 1930s). Removing the nourishment projects from the counties indicated in Table 4.1 and splitting the data set roughly in half with regard to time provides an indication of stability. Prior to the 1930s, a positive shoreline change rate of +0.37 ft/yr existed while the post 1930s rate is similar, +0.33 ft/yr. Since the added effect of nourishment projects is no longer present, these two rates are lower than the long term shoreline change rate. Examining these three rates suggests that Florida's shoreline is relatively stable over time. However, Table 4.2 shows that while Florida's east coast is accreting at a steady pace, the individual county fluctuations vary considerably. This is due primarily to the effects of inlets (storm damage is reduced for these larger time periods). Therefore it is necessary to view the counties with and without the effects of their respective inlets. This will be done in Section 4.6.

4.4.2 West Coast

Florida's west coast has lower wave energy and a smaller littoral transport. On an overall average, the entire west coast is almost relatively stable with regard to net shoreline change, however. there is as much internal fluctuation as on the east coast, only lower in magnitude. This can be shown by combining the individual counties as done for the east coast. Table 4.3 gives the long term changes per year for the west coast as well as the number of monuments included in each survey area. The monuments are roughly 1000 feet apart as on the east coast. As with Table 4.1, these long term rates cover all available data and therefore include the effects of nourishment. The six upper west coast counties have a long term erosion rate of −0.34 ft/yr while the lower six west coast counties have accreted at +0.41 ft/yr. Therefore, the sandy shoreline of the west coast of Florida has a long term change rate of only +0.02 ft/yr.

4.5 Florida's Coastline

Combining the long term shoreline change rates for the east and west coasts (from Tables 4.2 and 4.3 respectively) provides a long term shoreline change rate for Florida. Since 1851, the coastline of Florida has been accreting at an average of +0.27 ft/yr. The west coast inlets have seen less modification and smaller scale changes than those on the east coast. This is due in part to the presence of wider, deeper and better maintained inlets on the east coast as a result of heavier commercial waterborne traffic and more high population centers along with increased industry. The lower longshore sediment transport (see Figure 1.3) on the west coast results in a lesser potential impact as a result of inlet modification. These factors have contributed to a lower average shoreline change on the west coast than on the east coast. On average, the west coast has stayed constant (+0.02 ft/yr) since 1851. The east coast has averaged an accretion rate of +0.51 ft/yr during the

Table 4.3: Long Term Shoreline Change Rate For Florida's West Coast Counties and the Years of Survey Coverage. Some of the Shoreline Change Rates are Influenced by Nourishment Projects.

COUNTY	NUMBER OF MONUMENTS	YEARS	SHORELINE CHANGE RATE *feet/year*
Escambia	214	1856–1978	−0.40
Okaloosa	50	1871–1987	+0.34
Walton	127	1872–1977	−0.46
Bay	144	1855–1977	−1.16
Gulf	162	1857–1979	−0.45
Franklin	239	1856–1979	+0.18
Pinellas	192	1873–1987	+0.91*
Manatee	67	1874–1986	−0.48
Sarasota	183	1883–1987	+0.13*
Charlotte	68	1860–1988	+1.13*
Lee	239	1858–1982	−0.02
Collier	148	1885–1988	+0.86*

* Influenced substantially by nourishment projects.

same time period. A large part of this is a result of inlets. Adding up only the volumes of dredged sand due to inlet construction as discussed in the earlier section on east coast inlets provides a sum of roughly 66.4 million cu. yds. of sediment. This value rises much higher if all maintenance dredging to date is included. Over 50% of this sand has been placed on the shoreline or in a vicinity where it will affect the shoreline. So, the east coast is indeed accreting, but is it all due to natural causes? Comparing the shoreline change rates up to and after the 1930s doesn't provide many answers to this question. Prior to the 1930s, which includes the construction and training of 13 of the 19 east coast inlets, Florida accreted an average of +0.37 ft/yr. Remember that the cutting of an artificial inlet produces a large volume of sediment, part of which has ended up on the neighboring shoreline. Since the 1930s, the shoreline change rate has decreased to +0.33 ft/yr ; a time period which includes less inlet training and modification, but increased sand bypassing and beach nourishment.

Table 4.4: Shoreline Change Rates for East Coast Inlets Before and After Training. Updrift and Downdrift Shorelines Within Inlets Influence. Rates Found From Historical Charts are Accompanied by an $*$.

INLET	UPDRIFT SHORELINE		DOWNDRIFT SHORELINE	
	BEFORE *ft/yr*	AFTER *ft/yr*	BEFORE *ft/yr*	AFTER *ft/yr*
St. Augustine	+1.60	+0.32	+5.10	+3.32
Matanzas	+1.72	+4.12	−0.29	−1.61
Ponce de Leon	+2.19	+6.75	+2.85	−2.72
Port Canaveral	+9.37	+12.82	+5.22	−1.18
Sebastian	+1.48*	+1.67	+1.09*	−0.76
Ft. Pierce	*N/A*	+4.06	*N/A*	−3.11
St. Lucie	*N/A*	+3.11	*N/A*	−21.18
Jupiter	*N/A*	+1.06	*N/A*	−0.38
Lake Worth	*N/A*	+8.05[a]	*N/A*	+3.60[a]
South Lake Worth	*N/A*	+1.22	*N/A*	−0.20[b]
Boca Raton	*N/A*	−0.35	*N/A*	−0.89
Hillsboro	+0.29	−0.36	*N/A*	−0.04
Port Everglades	+0.28*	+1.42	*N/A*	−0.69
Bakers Haulover	*N/A*	+1.64	*N/A*	+0.94[c]

[a] This includes substantial recovery from an initially eroded condition due to jetty construction.

[b] The immediate post-construction survey includes substantial erosion due to inlet construction.

[c] Includes effects of a small beach nourishment project.

4.6 Effects of Inlets

The next logical step is to examine shoreline change rates associated updrift, downdrift and within the entire shoreline that is under the influence of each inlet. This is done both before and after the construction associated with each specific inlet.

Table 4.4 presents the shoreline change rates for the updrift and downdrift shorelines within the influence of the inlet. Before and after training rates are provided when possible. Unfortunately it is often not possible to establish accurate shoreline change rates before training due to a lack of precise data during that time. An asterisk, "*" in Table 4.4 (also in Table 4.5), denotes a change rate obtained from historical shorelines at each DNR monument. In some instances, these rates were found to be fairly reliable and were therefore

Table 4.5: Shoreline Change Rates for East Coast Inlets Before and After Training. Average Rate for Entire Shoreline Influenced by Inlet. Rates Found From Historical Charts are Accompanied by an $*$.

INLET	BEFORE TRAINING *feet/year*	AFTER TRAINING *feet/year*
St. Augustine	+3.82	+2.22
Matanzas	+0.71	+1.25
Ponce de Leon	+2.52	+2.01
Port Canaveral	+7.89	+5.82
Sebastian	+1.29$*$	+0.49
Ft. Pierce	*N/A*	+0.47
St. Lucie	*N/A*	−9.03
Jupiter	*N/A*	+0.26
Lake Worth	*N/A*	+5.83[a]
South Lake Worth	*N/A*	−0.72[b]
Boca Raton	*N/A*	−0.61
Hillsboro	−0.51	−0.20
Port Everglades	*N/A*	+0.37
Bakers Haulover	*N/A*	+0.27[c]

[a] This includes substantial recovery from an initially eroded condition due to jetty construction.

[b] The immediate post-construction survey includes substantial erosion due to inlet construction.

[c] Includes effects of a small beach nourishment project.

included. Wherever a *N/A* is displayed, no shoreline change rate could be obtained that was considered accurate for the entire influenced shoreline. Table 4.5 is a combination of shoreline change rates presented in Table 4.4.

An average shoreline change rate can be found for the updrift and downdrift shorelines. Since training, the updrift shorelines have accreted +2.64 ft/yr while the downdrift shorelines have eroded -2.07 ft/yr. These combine for an average shoreline change rate of +0.22 ft/yr within the influence of the inlets on the east coast of Florida. This shows a positive change due to the training of inlets. It must be remembered that this is the shoreline within the inlet's influence and that the same positive effects are not necessarily assured for the Florida coastline as a whole. Therefore each county must be considered with and without the shoreline associated with inlets. Since Flagler County has no such shoreline and the northern inlets were omitted due to complications; Nassau, Duval and Flagler Counties are not included in this part of the study.

Table 4.6 presents the shoreline change rates after training with and without the shorelines influenced by inlets. Some of the values are misleading. Cape Canaveral, for instance shows a large gain due to the inclusion of the inlet. This is because Cape Canaveral contains only the updrift shoreline of Port Canaveral Entrance, therefore it is easier to look at average rates instead of comparing counties. The average rates provide an indication of the negative effects of inlets. The shoreline without the effects of inlets is accreting at an average value of +0.67 ft/yr. When the inlets are included, the average shoreline change rate drops to +0.57 ft/yr.

Finally, Table 4.7 presents the human influence of training and cutting an inlet. It should be noted that these values still include some effects of beach nourishment that due to the nature of the data are unremovable. These values also include some maintenance dredging and bypassing. The natural shoreline change rate is a compilation of rates. Wherever possible (see Tables 4.4 and 4.5) the shoreline change rate before training was used since it is the most precise for that specific area. Where this was not feasible, the long term

Table 4.6: Shoreline Change Rate After Training for East Coast Counties With and Without Influenced Shorelines Removed.

COUNTY	SHORELINE CHANGE RATE AFTER TRAINING	
	WITHOUT INLETS *feet/year*	WITH INLETS *feet/year*
St. Johns	+3.11	+2.71
Volusia	+1.39	+1.44
Cape Canaveral	−0.82	+0.73
Brevard	+0.61	+0.60
Indian River	+0.87	+0.46
St. Lucie	−0.55	−0.18
Martin	−2.97	−5.12
Palm Beach	+0.02	+0.30
Broward	+2.01	+0.62
Dade	+1.88	+1.44

shoreline change rate for the county encompassing the inlet was modified. The shorelines influenced by inlets and beach nourishment projects were removed to obtain as natural a shoreline change rate as possible. Removing the natural shoreline changes from the shoreline changes at each inlet leaves a shoreline change rate that is a result only of the inlet. The average influenced rate for these inlets is an erosional value of -0.69 ft/yr. Note that this includes the inflated shoreline change rate of Lake Worth Inlet (see Section 4.2.9), the nourishment on the south beach of Hillsboro Inlet and maintenance dredging. Therefore the erosional influence of training an inlet is at the very minimum -0.69 ft/yr and this effect extends over an approximate distance of 514,000 feet. Assuming a depth of vertical profile response of 27 feet, the associated average volumetric loss is 0.35 million cubic yards of sand per year. Using 1926 as the average start date of inlet construction and training gives a period of record of 61 years. Therefore the associated volumetric loss due to the training of the inlets on the east coast of Florida is 21.6 million cubic yards of sand.

Table 4.7: Shoreline Change Rate for the Human Influence of Training the Inlets on the East Coast of Florida. Human Influence is the Shoreline Change Rate of the Inlet with the Natural Shoreline Change Rate Removed.

COUNTY	SHORELINE CHANGE RATE INLET *feet/year*	 NATURAL *feet/year*	 HUMAN INFLUENCE *feet/year*
St. Augustine	+2.22	+3.82	−1.60
Matanzas	+1.25	+0.71	+0.54
Ponce de Leon	+2.01	+2.52	−0.51
Port Canaveral	+5.82	+7.89	−2.07
Sebastian	+0.49	+1.29	−0.80
Ft. Pierce	+0.47	−1.19	+1.66
St. Lucie	−9.03	−1.82	−7.21
Jupiter	+0.26	+0.09	+0.17
Lake Worth	+5.83	+0.09	+5.74[a]
South Lake Worth	−0.72	+0.09	−0.81[b]
Boca Raton	−0.61	+0.09	−0.70
Hillsboro	−0.20	−0.51	+0.31
Port Everglades	+0.37	−0.12	+0.49
Bakers Haulover	+0.27	+0.03	+0.24[c]

[a] This includes substantial recovery from an initially eroded condition due to jetty construction.

[b] The immediate post-construction survey includes substantial erosion due to inlet construction.

[c] Includes effects of a small beach nourishment project.

4.7 Sea Level Rise

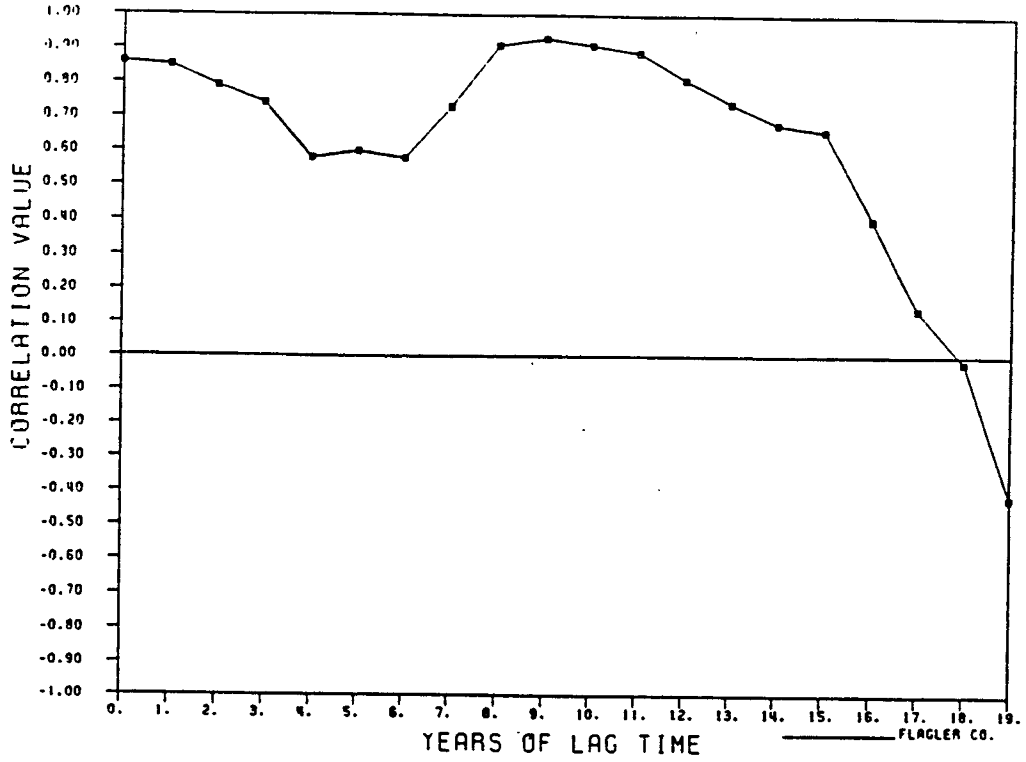
The available shoreline position data combined with the sea level information provided a basis for evaluating the Bruun Rule. The comparison of historical sea level rise data and shoreline change data yielded results that are not consistent with the Bruun Rule which, as noted before, associates a rise in sea level with shoreline recession. For the east coast of Florida, an average relationship, based on the Bruun Rule is calculated as follows. Average values for the ten counties examined are:

- $h_* = 14 \rightarrow 19\,\text{feet}$
- $B = 6 \rightarrow 8\,\text{feet}$
- $L = W_* = \left(\frac{h_*}{A}\right)^{3/2}$

where A is the equilibrium beach profile scale parameter which Dean (1990) found to be roughly $A = 0.18\,\text{ft}^{1/3}$ for the middle of the east coast of Florida. This yields a Bruun Rule range of: $\Delta Y = -(40 \rightarrow 60)\,\Delta Z$ where ΔY is the change in shoreline with a positive value indicating advancement and a positive ΔZ indicates a rise in sea level. The evaluation, carried out in accordance with Equation 3.1, showed trends contradictory to theory for ten of the twelve counties tested. A rising sea level corresponded to an accreting shoreline in all but Broward and Martin counties. If a linear relationship is assumed for each county, an average empirical correlation can be found that corresponds to the above theoretical Bruun Rule, $\Delta Y = +\,65.3\,\Delta Z$. Note again that the positive sign is contrary to the concept of the Bruun Rule. The validity of this correlation is discussed later in this section.

The strongest correlation values were found in the first ten years of lag, $\tau = 0 \rightarrow 10$, with some of the values as high as $r(\tau) = 0.99$, however, for these cases, there were very few data points. Thus the results should be interpreted accordingly. Many of the correlation values for $\tau \geq 15$ years are not as accurate as those for lower τ values. This is a result of shorter overlap. The sea level rise data extend from 1897–1980, therefore, any shoreline change, ΔY, that starts before 1916 (1916-19 years is 1897) will be less accurate. As τ

grows, ΔY is held constant and ΔZ is recalculated with data offset one year back for each year τ grows. Once the sea level rise data for a ΔZ starts at 1897, it can no longer start one year back, therefore the sea level change value is calculated for one year less. As ΔZ covers less years, $r(\tau)$ becomes less accurate. Figures 4.39 and 4.40 present some of the counties as examples and shows the lack of consistency between counties. All of the positive $r(\tau)$ values indicate a shoreline accretion as sea level rises while $r(\tau) = -1$ indicates perfect agreement with the Bruun Rule. The problem with $r(\tau)$ is that it can be quantitatively misleading in these cases. Figure 4.41 presents two different τ values, each of which has a correlation of $r(\tau) = 0.99$, and the ΔY and ΔZ values which produced them. Both $r(\tau)$ values are considered strong correlations based on their 1 % deviance from a perfect correlation, $r(\tau) = \pm 1$, however Figure 4.41 shows that a dominance by one point can artificially bias the correlation when there are only three data points. Therefore $r(\tau)$ was recalculated for the entire east coast by combining all ΔY and ΔZ values giving each correlation a minimum of 32 data points and thereby removing the effect of dominance by a few points. These combined values are presented in Figure 4.42 and no strong correlation is indicated for any lag time. The largest correlation value is 0.41 and Figure 4.43 presents the 32 data points used for this correlation. However all of the $r(\tau)$ values for $\tau \leq 15$ years are positive which is again contrary to the Bruun Rule.



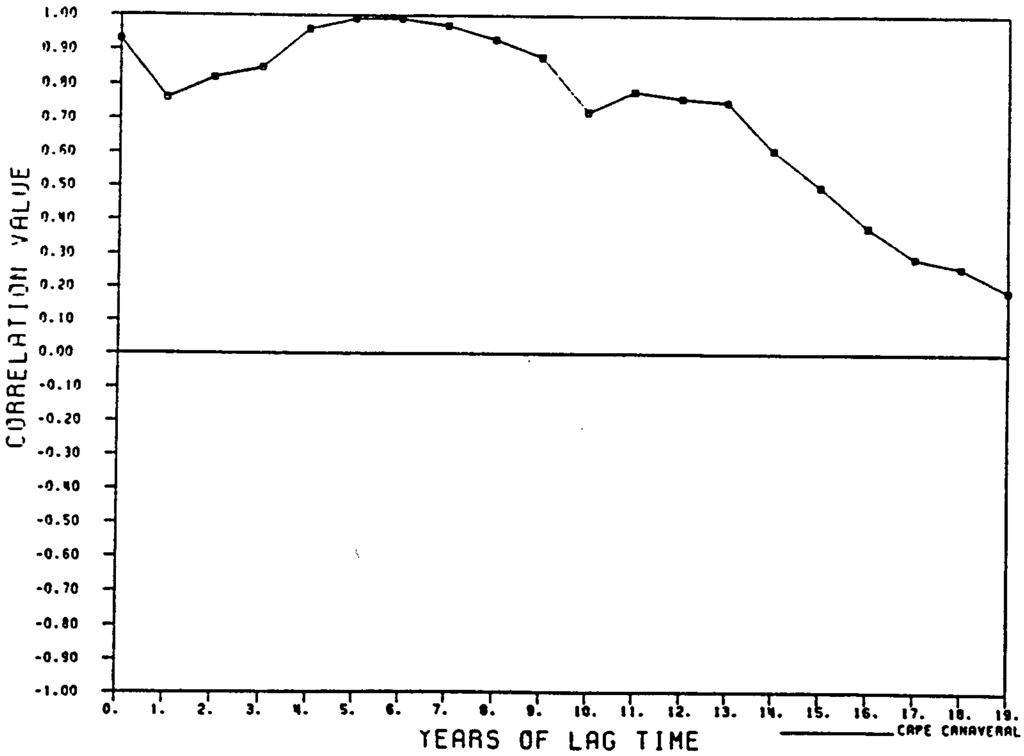


Figure 4.39: Sea level rise correlation, $r(\tau)$, values for Flagler and Cape Canaveral Counties for up to 19 years of lag.

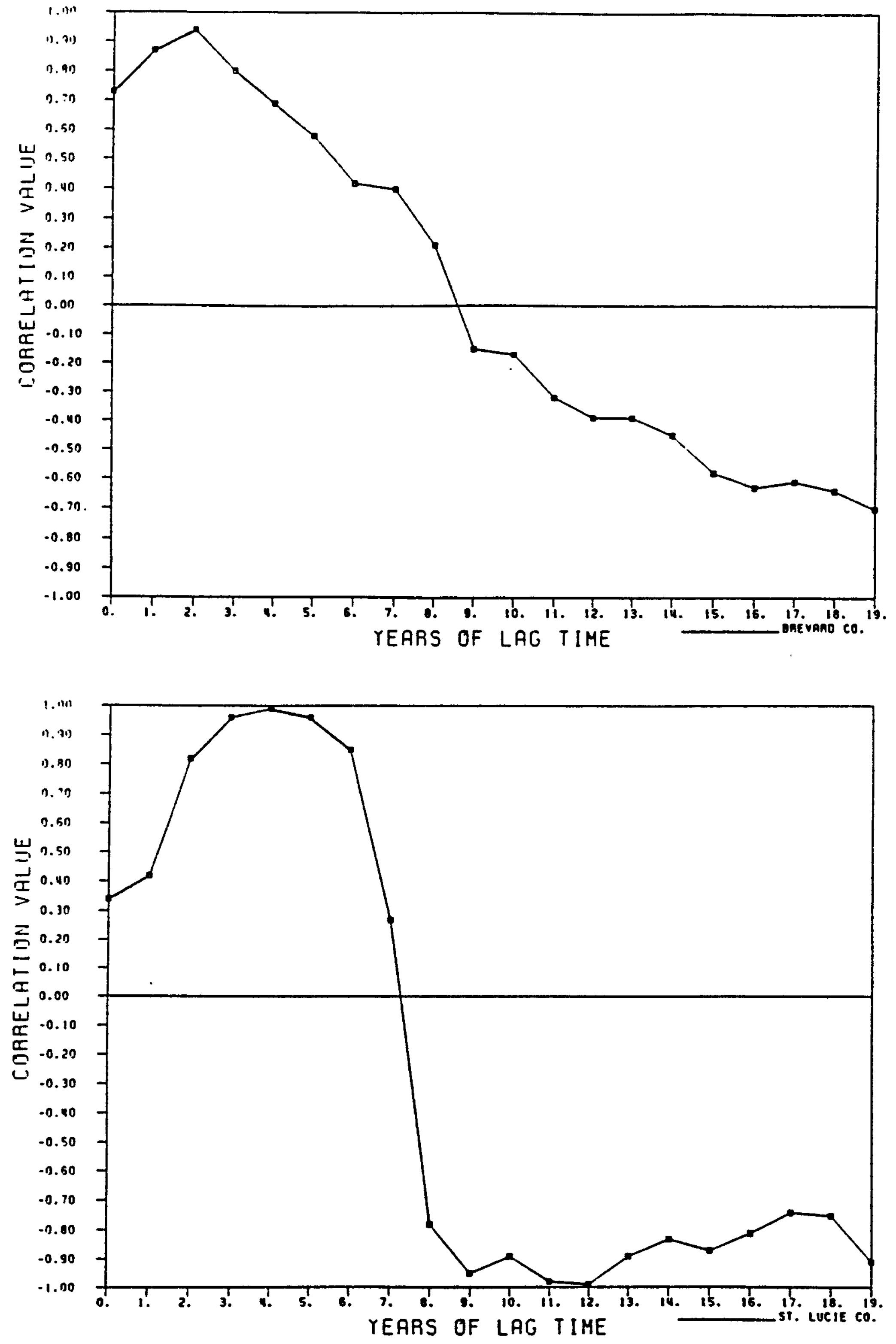


Figure 4.40: Sea level rise correlation, $r(\tau)$, values for Brevard and St. Lucie Counties for up to 19 years of lag.

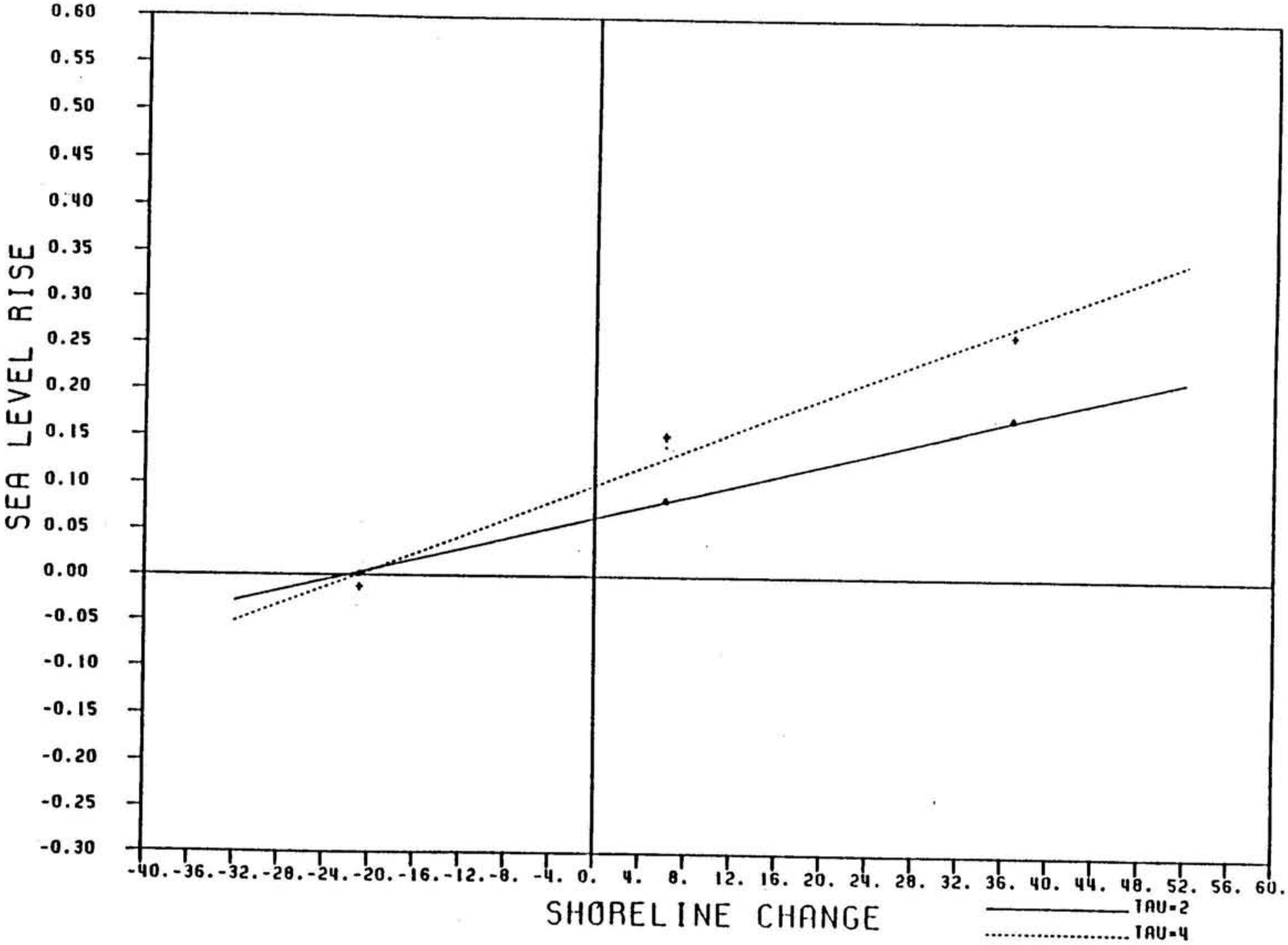


Figure 4.41: Illustration of two identical correlation values, both equal to 0.99.

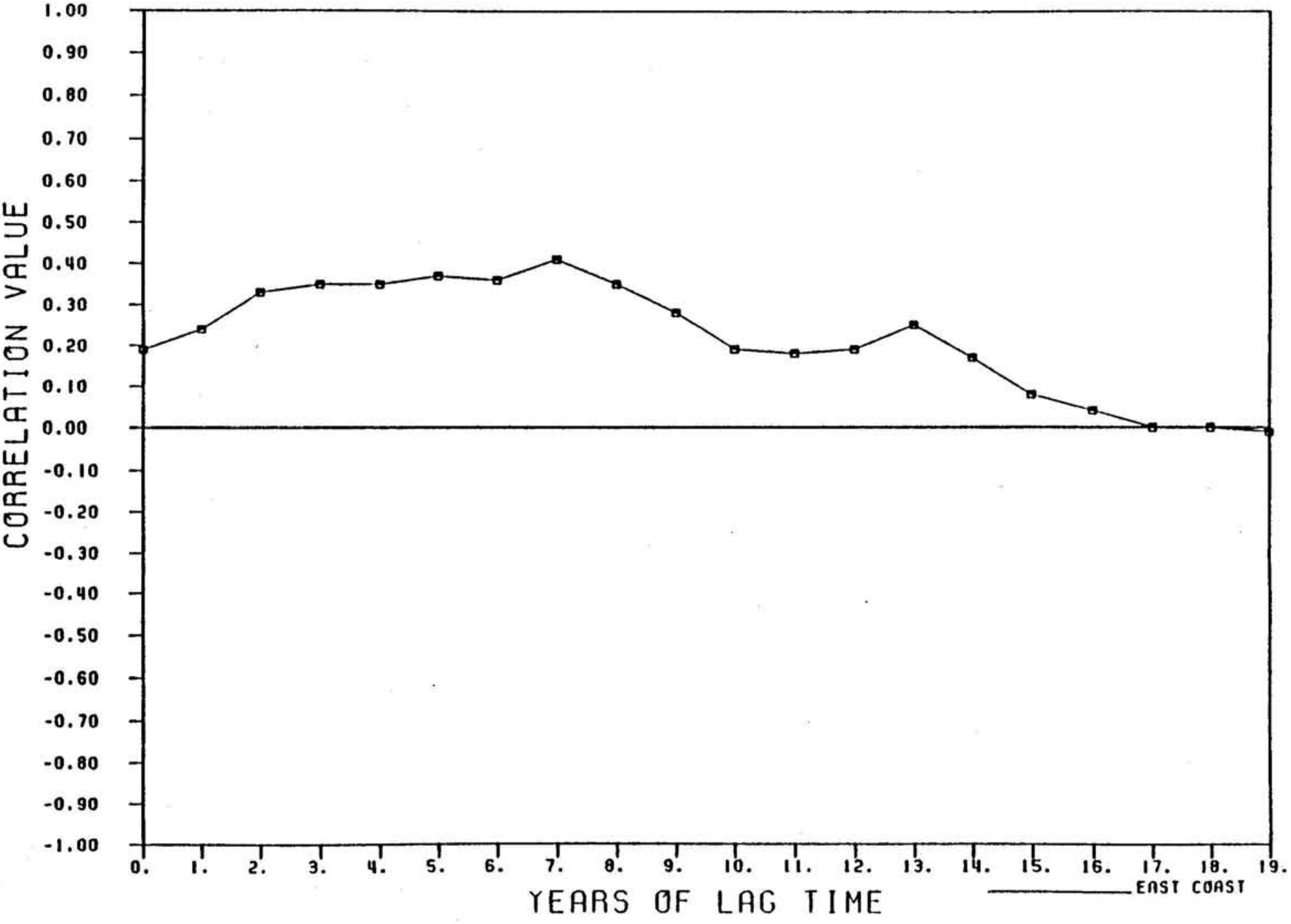


Figure 4.42: Sea level rise correlation, $r(\tau)$, values for the east coast of Florida.

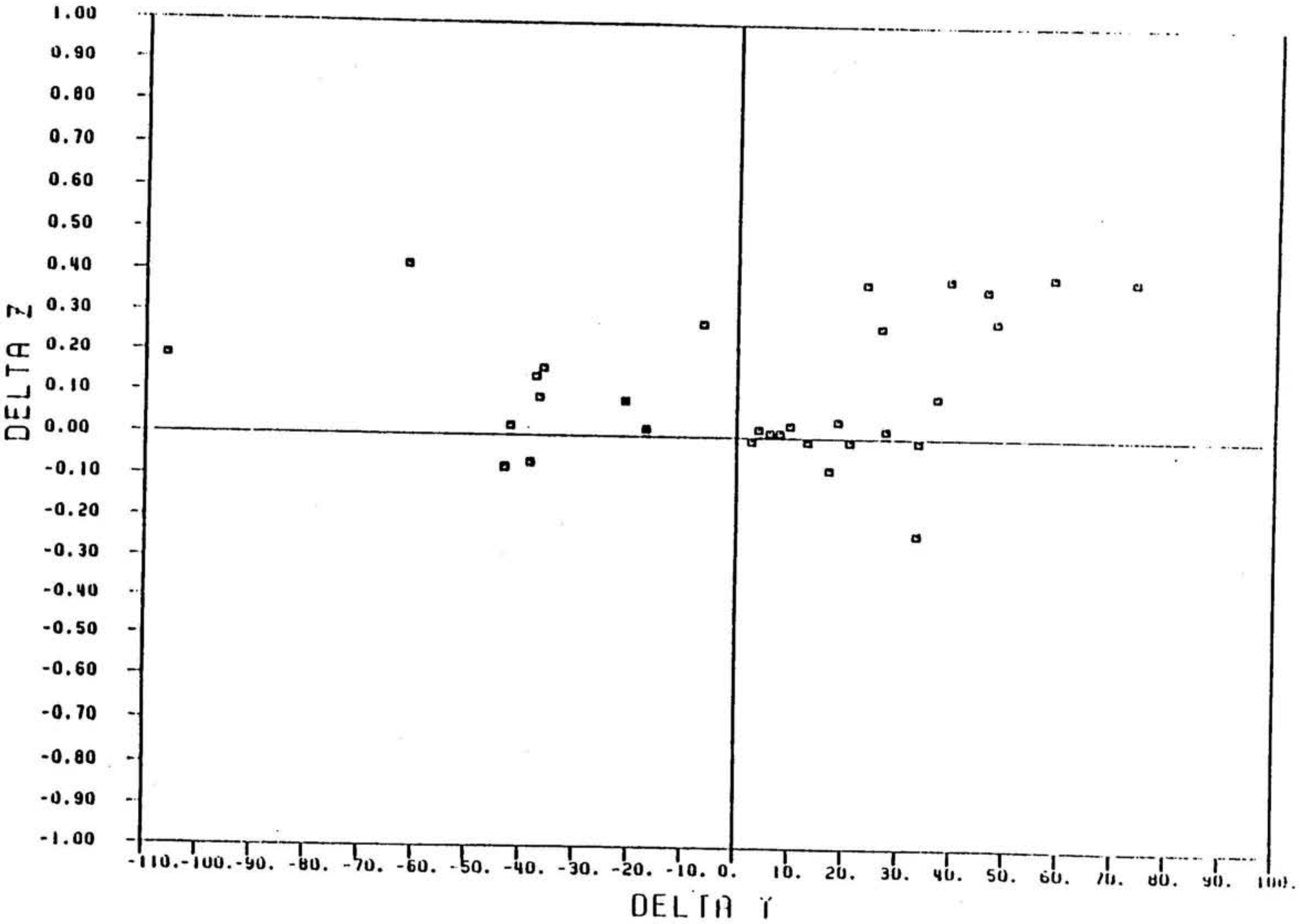


Figure 4.43: Data points for $\tau = 7$ from the previous figure.

CHAPTER 5
SUMMARY AND CONCLUSIONS

The study undertaken in this thesis has resulted in quantitative findings from which conclusions can be drawn. These findings are based upon the analysis of historical records, shoreline position data compiled by the Florida Department of Natural Resources and tide gauge data measured by the National Ocean Service. It was found that:

1) The east coast of Florida (roughly 360 miles) during 1851–1989 has been accreting at an average rate of +0.51 feet per year.

2) The twelve counties that comprise the sandy shoreline along the west coast of Florida (roughly 345 miles) during 1855–1988 have been accreting at a rate of +0.02 feet per year.

3) This results in an average long term shoreline change rate for the sandy coast of Florida of (accretion) +0.27 feet per year.

The altering of the coast will incur side effects. The building of structures, creating of artificial inlets and the geographic fixing of natural inlets results in changes, sometimes extreme, to the natural shoreline. Inlets (especially trained inlets) are a shoreline modification which cause a net loss in sediment as well as inducing shore-normal variations. This effect was determined for all fourteen of the east coast inlets studied. The shoreline change rate for each inlet during the time period after the creation or modification of the inlet was found. These rates excluded the effects of beach nourishment but not the effects of maintenance dredging or sediment bypassing. A natural shoreline change rate free of the effects of inlets and nourishment was determined. The removal of the natural shoreline change rate from the shoreline change rate at each inlet provides a shoreline change rate that is primarily influenced by the human intervention on the shoreline. The training of the east coast inlets studied has caused an additional -0.69 feet per year of erosion to the shoreline (roughly 100 miles) within the influence of these inlets. The major impact of this is felt on the downdrift shorelines which in addition are experiencing the anti-symmetric shoreline changes due to the placement of jetties.

Correlation on a county by county and entire east coast basis were carried out as a test of the Bruun Rule. These correlations generally provided results contrary to the Bruun Rule. It was found that:

1) There is no correlation over 0.41 (with ±1.0 indicating a perfect correlation) between a rise in sea level and a change in shoreline position for the east coast as a whole.

2) There is no indication that a specific lag time (between $0 \rightarrow 19$ years) exists between a rise in sea level and a change in shoreline position.

3) Most correlation values, however weak, are positive. This indicates a shoreline advancement with a rising sea level which is contrary to the Bruun Rule.

The long term shoreline monitoring program in Florida has resulted in data sets which are extremely valuable to understanding the natural and altered shoreline segments and developing rational and effective management programs for the State's beaches. These data collection programs that have provided the basis for this study should continue to be conducted and the results analyzed further. Although it is difficult to remove the effects of beach nourishment and bypassing from the natural changes in shoreline position, this must be undertaken in order to better judge the effects of sea level rise. The data suggest that Florida is accreting naturally. Thus as long as the downdrift shorelines of inlets are properly replenished, preferably through bypassing, existing storm protection and economic benefits will be maintained. Sea level rise response is still largely unknown and in order to better understand it, accurate shoreline changes due to natural causes must be known as accurately as possible. Sea level rise should continue to be compared with shoreline changes to attempt to better understand it. Because of the lack of correlation between shoreline and sea level changes found here, a renewed emphasis on this problem is warranted.

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APPENDIX A
LONG TERM SHORELINE CHANGE RATES

A.1 Introduction

This appendix is a compilation of all of the long term shoreline change rates for each county in Florida that has a predominately sandy shoreline. As noted before, Cape Canaveral is considered as a separate county instead of part of Volusia and Brevard Counties. Two graphs are presented for each county. The upper panel presents the long term shoreline change rate at each DNR monument throughout that county. The lower panel presents the same data in histogram format. Each change rate consists of all of the historical shoreline position data that are considered reliable from the mid to late 1800s to the most recent data available. This provides shoreline change rates that are relatively free from non-representative storm and seasonal fluctuations. However,in some cases, the rates do include the effects of beach nourishment. The shoreline change rates presented have been determined by a least squares fit to the data available at each monument. To better understand the shoreline changes, a corresponding histogram is included with each county. Histograms for the entire east coast and the lower and upper west coast have also been included. The use of the histogram, provides a means to better understand the distribution of the erosion or accretion rates throughout the county. In general, the distribution of the west coast counties is more symmetric about the $\frac{dy}{dt} = 0.0$ ft/yr axis (x-axis) and the distribution has fewer outlying points than the east coast counties. This is primarily due to the greater shoreline change rates within the shorelines associated with the east coast inlets than those with the west coast inlets. Considering the greater magnitude of longshore transport along the east coast and the larger and more numerous modifications that have been undertaken on the east coast inlets, the greater spread on the histograms is not surprising. Each histogram is comprised of a shoreline change rate increment of ±0.5 ft/yr along the horizontal axis with the number of monuments in that county that have the corresponding erosion or accretion rate along the vertical axis. The lower and upper limits on the horizontal axis are the same on all graphs for easy reference.

A.2 East Coast Counties

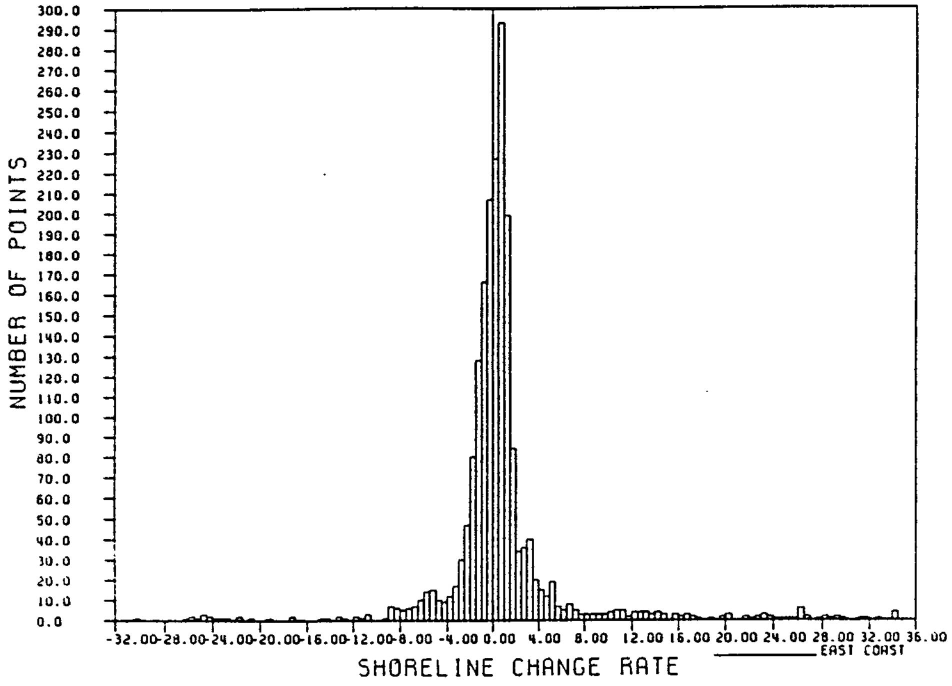

Figure A.1: East Coast of Florida: Histogram of long term shoreline change rates in feet per year.

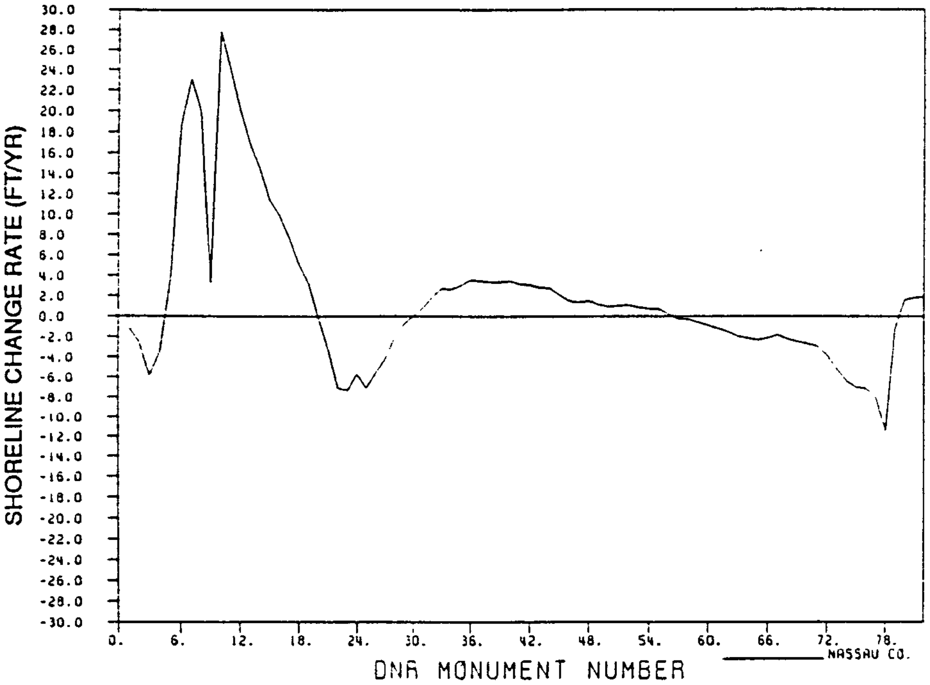

Figure A.2: Nassau County: Long term shoreline change rates in feet per year for the entire shoreline during the period 1857–1980.

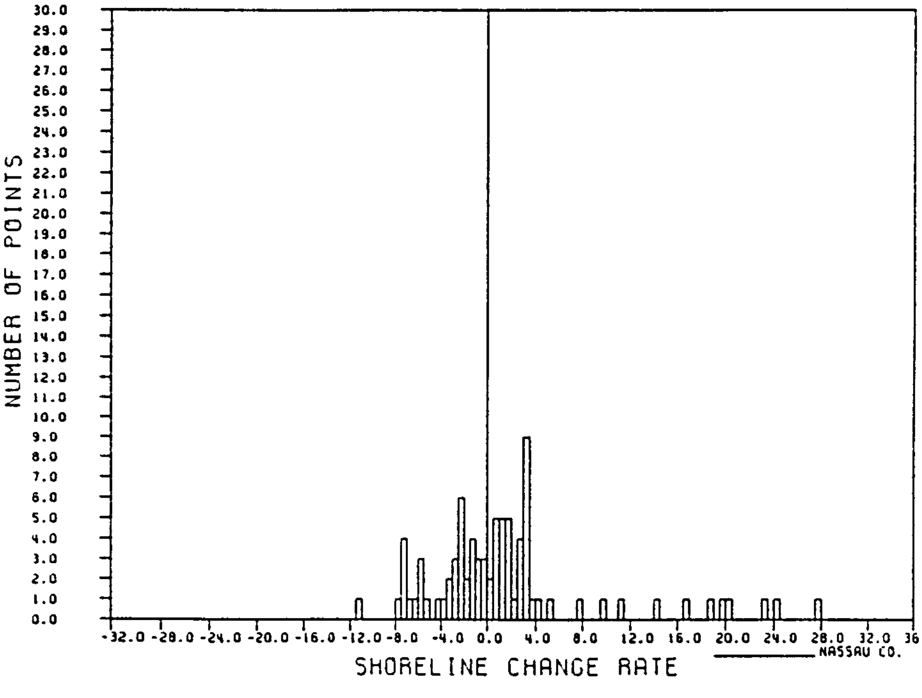

Figure A.3: Nassau County: Histogram of long term shoreline change rates in feet per year during the period 1857–1980.

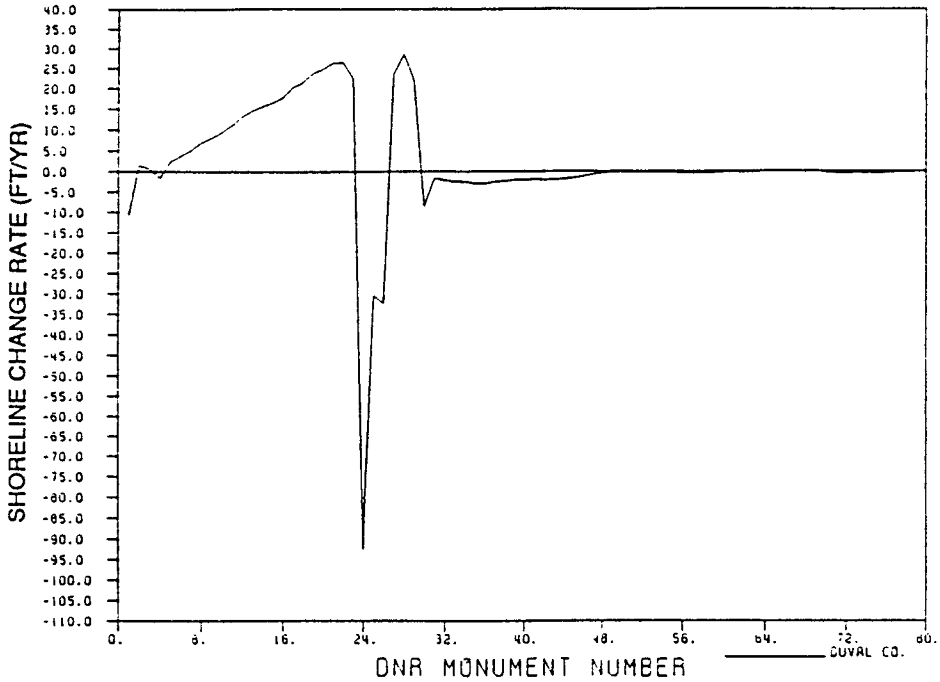

Figure A.4: Duval County: Long term shoreline change rates in feet per year for the entire shoreline during the period 1853–1979.

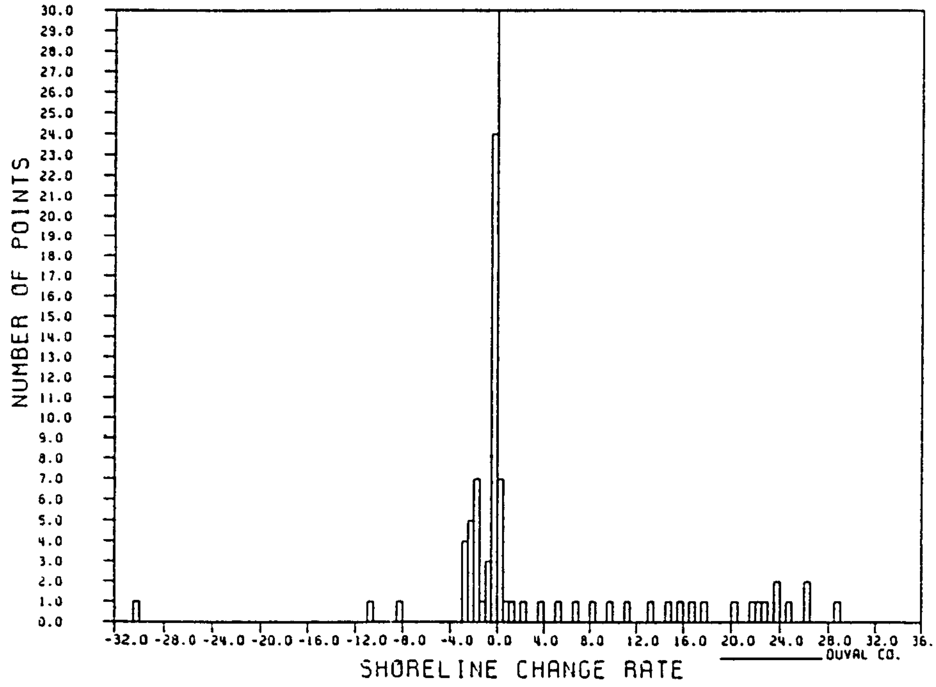

Figure A.5: Duval County: Histogram of long term shoreline change rates in feet per year during the period 1853–1979.

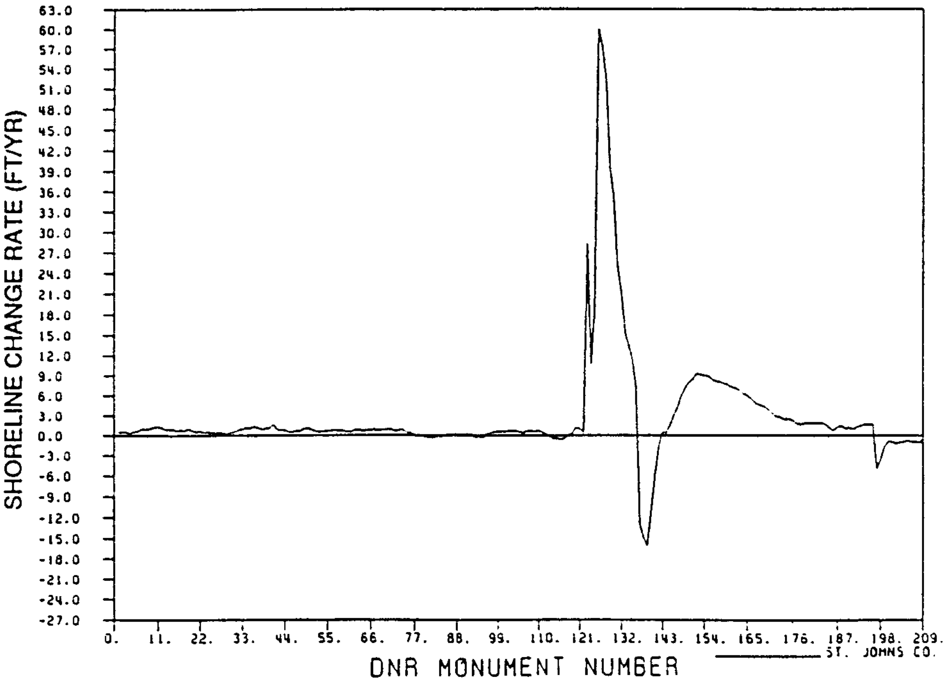

Figure A.6: St. Johns County: Long term shoreline change rates in feet per year for the entire shoreline during the period 1858–1986.

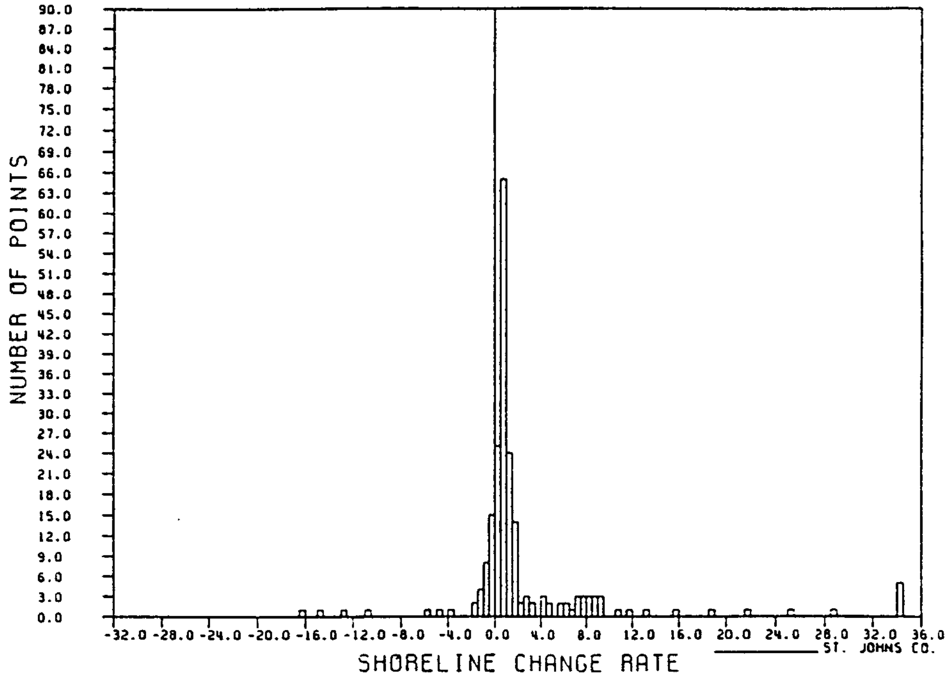

Figure A.7: St. Johns County: Histogram of long term shoreline change rates in feet per year during the period 1858–1986.

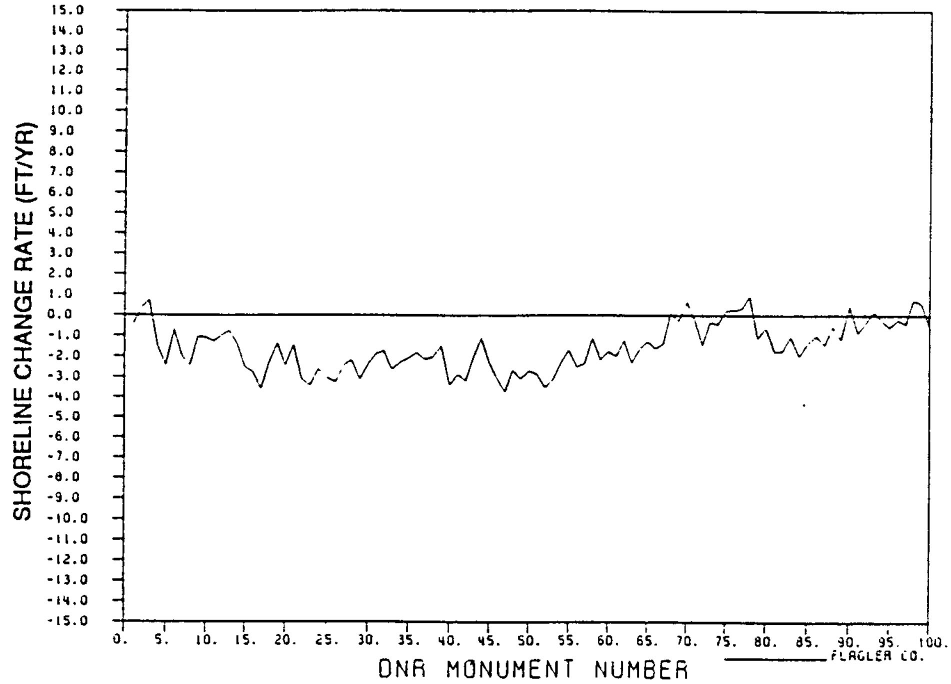

Figure A.8: Flagler County: Long term shoreline change rates in feet per year for the entire shoreline during the period 1872–1979.

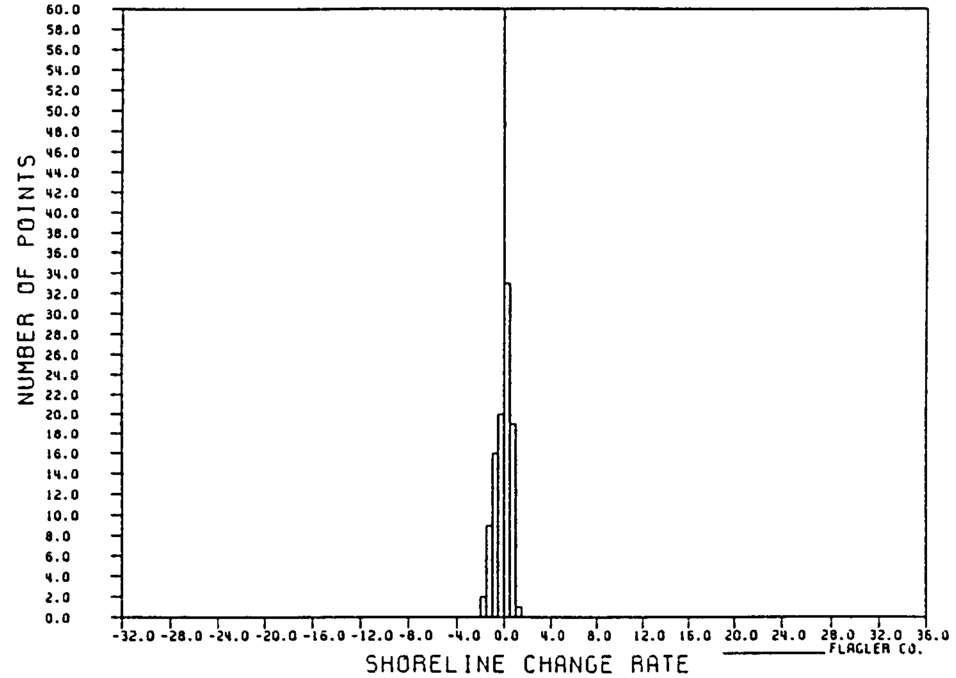

Figure A.9: Flagler County: Histogram of long term shoreline change rates in feet per year during the period 1872–1979.

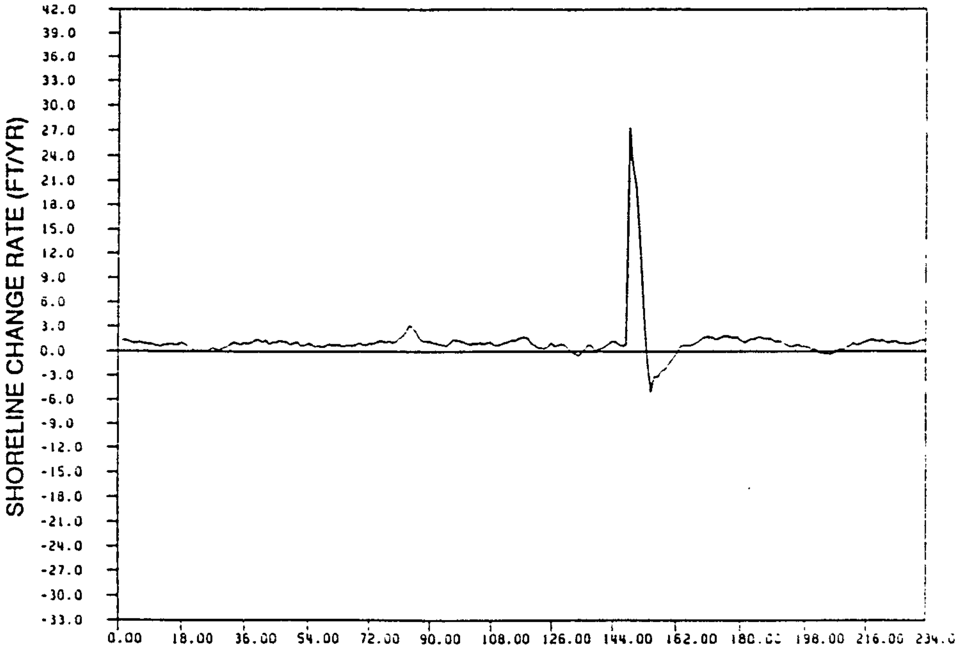

Figure A.10: Volusia County: Long term shoreline change rates in feet per year for the entire shoreline during the period 1873–1989.

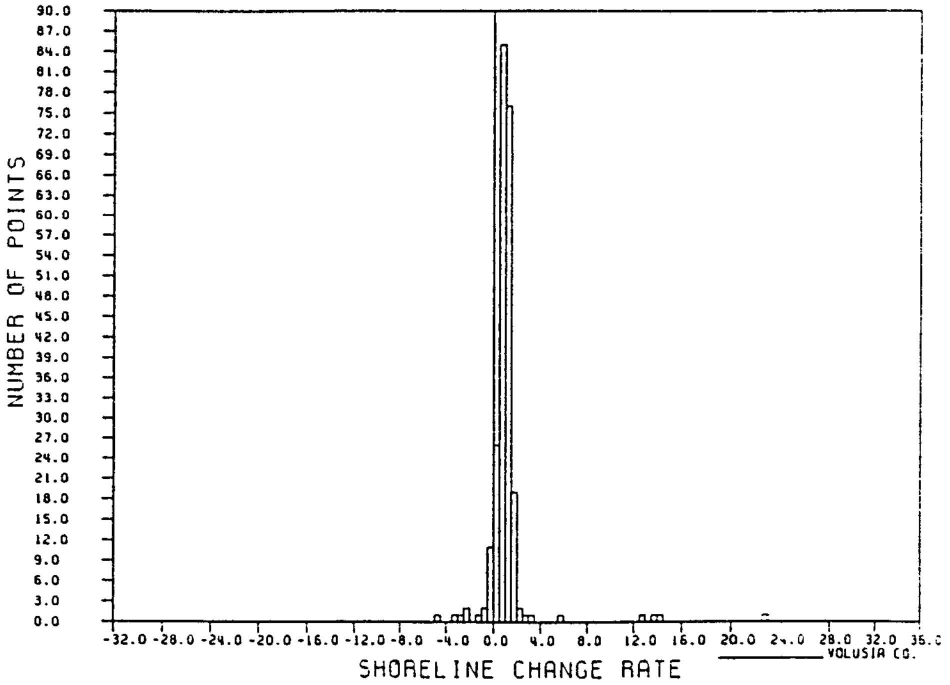

Figure A.11: Volusia County: Histogram of long term shoreline change rates in feet per year during the period 1873–1989.

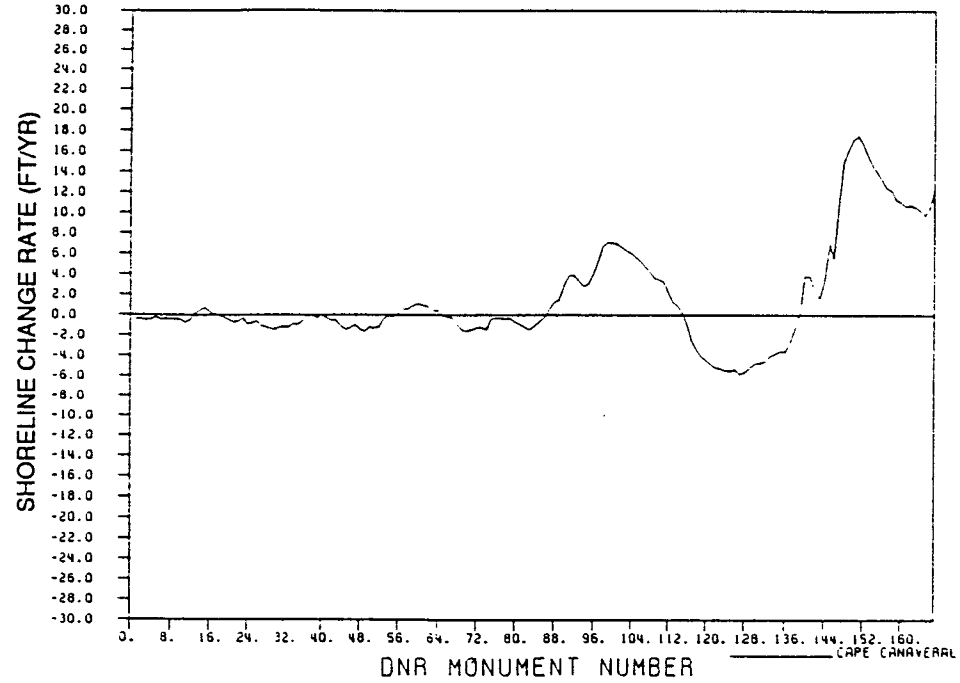

Figure A.12: Cape Canaveral: Long term shoreline change rates in feet per year for the entire shoreline during the period 1874–1976.

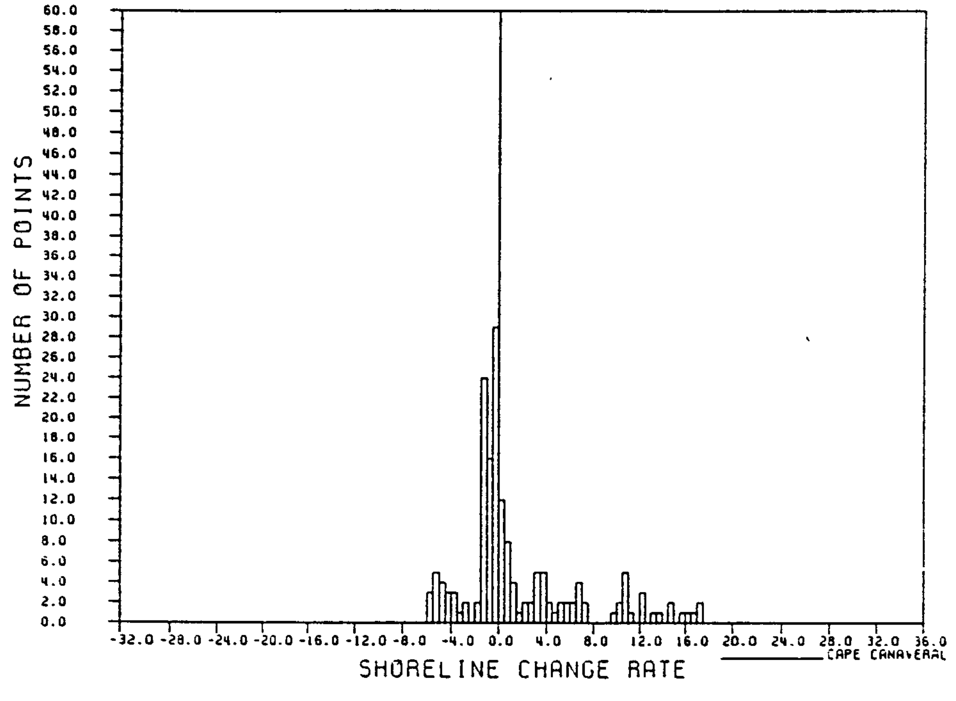

Figure A.13: Cape Canaveral: Histogram of long term shoreline change rates in feet per year during the period 1874–1976.

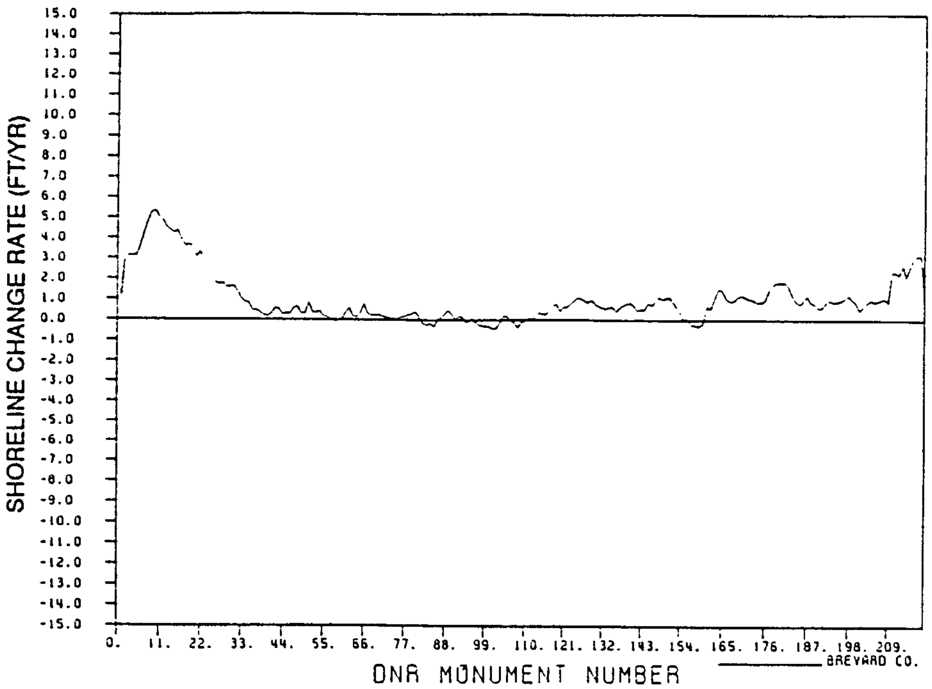

Figure A.14: Brevard County: Long term shoreline change rates in feet per year for the entire shoreline during the period 1877–1986.

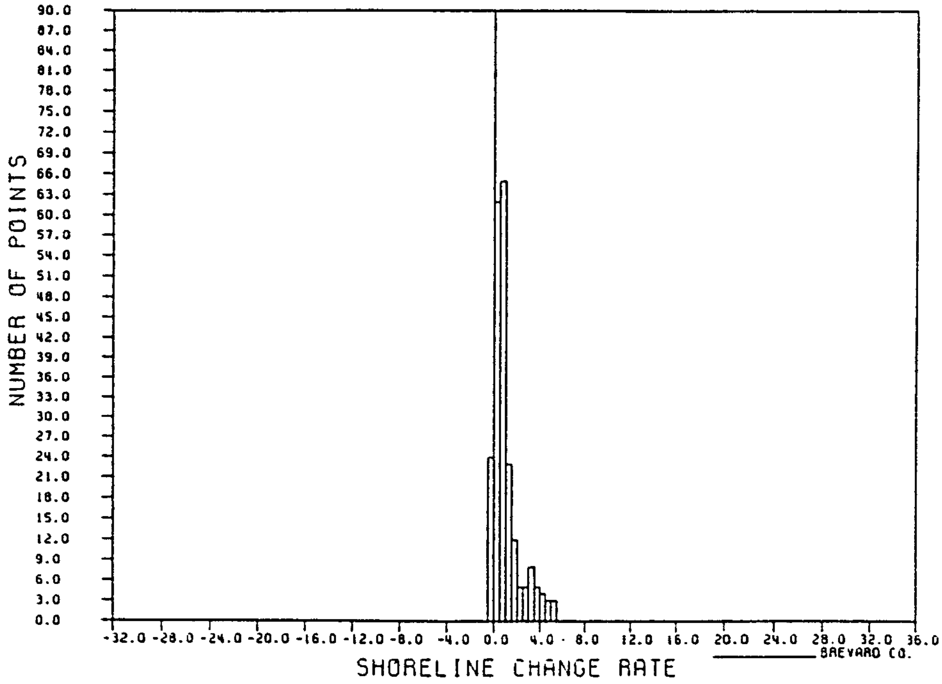

Figure A.15: Brevard County: Histogram of long term shoreline change rates in feet per year during the period 1877–1986.

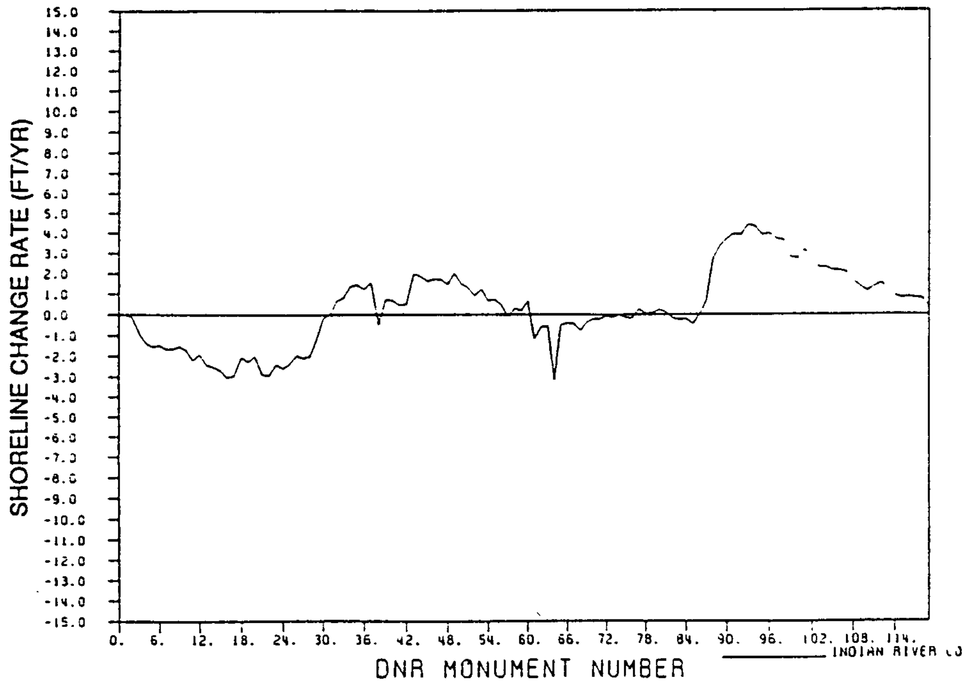

Figure A.16: Indian River County: Long term shoreline change rates in feet per year for the entire shoreline during the period 1882- -1986.

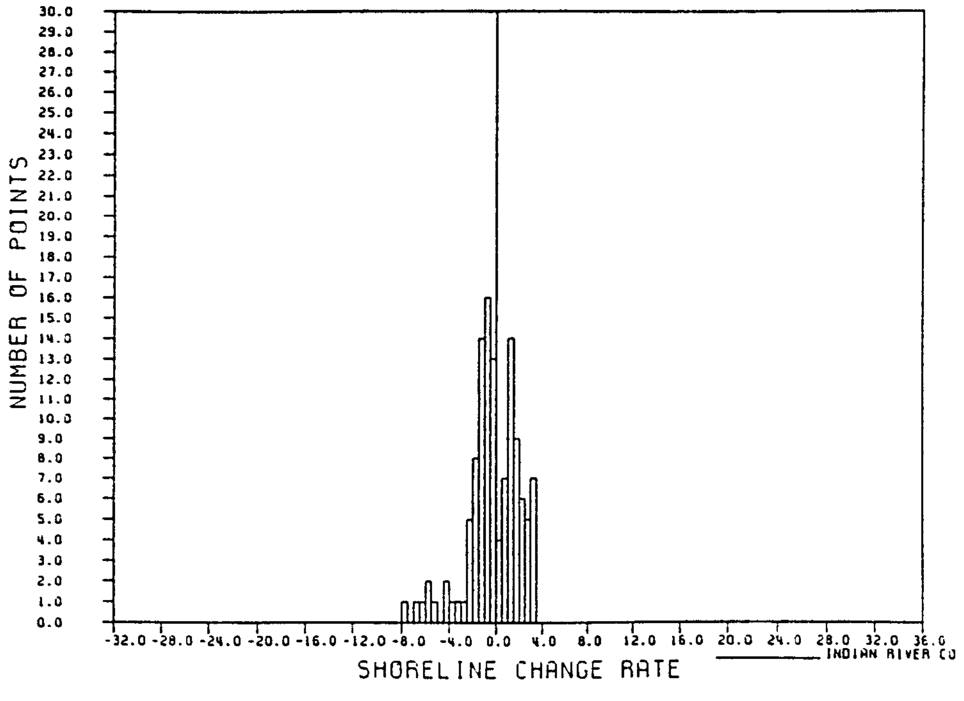

Figure A.17: Indian River County: Histogram of long term shoreline change rates in feet per year during the period 1882–1986.

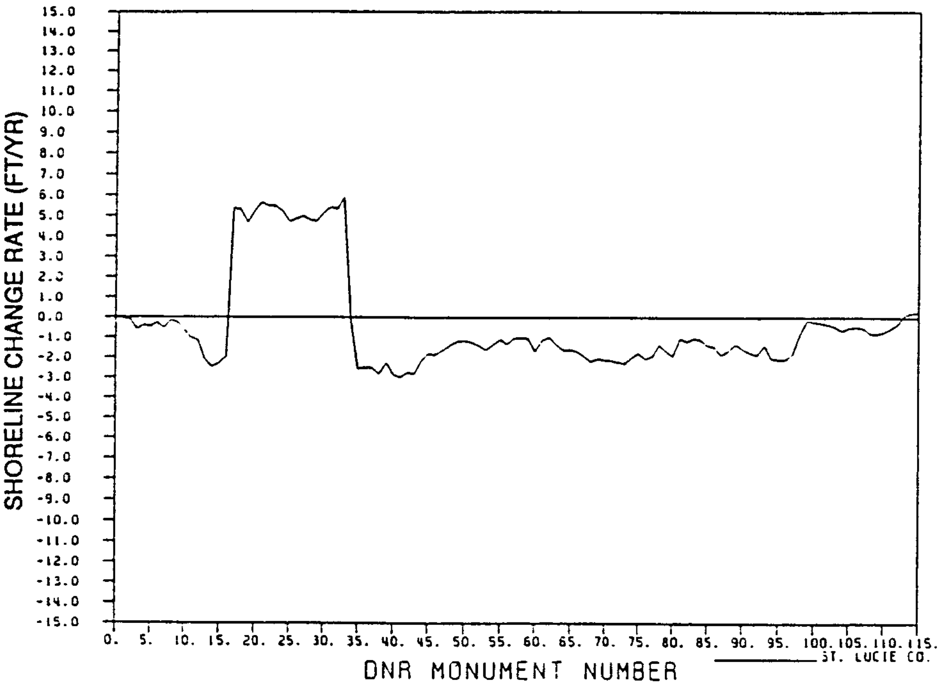

Figure A.18: St. Lucie County: Long term shoreline change rates in feet per year for the entire shoreline during the period 1883–1987.

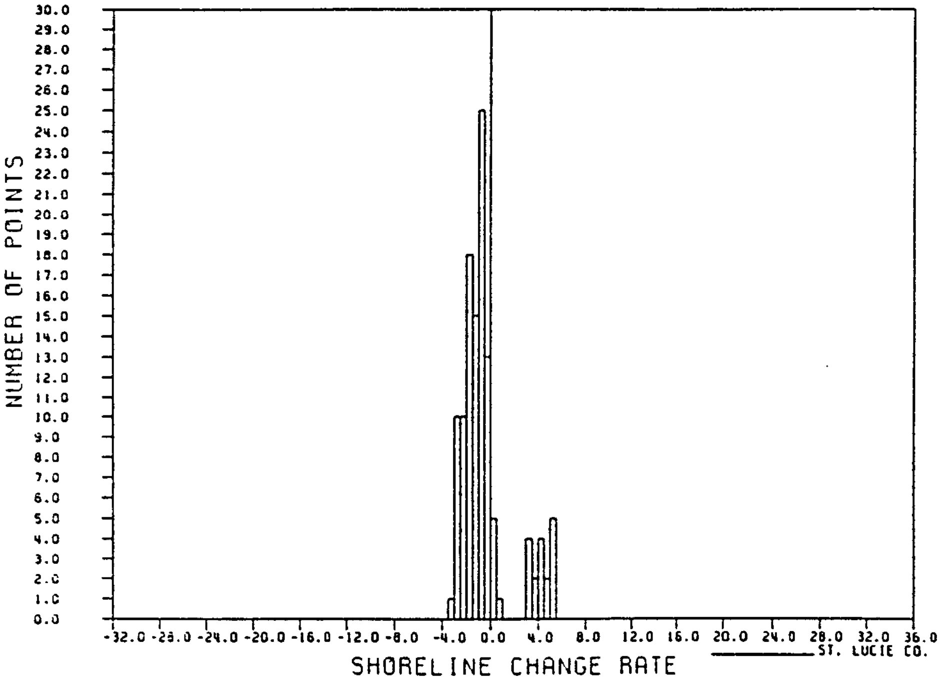

Figure A.19: St. Lucie County: Histogram of long term shoreline change rates in feet per year during the period 1883–1987.

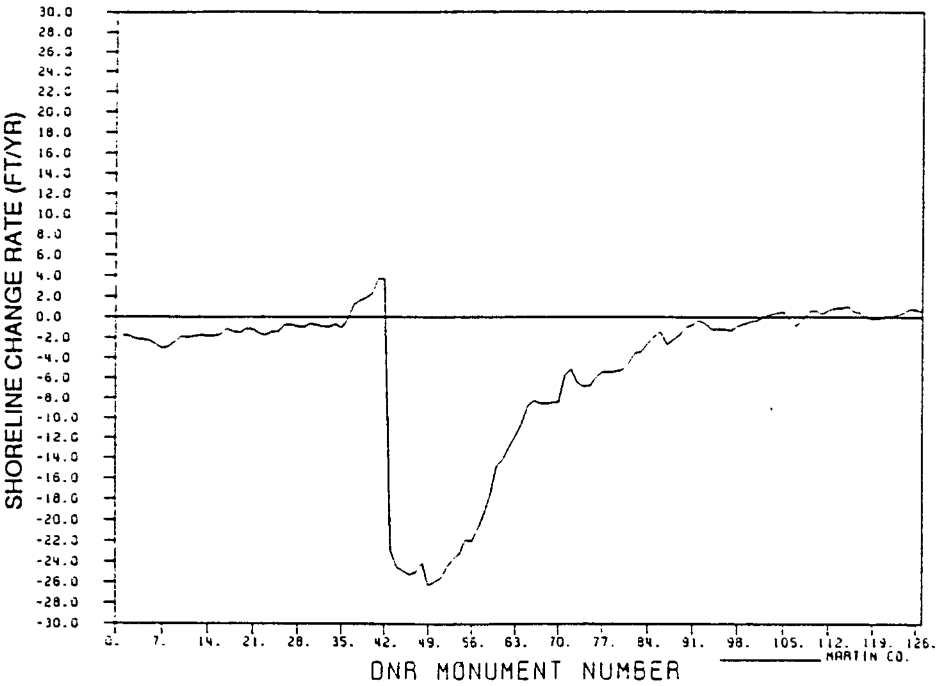

Figure A.20: Martin County: Long term shoreline change rates in feet per year for the entire shoreline during the period 1883–1984.

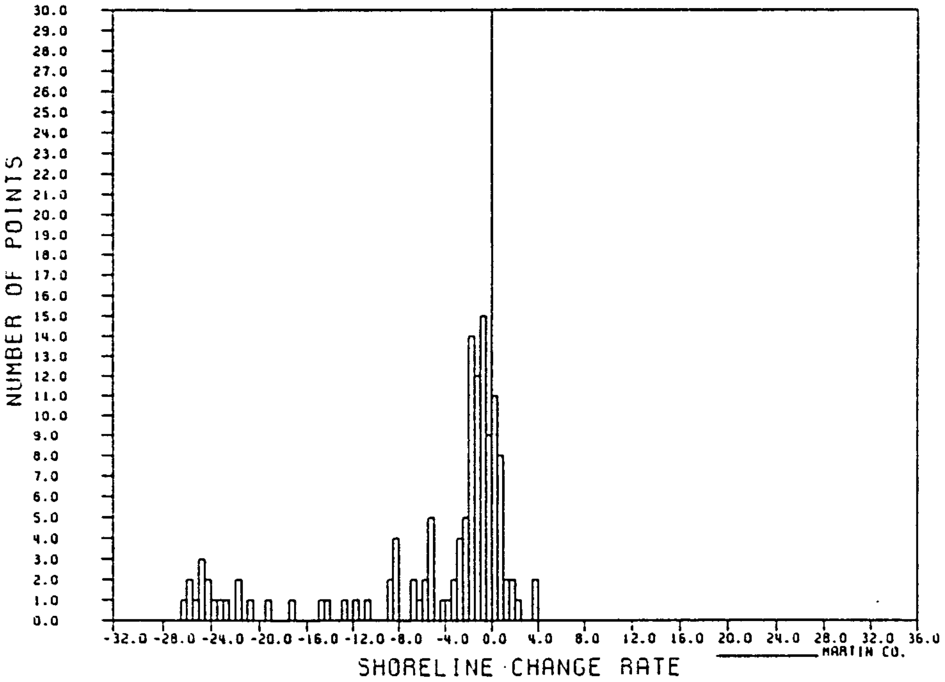

Figure A.21: Martin County: Histogram of long term shoreline change rates in feet per year during the period 1883–1984.

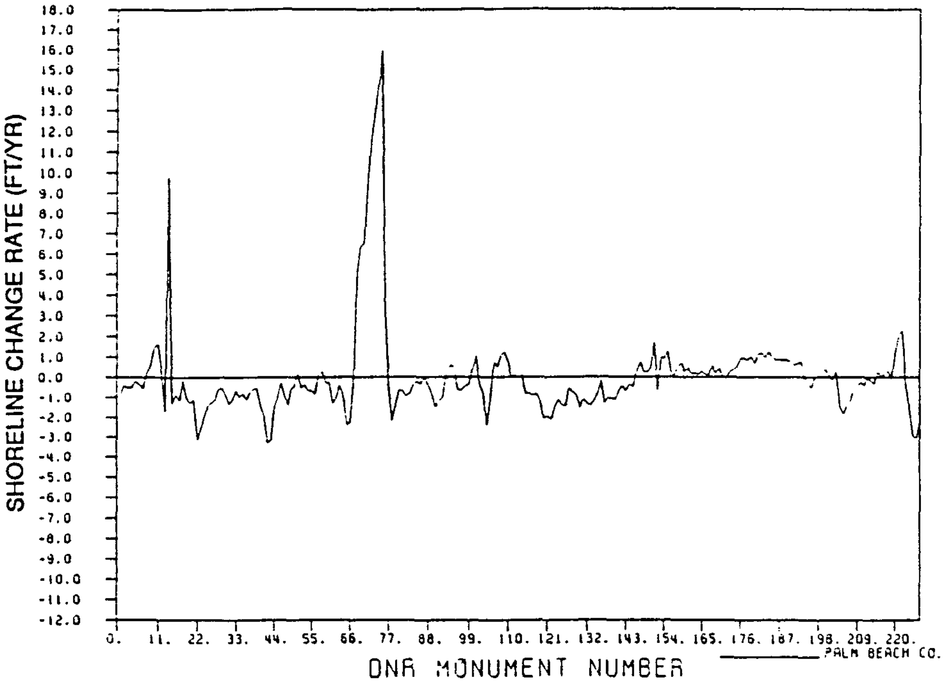

Figure A.22: Palm Beach County: Long term shoreline change rates in feet per year for the entire shoreline during the period 1883– 1980.

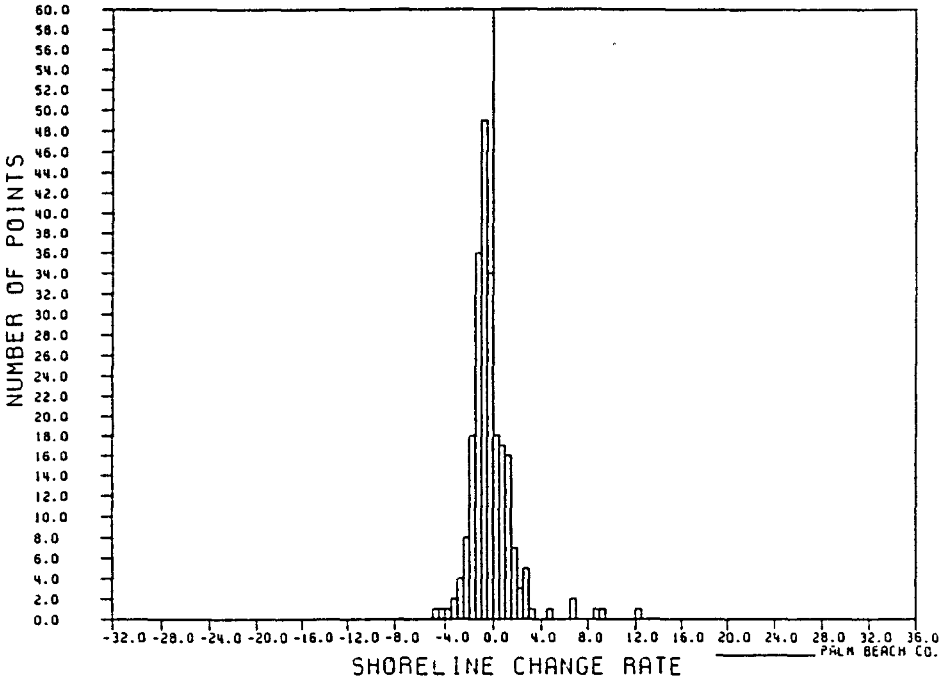

Figure A.23: Palm Beach County: Histogram of long term shoreline change rates in feet per year during the period 1883–1980.

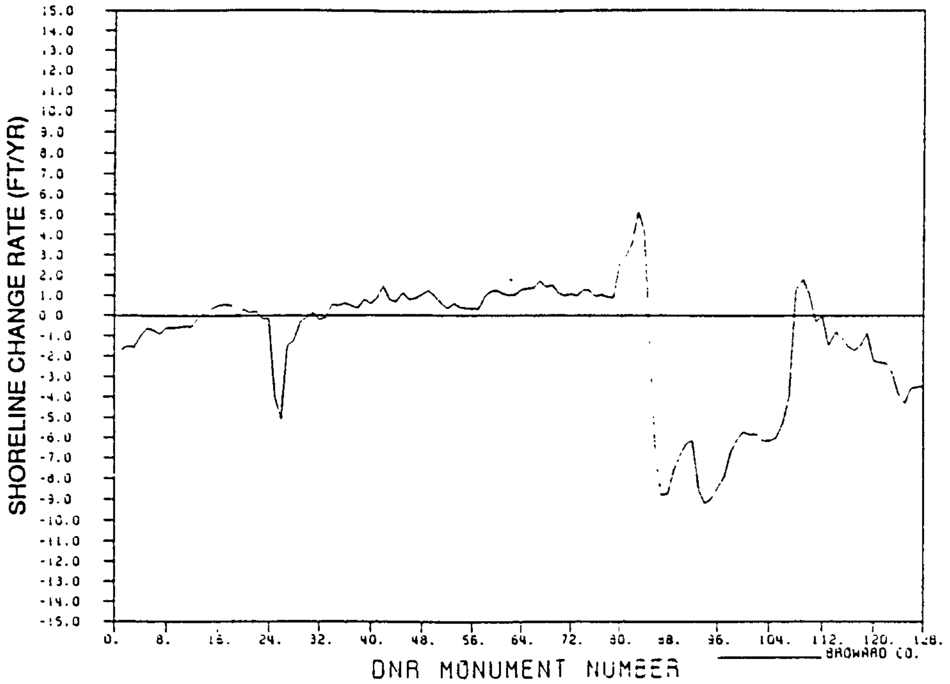

Figure A.24: Broward County: Long term shoreline change rates in feet per year for the entire shoreline during the period 1883–1985.

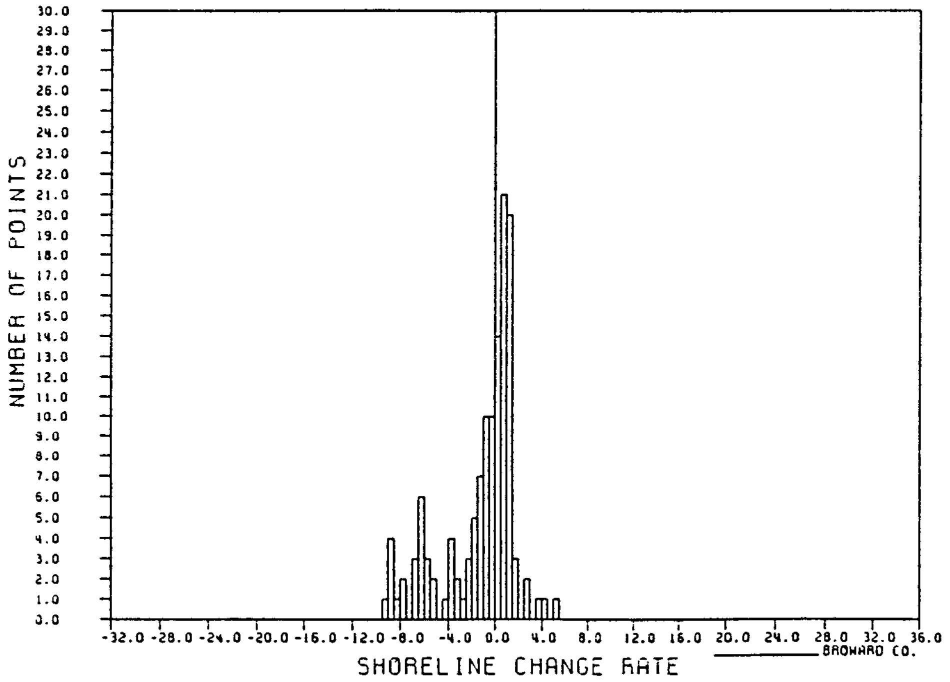

Figure A.25: Broward County: Histogram of long term shoreline change rates in feet per year during the period 1883–1985.

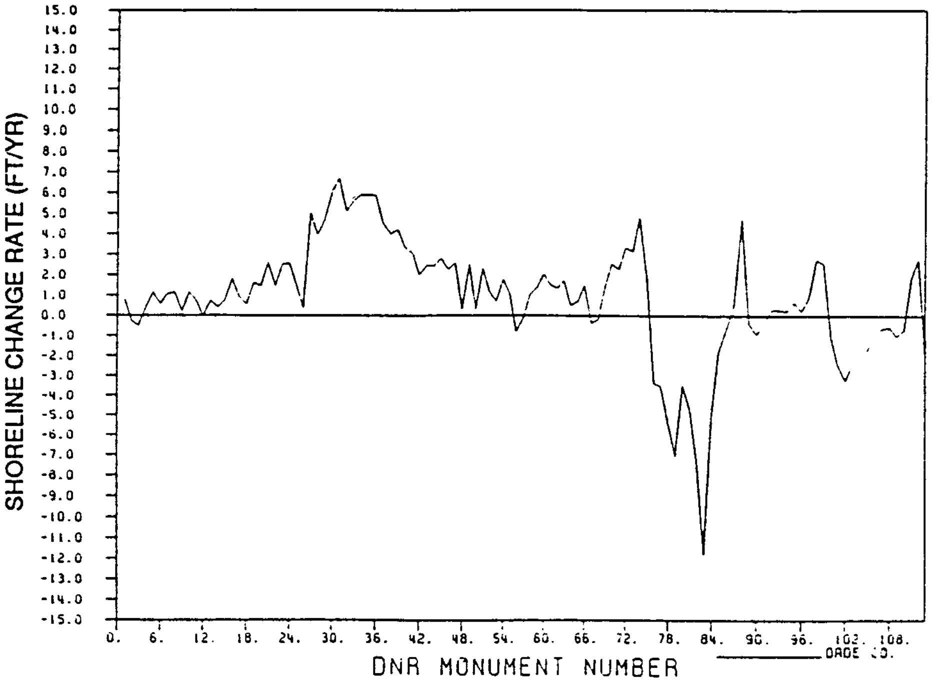

Figure A.26: Dade County: Long term shoreline change rates in feet per year for the entire shoreline during the period 1851–1986.

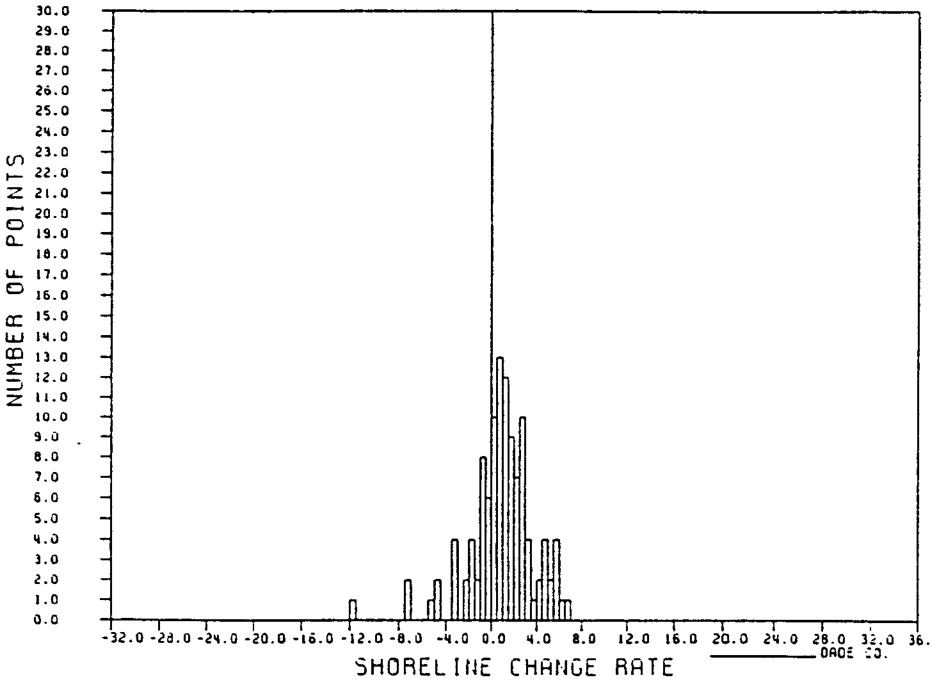

Figure A.27: Dade County: Histogram of long term shoreline change rates in feet per year during the period 1851–1986.

A.3 West Coast Counties

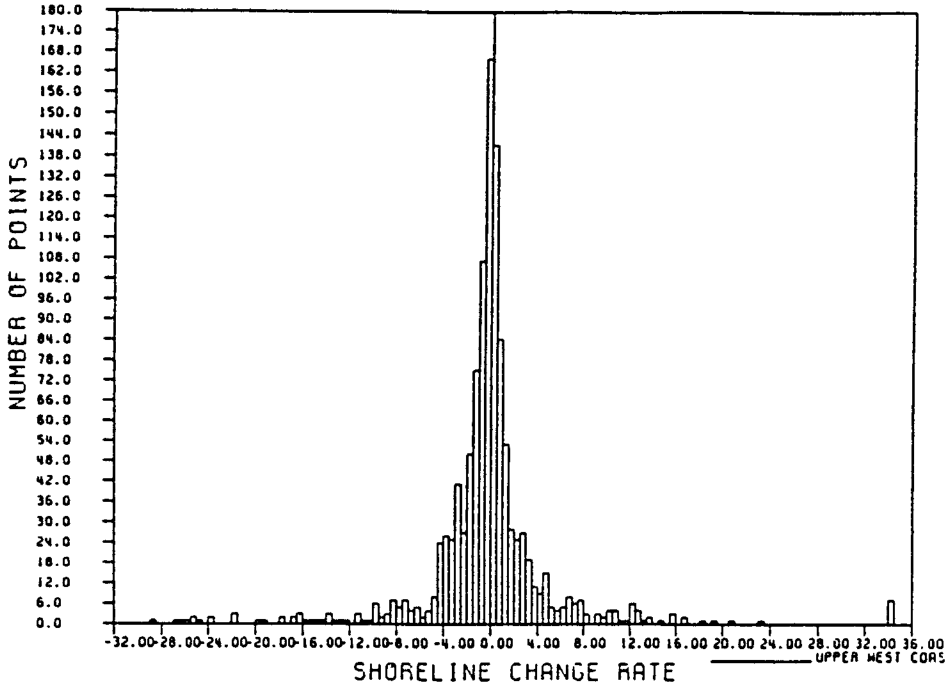

Figure A.28: Upper West Coast of Florida: Histogram of long term shoreline change rates in feet per year.

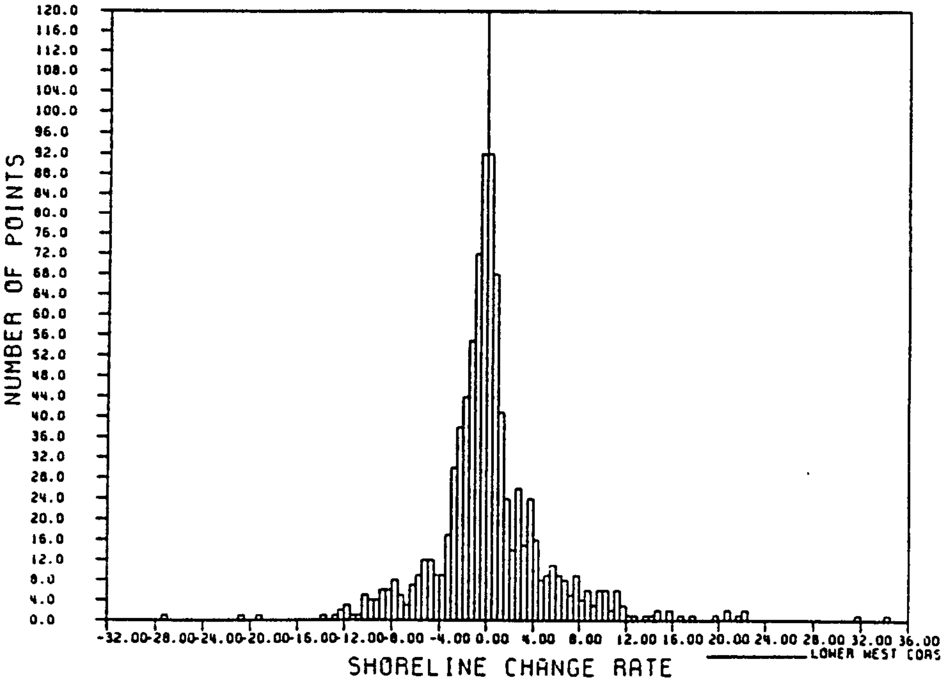

Figure A.29: Lower West Coast of Florida: Histogram of long term shoreline change rates in feet per year.

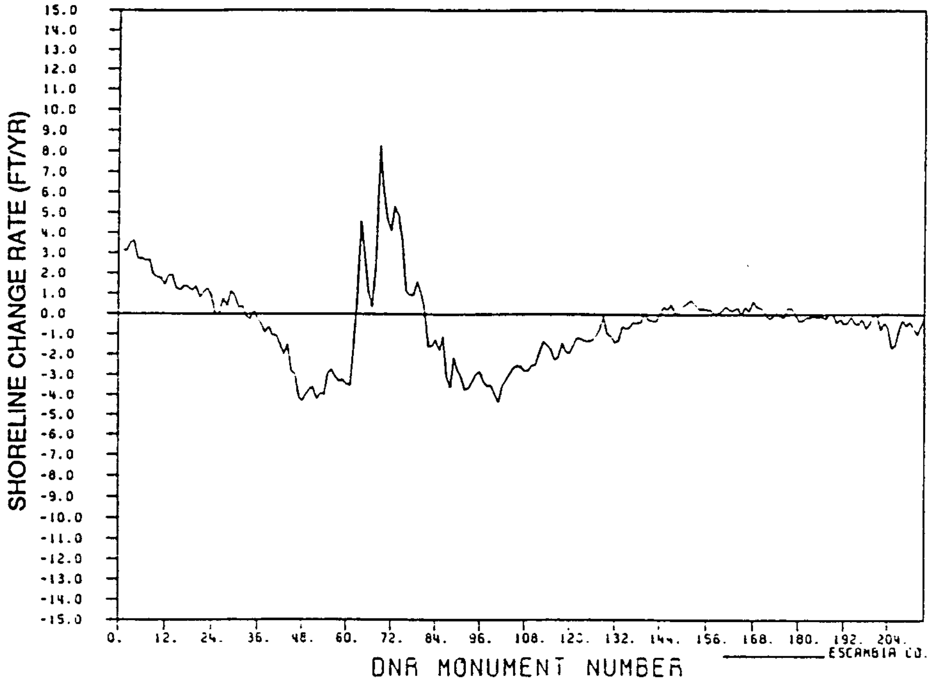

Figure A.30: Escambia County: Long term shoreline change rates in feet per year for the entire shoreline during the period 1856–1978.

Figure A.31: Escambia County: Histogram of long term shoreline change rates in feet per year during the period 1856–1978.

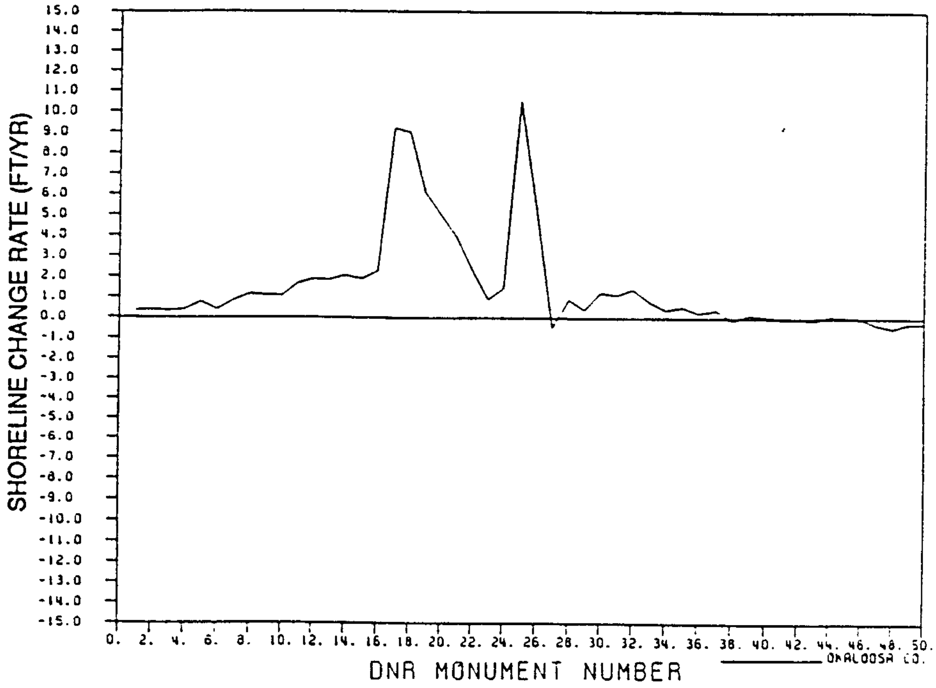

Figure A.32: Okaloosa County: Long term shoreline change rates in feet per year for the entire shoreline during the period 1871–1987.

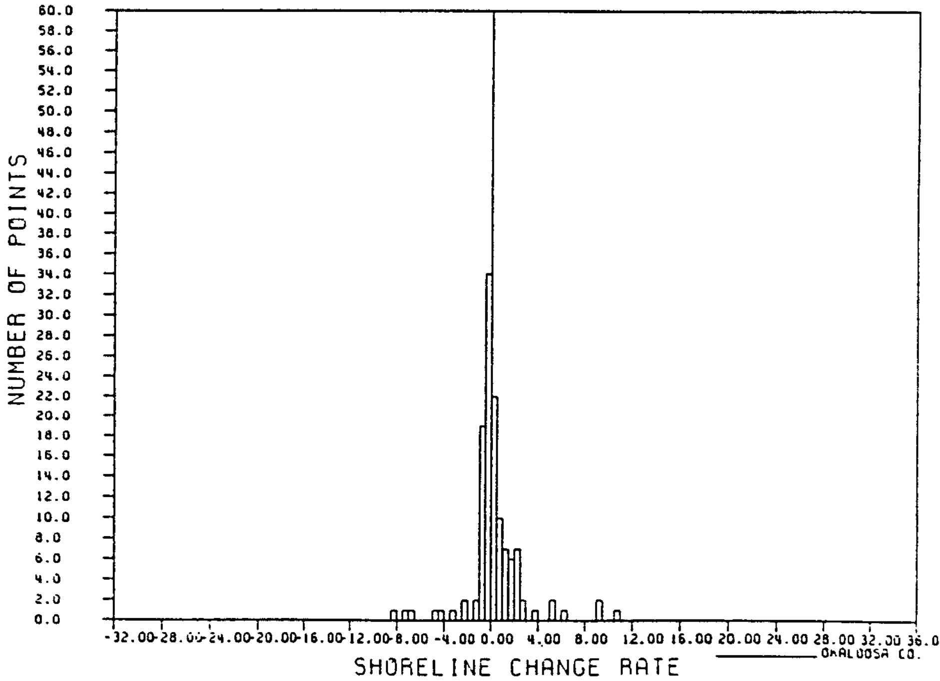

Figure A.33: Okaloosa County: Histogram of long term shoreline change rates in feet per year during the period 1871–1987.

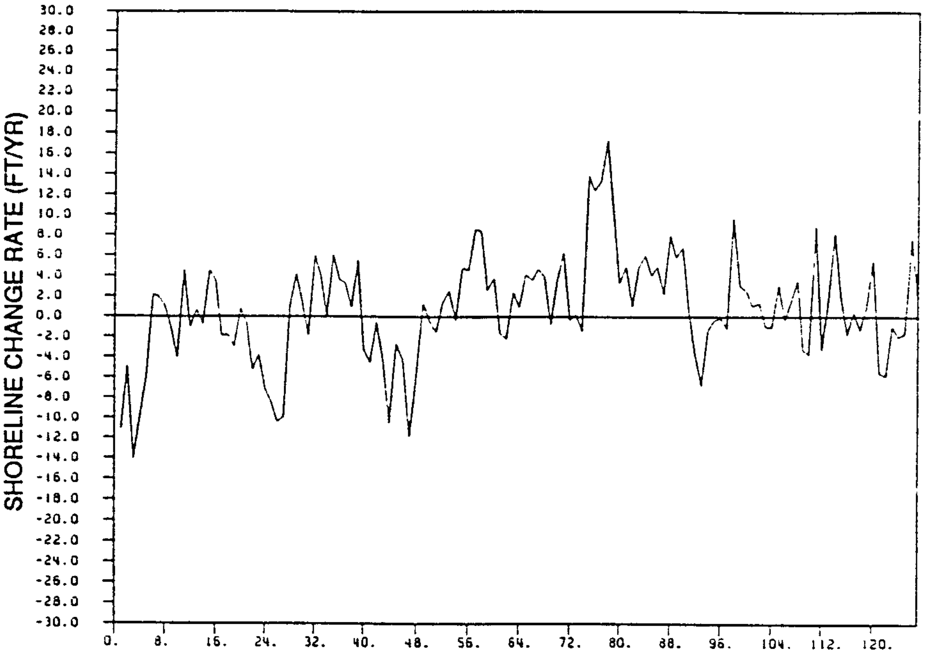

Figure A.34: Walton County: Long term shoreline change rates in feet per year for the entire shoreline during the period 1872–1977.

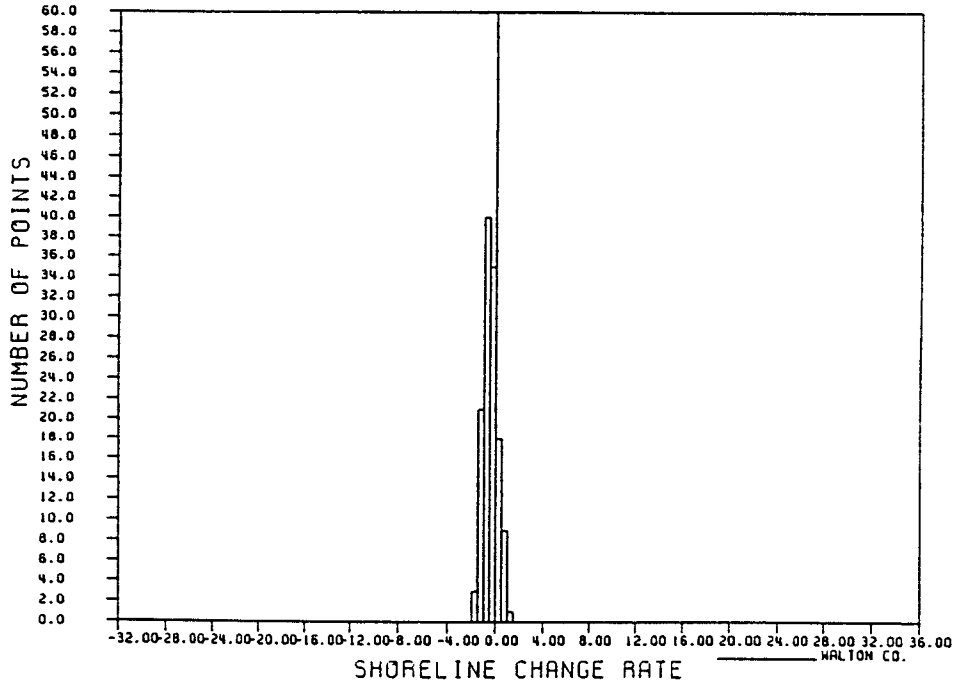

Figure A.35: Walton County: Histogram of long term shoreline change rates in feet per year during the period 1872–1977.

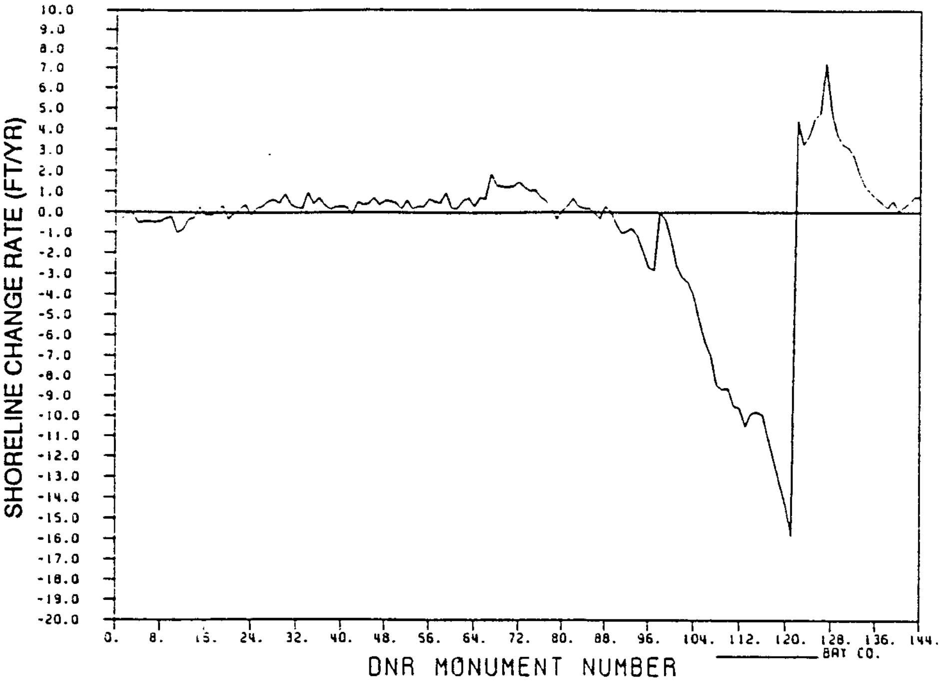

Figure A.36: Bay County: Long term shoreline change rates in feet per year for the entire shoreline during the period 1855–1977.

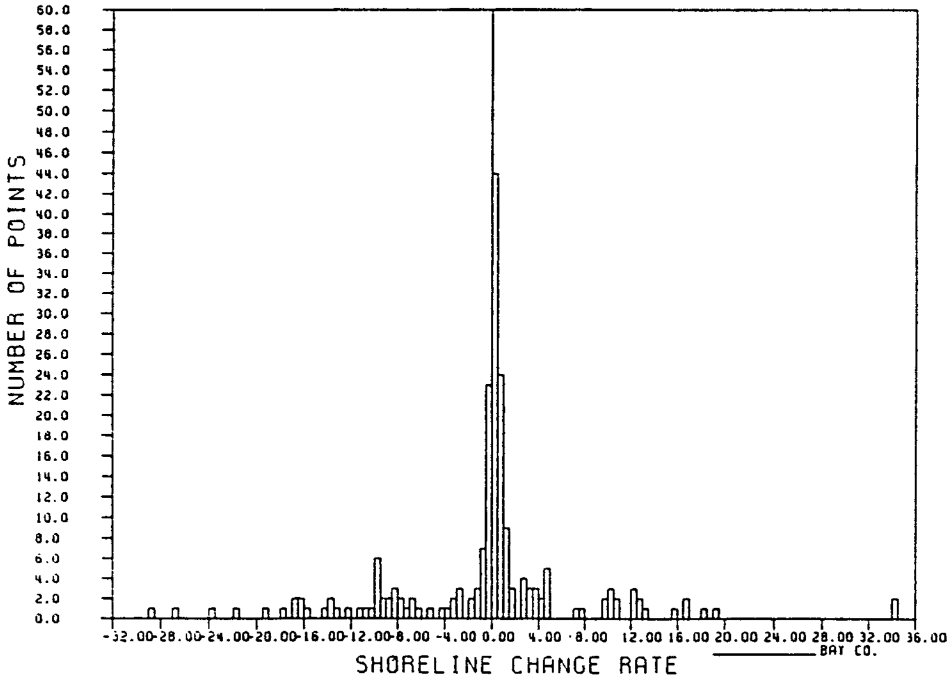

Figure A.37: Bay County: Histogram of long term shoreline change rates in feet per year during the period 1855–1977.

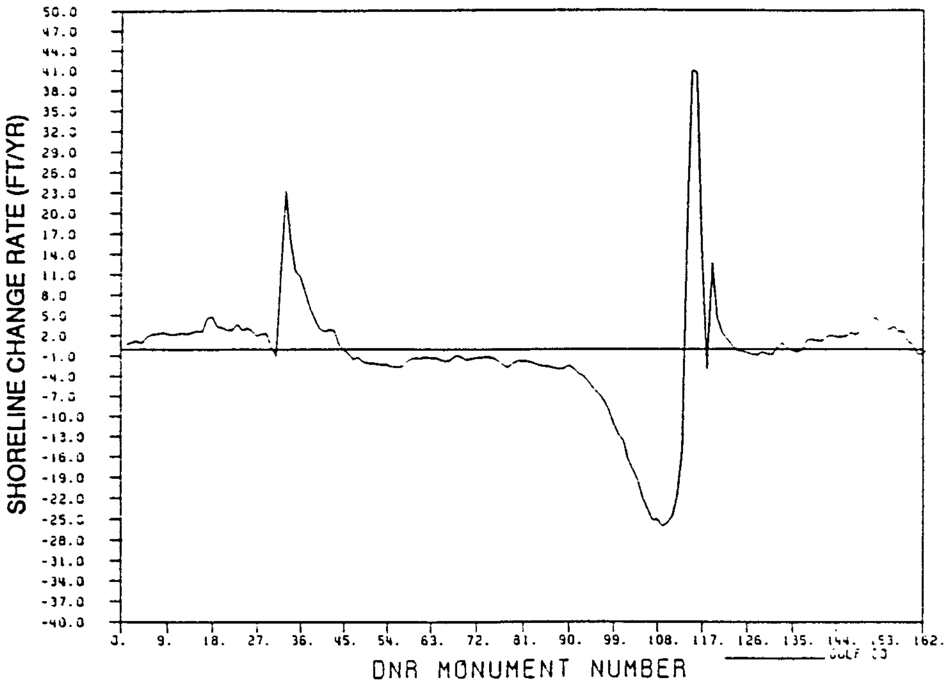

Figure A.38: Gulf County: Long term shoreline change rates in feet per year for the entire shoreline during the period 1857–1979.

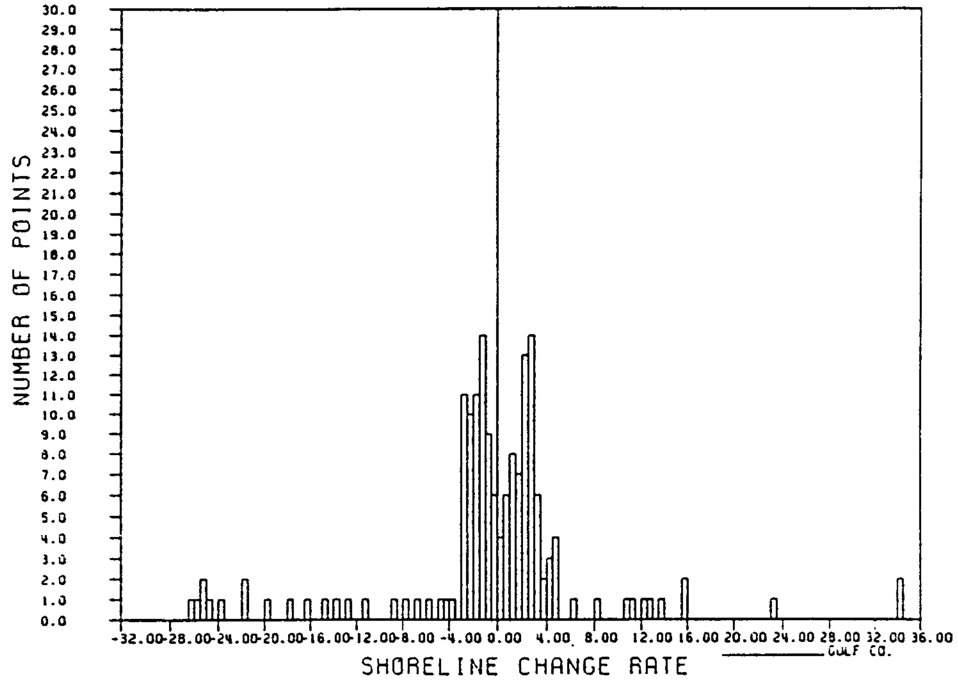

Figure A.39: Gulf County: Histogram of long term shoreline change rates in feet per year during the period 1857–1979.

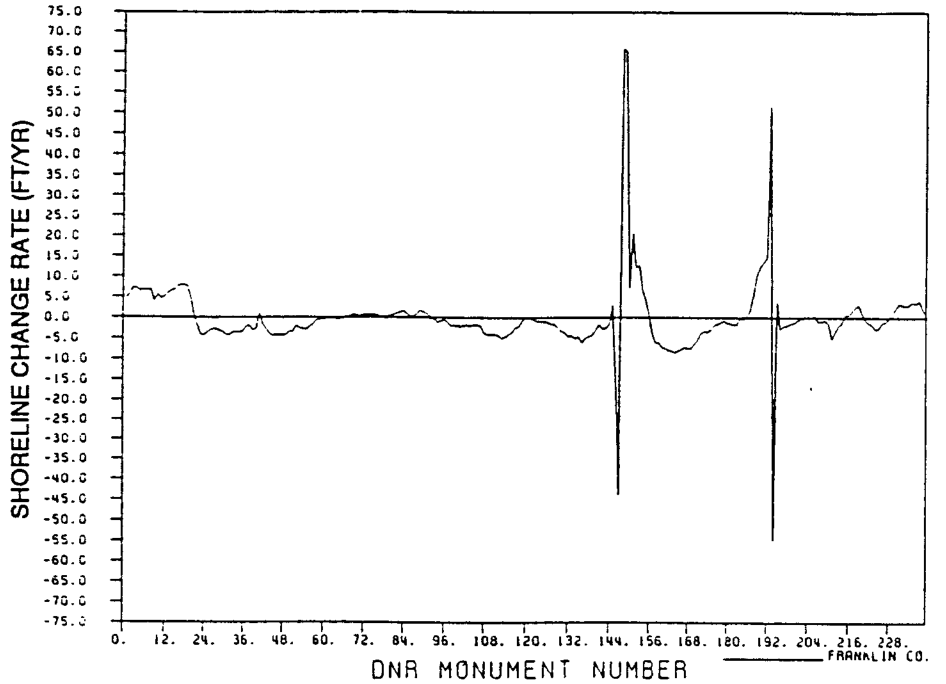

Figure A.40: Franklin County: Long term shoreline change rates in feet per year for the entire shoreline during the period 1856–1979.

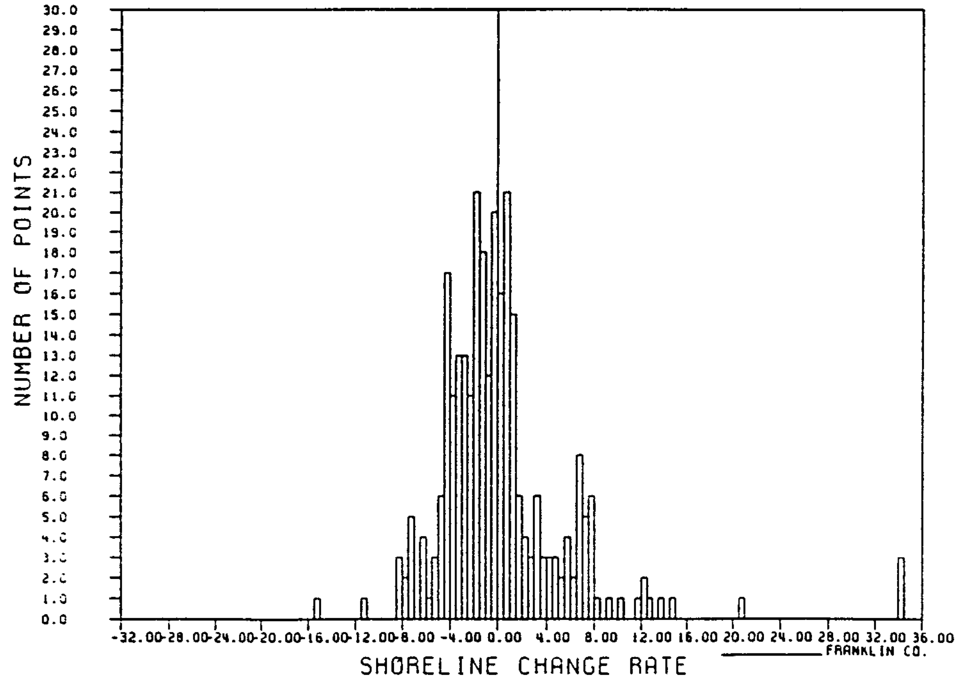

Figure A.41: Franklin County: Histogram of long term shoreline change rates in feet per year during the period 1856–1979.

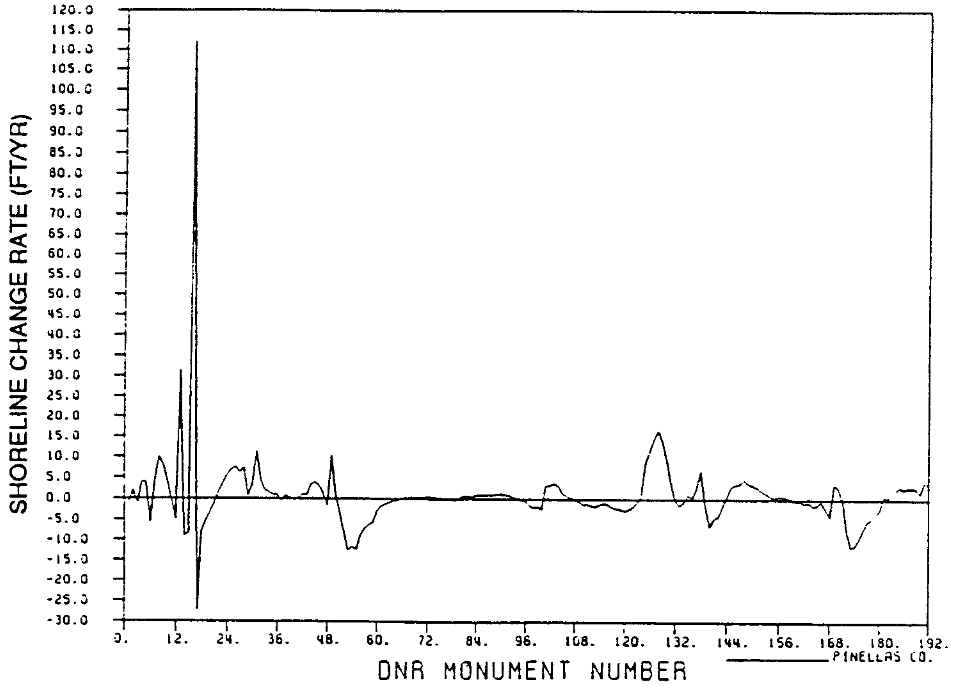

Figure A.42: Pinellas County: Long term shoreline change rates in feet per year for the entire shoreline during the period 1873–1987.

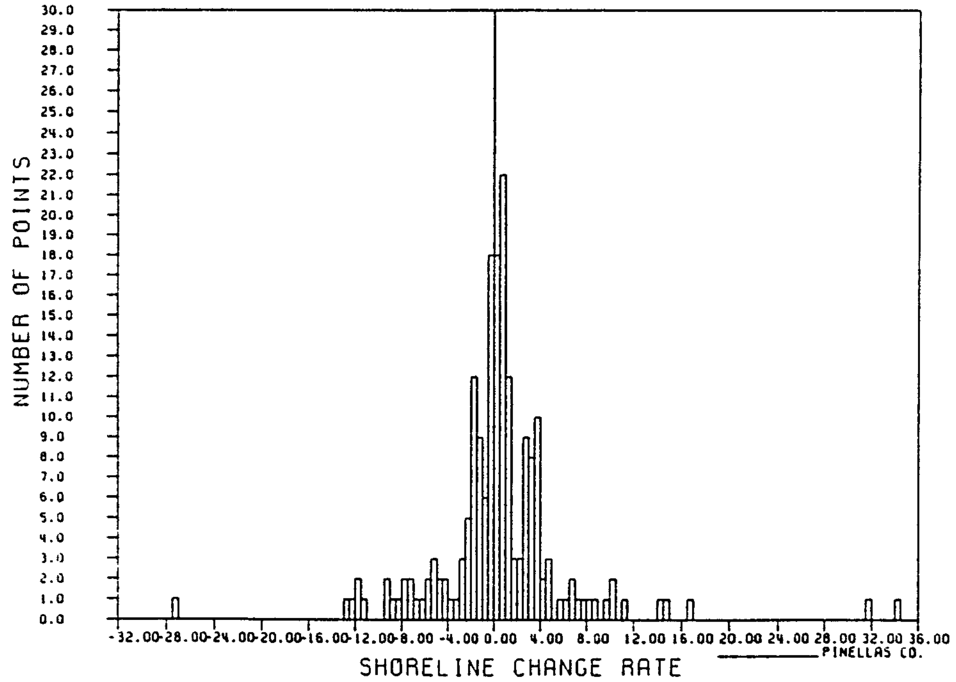

Figure A.43: Pinellas County: Histogram of long term shoreline change rates in feet per year during the period 1873–1987.

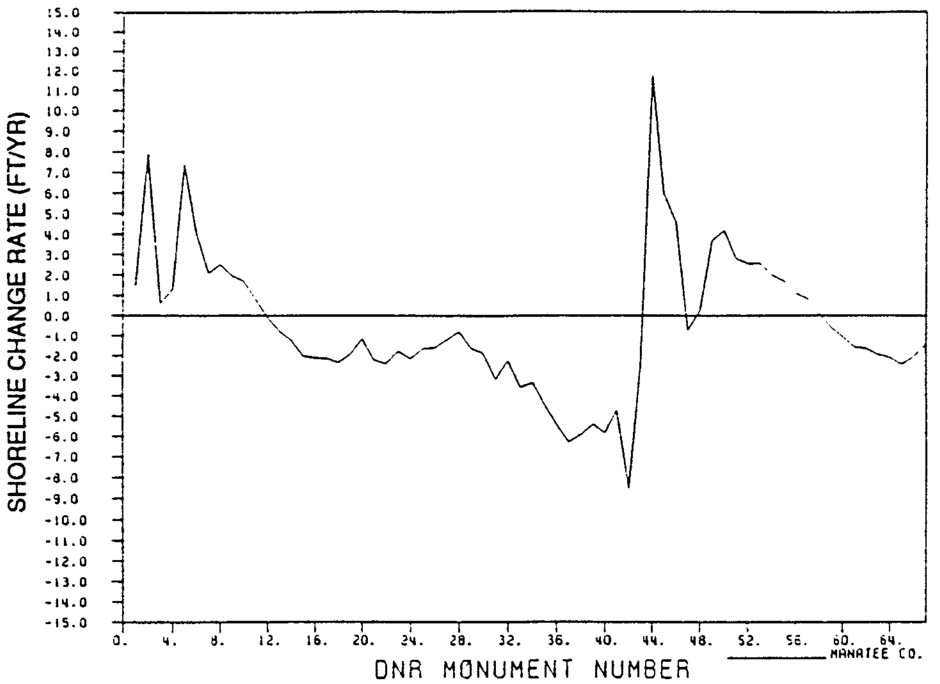

Figure A.44: Manatee County: Long term shoreline change rates in feet per year for the entire shoreline during the period 1874–1986.

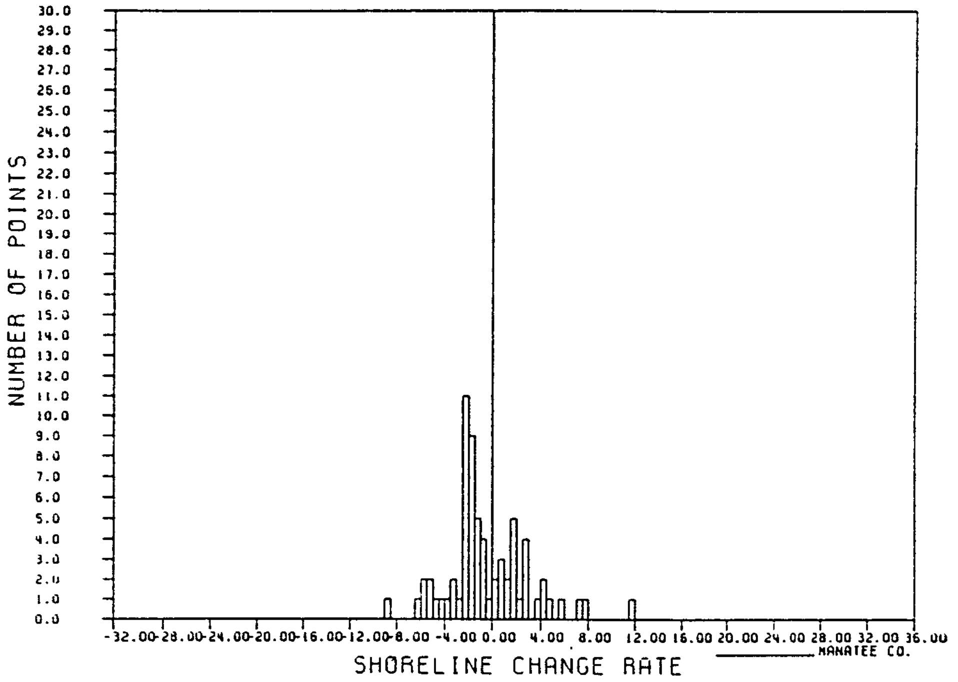

Figure A.45: Manatee County: Histogram of long term shoreline change rates in feet per year during the period 1874–1986.

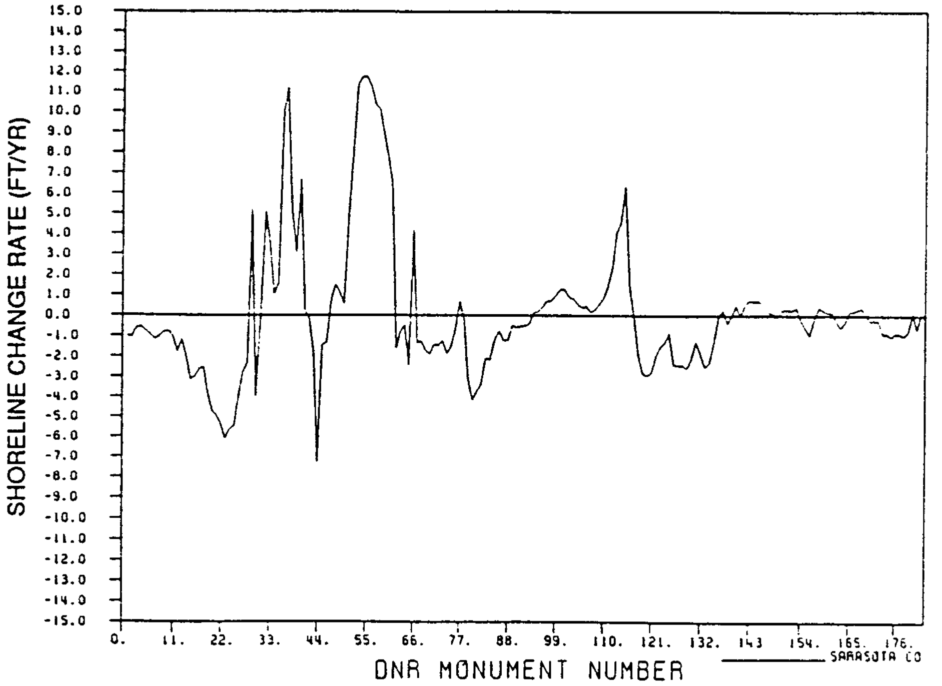

Figure A.46: Sarasota County: Long term shoreline change rates in feet per year for the entire shoreline during the period 1883–1987.

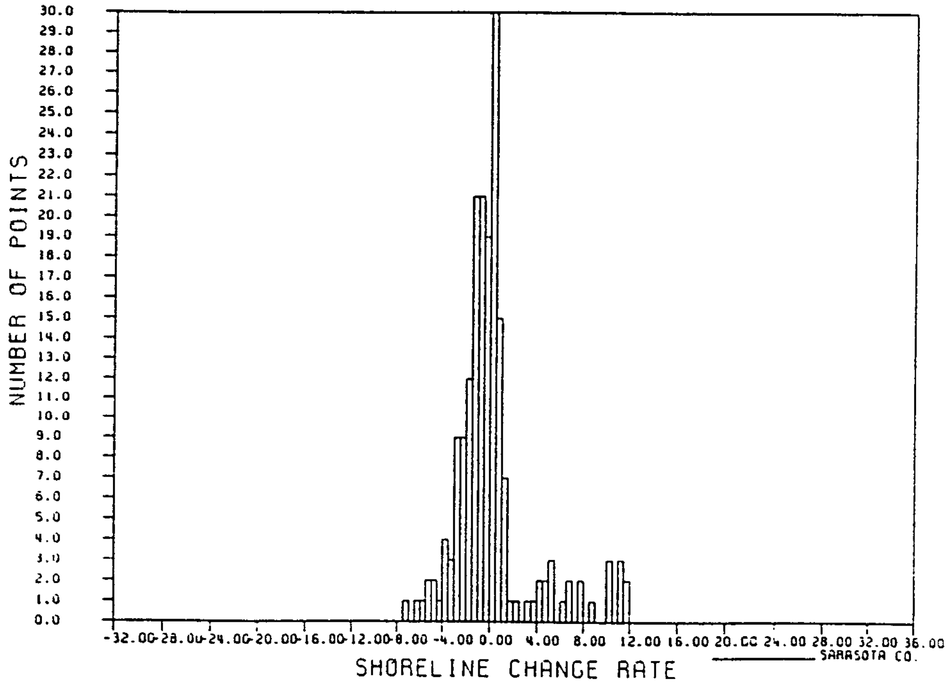

Figure A.47: Sarasota County: Histogram of long term shoreline change rates in feet per year during the period 1883–1987.

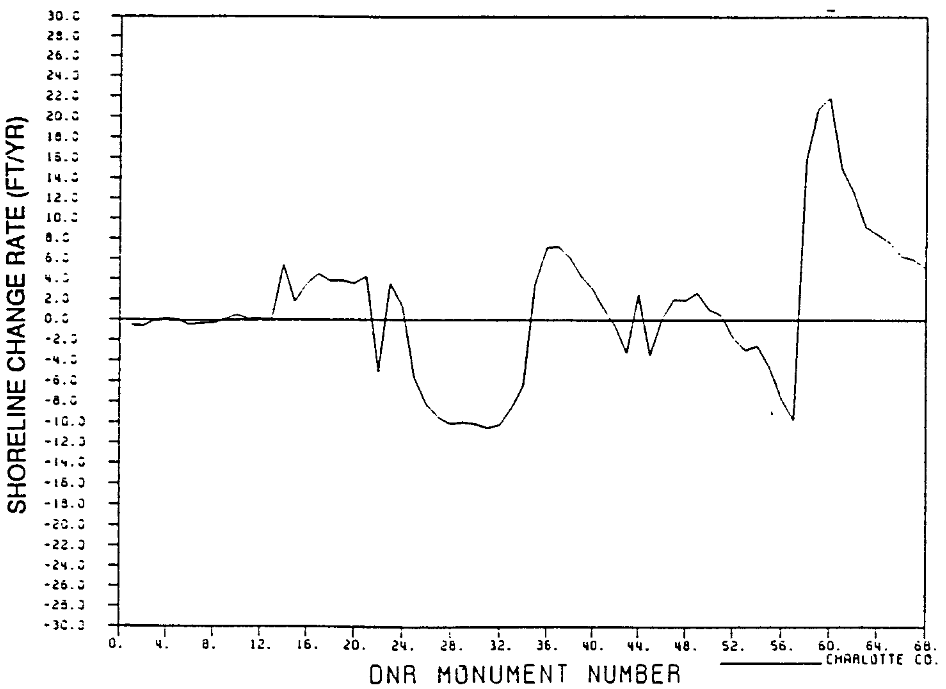

Figure A.48: Charlotte County: Long term shoreline change rates in feet per year for the entire shoreline during the period 1860–1988.

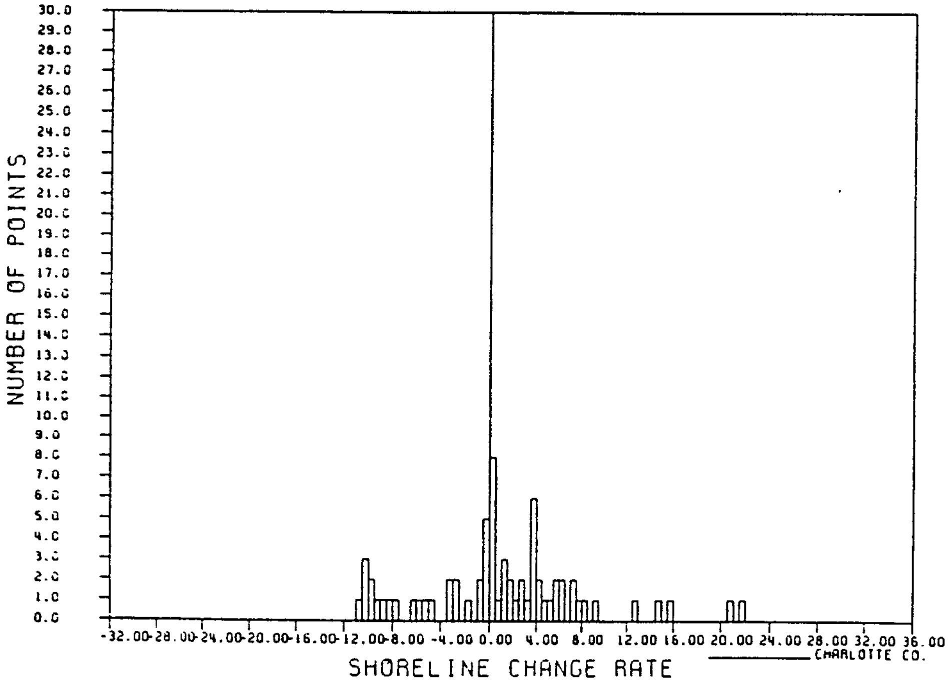

Figure A.49: Charlotte County: Histogram of long term shoreline change rates in feet per year during the period 1860–1988.

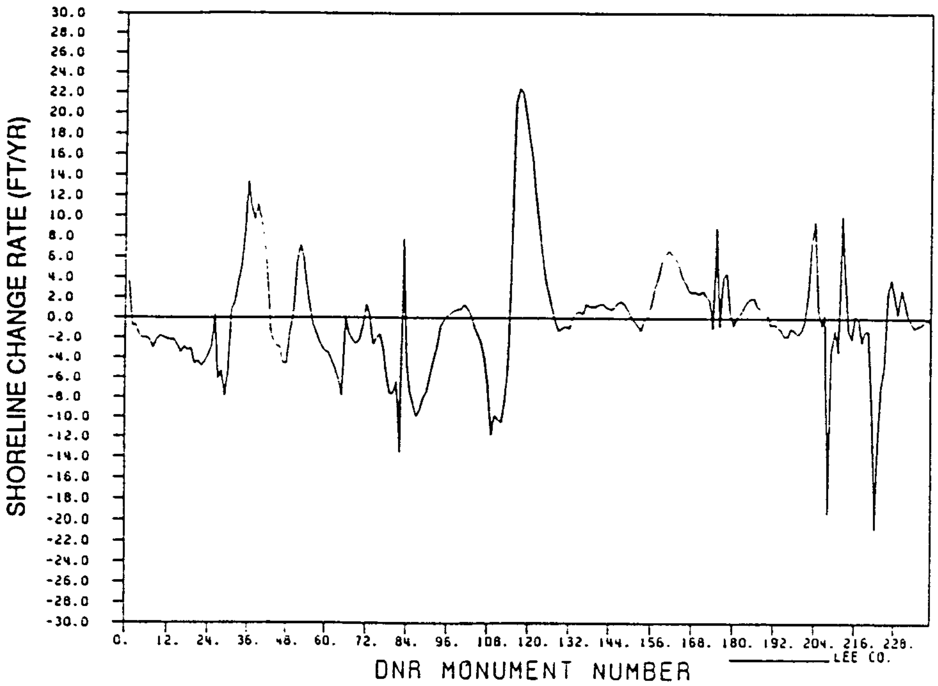

Figure A.50: Lee County: Long term shoreline change rates in feet per year for the entire shoreline during the period 1858–1982.

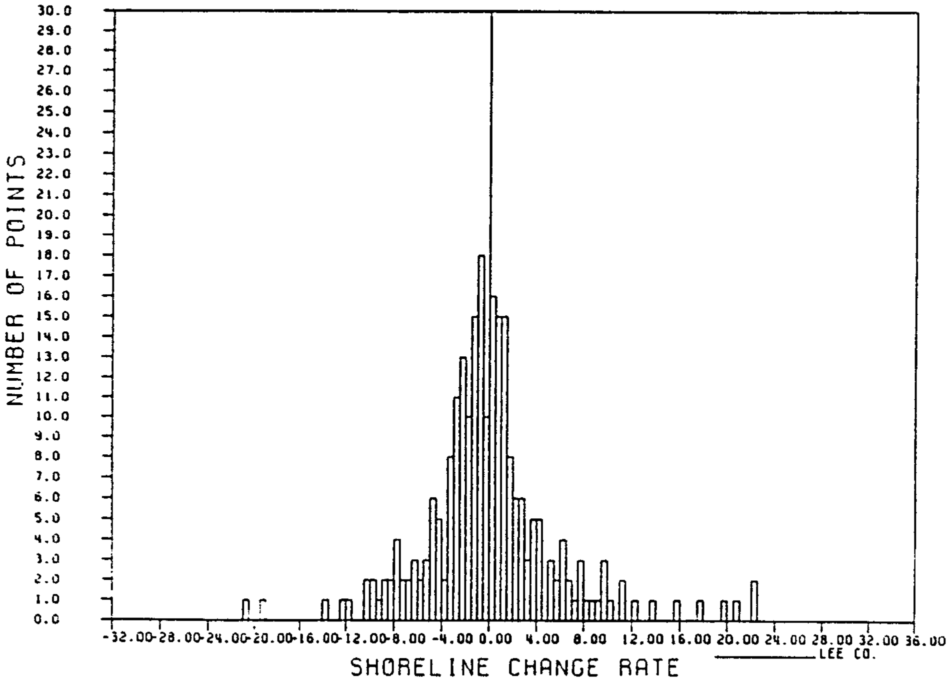

Figure A.51: Lee County: Histogram of long term shoreline change rates in feet per year during the period 1858–1982.

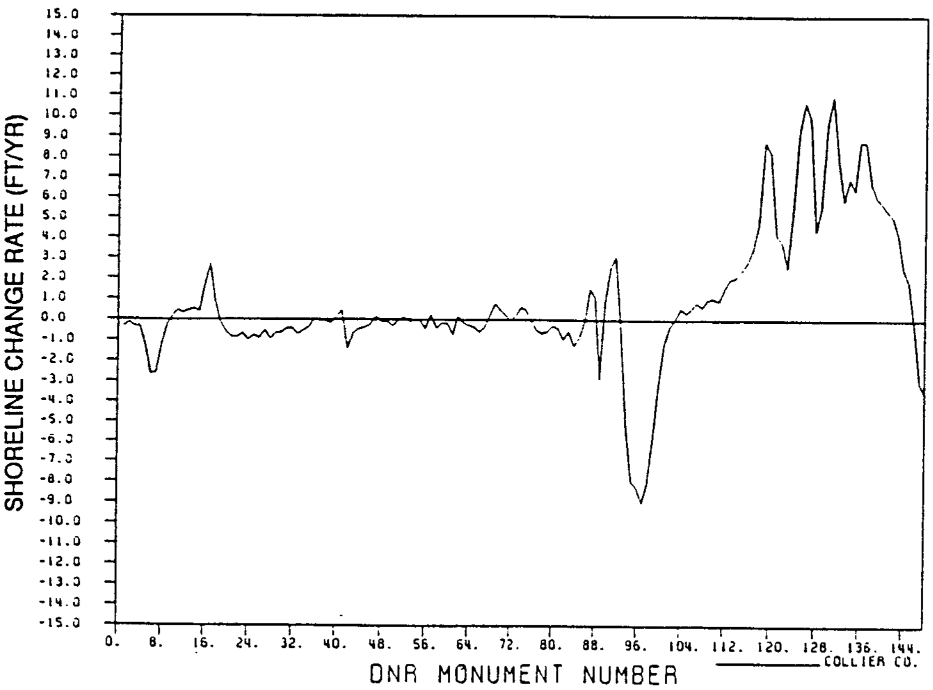

Figure A.52: Collier County: Long term shoreline change rates in feet per year for the entire shoreline during the period 1885–1988.

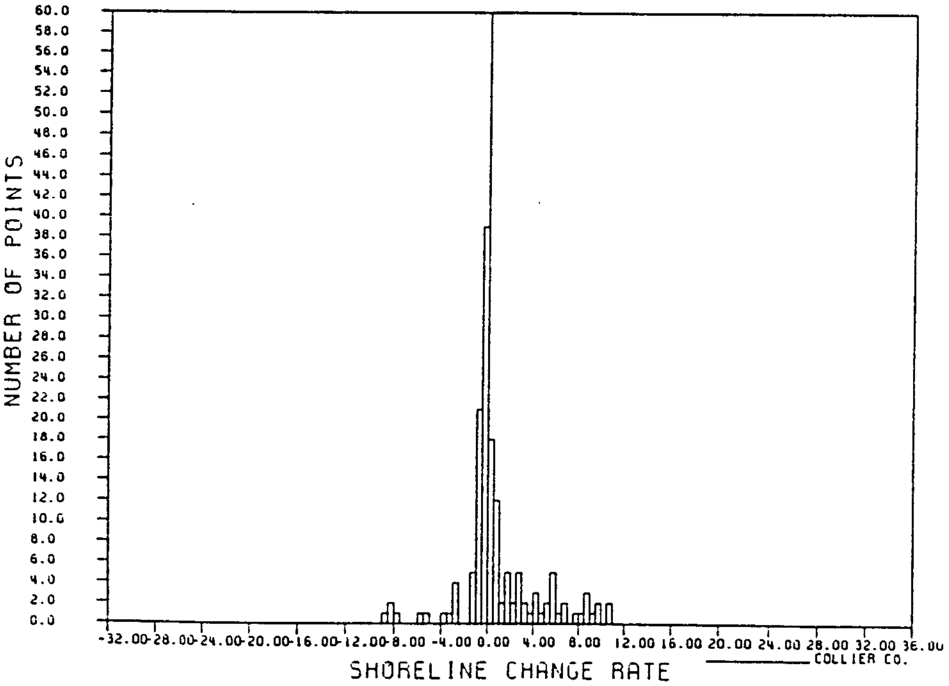

Figure A.53: Collier County: Histogram of long term shoreline change rates in feet per year during the period 1885–1988.