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Calculating Long-Term Shoreline Recession Rates Using Aerial Photographic and Beach Profiling Techniques

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ABSTRACT

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Quantifying measurement error and precision may be the most difficult step of shoreline recession rate calculations. Calculation of long-term shoreline recession rates based on aerial photograph analysis reflect only the shoreline positions at the time of photography. Conventional methods of long-term recession rate calculation were combined with beach profiling techniques in order to quantify potential errors that can be produced by short-term variations in shoreline position. Monthly beach profiling of a typical northeastern/mid-Atlantic microtidal and wave-dominated shoreline demonstrated short-term shoreline position changes of up to 20 m over a one year period. Average long-term shoreline recession rates in this area were 1.2 m/yr ± 1.0 m/yr. Short-term shoreline position changes were the largest source of error in the long-term recession rate measurements. This emphasizes that photographed shorelines do not necessarily represent the seasonal mean shoreline position, particularly in locations where shorelines characteristically exhibit relatively large short-term variations in shoreline position.

ADDITIONAL INDEX WORDS: *Coastal erosion, shoreline position, survey methods, rate calculations, beach.*

INTRODUCTION

Changes in shoreline position have been quantified using a variety of techniques and data bases. Studies examining long-term shoreline dynamics have generally utilized maps and charts (TANEY, 1961) or vertical aerial photographs (DAVIS, 1976; DOLAN *et al.*, 1979, 1980; LEATHERMAN, 1979, 1983; LEATHERMAN and ZAREMBA, 1986; STAFFORD, 1971; STAFFORD and LANGFELDER, 1971; WAHLS, 1973). Short-term shoreline dynamics are typically measured using beach profiling techniques (*e.g.*, BOKUNIEWICZ, 1981; DEWALL, 1979; DEWALL *et al.*, 1977; MCCANN, 1981). Aerial photographs are most commonly used to measure long-term shoreline position changes which have occurred since the advent of high-resolution, large-scale vertical aerial photography (circa 1930). Aerial photographs are frequently used to quantify changes along 10 to 100 km lengths of shoreline. In contrast, beach profiling is generally limited to smaller (*i.e.*, less than 10 km) lengths of shoreline. Beach profiling surveys are typically repeated at regular intervals in order to measure relatively short-term (daily to annual) variations in shoreline position and beach volume.

Maps and charts are seldom used for quantitative long-term shoreline position measurements because most are small scale, many are restricted to areas adjacent to ports and shipping lanes (STAFFORD and LANGFELDER, 1971), and "some are of questionable accuracy" (DOLAN *et al.*, 1979). Historical maps and charts are particularly subject to inaccuracies (LEATHERMAN, 1983). Thus, DOLAN *et al.* (1979) concluded that high-resolution measurements of changes in shoreline position are best accomplished using either large-scale vertical aerial photographs or beach profiling.

The accuracy and precision of aerial photographic measurements are mainly limited by the accuracy of the photographs and base maps used, and by the precision with which the photographs and base maps can be superimposed (DOLAN *et al.*, 1979, 1980; STAFFORD, 1971; STAFFORD and LANGFELDER, 1971). Preci-

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sion is also limited by difficulties in locating shoreline position, typically taken as the high water line (DOLAN *et al.*, 1979, 1980; LEATHERMAN, 1979, 1983). Quantifying measurement error (*e.g.*, DOLAN *et al.* 1980) is probably the most difficult and critical step in any measurement of long-term shoreline position changes. Beach profile measurements are generally subject to the limitations of conventional surveying techniques.

A common assumption, often unstated, is that the aerial photographs used in shoreline position studies record the seasonal mean shoreline position and configuration. DOLAN *et al.* (1980) pointed out that calculations based on aerial photographs, in addition to being subject to a variety of measurement errors, reflect only the shoreline positions at the time of photography. Beach profiling studies along the wave- and storm-dominated shorelines of the northeastern United States (BOKUNIEWICZ, 1981; DEWALL, 1979; DEWALL *et al.*, 1977; MCCANN, 1981) have shown that shoreline positions and beach volumes fluctuate on a variety of time scales in response to seasonal and storm-induced variations in coastal processes. The magnitudes of these short-term changes may be comparable to the magnitudes of long-term changes in shoreline position measured over time spans of decades. This suggests that the assumption of "seasonal mean shoreline position" used in aerial photographic analyses may not always be valid.

Some studies have utilized post-storm aerial photographs (LEATHERMAN, 1979; LEATHERMAN and ZAREMBA, 1986; WAHLS, 1973). These photographs clearly do not record seasonal mean shoreline positions or configurations. Instead, this technique assumes that post-storm shorelines typically attain a characteristic post-storm configuration. It is not clear whether or not this approach circumvents the problem of short-term variability; this technique will not be discussed here. Erosional headland or seacliff-dominated coasts (*e.g.*, KUHN and SHEPARD, 1984) are less affected by short-term variability, compared to the littoral coastlines which will be discussed here.

The goal of this study was to combine conventional methods of vertical aerial photographic analysis and beach profiling to quantify measurement errors and precision of long-term shoreline change studies, thus providing results having well defined limits of accuracy. This was accomplished by combining the relative magnitudes of short- and long-term variability in shoreline position along a representative stretch of coastline with the usual inherent measurement errors of map and aerial photo analysis. Short-term variability was quantified in order to determine its effect on the accuracy of long-term shoreline position measurements.

STUDY AREA

The shoreline examined in this study is a barrier beach 1.2 km in length fronting Mecox Bay on the south shore of Long Island, New York (Figure 1). The mean ocean tidal range in this area is 0.9 m and the spring tidal range is 1.1 m (NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, 1984). Wave climate data collected 3 km west of the study area from January to December, 1971, indicated that the mean wave height was approximately 0.6 m whereas maximum height, was approximately 1.8 m (U.S. ARMY CORPS OF ENGINEERS, unpublished data). According to HAYES (1979), mean tidal ranges of 0.9 m and mean wave heights of 0.6 m should produce a "microtidal wave-dominated" shoreline. The narrow, 400 m wide linear barrier beach across the seaward side of Mecox Bay and the barrier islands west of the study area are characteristic of this class of shoreline and are representative of large portions of northeastern and mid-Atlantic United States coastlines.

An ephemeral tidal inlet, Mecox Inlet, is located in the center of the study area. This unstabilized inlet is the only open-channel connection between the bay and the ocean and is typically open for periods of one to two weeks seven times per year. The beach adjacent to the inlet has not been modified by filling or groin-building. DOLAN *et al.* (1979) did not examine shorelines adjacent to inlets because of concern that the high variability of inlet-influenced shorelines would bias long-term shoreline position measurements. Although Mecox Inlet is located in the center of the study area, inlet-related effects are short-term and are confined to beaches immediately adjacent to the inlet (SMITH and ZARILLO, 1988). These short-term, inlet-related changes are an order of magnitude smaller than seasonal or storm-induced

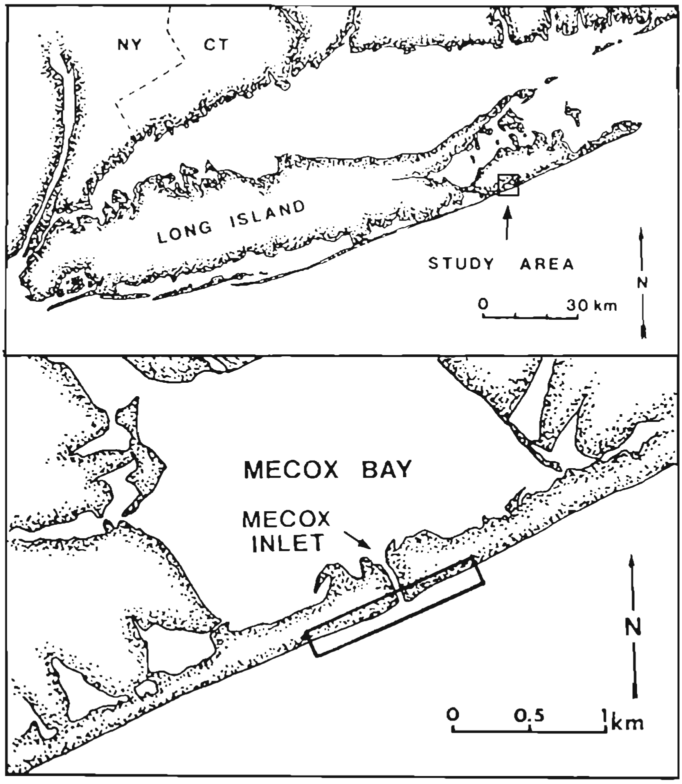

Figure 1. (Top). Location of study area on Long Island. (Bottom). Section of barrier beach shoreline examined during this study.

changes in beach volume and shoreline position in the study area.

METHODS

Long- and short-term changes in shoreline position were measured on a 1.2 km length of barrier beach fronting Mecox Bay using aerial photographic and beach profiling techniques. Short-term shoreline position changes were measured over 13 months using the EMERY (1961) method of beach profiling. Short-term data quantified the potential effects of seasonal variability and storm-induced changes on the precision of long-term shoreline position measurements. Long-term changes in shoreline position were measured between 1938 and 1984 using a variation of conventional aerial photographic techniques described in STAFFORD (1971), STAFFORD and LANGFELDER (1971), WAHLS (1973), DOLAN *et al.* (1979, 1980), LEATHERMAN (1979, 1983), COOKE (1985), and LEATHERMAN and ZAREMBA (1986).

Long-Term Measurements

Long-term shoreline position changes were measured from vertical aerial photographs taken on June 30, 1938, and March 24, 1984. First a 1:2400 scale Suffolk County, New York, topographic map was chosen as a base map and field checked for accuracy. The map's accuracy was determined by surveying ground distances between five pairs of reference points within the study area and appearing in the 1938 and 1984 photographs. Reference points consisted of the corners of clearly identifiable structures, road-driveway intersections, and the point at which a road ended. The base map was determined to be more accurate than the precision with which measurements could be made on the map (± 1 m). A mylar copy of the base map was used throughout the study in order to eliminate error introduced by stretching or shrinkage.

Next, the aerial photographs were projected onto the base map using a Bausch and Lomb *Zoom Transfer Scope* and oriented and enlarged in order to match reference points. This procedure rectified scale differences between the two photographs due to camera altitude and tilt (STAFFORD and LANGFELDER, 1971). Each projection was positioned to ± 1 m by this process.

On vertical aerial photographs, scale varies radically outward from the center (primary point) of the photograph. In addition, scale varies in response to topographic relief. These scale variations are inherent features of the photograph. They affect the accuracy of the photograph since they make high-relief reference points (*i.e.*, houses on dunes) appear to shift radially outward. Radial displacement effects and scale variations could not be corrected but were minimized by choosing photographs which centered the study area. The maximum error due to radial distortions was estimated at ± 3 m at high-elevation reference points (houses on dune tops) at the ends of the study area. This estimate was based on calculations of radial displacement using an assumed aircraft elevation and known ground distances and elevations.

The water and high water lines of the projected photographs were traced onto the base map. The high water line (HWL) is a commonly used shoreline indicator and appears as a tonal change on the beach face due to differences in water content of the sand. The HWL migrates from 1 to 2 m horizontally (DOLAN *et al.*, 1980) as a function of beach slope, wave height, and tidal range (EVERTS and WILSON, 1981). DOLAN *et al.* (1980) considered a 2 m migration typical for medium sand beaches having slopes of 3 to 6 degrees. Intertidal beach slopes in the study area were typically 5.5 degrees. This study assumed that the positions of the two high water lines (1938 and 1984) were each subject to an uncertainty of ± 2 m.

The HWL was not visible in the 1938 photograph, which was taken approximately 50 minutes after predicted high water in the study area (1985, NATIONAL ARCHIVES, personal communication; U.S. COAST AND GEODETIC SURVEY, 1938a). Therefore, the 1938 water line was substituted for the HWL. According to unpublished U.S. COAST AND GEODETIC SURVEY data (1938b), tidal elevations measured on the day of the photograph exceeded predicted elevations by about 30 percent, although predicted tidal *ranges* were similar on the dates of the 1938 and 1984 photographs (U.S. COAST AND GEODETIC SURVEY, 1938a; NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, 1984). This would have displaced the water line (seen in the 1938 photograph) landward beyond the mean HWL. This combination of circumstances reduced the distance between the 1938 and 1984 shorelines, eliminating any artificial inflation of shoreline recession values.

The position of each traced HWL was measured along shore-normal transects to ± 1 m relative to an arbitrary baseline. The transects were spaced at approximately 50 m intervals along the 1.2 km section of beach bounded by short-term beach profile lines (Figure 2).

Long-term shoreline positions were measured to ± 12 m. This value for total error reflects errors due to inherent inaccuracies of the base map and photographs, the natural variability of HWL position, and measurement error. These errors were listed in Table 1.

Short-Term Shoreline Position Changes

Short-term variability in shoreline position was quantified using 13 sets of monthly beach profile measurements. Twelve benchmarks were established at approximately 100 m intervals along the 1.2 km section of shoreline within the study area (Figure 3). These beach profiles were measured at approximately spring low water from March 1985 to March 1986 using the EMERY (1961) method of beach profiling. Emery estimated that this method was accurate within the variations in beach profile due to small-scale features. During this study elevations were measured to the nearest centimeter and horizontal distances to the nearest 2 cm. Repeat surveys indicated that this method was precise to ± 5 cm in elevation and ± 15 cm in the horizontal. Additional beach profile measurements were made within two days before and after the landfall of Hurricane Gloria (September 27, 1985).

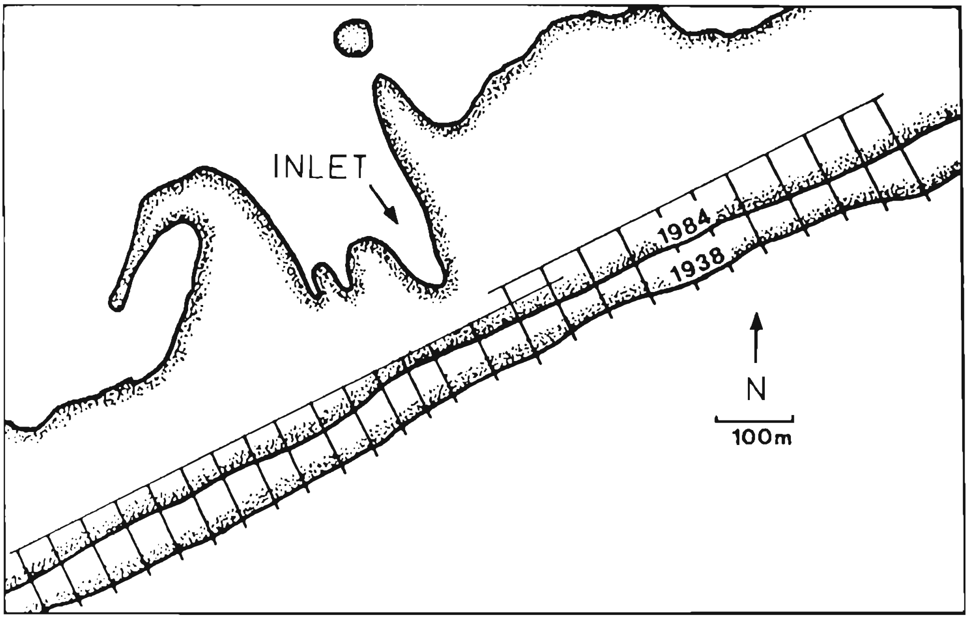

Figure 2. Locations of shore-normal transects used to measure long-term changes in shoreline position. The 1938 and 1984 shoreline positions are also shown.

Table 1. *Errors in measurements of long-term changes in shoreline position.*

Source* (Explanation)	Value (+/− m)
Base map accuracy (inherent feature of map)	1
Overlay of projected photos (human error)	
1938 photograph	1
1984 photograph	1
Radial distortion (inherent feature of photos)	3
HWL position (natural variability)	
1938 HWL	2
1984 HWL	2
Shoreline position measurement (human error)	
1938 shoreline	1
1984 shoreline	1
TOTAL ERROR	12

*Note: This is the order presented in the text.

SHORELINE POSITION CHANGES

Short-Term

Short-term beach profile measurements indicated that the shoreline position, averaged over the *length* of the study area, migrated across a 20 m wide swath of shoreface during the 13-month study (Figure 4). Figure 4 shows average shoreline position for each month, measured from the dune scarp to HWL, as "beach width." The average cumulative beach volume for the study area is shown for reference on the bottom of Figure 4. The 20 m range in shoreline position does *not* reflect the effects of Hurricane Gloria, which was regarded as an unusual event within the time frame of this 13-month study.

Two minima in beach width occurred in November 1985 and March 1986. Observations suggested that beach width minima occurred after periods of increased wave activity. Beach widths remained fairly constant (44 to 48 m) throughout most of the study, fluctuating within a 20 m range. Other studies (*e.g.*, BOKUNIEWICZ, 1981; MCCANN, 1981) have measured seasonal variations in beach width. During this study beach *volumes* appeared to vary seasonally whereas *widths* remained relatively constant, with the exception of changes produced by Hurricane Gloria (Figure 4).

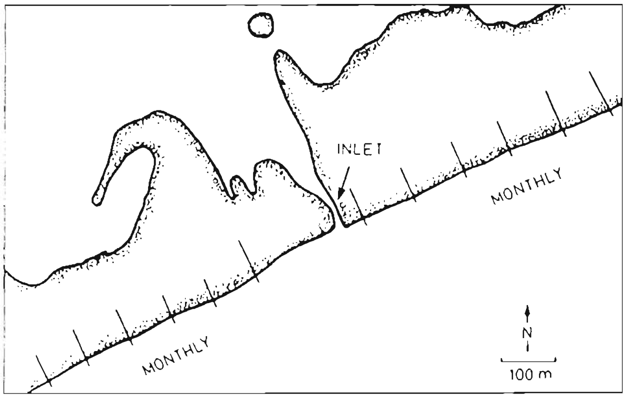

Figure 3. Locations of the 12 beach profile lines used during the 13-month study of beach widths and volumes.

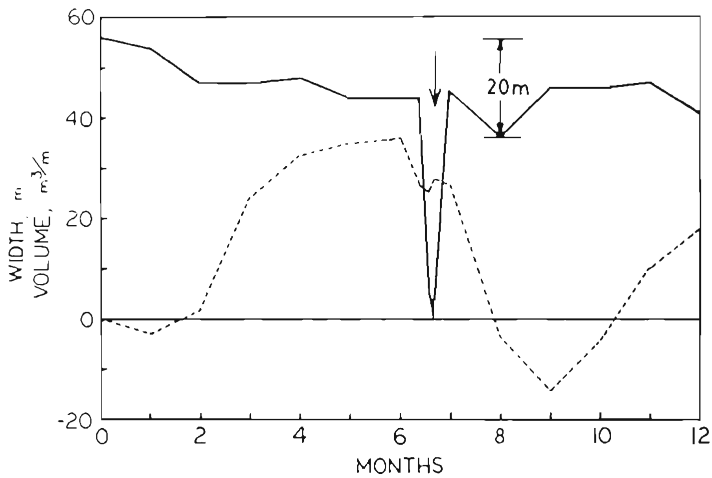

Figure 4. Beach widths and volumes averaged over the 1.2 km study area, from March 1985 to March 1986. Widths are shown by the solid line, volumes by the dashed line. Arrow indicates landfall of Hurricane Gloria (September 27, 1985).

Long-Term

An important source of error in the long-term shoreline change measurements is apparent from the observation that short-term shoreline positions migrated across a 20 m swath of shoreface. The possibility that the 1938 and 1984 shorelines seen in the two photographs might be displaced in *opposite* directions away from each other and might lie at the opposite ends of their "20-meter ranges" suggests that long-term changes in shoreline position might be subject to an error of ± 40 m. In this case, long-term position change calculations would be subject to a total error of ± 52 m.

Long-term changes in shoreline position consisted exclusively of shoreline recession. Recession distances averaged 53 ± 52 m over the entire study area and ranged from 35 m in the east to 71 m in the west (Figure 2, Table 2). The average recession rate for the entire study area was 1.2 ± 1.1 m/yr for the 46-year period (Table 2). Recession rates ranged from 0.8 m/yr (east) to 1.6 m/yr (west) but there was no systematic variation that could be attributed to the presence of an ephemeral inlet within the study

Table 2. *Shoreline recession distances and rates, 1938 to 1984.*

Transect (number)	Recession Distance* (m)	Recession Rate** (m/yr)
1	49	1.1
2	35	0.8
3	39	0.8
4	37	0.8
5	54	1.2
6	52	1.1
7	51	1.1
8	39	0.8
9	37	0.8
10	43	0.9
11	48	1.0
12	52	1.1
	Inlet position	
13	62	1.4
14	63	1.4
15	71	1.6
16	65	1.4
17	55	1.2
18	54	1.2
19	55	1.2
20	57	1.2
21	64	1.4
22	65	1.4
23	63	1.4
24	54	1.2
25	59	1.3
26	62	1.4
27	56	1.2

*Note: Shoreline recession distance measurements are subject to a maximum uncertainty of +/− 52 m.
**Note: Recession rates are subject to an uncertainty of +/− 1.1 m/yr.

area. These results indicate that there was little or no significant change over much of the study area. This apparent lack of significant long-term change is due to a consideration of the effects of short-term variability on the accuracy of long-term measurements of shoreline position change.

DISCUSSION

The average shoreline recession rate calculated in this study (1.2 ± 1.1 m/yr) is comparable to the 1.5 m/yr recession rate calculated by TANEY (1961) for the shoreline in the vicinity of Mecox Bay between 1933 and 1956. Taney determined that shoreline recession rates in the Mecox Bay area varied from 0.6 m/yr between 1838 and 1933 to 1.5 m/yr between 1933 and 1956. In addition, Taney showed that shoreline positions in the vicinity of Mecox Bay (and along the south shore of Long Island in general) vary on a time scale of decades. The accuracy of the nautical maps and charts that Taney used for the older time interval is uncertain. Therefore, the 0.6 m/yr recession rate he calculated may be less accurate than the more recent value of 1.5 m/yr. However, even if Taney's values are considered completely accurate, short-term variations in shoreline position could easily account for all of the differences between Taney's shoreline recession rates and the rates calculated during this study.

Long-term shoreline recession rates calculated along the mid-Atlantic coast (using aerial photographs) typically average about 1.5 m/yr (DOLAN *et al.*, 1979; WAHLS, 1973) whereas recession rates on Cape Cod, Massachusetts, are frequently 0.5 to 1.5 m/yr, depending on location (LEATHERMAN and ZAREMBA, 1986). Analyzing a variety of published and unpublished data, MAY (1983) calculated recession rates of 1.5 m/yr for barrier islands (New York to North Carolina) and 1.3 m/yr for "sand beaches" (Massachusetts to New Jersey). These recession rates are similar to the rates calculated for the shoreline adjacent to Mecox Bay. Again, short-term variations in shoreline position could easily account for the differences between recession rates in these different locations.

Long-term recession rates calculated for many northeast and mid-Atlantic United States coastlines are remarkably consistent in light of the rather large short-term variations in shoreline position measured during this study. Assuming that the similar long-term recession rate values are correct, a possible explanation for this consistency is that conventional long-term shoreline position measurements generally utilize photographs that reflect seasonal mean shoreline positions. However, in one of the few papers that quantifies the errors involved in long-term shoreline position change measurements, DOLAN *et al.* (1980) suggested that 1.2 to 16.4 m/yr variations in long-term erosion rates were larger than year-to-year changes in beach systems. This study suggests that this variability may be partly due to unquantified short-term fluctuations in shoreline position.

It may be possible to use aerial photographs in order to reduce the uncertainty produced by short-term variability in shoreline position. A series of photographs bracketing the date (and photograph) of interest could be used to qualitatively assess the magnitude of short-term shoreline position variability. Although this technique would rely on a series of random "snapshots" of the shoreline in question, it could be used to qualitatively answer some questions about the relative importance of short-term variability.

CONCLUSIONS

Calculations based on aerial photography and other "one-shot" mapping techniques are invariably biased by shoreline positions at the time of mapping. Short-term fluctuations in shoreline position may be quite large, sometimes as large as the long-term changes that are being measured. Because of this variability, the assumption that the mapped shoreline reflects "seasonal mean shoreline position" must be used with caution. In addition, since recession rates of the magnitudes calculated in this and other studies are smaller than many month-to-month variations in shoreline position, long-term recession rates cannot be measured using monthly beach profile measurements even if continued for several years.

This study combined conventional methods of aerial photographic shoreline mapping and beach profiling in order to quantify errors due to short-term variations in shoreline position. The results of this study suggest that short-term changes in shoreline position may be the single largest source of error in quantitative calculations of long-term shoreline position change. Previous calculations of long-term recession rates may be subject to large errors due to unquantified short-term variations in shoreline position.

Another conclusion of this study is that a long interval between aerial photo sets is required to establish a significant net change in shoreline position that is greater than short-term variability. Examination of Table 2 shows that in the present study area net recession over a 46-year period only slightly exceeds, on the average, uncertainty due to the combination of measurement error and short-term variability in beach width.

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□ ZUSAMMENFASSUNG □

Die Quantifizierung von Meßfehlern und die Präzison der Messung sind wahrscheinlich die schwierigsten Faktoren bei der Berechnung der Küstenrückverlagerungsgeschwindigkeit. Die Berechnungen von Küstenverlagerungen über längere Zeiträume, die auf Luftbildaufnahmen basiern, spiegelt nur die Lagezustände der Küstenlinien zur Zeit der jeweiligen Aufnahmen wider. In Ergänzung zu den konventionellen Methoden zur Berechnung der Küstenverlagerung werden morphometrische Karten des Strandes angefertigt um die möglichen Fehler, die durch kurzfristige Schwankungen der Küstenlinie entstehen können, zu quantifizieren. Monatliche morphometrische Aufnahmen einer typischen nordost-/mittelatlantischen, mikrotidalen und durch Wellen geprägten Küstenlinie zeigte, daß kurzzeitige Schwankungen der Küstenlinie von bis zu 20 m in einem Jahr auftreten können. Die durchschnittliche Langzeit-Küstenverlagerungsrate beträgt in diesem Gebiet 1,2m/a ± 1,0 m/yr. Die kurzfristigen Schwankungen stellen die hauptsächliche Fehlerquelle bei den Messungen der Langzeit-Küstenverlagerung dar. Dies weist verstärkt darauf hin, daß Luftbildaufnahmen von Küstenlinien nicht notwendigerweise die jahreszeitliche durchschnittliche Position der Küstenlinie repräsentieren, insbesondere an Lokalitäten, wo der Verlauf der Küstenlinie vergleichsweise großen Kurzzeit-Schwankungen unterworfen ist.—*Ulrich Radtke, Geographisches Institut, Universität Düsseldorf, F.R.G.*

□ RÉSUMÉ □

L'étape la plus difficile à franchir pour estimer le recul du rivage est de quantifier les erreurs de mesure et leur précision. Les calculs de taux de recul du rivage à long terme reposent sur l'analyse de photographies aériennes qui donnent le position du rivage instantané au moment de la prise de vue. Les méthodes conventionnelles d'estimation de recul à long terme ont été combinées à un profilage des plages pour pouvoir quantifier les erreurs qui peuvent être générées par les variations à court terme de la position du rivage. Le profilage mensuel d'une plage typique du NW de l'Atlantique moyen de type microtidal et dominé par les houles présente une vatiation atteignant 20 m sur un an. Les taux moyens de recul dans cette zone sont de 1,2 m/an ± 1. Ce sont les changements à court terme qui sont les sources les plus importantes d'erreurs du calcul des taux de recul à long terme. Ceci souligne le fait que les photographies de rivages ne représentent pas forcément la position moyenne saisonnière du rivage, surtout là où d'importantes variations à court terme sont enregistrées.—*Catherine Bressolier, Labo. Géomorphologie E.P.H.E., Montrouge, France.*

□ RESUMEN □

La cuantificación del error y la precisión de medida puede ser la etapa más dificil en los cálculos de la velocidad de recesión de la linea de costa. Los cálculos de las velocidades de recesión a largo plazo, basados en la fotografia aérea, reflejan sólo las posiciones de la linea en el instante de la fotografia. Los métodos convencionales de cálculo de la recesión a largo plazo se combinan con técnicas de perfil de playas para cuantificar los errores potenciales que pueden producirse por las variaciones a corto plazo en la posición de la linea de costa.

El perfilado mensual de una linea de costa tipica micromareal y dominada por el oleaje en el Nordeste Atlántico demuestra que las variaciones a corto plazo en la posición de la linea de costa pueden ser de hasta 20 m en el periodo de un año. La velocidad media de recesión a largo plazo con ese área es de 1.2 m/año ± 1.0 m/año. Los cambios de posición de la linea de costa a corto plazo fueron las mayores fuentes de error en las medidas de la velocidad de recesión a largo plazo. Esta remarca que las lineas de costa fotografiadas no representan necesariamente su posición media estacional, especialmente en aquellos lugares donde la linea de costa presenta variaciones a corto plazo relativamente importantes.—*Department of Water Sciences, University of Cantabria, Santander, Spain.*