Temporal and Spatial Variations in Shoreline Changes and their Implications, Examples from the Texas Gulf Coast

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TEMPORAL AND SPATIAL VARIATIONS IN SHORELINE CHANGES AND THEIR IMPLICATIONS, EXAMPLES FROM THE TEXAS GULF COAST[1,2]

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ABSTRACT: Shoreline changes from sandy oceanic coasts worldwide show temporal and spatial variations that are similar to, and exemplified by, composite data from the Texas coast for four time periods extending from 1850 to 1975. The quantitative data, which exhibit remarkably similar distributions for the first two and latter two periods, show that both total length of eroding coast and rates of erosion have substantially increased since 1955–60. As a result, some shoreline segments that prograded following sea-level stillstand are presently eroding.

Spatial variations in shoreline changes occur on regional and local scales. Regional tendencies toward accretion or erosion closely correspond with physiographic provinces, which in Texas are defined by transgressive and regressive beaches and barriers. Within each province, rates of accretion and erosion display periodicities that are irregular to quasi-sinusoidal in form and are attributed to shoreline rhythms resulting from differential rates of sediment transport.

Natural processes, such as decreases in sediment supply and continued relative sea-level rise are largely responsible for long-term shoreline retreat. Short-term (historical) shoreline changes reflect the long-term trends, but they also reflect secular sea-level variations and human activities. The latter, in the form of coastal engineering modifications, are clearly responsible for the highest short-term rates of accretion and erosion.

On the Texas coast nearly half of the total beach sand supplied by updrift erosion, presently a major sediment source, has been trapped by jetties at harbor entrances. This impoundment of sand at impermeable barriers together with reduced sediment influx from damming of rivers suggest that anthropogenic augmentation of natural shoreline erosion will likely increase from local to regional effects.

INTRODUCTION

Sandy coastal areas of the world commonly exhibit temporal and spatial variations in shoreline changes. This study examines regional and local differences in shoreline movement, their time-dependent variability, and their relationship to natural alterations in physical processes and subsequent evolution of the Texas Gulf Coast during the past few thousand years (Fig. 1).

The study is based on shoreline changes determined for the 590 km Texas Gulf Coast from topographic maps and aerial photographs spanning four time periods (see Morton, 1977a for previous work, quality of data, operational procedures, and possible sources of error). In spite of certain limitations, the data are adequate for analyzing time-dependent variations in shoreline changes and for demonstrating that not only has total length of eroding shoreline increased during the past two decades, but rates of shoreline erosion have also increased significantly in some areas. Such accelerations suggest important, perhaps long-term alterations in coastal processes.

RATES OF SHORELINE CHANGE

Spatial Variations and Shoreline Rhythms

Rates of shoreline change for sandy beaches worldwide exhibit distinct maxima and minima when data for individual time periods are viewed laterally along the coast (Fig. 2). Except for protuberances—at tidal inlets, river mouths, and man-made channels—patterns for variable rates are irregular to quasi-sinusoidal considering vertical exaggeration of the graphs. Similar patterns have been illustrated by Edelman (1967), Valentin

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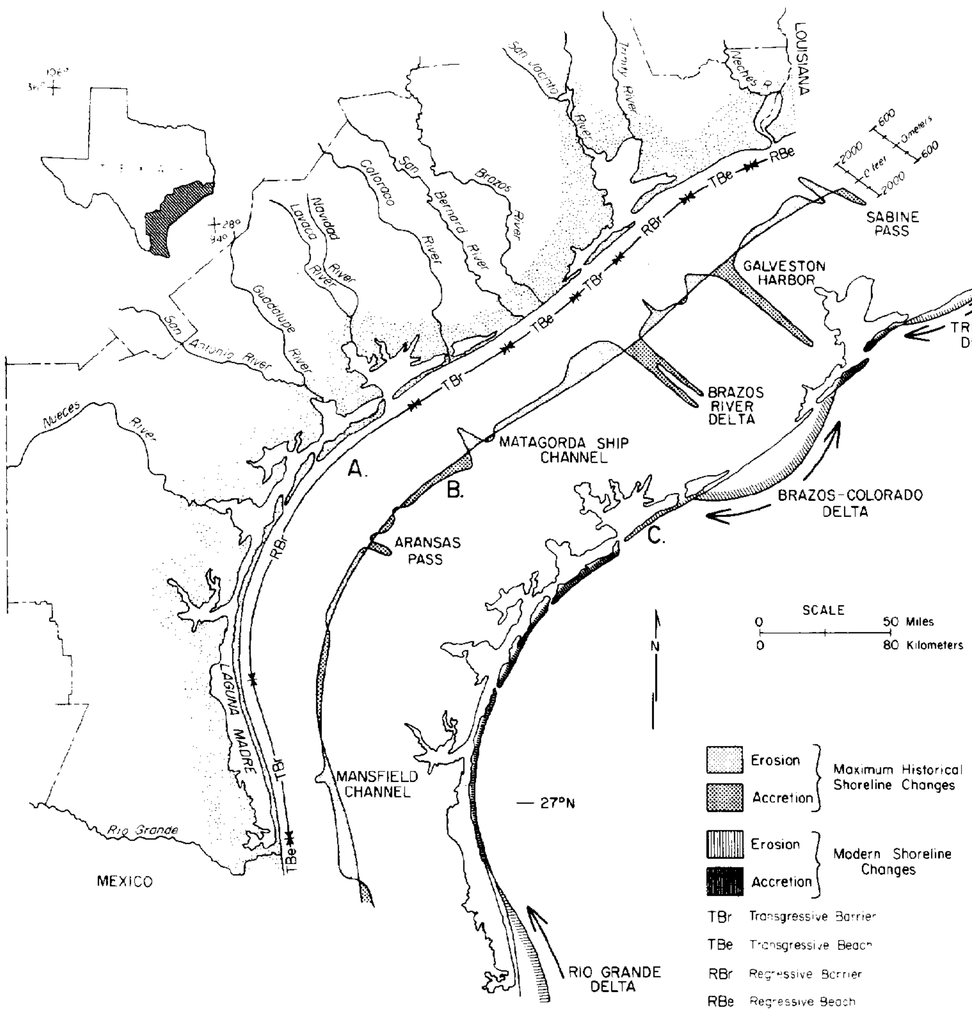

FIG. 1.—Maps showing (A) morphogenic provinces of the Texas coast, (B) maximum shoreline changes between 1850–83 and 1973–75, and (C) hypothesized late Holocene shoreline showing major promontories and littoral drift cells.

(in Doornkamp and King, 1971), Goldsmith (1976), and Dolan et al. (in press) and presented in tabular form by Cocco (1976) among others. Data from these studies and data for the Texas coast show that some time-dependent oscillations are spaced 2.5 to 3 km apart and other oscillations have spacings of 5 to 7 km.

The variable rates of change are related to beach processes and the formation of intermediate scale shoreline rhythms (see Bajorunas and Duane, 1967; Dolan et al., 1974; and Sonu, 1973, for review and references). The shoreline rhythms are manifested by accelerated and decelerated shoreline movement in comparison to adjacent areas. Apparently accelerated accretion or decelerated erosion (Fig. 2) results from greater sediment storage, whereas decelerated accretion or accelerated erosion suggests greater sediment transport. Many sandy coasts are broadly arcuate with relatively smooth shorelines along any given segment and this simplicity is maintained, at most sites, by compensating accelerations or decelerations for subsequent time periods.

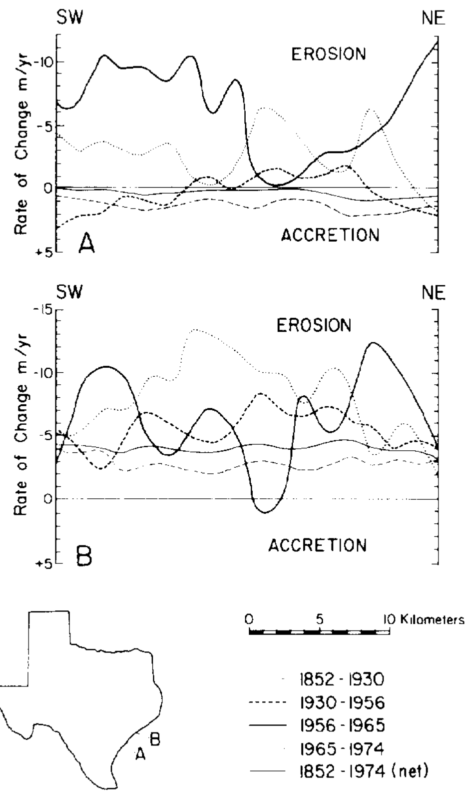

FIG. 2.—Variable rates of shoreline change plotted for (A) a segment of Matagorda Island showing recent erosion but relatively stable net conditions and (B) an erosional segment on the western flank of the Brazos-Colorado delta. Segment A is located 16.5 km west of Pass Cavallo. Segment B is located 6.5 km west of the new Brazos River.

In this manner, major excursions tend to cancel one another so that overall net changes for a particular segment are similar, as general shoreline orientation is maintained. The net changes also depend largely on shoreline behavior during the earliest period (Fig. 2) which also included the most time.

Spatial variations in rates of change are clearly a wave phenomenon. Goldsmith (1976) related differential rates of net shoreline changes for the Virginian Sea to a nonuniform distribution of energy from refracted waves. Dolan et al. (in press) proposed that edge waves were responsible for differential rates of shoreline change along a segment of the North Carolina coast. These processes are not mutually exclusive and they could explain shoreline periodicities along the Texas coast. Unfortunately, edge waves impinging on the continental margin of the northwest Gulf of Mexico have received little attention and, therefore, wave analyses adequate for testing this explanation are not presently available.

Temporal Variations

Shoreline segments that have exhibited unidirectional movement since the mid- to late-1800's are eroding at relatively high rates and are located west of Sabine Pass, up- and down-coast from the Brazos River, and south of Mansfield Channel (Fig. 1B). In these same areas, thin beach deposits overlie dominantly muddy delta-plain sediments associated respectively with the Pleistocene Trinity and Holocene Brazos-Colorado and Rio Grande deltas (McGowen et al., 1977). Except for local reversals caused by jetty construction, major reversals in shoreline movement occurred where formerly accreting segments began to erode after 1955–60. This occurred, for example (Fig. 1B), north of Aransas Pass (Matagorda and San Jose Islands), and north of Mansfield Channel (central Padre Island). Recent erosion in the latter area is particularly significant because it has received a continuous supply of sand for centuries from converging littoral drift currents (Watson, 1971). In recent years (1965–70 to 1973–75) nearly 80% of the Texas coast has been erosional, with annual losses of approximately 160 ha per year.

When rates of change for the Texas coast are grouped by time period, they exhibit remarkably similar distributions (Fig. 3). From 1850–83 to 1930–37, and from 1930–37 to 1955–60, the distributions were relatively symmetrical with central tendencies near zero, probably reflecting near equilibrium between sediment supply and sediment removal. Rates of change during those two time periods were generally ± 2 m/yr or less; however, rates of change for subsequent time periods have drastically increased and shoreline erosion is prevalent (Fig. 3). After 1955–60, the total length of eroding shoreline increased from 55% to nearly 80%. At present, 45% of the shoreline is eroding at more than 3.5 m/yr as compared to between 8% and 16% for the previous two time periods.

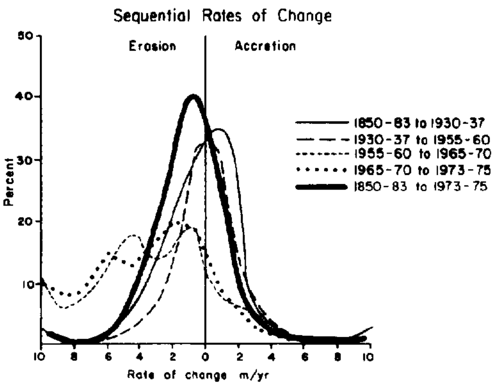

FIG. 3.—Distributions of sequential and net rates of shoreline change. Data are expressed as percent of total sample (n) because n varied from 326 to 385.

Accelerated rates of shoreline movement are also shown by absolute rates of areal changes (combined accretion and erosion disregarding sign). Absolute areal changes have increased three-fold from 105 ha/yr (1850–83 to 1930–37) to 308 ha/yr (1965–70 to 1973–75). At the same time, rates of total net losses dramatically increased from 10.5 ha/yr to 160 ha/yr. The distribution of net rates of shoreline change (Fig. 3) also shows erosional tendencies reflecting increased rates of erosion since 1955–60, but net rates of change primarily reflect conditions during the earliest time period.

SPATIAL VARIATIONS RELATED TO MORPHOGENIC PROVINCES

In order to place historical shoreline changes in proper perspective it is important: 1) to evaluate the broader aspects of Holocene shoreline changes, 2) to better understand the dynamics of shoreline evolution, and 3) to recognize major turning points in spatial and temporal trends of shoreline movement. One way of evaluating these elements is by establishing relationships between historical shoreline changes and physiographic provinces such as those reported by Hubbard et al. (1977), Cocco et al. (1975), and Morgan and Larimore (1957). The morphogenic provinces presented in Figure 1 rely on previous shoreline classifications for the Texas coast, but they also incorporate dune characteristics, washover density, barrier width, barrier flat morphology, and sedimentological data for the beaches and adjacent inner shelf environments.

Excellent descriptions of late Quaternary sea levels and general development of the Texas coast were provided by Barton (1930), Shepard (1956), LeBlanc and Hodgson (1959), Curray (1960), Bernard and LeBlanc (1965), Nelson and Bray (1970), McGowen et al. (1977), and Wilkinson and Basse (1978). Morton (1977a), used prior interpretations and additional morphological, sedimentological, and geophysical data, to explain shoreline evolution during the past few thousand years. Apparently, the Pleistocene Trinity deltaic headland along the upper Texas Coast (Barton, 1930) and the Holocene Brazos-Colorado and Rio Grande deltaic headlands (Price, 1954) were major promontories when the sea approached its present level. These promontories caused wave refraction and, consequently, the formation of three littoral drift cells (Fig. 1C). The interheadland areas were sites of beach and barrier progradation, as indicated by accretion ridges on the central and upper coast (Shepard, 1956; LeBlanc and Hodgson, 1959). As the deltaic headlands retreated, longshore and onshore currents supplied sediment to the interdeltaic bights according to the process-response model proposed by May and Tanner (1973). Prolonged erosion of the apexes modified littoral drift directions such that today there is only one major littoral drift cell centered about 27°N latitude (Fig. 1C). The spatial distribution of beach processes and related shoreline movements have resulted in geomorphic features that pass transitionally from transgressive beaches at headland apexes to transgressive barriers and finally to regressive barriers or regressive beaches in the zones of littoral drift convergence (Fig. 1A).

The morphogenic classification and shoreline evolution are supported not only by the location of accretion ridges, but also by: 1) the distribution of relict sediments on the inner continental shelf (McGowen and Morton, 1979); 2) unpublished engineering borings as well as published subsurface borings of the barriers (Shepard, 1956; Fisk, 1959; Rusnak, 1960; Bernard et al., 1970; Hunter and Dickinson, 1970; Wilkinson, 1975; Wilkinson et al., 1975; Wilkinson and Basse, 1978); and 3) the morphology of transgressive barriers flanking the Brazos-Colorado and Rio Grande deltas. These transgressive barriers apparently formed by lateral encroachment of lagoons behind mainland beach ridges and by coalescence of small lakes on floundering flanks of the delta plains. Such headward lagoonal extension (Field and Duane, 1976), which is equivalent to dune-beach ridge submergence (Hoyt, 1967), gives rise to barriers that are youngest at their juncture with the headland and, conversely, are progressively older away from the headland. These age relationships are opposite to those for barriers formed by spit migration, an important distinction when considering barrier island formation.

Under the broad morphogenic classification highest historical erosion rates occur along transgressive beaches near headland apexes (McGowen et al., 1977) where wave energy is concentrated and where sand is sparse in mud-dominated deltas. Erosion rates decrease progressively away from the apexes as functions of shoreline alignment, backbeach elevation, and sand thickness. Under uniform relative sea-level conditions beach and barrier sands usually increase in thickness away from headland apexes and attain maximum thicknesses along regressive barrier segments (see preceding list of barrier borings).

Considering the entire Texas coast, transgressive and regressive landforms (Fig. 1A) are nearly equally represented (52% versus 48%), another indication of near equilibrium between sediment supplied to and removed from the beaches on a geological time scale. Regressive barriers constitute slightly more of the shoreline (45%) than transgressive barriers (34%) whereas transgressive beaches and regressive beaches respectively represent 18% and 3% of the shoreline.

In spite of the near balance between transgressive and regressive landforms, the historical shoreline data (Fig. 3) confirm that formerly accretionary segments are presently eroding. Recent erosion of accretionary beach ridges has been described elsewhere by Tanner and Stapor (1971), Tanner (1975), and Cocco (1976) among others.

EVALUATION OF NATURAL PROCESSES AND HUMAN ALTERATIONS

Relative Sea-Level Conditions

One factor that may affect shoreline movement is relative sea-level position. The major components of this variable are: 1) eustatic sea-level rise, 2) subsidence, and 3) secular sea-level variations. At present the first and third components are relatively minor overall and they operate on different time scales; the former is important over geological time and the latter over historical time.

Subsidence.—Compactional subsidence operates primarily on a geologic time scale, but increased subsidence from ground-water withdrawal and hydrocarbon production is important on a historical time scale in some areas. As already stated, long-term erosional shorelines along the Texas coast are related primarily to deltaic headlands. Moreover, delta plains are a major locus of compactional subsidence (Morgan, 1977), and these erosional deltaic headlands are also spatially related to sites of potentially active faults displayed on high resolution sparker profiles from the inner continental shelf (McGowen and Morton, 1979).

In order to compare data for geological and historical time scales, rates of subsidence and concomitant rates of shoreline retreat were estimated for a postulated strandline of the Holocene Brazos-Colorado delta (Fig. 1C). The submerged strandline, which is delineated by an arcuate trend of coarse sediments containing high concentrations of shell and rock fragments (Morton and Winker, 1979), lies about 14 km offshore from the Brazos river mouth in 19 m of water. Average long-term (geological time) rates of subsidence and shoreline retreat were maximized by assuming that depth of scour during shoreline retreat was negligible, and that the strandline was formed about 7,500 years B.P. (Winchester, 1971). The subsidence rate estimated from these data, about 0.25 cm/yr, is well below the range of extant subsidence rates (0.49 to 1.28 cm/yr) reported for the area by Swanson and Thurlow (1973). Rate of shoreline retreat calculated from the same basic data is about 2 m/yr, a value considerably less than average net rates of retreat

(4 m/yr) for the western flank of the Brazos-Colorado headland (Fig. 2).

These estimates suggest that historical rates of shoreline retreat (Morton and Pieper, 1975b) and subsidence (Swanson and Thurlow, 1973) are considerably greater than geological rates for these variables. Furthermore, regional subsidence has probably been negligible since sea level reached its present position as shown on some regressive barriers by the elevations of accretion ridges that are nearly uniform and consistent with modern beach elevations (LeBlanc and Bernard, 1954).

Secular Sea-Level Variations.—Numerous authors describe shoreline erosion attendant with relative sea-level rise, but little is known about the short-term effects of slightly lower water levels that occur with secular sea-level variations (Hicks, 1972; Hicks and Crosby, 1975). White et al. (1978) suggested that droughts could cause apparent shoreline accretion, and, indeed, some of the Texas shoreline data are for severe drought periods such as the late-1800's, late-1930's, and mid-1950's. During the same drought periods sea level was lowered (Fig. 4). Thus, one might speculate that the early data are biased toward accretion because of climatic variations; however, there is adequate field evidence from beach and dune positions to substantiate shoreline accretion after the mid- to late-1800's. It seems certain, therefore, that documented shoreline movements reflect various physical processes in addition to short-term fluctuations in sea-level datum.

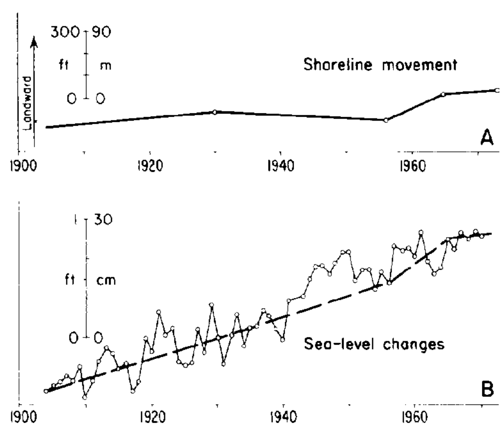

FIG. 4.—Average shoreline movement and sea-level changes for comparable periods of time, Galveston Island. Shoreline movement for each of the four periods represents an average of 18 data points equally spaced along the 27.5 km West Beach segment. Dashed line in B represents sea level for the same years as in A. Shoreline data from Morton (1974); sea-level data from Hicks (1972).

In recent years, the relative rise in sea level has been substantial (Hicks and Crosby, 1975), and it may explain part of the recent acceleration in shoreline erosion (El-Ashry, 1971). A high correlation between site specific shoreline changes and secular sea-level variations is not expected because interactions between littoral processes and shoreline behavior are complex. Furthermore, the data bases used for comparison are considerably different; shoreline data represent instantaneous positions whereas sea-level data are yearly averages. In spite of these limitations, there is reasonable agreement between shoreline movement and sea-level changes (Fig. 4) where records of sufficient duration are available for such a comparison.

Sediment Supply

Another important factor affecting shoreline movement is sediment supply. Major sediment sources for beach and barrier development were the inner shelf, riverine discharge, and updrift shoreline erosion (Bird, 1969). Local sediment sources including late Pleistocene and early Holocene deposits on the shelf were proposed for the Texas coast by Shepard (1956), van Andel (1960) and McGowen et al. (1972). However, this source has probably diminished due to equilibration of the inner shelf profile as suggested by Shepard (1960) and Tanner (1975). Gradual diminishment of shelf sand as a major sediment source leaves only riverine discharge and updrift shoreline erosion.

Riverine Supply.—Of the four Texas rivers that debouch directly into the Gulf of Mexico (Fig. 1), only the Rio Grande and Brazos River are potentially major suppliers of sand to Gulf beaches. The San Bernard and Colorado Rivers have not been major contributors in historical time because the former drains a small area (1900 km^2) and the latter prograded into Matagorda Bay until 1932 when a channel was dredged across Matagorda Peninsula (Kanes, 1970). Flow of the

Colorado River is regulated and substantial volumes of sediment are still deposited in the dredged channel and delta; what little sand reaches the Gulf is not enough to retard erosion even at the river mouth (Morton et al., 1976).

More important, however, are the recent studies suggesting that the Brazos River and Rio Grande may now be minor contributors of sediment. Historical records and sediment analyses for the Brazos River were used by Mathewson and Minter (1976) to evaluate the effects of stream regulation and reservoir sedimentation on sand supply. They calculated that the Brazos River delivers about 860,000 m^3 per year to Gulf beaches, which is only 30% of the calculated rate for pre-dam periods. On the basis of these estimations, Mathewson and Minter (1976) concluded that reductions in sand supply adequately explain the recent increased erosion in the vicinity of the Brazos delta. Similar attempts to quantify bed load transported by the Rio Grande have not been made, but if yearly records are any indication, then reductions in sediment supply have been greater for the Rio Grande (Morton and Pieper, 1975a) than for the Brazos River (Morton and Pieper, 1975b). After construction of Falcon Dam in 1955, discharge and suspended sediment for the lower reaches of the Rio Grande diminished more than 80% and 95% respectively.

These estimated and inferred reductions in supply of beach sand follow perhaps even greater pre-historic reductions due to (1) natural diversion of the Colorado River into Matagorda Bay (McGowen et al., 1976) and (2) decreases in fluvial discharge associated with post-glacial climatic changes. Climatic reductions in discharge were recognized by Dury (1965) based on valley meanders of some Texas coastal streams including the Brazos River. Using these same criteria, Epps (1973) calculated that bankfull discharge for the ancestral Brazos was 5 to 9 times greater than extant discharge. Undoubtedly the Rio Grande has experienced similar long-term reductions in discharge and sediment supply.

Littoral Drift and Shoreline Erosion.—Rates of littoral drift are more difficult to evaluate than riverine supply because available data are site specific and sometimes differ by an order of magnitude because of different assumptions and sources of data. Littoral drift estimates have come from annual maintenance dredging records (Carothers and Innis, 1962), impoundment at jetties (Johnson, 1956; Hansen, 1960; Weiser and Armstrong, 1963), spit accretion (Mason and Sorensen, 1972), sediment tracer studies (Hall, 1976), and theoretical calculations based on wave parameters and current velocities (Watson and Behrens, 1970; Hall, 1976). Collectively these studies show that annual net transport rates range from 15,000–300,000 m^3 where sand is sparse and from 100,000–300,000 m^3 where sand is abundant.

The aforementioned littoral drift rates only concern estimates of sediment in motion, they do not consider sediment sources and sinks. One time-averaged measurement of sediment supplied by updrift shoreline erosion can be obtained by taking net areal erosion (4140 ha) for the 115 year study period and applying the areal to volumetric conversion factor used by the U.S. Army Corps of Engineers (1974). This provides an estimate of nearly 3,000,000 m^3 of sediment supplied annually by shoreline erosion. Even if the quantitative relationship used by the Corps of Engineers overestimates by a factor of ten, which is unlikely, the estimated contribution from shoreline erosion (300,000 m^3) is roughly the same as highest estimates for littoral drift.

Coastal Structures.—Several assumptions were made in order to estimate the amount of sediment removed from the littoral drift system by impermeable barriers (jetties) along the Texas coast. The first assumption was that impounded material is predominantly sand. This assumption is supported by grain size analyses of beach and nearshore bottom samples adjacent to harbor entrances. Secondly, it was assumed that, in the absence of precise volumetric measurements, areal measurements of accretion and erosion would provide adequate estimates of volumetric gains and losses without using an uncertain conversion factor which is also a constant.

It was also assumed, as suggested in previous sections, that during the past century beach accretion was supplied primarily by updrift beach erosion. Indeed, the data suggest that sediment supplied by shoreline erosion was greater than that deposited by shoreline accretion. Total net losses along the Texas coast between the late 1880's and 1974–75 were nearly 7200 ha whereas total net accretion for the same period was about 3100 ha. Of the latter amount, 2250 ha were associated with jetty construction. Disregarding differences in beach substrate and other sediment sources, unadjusted accretion at jetties accounts for about one-third of the unadjusted total net erosion. If some sediment eroded nearshore was deposited in areas other than the beach, for example in washovers or tidal deltas, then accretion at jetties represents an even higher proportion of sediment supplied to the beach. Conversely, if riverine sources were more important than shoreline erosion, then accretion at jetties represents a lower proportion of sediment supplied to the beach.

Perhaps the most difficult sediment supply estimation is the relative proportion of sand derived from principally mud substrates. Erosion of deltaic headlands (Fig. 1) supplies considerable reworked mud, but the percentage of sand is low, probably no more than 15–25%. These estimates come from: 1) areal distribution of sand and mud displayed on geologic maps (Fisher et al., 1973), and 2) the knowledge that suspended-load streams, characteristic of most of the Holocene and Pleistocene fluvial-deltaic systems, transport less than 15% bed load (Schumm, 1963). Based on these estimates, the erosional areas underlain by mud substrates were reduced 75%. The total adjusted net losses (3125 ha) provide a better estimate of sand contributed by shoreline erosion.

Shoreline accretion estimates were also reduced because beach progradation at jettied inlets was probably supplied not only by updrift erosion but also by landward transport of sediment eroded from ebb-tidal deltas (Morton, 1977b). Sediment volumes reported by Morton (1977b) were used to estimate offshore sand contributions that ranged respectively from 13% to 100% at Sabine Pass and Aransas Pass; accordingly, littoral-drift accretion attendant with jetty construction was reduced from 2250 to 1725 ha. In the final analysis these adjusted data suggest that, on the Texas coast, impermeable jetties are collectively the greatest sediment sink, trapping more than 50% of the sand supplied by shoreline erosion since their construction. Thus, reductions in present sediment supply from natural causes may be surpassed by human activities that disrupt longshore drift and store large volumes of sediment.

DISCUSSION

Judging from relict river morphology (Dury, 1965) and widespread occurrences of beach ridges (Davies, 1961; Allen, 1965; Nossin, 1965; Bigarella, 1965; Curray et al., 1969), sediment supply was abundant and accretion dominated in many coastal areas as sea level approached its present position. But natural conditions that promoted shoreline accretion have ceased to be effective following diminution of shelf supplies and marked decreases in riverine discharge, so that many beach-ridge complexes are now eroding (Tanner and Stapor, 1971).

Many shorelines throughout the world are eroding (Shepard and Wanless, 1971; Tanner, 1975) and it seems highly improbable that human activities are responsible for such ubiquitous erosion. The uncertainty of human effects on regional shoreline changes stems from a lack of precise quantitative data for sediment budget and relative sea-level conditions preceding human alterations. Furthermore, the hysteresis following human activities is poorly defined.

The available data suggest that long-term shoreline erosion in most coastal areas is largely due to natural (non-human) processes and conditions. The most recent historical changes, however, appear to be greatly influenced by human activities. The strongest indictments against human-induced shoreline changes are the unpredictable but rapid local responses attendant with engineering modifications. For example, maximum sustained rates of accretion (+75 m/yr) and erosion (−55 m/yr) documented for the Texas coast were associated with jetty construction and subsequent channel diversion at the mouth of the Brazos River (Morton and Pieper, 1975b). Rates of shoreline change at other man-altered channels are less spectacular, but they are still well above average and generally account for the distribution tails shown in Figure 3.

The present study supports the growing

body of data that suggests that oceanic shoreline erosion is largely the result of decreases in sediment supply and relative sea-level rise with major contributions from human activities in local areas. Anthropogenic causes will probably become even more important in the future, especially where coastal and river basin development is intensive. The recent acceleration in coastal erosion may be partly related to increased rise in relative sea-level (Hicks and Crosby, 1975), but it could also signal crossing an equilibrium threshold beyond which human alterations play a more important role.

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