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Beach and Shoreface Response to Sea-Level Rise: Ocean City, Maryland, U.S.A.

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ABSTRACT

Sea-level is one of the principal determinants of shoreline position. Sea-level rise induces or accelerates on-going shore retreat since deeper water decreases wave refraction, thus increasing littoral drift, and also allowing waves to arrive closer to shore before breaking. Tidal records from the US East and Gulf coasts indicate a relative sea-level rise of approximately 0.3m has occurred during the past century. Concomitantly, erosion has been prevalent almost everywhere along these sandy shorelines. Ocean City, Maryland, was selected as a case study site to determine historical shoreline changes and to project future beach erosion based on accelerated rates of sea-level rise. During the past 130 years (1850-1980), this shore has retreated approximately 75m and many highrise buildings at Ocean City are now threatened during storm conditions. Accelerated sea-level rise is expected to increase the rate of retreat by a factor of 2 to 5 based on analysis of present trends. This significantly reduces the planning time available for mitigating the hazard and increases the vulnerability of this urbanised barrier through time.

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1. INTRODUCTION

Sea-level has always been rising or falling throughout geological time relative to the land surface. The last major change in sea-level occurred during the most recent Ice Age, when sea-level was approximately 100m lower than at present. The rate of rise during the last several thousand years has slowed, but recent tide gauge data show a definite upward trend for sea-level along the US east coast (HICKS, DEBAUGH and HICKMAN, 1983). Sea-level may now be rising as fast as at any time during the Holocene transgression (GORNITZ, LEBEDEFF and HANSEN, 1982).

Relative sea-level rise is the summation of worldwide (eustatic) and local (isostatic) components. Subsidence due to the compaction of unconsolidated coastal sediments probably accounts for the bulk of the isostatic component in non-tectonic areas. The eustatic rise is due mainly to the thermal expansion of water (steric effect) and contributions of water due to melting glaciers.

An additional cause for concern is what effect the increasing levels of carbon dioxide in the atmosphere may be having now, and in the future, on the rate of sea-level rise. If recent trends continue, most scientists believe that the atmosphere CO_2 could double in the next century, largely resulting from the burning of fossil fuels. The US National Academy of Sciences has estimated that this doubling will induce a rise in the Earth's average surface temperature by 1.5-4.5°C (CHARNEY, 1979). Other gases released into the atmosphere by Man's industrial activity may double the warming effect expected from CO_2 alone. Such climatic warming will accelerate the worldwide rate of sea-level rise.

As sea-level rises, a number of complex and related interactions come into play. Most of these changes occur in concert, but individually can be seen to result in several distinct responses. Rising sea-levels cause a general retreat of the shoreline; over geological periods, this phenomenon is termed a marine transgression. This shoreline change is produced by erosion and/or inundation of the land. Classically, erosion is the physical removal of beach and cliff material, while inundation is the submergence of the otherwise unaltered shoreline. During at least the last century, there has been a significant rise in relative sea-level, which has resulted in pronounced shoreline recession along most US Atlantic and Gulf coast beaches (e.g. OERTEL and LEATHERMAN, 1985) and indeed along the large majority of sandy beaches worldwide (BIRD, 1976).

Coastal zones are inherently dynamic environments, being characterised by differing geomorphic processes and coastline configurations. To take account of such wide local variability in site and process, this study has combined analyses of historical trends and empirical approaches to model predictively changes at Ocean City, Maryland. Shoreline changes are estimated for a range of projected rates of sea-level rise (baseline, mid-low and mid-high) at particular time periods (2025, 2050 and 2075). In addition, results from several other approaches (e.g. Bruun Rule, sediment budget computation, and a numerical model) have been compared in terms of the predictions of future shoreline retreat.

2. HISTORICAL ANALYSIS

2.1 *Shoreline Changes*

Ocean City, Maryland, is situated on an Atlantic coastal barrier called Fenwick Island. The coastal city extends from the Delaware border to Ocean City Inlet (Fig.1). Net longshore transport of littoral sands is to the south, although there are seasonal reversals in trend. The average annual net longshore sand transport is estimated to be 115,000m^3 (US ARMY CORPS OF ENGINEERS, 1980).

A shoreline mapping procedure, termed Metric Mapping, has recently been developed to quantify historical shoreline changes with a high degree of accuracy (meets or exceeds National Map Accuracy Standards) and relatively low cost (LEATHERMAN, 1983). This automated technique has been designed to use rapid computation techniques to simulate the best photogrammetric techniques. A large data set of historical shoreline positions (mean-high-water level) is available from the National Ocean Service of NOAA. This information included US Coast & Geodetic Survey charts (now called NOS"T" sheets) for the years 1849-50, 1908, 1929-33, as well as vertical aerial photographs (1942, 1962-63 and 1977-80). Thus, six sets of historical shorelines were available for the study area, spanning approximately the last 130 years (1850-1980).

Historical shoreline changes at Ocean City are shown in Figure 1. The average rate of oceanside erosion over the 130 years of record has been 0.6m y^{-1}, but there has been much spatial variation (LEATHERMAN, 1986). In addition, the shore has not retreated by an equal amount each year. From 1929-1962, the shore retreated at a rate of about 1m y^{-1}. Since 1962, however, the shoreline of Ocean City has retreated by only 0.2m y^{-1}. This marked departure from the trend may be due to human modifications of the shore, by groyne construction, sand scraping, and some beach fill. However, it is more likely that the lull in hurricane activity since 1960 has been the key factor.

Along the mid-Atlantic Coast, both winter northeasters and summer hurricanes can cause significant beach erosion. Each winter Ocean City is subject to several northeasters, many of which cause moderately high storm surges and flooding. The northeaster in March 1962 was more destructive than any previously known storm to have affected the area, resulting in severe beach erosion and massive overwashing. (Hurricanes generally produce higher tides than northeasters but are much less frequent.) The last hurricane of significance to affect Ocean City was Hurricane Donna, which occurred on September 12, 1960. The lull in storm occurrence along the mid-Atlantic coast during the past two and a half decades has corresponded with the period of major coastal construction. Ocean City expanded greatly in the early 1970s with the construction of high-rise condominiums and hotels (Fig.2).

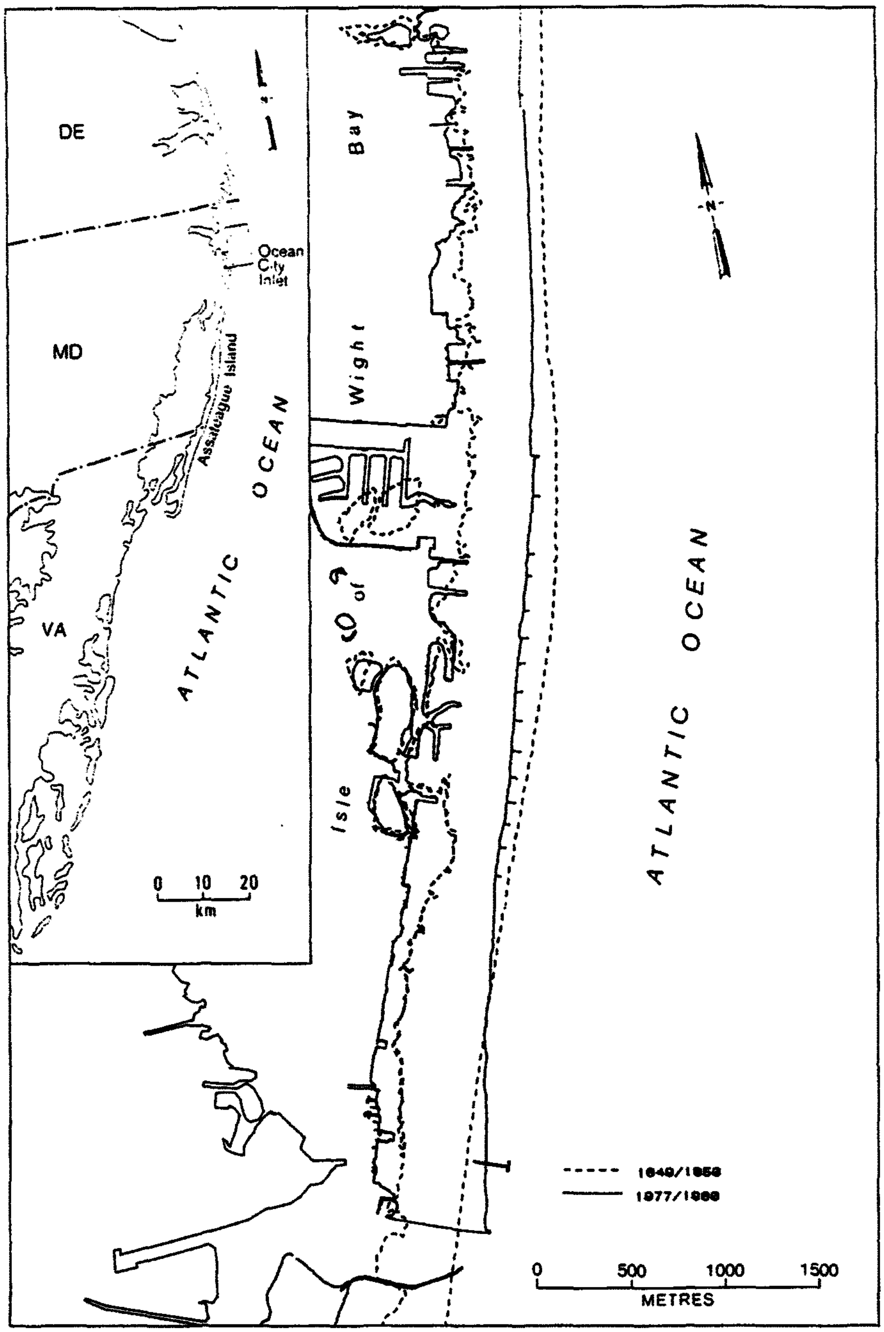

FIG.1. Historical shoreline changes (1850-1980) along Ocean City, Maryland, indicate a long-term erosion rate of 0.6m y^{-1}.

FIG.2.

The beaches along Ocean City are critically narrow, particularly during the high-energy winter months. Therefore, the current trend of recession exacerbates the problem and increases their vulnerability. Accelerated sea-level rise increases the rate of retreat by two to five times, thereby significantly reducing the planning time for hazard mitigation and making the urbanised area increasingly vulnerable.

2.2 *Shoreface Changes*

While the (mean high water line) shoreline has changed little over the last few decades in comparison to the historical trend, the adjacent shoreface has undergone substantial alteration. Bathymetric maps for the years 1962 and 1978 were available from NOAA-National Ocean Service. From these maps, profiles were drawn along 17 transects, measured perpendicularly to the Ocean City coast. All values within rectangular envelopes approximately 0.5km wide and 1.0km long, centered along the sketched transects, were individually digitised. Each map was orientated in space by digitising four map coordinates before transect values were digitised. A modified Surface II programme retrieved each transect within its envelope of stored values. Therefore, inaccuracies of adjusting map scales and directionally stretching transposed maps were avoided (SALLENGER, GOLDSMITH and SUTTON, 1975).

Table 1 presents a subset of the data, extending from 21st to 86th Streets, so as not to be influenced by any major shoreline engineering structure (e.g. the Ocean City Inlet jetties and resulting updrift accretion at South Ocean City in Fig.1). While there is considerable variation, these results are statistically significant. It is clear that the shoreface is becoming steeper through time as the -9m isobath has moved farther landward than the -6m, which in turn has out-distanced the -3m isobaths.

Human influence may be inhibiting the erosion of the exposed portion (above-water) of the beach relative to the submerged shoreface (underwater portion). While there has been some limited beach fill and bulldozing of sand from the beach face to build dunes, groynes would probably be much more effective in steepening the offshore profile, and hence slowing or even stopping shore retreat. However, groynes at most only extend as far as the -3m isobath so that they have no effect on erosion offshore. More likely, the pronounced lull in major coastal storm activity, notably the absence of any landfall or close-to-shore tracking hurricanes, has been responsible for this disequilibrium (through steepening) of the shoreface profile.

It appears that the shoreline remains in approximately the same location for a period of time, acting as a hinge as the adjacent shoreface steepens. It is not known at present what angle of shoreface inclination will be in equilibrium. Clearly, the recent continuing trend in the bathymetric data towards greater steepening indicates that the present angle is not in equilibrium. Assuming that the equilibrium angle of inclination for the shoreface occurred sometime during the survey period (1850-1965), the next major coastal storm is liable to erode the shore substantially restoring the shoreface angle back towards its equilibrium angle (MOODY, 1964).

It is a well-established geological principle that much geomorphic activity is often accomplished in quantum steps (HAYES, 1967; LEATHERMAN, 1981). Therefore, a major coastal storm would provide the impetus by shifting and redistributing nearshore sands to reverse the steepening trend of the shoreface. At this point, the shoreface returns to its minimum

TABLE 1: Beach and Shoreface Changes at Ocean City, Maryland (1962-1973) based on 9 transects between 21st and 86th Streets

	Shoreline	Isobaths -3m	Isobaths -6m	Isobaths -9m
Mean Retreat (m)	9.1	40.0	46.1	34.4
Standard Deviation of Observations	17.0	26.5	35.3	62.7
Standard error of the Estimate of the Mean Retreat	5.7	8.8	11.8	23.7
Percentage Confidence Level for the Mean Retreat Exceeding Zero (%)	90-95	99.5-99.95	99.5-99.95	90-95
Percentage Confidence Level for the Mean Contour Retreat Exceeding the Mean Shoreline Retreat	-	99.5-99.95	97.5-99	75.0-80

TABLE 2: Relative Sea-Level Rise Scenarios: Cumulative Rise above 1980 Level[1]

Year	Current Trend	Mid-Range Low Estimate	Mid-Range High Estimate
2000	0.07m	0.12m	0.17m
2025	0.16m	0.34m	0.47m
2050	0.25m	0.65m	0.92m
2075	0.34m	1.08m	1.54m

1. Sea-level rose 0.18m from 1930-1980, (data from HICKS, DEBAUGH and HICKMAN, 1983; and HOLDAHL and MORRISON, 1974). Current trend estimates from HOFFMAN, KEYES and TITUS (1983) illustrate cumulative rise and include a 1.8mm y^{-1} local subsidence rate (1980 is the base year).

angle (post storm profile) and then continues to slowly steepen again through time until the next major storm.

In summary, the shoreface appears to undergo two phase adjustment through time. A long, quiescent phase of steepening, during which shoreline position is either stationary or retreating only slowly is followed by a brief stormy period during which the shoreface profile is flattened and there is rapid landward migration of the shoreline. Research is continuing which should provide the data necessary to quantify this process and formulate a predictive model.

3. PROJECTED SHORELINE CHANGES

The analyses of historical shoreline and shoreface profiles indicate the value of obtaining long-term data in order to filter out temporal and spatial short-term anomalies. The shifts in the 0.6m isobath were assumed to provide the best estimate of the mean annual erosion rate in the long term. The shoreface has probably experienced several cycles of slope change corresponding to climatic cycles of storm and fairweather conditions, but these oscillations are averaged out over the 130 year time period (1850-1980).

Projecting future shoreline positions from historical data requires several assumptions to be made. First, the relationship between past erosion and sea-level trends must be established. Records from nearby tide gauges (HICKS, DEBAUGH and HICKMAN, 1983) indicate that from 1930-1980 the relative sea-level rise was 0.18m. The littoral nodal point for the Delmarva coastal compartment is believed to be located near Bethany Beach, Delaware (US ARMY CORPS OF ENGINEERS, 1980; Fig.1), so over hundreds of years the littoral influx and outflux of sand at Ocean City has probably remained approximately equal, except near the jetty. If this is correct, then the long-term losses of sand to the offshore, evident along the Ocean City shoreline, are due to historical sea-level rise, which has averaged approximately 0.36m per century. It has been assumed that rates of sea-level rise is the basis for the prediction of future shoreline shifts and erosion.

The sea-level rise scenarios were taken from HOFFMAN, KEYES and TITUS (1983); nine rise/year combinations were selected from the projected sea-level rise curves. Table 2 presents the algebraic sum of the projected sea-level rise and land subsidence to yield the relative sea-level rise for Ocean City, Maryland. The empirical technique of projecting future shorelines using trend lines is a good first order estimate. In this case, the shoreline response is based on the historical trend with respect to the local sea-level changes during that time period. This procedure accounts for the inherent variability in shoreline response based on differing coastal processes, sedimentary environments, and coastline exposures (LEATHERMAN, 1985).

The relationship between sea-level rise and shoreline movement is formulated by assuming that the amount of historical retreat is directly correlated with the rise rate of sea-level, so that a three-fold increase in the rise rate will result in a three fold increase in the retreat rate, so long as lag effects in shoreline responses are small compared to overall accuracy of extrapolation.

Shoreline change was projected for current trends as well as mid-range low and mid-range high projections. This trend analysis has been compared with results using the Bruun Rule (BRUUN, 1962), sediment budget analysis (EVERTS, 1985) and a numerical model (KRIEBEL and DEAN, 1985), for details of the methodologies refer to the original authors. The data have been compiled here to indicate the range of predicted values produced by radically different approaches.

For current trends, the trend projection (LEATHERMAN, this paper), except for the Bruun Rule estimate which simply involves two-dimensional sediment transfers, is more conservative than the others. By 2025, trend project estimates that the shore will erode 26m, whereas the other methods place the retreat at about 47m. For the mid-range low scenario (year 2025), the various estimates predict a shore retreat of 55-73m range, following a 34cm rise in sea-level (Table 2), whereas the estimates range from 66-83m for the mid-range high scenario. By 2075, the erosion estimates range from 140-215m for the mid-range low scenario and from 168-268m for the mid-range high scenario. All the methods yield estimates within a factor of two, except for the unadjusted Bruun Rule (Table 3), which does not account for coastal areas with significant alongshore losses of sediment.

TABLE 3: Projected shoreline retreat in metres during the 21st century for Ocean City Maryland based on four models and under three sea level rise scenarios. The models are (1) trend analysis (this paper), (2) Bruun Rule (BRUUN, 1962), (3) Sediment budget analysis (EVERTS, 1985) and (4) a numerical model (KRIEBEL and DEAN, 1985).

CURRENT TRENDS	1	2	3	4
2000	12	5	21	20
2025	26	11	47	47
2050	41	17	73	70
2075	56	23	99	95
MID-RANGE LOW	1	2	3	4
2000	20	7	26	22
2025	56	22	73	55
2050	105	43	132	93
2075	174	70	215	140
MID-RANGE HIGH	1	2	3	4
2000	27	12	29	26
2025	76	32	83	66
2050	147	63	156	107
2075	249	105	268	168

4. DISCUSSION AND CONCLUSIONS

Barrier islands, such as Fenwick Island upon which Ocean City, Maryland has been constructed, change position and shape, depending upon the relationship between sand supply, wave energy, and sea-level. There are essentially no new sources of sediment for the barrier beyond that already in the sand-sharing system or in transit through the coastal sector (littoral drift), consequently shoreline position responds to storms, coupled with long-term changes in water level.

Although storms are responsible for major coastal alterations, it is uncertain whether storms in the absence of water-level changes could continue to alter the shoreline. Wave-driven longshore transport would continue to erode headlands, to build spits, and to fill concavities, so static shoreline conditions are never likely to be achieved. Along straight barrier shorelines this effect is minimised. However, beach stability in a two-dimensional sense (Bruun Rule) should theoretically be reached as shown by wave-tank tests.

Perhaps a constructive way of viewing the allied roles of sea level and wave energy is that sea level adjusts the stage for profile adjustments by coastal storms. Long-term sea-level rise disturbs the equilibrium of the beach/nearshore profile so that sporadic storms accomplish the geological work in a quantum fashion. Certainly major storms are required to stir the bottom sands at great depths offshore and hence fully adjust the profile to the existing water level. Therefore, the underlying assumption is that each beach profile equilibrium will be the result of an interaction between water-level and a particular wave-climate.

The steepening offshore profile is a response to the fair-weather wave conditions during the past few decades and does not argue against the BRUUN (1962) formulation. Indeed, the Bruun Rule applies to the long-term (50-100 year) changes in an oceanic setting during which there has been an appreciable rise in sea-level (0.15-0.3m). These short-term perturbations in the "equilibrium profile", however, are significant to beach communities as they signal increased vulnerability to future major storms. Unfortunately, public attention is focussed on the exposed beach, and shoreface steepening continues largely unnoticed.

The fundamental difficulty of planning for sea-level rise is the present uncertainty about the probability and magnitude of the phenomenon. While coastal storms have been subject to many more scientific studies than sea-level rise induced-erosion, our ability to predict the likely range of sea-level rise already exceeds our predictive capability for many other factors that are routinely considered in decision-making, such as the severity of the next major storm (a frequency-magnitude relationship). The long-term planning for Ocean City, Maryland, must take into account the erosional potential of accelerated sea-level rise.

The ultimate question that must be addressed by coastal barrier communities is whether to try to hold the line as sea-level rises or to plan for a retreating shore. If the postulated acceleration in the rate of rise due to the greenhouse effect is realised even within the less extreme forecasts, over the next 50 to 100 years it will probably become too expensive to maintain a recreational beach; massive sea-walls will be needed to protect the high-rise buildings from the surf. Therefore, it is prudent to assemble and analyse all the coastal process and geomorphic information available and continually to update and refine data base as sea-levels rise. Coastal residents can then start to plan for the future risk, rather than have to wait and suffer the inevitable consequences as they occur.

5. ACKNOWLEDGEMENTS

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