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top of the mattress is usually approximately 2 ft above the low water plane facors this approach.

CONCLUSIONS

Whereas similar pile dikes and bank revetments constructed in the Savannah River prior to the present project have an excellent performance record, it is too early to report on the functioning of those constructed in the present project. It is known that the quantity of rock placed around the dikes will have to be adjusted and that additional dikes and revetments will have to be constructed as part of the future maintenance program. Field examinations will constitute an integral part of the maintenance program and it is to be expected that the Savannah District will issue such reports as to the adequacy of the navigation channel and the performance of its appurtenant works as cumulative experience may warrant.

ACKNOWLEDGMENTS

The present work is part of a series sponsored by the ASCE Task Committee on Channel Stabilization Works, with the purpose of advancing the knowledge and practice of the profession in this special field that is becoming increasingly important.

Journal of the

WATERWAYS AND HARBORS DIVISION

Proceedings of the American Society of Civil Engineers

SEA-LEVEL RISE AS A CAUSE OF SHORE EROSION

By Per Bruun,[1] F. ASCE

SYNOPSIS

It is an established fact that sea level is rising slowly and irregularly. Also, it seems to be true that erosion on most seashores built up of alluvial materials greatly exceeds accretion. The paper attempts to relate the two phenomena; rise of sea level and erosion.

RISE OF SEA LEVEL AND ITS RELATION TO SOLAR RADIATION

According to R. W. Fairbridge,[2] preliminary conclusions from studies of solar variations and climatic change indicate that "ice ages" are produced by normal variations in observed solar-controlled metereological effects that are reinforced, probably aperiodically in geological time, by terrestrial, topographic "accident."

According to Fairbridge, long-term metereological and historical records disclose multiple cycles (for example, 11-yr, 22-yr, 40-yr, 80-yr, 189-yr and 567-yr periods) related, in part, to sunspots, geomagnetic phenomena, and planetary motions. Mean, annual temperatures in temperate belts vary 2°C-3°C. The longer the period, the greater the effect in terms of snowfield accumulations or glacier ice melting. This concerns the world hydrologic balance and, thus, is reflected on world tide gages. Whereas

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1 Head, Coastal Engrg. Lab., Univ. of Florida, Gainesville, Fla.

2 "Eustatic Changes in Sea Level," by R. W. Fairbridge, "Physics and Chemistry of the Earth," Pergamon Press, Vol. 4, 1961, p. 99.

snow and ice accumulation advances directly in short steps, melting shows marked retardation. Major astronomic cycles with period of 21,000 yr, 40,000 yr, and 92,000 yr control absolute and hemispheric variations in effective solar radiation. Mid-latitude temperatures will vary 3°C-5°C. and will mainly influence the northern hemisphere, which contains 95% of the world's sensitive mountain glaciers.

The earth will remain relatively cool while Antarctica lies symmetrically about the South Pole. However, temperate belts will continue to be alternately glaciated and deglaciated every 40,000 yr to 90,000 yr.

HYPOTHESES RELATING TO DISPLACEMENT OF LAND AND SEA

Sea-level changes in the Quaternary have evoked some ingenious theories. It is now established that during the half-million-year Quaternary, the sea level has oscillated in a manner as rapidly and extreme as was ever before observed in geological history. During the warm, interglacial phases, the shorelines advanced inland leaving erosion cliffs, terraces, and platforms behind. During the cool, glacial phases the shorelines advanced seaward and new land was built up leaving ridges and plateaus emerged for later submergence.

The ice-age oscillations involved withdrawals of huge water masses from the sea on the polar land masses. The present volume of sea water is approximately 1370 x 10^6 cu km, but there is still a considerable quantity of water locked in the present-day continental ice caps and glaciers. For the Northern Hemisphere the glacier area is estimated to somewhat over 2 x 10^6 sq km; for the Southern Hemisphere 13 x 10^6 sq km, thus a total of 15 x 10^6 sq km or approximately 37.5 x 10^6 cu km of ice averaging 2.5 km thick. Because the area of ocean surface is 360 x 10^6 sq km, a total melting of 37.5 x 10^6 cu km of ice would cause a sea-level rise of 95 m (315 ft). Due to oceanic crustal lowering, marginal to rising continental areas, and to the fact that the rising sea would spill over enormous lowlands greatly expanding the present ocean area, the final level of the ocean might be perhaps only approximately 50 m above the present datum. (Present as used herein is in a geological rather than literal sense.)

The area of the last glaciation maximum has been determined at approximately 40 x 10^6 sq km or to approximately 40 x 10^6 sq km ice. This corresponds to the maximum measured fall of sea level, 100 m (330 ft), or to "the Wisconsin" glacial period in the United States. However, owing to the progressive build-up of Antarctica over four or five glacial cycles of the Pleistocene, the total removal of water may approach 200 m (660 ft).

Fig. 1, from Fairbridge,[2] gives an impression of these grand-scale fluctuations in sea level. It may be seen that the "deglacial geoid" continues downward, which phenomena can only be explained by an overall sea level lowering controlled by the tectonic shape of the ocean basins, or polar shift. The drowned sea mounts of the Pacific Ocean may be taken as an example.

The development of sea-table elevation during approximately the past 20,000 yr is depicted in Fig. 2 from Fairbridge.[2] Approximately 10,3000 years ago began the Finiglacial retreat of Scandinavia and the late Valders retreat in North America. Sea level rose rapidly at 20 mm to 30 mm a year until it reached 15 m below present datum. The movement apparently came

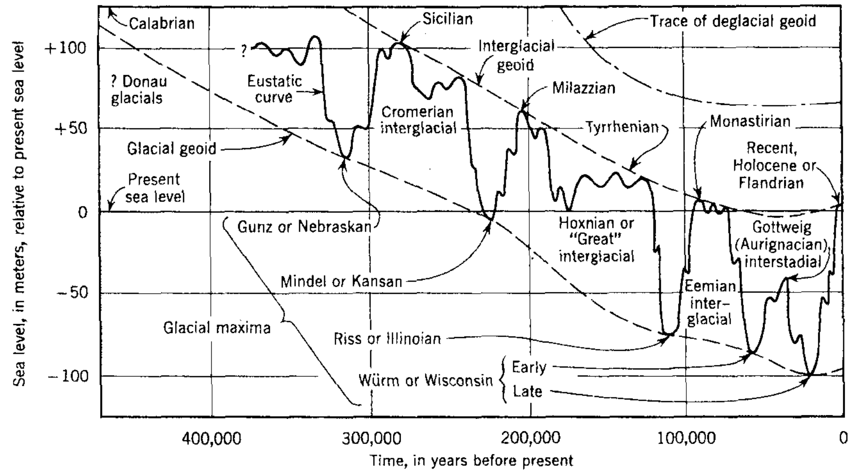

FIG. 1.—QUARTERNARY EUSTATIC OSCILLATIONS

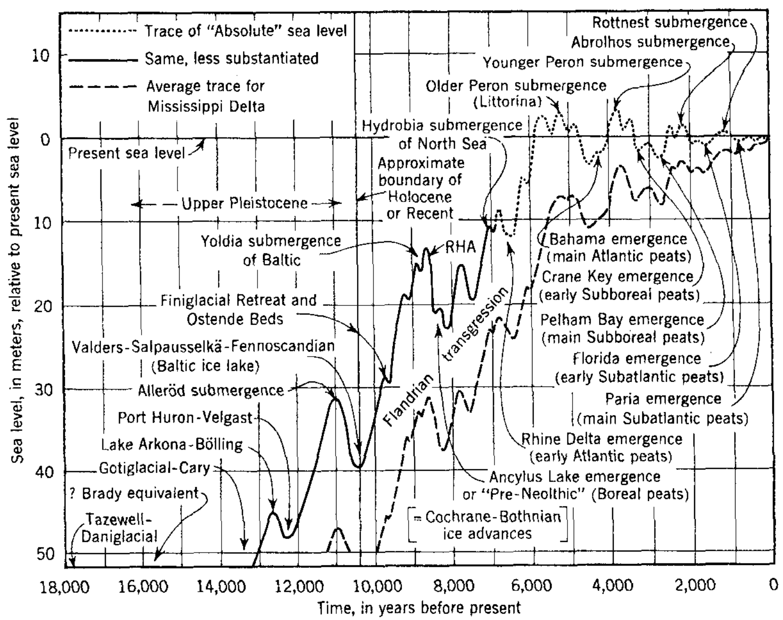

FIG. 2.—EUSTATIC OSCILLATIONS DURING THE POST-GLACIAL TRANSGRESSION

in sharp, jerky steps. The Mid-Recent or Middle-Littorina submergence is the culmination of the universal climatic and oceanic warming that began before the end of the Pleistocene. The level of the ocean rose at a remarkable rate. The highest position reached by this sea in most places was 3 m to 5 m above the present and occurred 5,000 yr to 6,000 yr B.P. Certain peat formations from 1.5 m to 2.0 m below surfaces in the Everglades south of Lake Okeechobee are dated fromthis period.

The so-called "Florida Emergence" that occurred approximately 2,100 to 1,600 years ago had sea-level elevations of approximately 2 m below present, probably adding 1/8 mile to 1 mile to the general Florida shores, depending on offshore bottom slope. It coincides with a slight advance of northern glaciers. From a historic point of view, it is interesting to note that this period covers the Roman Era and that data from Britain, Italy, and the Mediterranean suggest a low sea level at this time. Apart from notoriously unstable and volcanic areas, there is widespread evidence of the "drowning" of Roman coastal structures. The deep foundations of some ancient habor works may not have been so difficult to construct as they seem today. Climatically, the Florida Emergence coincides with a universal cool phase.

In examining the sea-table fluctuations of the past 100 yr, note that average world rise for the 1900-1950 period was 1.2 mm, annually, corresponding to the average rise since the Roman Era of approximately 2,000 mm. Meanwhile deglaciation can result in sea level rising at 25 mm or approximately 1 in. per yr. In the 1946-1956 period, the rise[2] was 5.5 mm per yr. H. A. Marmar[3] lists approximately 8 mm, annually, from 1930 to 1948, for the entire eastern seaboard of North America. Yet, an appreciable component in this sea-level rise, only approximately 20% is "eustatic" (overall sea level) is possibly due to a secular decelaration of the Gulf Stream. This decreases pressure differences between its right- and left-hand side caused by the Coriolis force. Such pressure fluctuation is noted in the annual changes in the difference of sea level between stations on opposite sides of the Gulf Stream; for example, between Miami and the West Bahamas. This difference is normally of the order of approximately 0.6 m (2 ft). The seasonal variation in water temperature (density of water) is clearly indicated in records along the Southeast coast of Florida where the maximum sea level occurs in September and October, apparently caused by the summer heating of the water, as explained by H. Stommel.[4]

Fig. 3 shows some water-level records for Florida coast cities based on data furnished by the Coast and Geodetic Survey, (United States Department of Commerce (USC&GS). In Fig. 3 the yearly value for each station represents the average height of sea level as determined by averaging the readings of the height of the sea at that station at the beginning of each hour throughout the year. In other words, each value is the average of nearly 9,000 hourly readings. At each station, the hourly heights of the sea were referred to a tide staff, the elevation of which could be kept constant by frequent leveling to a number of adequate bench marks. From this figure it can be seen that the rise in sea level in the 1930-1950 period has been up to 10 mm (0.03ft), on the east coast of Florida [Figs. 3(a) and 3(b)]. On the Gulf Coast [Figs. 3(c) and 3(d)], it has been up to 8 mm (0.025 ft) per year. Considering the 1930 to 1960 period, it can be seen that the rise of sea level has slowed down somewhat the last decade but may be increasing again. For the entire 1930-1960 period, rise has been 3 mm to 5 mm annually on the east coast of Florida and 3 mm to 4 mm annually on the Gulf side.

The consequences of the rises in sea level on shoreline movements are mentioned in a following section on "Theory of Erosion by Rise of Sea Level."

3 "Is the Atlantic Sinking? The Evidence from the Tide," by H. A. Marmar, Geological Review, Vol. 38, 1948, p. 652.

4 "The Gulf Stream," by Henry Stommel, Univ. of California Press, Los Angeles, Calif. 1960.

DIMENSION OF THE NEARSHORE LITTORAL DRIFT ZONE

The dimension perpendicular to the shore of the nearshore littoral drift zone depends on many factors including material, slope, wave, and current characteristics. It may be determined by comparison of shore sediments and offshore bottom sediments, but it is apparent, beforehand, that there will be no clear definition of this zone. Rather, the shore-sediment characteristics on the offshore bottom will gradually taper off with increasing depth and probably be replaced by "offshore sediments" of great variety. This leads to an examination of the so-called "continental shelf."

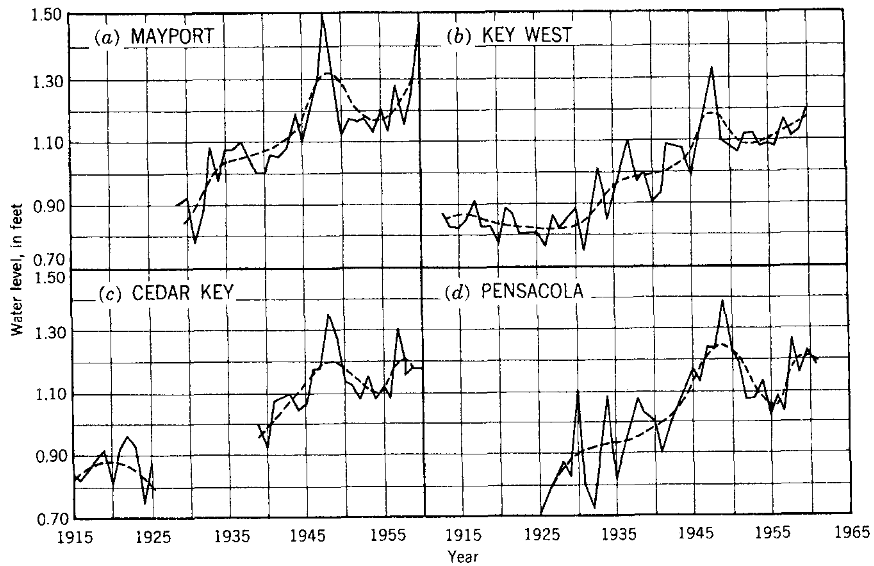

FIG. 3.—VARIATIONS IN AVERAGE YEARLY SEA LEVELS AT FLORIDA TIDE GAGES

The continental shelf is a region where continental and marine influences have acted alternately during successive emergences and submergences. Continental shelves have various origins. According to A. Guilcher,[5] the continental shelf is usually wide off low-lying continents and narrow or absent off

5 "Coastal and Submarine Morphology," by André Guilcher, John Wiley & Sons, Inc., New York, N. Y., 1958.

mountainous regions. The shelf is wide in northwestern Europe, in the Arctic off the USSR and the east and Gulf coasts of the United States. It is narrow in front of the Pacific coast of the United States. The average width of the shelf is approximately 40 miles. The continental shelf meets the continental slope at a slight angle, but this break of slope is not always at the same depth and is often difficult to locate precisely. It is usually found between 120 m and 180 m (70 to 100 fathoms).

The continental shelf has originated by various means. Shelves of limited width may consist of two parts: An inner abrasion platform, and an outer constructional form built up of material eroded during the formation of the inner part. The best example of a constructional form (with subsidence of the sediments) is the shelf off the east coast of the United States, that, to a high degree, was built up of eroded material from the Appalachian rocks. The coastal shelf of the Gulf of Mexico is the same type and has been formed by a great mass of material brought down by the Mississippi River and other streams.

If sea level remained constant for an extended period and if waves were the only important factor in sedimentation, the caliber of the sediments should decrease away from land. In reality, the distribution of sediment on the continental shelf is complex, and many factors seem to be involved in its configuration and composition. Pebbles have been found at great depths in a variety of places. Off Southern California, they have been dredged up from all depths between 18 m and 900 m (60 ft and 3,000 ft). These pebbles were probably in most cases deposited by currents.

Submarine currents may form ripple-marks on sandy bottoms. They have been photographed on George Banks, New England, at a depth of 225 m (750 ft) but they are known from depths up to 2,000 m (approximately 7,000 ft) in restricted straits in the Canaries and East Indies. This indicates that currents with eroding velocities (greater than approximately 0.3 m per sec or 1 ft per sec) exist.

The movement of material from the shore for depositing in the offshore area is probably a slow process by which various kinds of currents—including longshore currents, rip currents, and density currents—are active. With respect to the exchange of material between the shore and the offshore bottom, little is known about the rate of this process because many factors are involved, including the character of shore material and the characteristics of wave and current activity. Most likely, a distinction will have to be made between a short-range process of "fluctuation nature" and a long-range geological adjustment process. With respect to littoral-drift material, the observations by Parker Trask[6] are of particular interest.

Trask explains that present data clearly indicate that sand does move around the rocky California promontories. Meanwhile it seems to be clear that a little sediment is transported beyond a depth of 18 m (60 ft).

D. L. Inman[7] reports that bottom surveys at Scripps Institution of Oceanography, La Jolla, Calif., indicate that most seasonal, offshore-onshore interchanges of sand occur in depths of less than 9 m (30 ft) but that some seasonal effects may extend to greater depths. Inman describes the areal distribution pattern (for this particular location), that shows a pronounced alinement of

6 "Movement of Sand around Southern California Promontories," by Parker Trask, Technical Memorandum No. 52, Corps of Engrs., Beach Erosion Board, 1954.

7 "Areal and Seasonal Variations in Beach and Nearshore Sediments at La Jolla," by D. L. Inman, Technical Memorandum No. 39, Corps of Engrs., Beach Erosion Board, 1953.

sediment properties generally parallel to the beach. There are numerous possible interpretations of the alinement and banding of sediment attributes. Surf beats may be one explanation. Another may lie in the seaward transportation of sediment by diffusion, resulting from a horizontal gradient in concentration of suspended material from the surf zone where concentrations are high, to offshore areas where they are relatively low. In addition to seaward transportation by diffusion, it is well known that a net, onshore transportation of sediment occurs along the bottom because of the differential between onshore and offshore velocities associated with the orbital motion of nearshore waves.

The writer has described[8,9] deep-water erosion on the Danish North Sea Coast of up to 20 m (70 ft) depth.

From the previously noted studies, a reasonable assumption seems to be that with sandy shores of exposed Pacific or Atlantic type, the 18-m (60-ft) depth contour forms some kind of limit between "nearshore" and "deep-sea" littoral drift phenomena that, in this respect, means that short-term exchange of shore material and offshore bottom takes place inside (although not always up to) this depth. It should not be forgotten that the slope of the offshore bottom must be of significant importance. A very gentle slope will undoubtedly slow down transversal migration of material by giving rise to a considerable phase-difference between "action" (rise of sea level) and "reaction" (shore erosion). On the other hand, a very steep, offshore bottom will have the opposite effect manifested in a relatively quick response (in the form of erosion) to rise of water table. In as much as the slope and width of a littoral drift zone are closely connected, it could be expected that a wide "shelf" would demonstrate considerable phase displacement and higher stability than a narrow shelf. A narrow shelf may develop an "equilibrium profile" to a considerable depth indicating displacement of material from the shore to the offshore bottom. If the offshore bottom, such as the southeast coast of Florida at about 18-m (60-ft) depth, turns over to a steeper slope, the tendency to transfer of material to deep water by the assistance of gravity forces may be detectable in the shore stability as an increased shoreline recession.

THEORY OF EROSION BY RISE OF SEA LEVEL

Reference is made to Fig. 4. Consider an equilibrium profile.[8,9] If the water table rises a millimeter, the quantity of material needed to re-establish the same bottom depth over a width of shelf, b, is b times a.

Consider a shoreline that is in longshore quantitative equilibrium, which means that the same quantity of material that is passing in from the updrift side is also passing out downdrift. The quantity b a must be derived from erosion of the shore. This will give rise to a shoreline recession, x. If the elevation of the shore is e, the quantity eroded above sea level is x e. Meanwhile, in order to re-establish the original equilibrium bottom-profile, the entire profile must be moved shoreward by the same distance, x, up to depth, d, at distance, b, from the shoreline. The balance between eroded and deposited

8 "Coast Stability," by Per Bruun Danish Tech. Press, Copenhagen, Denmark, 1954.

9 "Coast Erosion and Development of Beach Profiles," by Per Bruun, Technical Memorandum No. 44, Corps of Engrs., Beach Erosion Board, 1955.

quantities by the two independent movements is expressed by

$$x\,e = a\,(b-x)\,d \quad \text{(1a)}$$

or

$$x(e + d) = a\,b \quad \text{(1b)}$$

To test the validity of this concept on a short-term basis, it will be necessary to look for a coastal area at which the phase-difference between rise of sea level and its influence on erosion is relatively small. This, as previously mentioned, will be true for an area with a steep, offshore bottom. Another assumption is that the edge of the continental shelf is no nearer the shore than at approximately the 18-m (60-ft) depth on the exposed Pacific or Atlantic shores.

Such a situation exists along the Southeast coast of Florida between Palm Beach and Miami. Yet part of the shore has rock reefs; and in the Hallandale-Miami Beach Area, a rocky, gently sloping "platform" exists between 12-ft and 20-ft depths. The distance of the 18-m (60-ft) contour from the shoreline

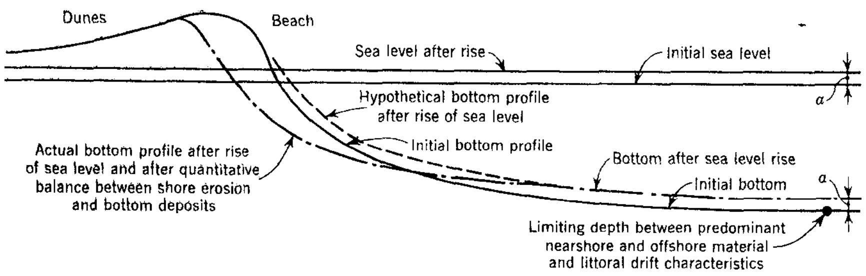

FIG. 4.—INFLUENCE OF SEA-LEVEL RISE ON THE DEVELOPMENT OF BEACH AND OFFSHORE PROFILE

is approximately 2,000 m. Introducing the following figures in Eq. 1b: x denotes the shoreline recession per year; a = the sea level rise per year b = 2, 000 m; e describes about 3 m (10 ft); and d = 18 m (60 ft); yields

$$x(3 + 18) = 2{,}000\ a$$

Referring to the preceding section on rise of the sea table, a rise of 1.2 mm per yr gives x = approximately 11 cm = 1/3 ft per yr. This figure is not in agreement with recent experience. Most likely the 2,000-m shelf is not wide enough to reflect very small but tough, long-term rises. In long-term periods, material is probably "tipping over" the edge of the shelf to deep water; thereby increasing erosion. It is, therefore, more likely that the development on this shore reflects the short-term rapid rises of sea level. Using the 6mm average figure for the rise in recent decades gives: x = approximately 57 cm per year = 2 ft per yr. With a 15-m (50-ft) depth on this short-term basis, x = approximately 2.4 ft.

The 2-ft to 2.5-ft shoreline recession per year is a realistic value when the shores not affected by inlets or groins are considered, but it should still

be borne in mind that even on a short-term basis, it is possible that (fine) material disappears in the deep waters past the edge of the shelf and that this will cause an increase of the shoreline recession.

On the upper east coast, the depth at 2,000 m from the shoreline is approximately 15 m (50 ft), whereas the 18-m (60-ft) contour is from 1.5 miles (St. Augustine-Daytona) to 5 or 6 miles (New Smyrna) out. South of Cape Canaveral to Sebastian Inlet, the 15-m (50-ft) contour is approximately 4,000 m out, while the 18-m (60-ft) contour is from 5 to 8 miles out. Between South Fort Pierce Beach and St. Lucie Inlet, the 15-m (50-ft) contour is 8,000 m out and the 18-m (60-ft) contour is 4 to 6 miles out. Bottom slope between 15-m to 18-m (50-ft and 60-ft) depths is gentle in these areas and will considerably retard the transfer of material seaward. It is not likely, therefore, that the effect of short-term, rapid sea-level rises will make themselves felt on the bottom areas between 15-m to 18-m (50-ft and 60-ft) depths. On the other hand, it may be possible to trace the long-term influence. Introducing, in Eq. 1(b) the following figures for the areas north of Cape Canaveral to Daytona Beach and from the Cape south to about St. Lucie Inlet: a = 1.2 mm per yr; b = approximately 5 miles or about 8,000 m (average); e = 4.5 m (15 ft); and d = 18 m (60 ft); yields

$$x(4.5 + 18) = (8{,}000)\ (0.0012)$$

$$x = 0.43 \text{ m or approximately } 1.4 \text{ ft}$$

This figure also seems realistic when an extended period of time is considered. With respect to the development on a short-term basis (from 1945 or 1950 to 1960), the figures a = 6 mm per year; b = 2,000 m (North of Canaveral, New Smyrna and Daytona); e = 4.5 m (15 ft); and d = 15 m (50 ft); yield

$$x(4.5 + 15) = (2{,}000)(0.006)$$

$$x = 0.6 \text{ m or 2 ft per yr}$$

which is probably a realistic average figure for recent years—perhaps a little on the high side. It should be remembered that the recording of shoreline movements on a short-term basis involves many uncertainties.

Similar considerations for the Gulf shores are only possible for the upper west coast in as much as the lower west coast is penetrated with inlets and passes to such an extent that they dominate the erosion situation. For the upper Gulf Coast (Santa Rosa Island), the 18-m (60-ft) contour is located on the average 3,000 m from the shore, and beyond this contour the bottom slope is gentle, although no abrupt change in slope occurs at the 18-m (60-ft) depth. Introducing in Eq. 1b the following figures: a = 1.2 mm per yr; b = 3,000 m; e = about 4 m (13 ft); and d = 18 m (60 ft); yield

$$x(4 + 18) = (3{,}000)(0.0012)$$

$$x = 0.16 \sim 1/2 \text{ ft per year}$$

which probably is a realistic figure in as much as these shores are rather stable although slight erosion is visible on some of the dunes. It may be asked why a higher figure corresponding to the more rapid rise in sea level in recent years is not used as on the lower east coast? The most logical answer to this question seems to be that said shore, as already mentioned, is stable and does not reflect any response to the rapid rises that, as demonstrated by

Fig. 3, is not either as rapid on the Gulf as it is on the east coast. Consequently, it must be assumed that the development because of the modest wave action is tough and does not respond to quick (but still modest-size) changes.

Model experiments described by George Watts, M. ASCE,[10] on the effect of tidal action on wave-formed beach profiles give certain information on the behavior of profiles with a fluctuating water table. These results should not be transferred, uncritically, to field (prototype) conditions. Although they do not interfere with the previously noted approach, they are of a qualitative nature, only.

An analytical approach based in part on the results from the southeast coast of Florida will be made.

Assuming an equilibrium profile, as indicated in Fig. 4, following the equation

$$y^{3/2} = p\,x \qquad (2)$$

in which y is the depth at distance, x, from the shore[8,9] and using the results from the southeast coast of Florida where a rapid rise in sea level of "a" millimeters causes a shoreline recession of "100 a," the intersection point between the old and the new profile corresponding to the rise "a" is found by means of Eq. 2 and

$$(y + a)^{3/2} = p(x + 100\,a) \qquad (3)$$

The mathematical expression for the intersection point is, unfortunately, complex and it is easier to find the point using a numerical method.

For the steep profiles on the southeast coast of Florida, $p \sim$ approximately 0.04 (x and y in metric system). With a rise of 1 m, that is 6 mm per yr in 167 yr, or 1.2 mm per yr in 830 yr, the theoretical shoreline recession will be approximately 100 m (335 ft). The intersection point between the old profile without rise in water level and the new profile corresponding to 1 m rise in water level is at a distance of approximately 135 m (450 ft) from the original shoreline and at a depth of approximately 2 m (7 ft) in the original profile (235 m from shore in the new profile at a depth of 3 m).

A 0.3-m (1-ft) rise of the sea level, that may come in 50 yr to 100 yr, may cause shoreline recessions of more than 100 ft on the southeast coast where many beaches at this time (1961) are too narrow to meet that kind of development. This unfortunate situation can only be adequately handled by means of artificial nourishment with suitable sand material.

HOW MUCH MATERIAL IS NEEDED TO MAINTAIN THE FLORIDA SHORES?

It is generally known that erosion is partly a long-range geological process initiated and maintained by nature itself, and is partly caused by man's interference with nature not least in the form of improved inlets—whether these inlets are only dredged or are also jetty-protected and by inadequately designed coastal structures including groins and sea walls. The improved inlet is often responsible for considerable shoal-formations in the sea as well as in the bay or lagoon. In this way, material needed for maintenance of the downdrift-side shores is "wasted to no purpose," and the usual result is an often heavy increase of erosion on the downdrift side (for example, at Palm Beach, Fla).

10 "Laboratory Study of Effect of Tidal Action on Wave-Formed Beach Profiles," by George Watts, Technical Memorandum No. 52, Corps of Engrs., Beach Erosion Board, 1954.

The total annual erosion along the approximately 1,000 miles of sandy shore in Florida has been estimated[11] to be 10 to 20 million cubic yards. With reference to the computed figure for erosion based on rise of sea level, the following quantitative estimate on natural erosion may be made:

East Coast: (an average of 1.5 ft natural recession per year) approximately 700,000 yd (23) $\left(\frac{1.5}{3}\right)$ = 8,000,000 cu yd

Upper Gulf Coast: (an average of $\frac{1}{2}$ ft natural erosion per year) approximately 400,000 yd (23) $\left(\frac{1}{6}\right)$ = 1,500,000 cu yd

Lower Gulf Coast: estimate based on shoreline recessions = 1,500,000 cu yd

TOTAL: 11,000,000 cu yd

The man-made erosion was estimated to be one-third of the natural erosion[11] and is predominant only in some few areas of limited size particularly at the improved inlets. This adds about 4,000,000 cu yd, making a total of 15,000,000 cu yd or close to the estimate based on actual observations of shoreline movements counting on a short-term basis on an equal landward movement of the depth contour down to 25 ft. This manner of computing erosion quantities assumes that the sea level is constant for a limited period of time. Its assumption is based on surveys of beach and bottom profiles in recent years.

PREDICTION OF SHORE DEVELOPMENT FOR THE IMMEDIATE FUTURE

With respect to the development in sea-level rise during the next few hundred years, it seems to be a general agreement between scientists in the meteorological, climatological, geophysical, and geological fields that (concerning the grand-scale development) the earth is on its way into another glacial period. By comparison with the duration of past interglacial and glacial episodes in the earth's history, it is believed that the new glacial period may be only 10,000 yr to 15,000 yr away. Such a prospect, with its accompanying ice sheets devastating northern lands and settlements is an unfortunate one to contemplate in terms of physical, economic, or political consequences. The countries to be hurt are Canada, the Scandinavian countries, the USA and the USSR. We are, at present, apparently in a short-term, general, world-wide warming trend. In the United States, the rise in mean annual temperature, since 1920, has been approximately 2°C. according to E. Dorf,[12] and the rise

11 "Florida Coastal Problems," by P. Bruun, F. Gerritsen, and W. H. Morgan, Coastal Engineering No. VI, Council on Wave Research, Calif., 1958.

12 "Climatic Changes of the Past and Present," by Erling Dorf, American Scientist, Vol. 48, 1960, p. 341.

in winter temperatures has been approximately twice as much as that in summer temperatures. The rises are unequally distributed.

In recent years it became evident that the Greenland and Alaskan glaciers retreated. At the same time, the codfish from the Atlantic, because of the warming up, replaced the seals in the waters along the coast of Greenland changing the Greenlanders to fishermen (instead of hunters).

With respect to Antarctica the situation may be different. H. Wexler[13] examined eight different ice budgets for the Antarctic Ice Sheet and found that five of these budgets call for rates of increase of the ice that are in good agreement. The observed rise in sea level of the world's ocean would appear to contradict the removal of water required to nourish the Antarctic Ice Sheets. The thermal expansion of ocean waters caused by an increased absorption by the ocean of solar radiation has been invoked to resolve this contradiction but due to the lack of adequate data on long-period thermal changes at all depths of the world's oceans, it still seems unreliable at this time to state that the Antarctic Ice Sheet is either increasing or decreasing. Evidence exists that the glaciers may stop their retreat in the not too distant future if they have not already stopped retreating.

The conclusions from this data seems to be that, for a relatively short period of time, a rise in sea level of the total order indicated by the small fluctuations in Fig. 2 (1 m or 3 to 4 ft) may be expected. Even a rise of only 0.3 m (1 ft), that, as previously noted, may come in 50 yr to 100 yr, will have serious consequences for the erosion situation along the Florida shores, because it may give rise to shoreline recessions of the order of 100 ft or more on the southwest coast of Florida. It is evident that there is a time lag between the rise of the water table and the reaction in the form of erosion. This lag is more pronounced for the gentle sloping, northeastern Florida shores, than for the steep southeastern Florida shores where reactions to fluctuations come more rapidly. These steep shores present less stability than the "flat" shores and any change from rising to lowering, or neutral position of the sea table seems to be reflected more rapidly in these steep-slope shores. With gentle-slope shores (such as the northwestern and western Florida shores) there may be more phase-lag between rise of sea level and erosion. This also means that the steep-slope shore with lowering of the sea level may stop eroding before the gentle-slope shore slowly turns a tendency to erosion into a tendency to accretion. This is all under the assumption that the shores being studied are equilibrium-profile shores with maturity of configurative development.

SUMMARY AND CONCLUSION

1. Eustatic changes are overall changes of the sea level that are independent of land movements and that have many different causes. During the Quaternary, two major and several minor effects are noticeable:[2]

(a) Climatically controlled glacio-eustasy, involving vertical oscillations of a few meters up to 100 m or 125 m (300 ft to 400 ft) in periods ranging from 550 yr to 90,000 yr; and

[13] "Ice Budgets for Antarctica and Changes in Sea Level," by H. Wexler, Journal of Glaciology, Vol. 3, No. 29, 1961.

(b) geodetic change, associated with either the shape of major ocean basins or with the shape of the geoid in respect to the spheroid, perhaps associated with a polar shift. Several minor geophysical effects are to be expected from glacial loading and unbalancing effects on the globe but their roles have not yet been analyzed.

Analysis in detail of the eustatic effects and their timing over the last 15,000 yr shows that a close correlation is observable between minor oscillations of sea level and climatic events. Every recorded glacial advance of the past 5,000 yr is matched by a eustatic lowering of the order of 3 m to 7 m (10 ft to 22 ft). Pollen analysis from non-glaciated areas confirms that these are climatically cool phases. In the arid American West (New Mexico, and so forth), each of the younger cool phases corresponds to a drought; in temperate belts they are marked by pluvial events.

2. The earth is, at present, in an interglacial stage, but heading toward another glacial stage, perhaps 10,000 yr to 15,000 yr hence.

3. Though marked by minor alternating colder and warmer cycles; the present short-term, general trend of increasing warmth should continue for at least two to three hundred years over most of the lowland regions of the northern hemisphere.

4. Sea level has been relatively stable during the past 5,000 yr, but minor fluctuations up to 3 m to 7 m (10 ft to 20 ft) have occurred. Since the Roman Era, 1,500 to 2,100 years ago, sea level has risen approximately 2 m (7 ft) or an approximate average of 1.2 mm per yr.

5. During the past hundred years, the lowest point of sea level occurred in 1890; the mean annual rise from 1900-1950 was 1.2 mm. The fastest decade was 1946-1956 with 5.5 mm, but patterns vary somewhat if plotted ocean by ocean. The entire eastern seaboard of North America shows an anomalously high, apparent rise of sea level. An appreciable component in the sea-level rise (approximately 20% of which is eustatic) is possibly due to a secular deceleration of the Gulf Stream. For the 1890-1960 period, there is on the East Coast a progressive rise of sea level that is at least 50% greater than any other large departure from other parts of the world. The very rapid rise between 1930 and 1950 has slowed down in the 1950 to 1960 period (as seen from Fig. 3).

6. The effect of sea-level rise seems apparent in the development of erosion along the Florida shore:

Based on the assumption (reasoned in part by the work done by marine geologists) that the 18-m (60-ft) depth contour seems to be the outer limit for the nearshore littoral drift and exchange zone of littoral material between the shore and the offshore bottom area, it is assumed that the offshore bottom for any rise in sea level will undergo a gradual adjustment process tending to keep its "equilibrium form." By this process, the bottom may be raised together with the sea level until it is covered by the same depth of water at the same distance from the (new) shoreline as it was before the rise. The material needed to raise the bottom is assumed to come from the corresponding shore area by movement of material by transversal (rip) currents and by diffusion currents.

7. The rate of the development described above will probably depend to a large extent on the slope of the offshore bottom. Steep profiles are probably more sensitive to short-term rises in sea level than to long-term rises.

Gently sloping profiles may respond to long-term changes only and demonstrate a pronounced phase-lag between rise of sea level and effect on erosion. If the same bottom profile has a nearshore steep part as well as an offshore flat part, the steep part may respond to the short-term fluctuations whereas the profile as a whole, including its flat, offshore part, may respond to the long-term rise of sea level.

8. The validity of the previously noted concept was tested on shoreline recessions on the Florida shores. It appears that the steep profiles along the southeast coast follow the short-term rises of the sea water table (6 mm, annually, in recent years), while the more gently sloping profiles on the northeast and upper Gulf coasts follow the long-term rises of the sea water table (1.2 mm, annually, 1900-1950). With respect to the influence on erosion of the long-term rises of the sea water table on the southeast coast, the width of the 0-m to 18-m (0 to 60-ft) bottom area (up to about the edge of the shelf) seems to be too small to reflect long-term rises. During more extended periods of time, material is probably lost to deeper water outside the 18-m (60-ft) depth contour.

9. The seriousness of the rise of sea level with respect to erosion is demonstrated by the computed results. Even a rise of only 0.3 m (1 ft), that may come in 50 yr to 100 yr, may cause shoreline recessions of more than 35 m (100 ft) with the possibility of much higher recessions in marsh and other low shore areas.

10. Quantitative estimates of the erosion along the Florida sand shores based on computed shoreline recessions caused by rise of the sea water table give an erosion of 11,000,000 cu yd per yr. This quantity does not include the man-made (inlet) erosion that is estimated to be approximately 4,000,000 cu yd per yr. The total is approximately 15,000,000 cu yd. The quantity of accretion is unknown; but, in as much as few shores accrete, it will hardly amount to more than a small fraction of the erosion. Material deposited on shoals is disregarded.

11. It is desirable to test the validity of the assumptions on transfer of material perpendicular to the shoreline. It seems reasonable to assume that such tests can be accomplished, indirectly, by analyses of bottom-material characteristics as compared with beach-material characteristics. A direct method would be tracing of material eroded on steep shores during extreme storms using radio-active or luminescent tracers. Such a method would, needless to say, include some uncertainties and will probably, because of the time limit, indicate more narrow widths than the actual "exchange widths" as referred to herein. It is self explanatory that the previously noted theory should be tested at other places where field data are available for comparison.

12. The only way in which the problem of sea-level rise can be handled is by artificial nourishment to replenish the material eroded and by the construction of dykes or sea walls of proper elevation. Such large scale operations are already badly needed at many places in Florida to cope with storm tides. Most likely it will be necessary to secure part of this material from the offshore bottom simply because no source of material is available on land within reasonable distance. New type dredging equipment may have to be developed to accomplish such a task.[14]

14 Discussion by Per Bruun, of "Shark River Inlet By-Passing Project," by W. Mack Angas, Proceedings, ASCE, Vol. 87, No. WW 2, May, 1961.

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DISCUSSION

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