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Relationship Between Concavity and Convexity of a Coast and Erosion and Accretion Patterns

V. Chris Lakhan and David A. Pepper

Department of Geography and Resource Management
University of Windsor
Windsor, Ontario, Canada N9B 3P4

ABSTRACT

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This study investigates whether or not there is a distinct relationship between a coastline's configuration (concavity/convexity) and its tendency toward either erosion or accretion. Empirical erosion/accretion data from Guyana's Demerara coast are analyzed using coastal classification averages and linear regression. The results show no systematic linear relationship between a coast's angular measure of concavity and convexity and its tendency to either erode or accrete. The findings of the study suggest that convex coasts on the whole may have a greater tendency toward accretion than either straight or concave coasts. Various reasons can be given as to why Guyana's coast does not conform to the established idea of increased accretion at concave-shaped sites and greater erosion at convex-shaped sites. One possible explanation lies with the occurrence of repeated patterns of mud bank evolution, migration and stabilization which affect the time when and the locations where the Guyana coast is being eroded or aggraded.

ADDITIONAL INDEX WORDS: *Guyana, coastal configuration, bays, headlands, aggradation, degradation, mud banks.*

INTRODUCTION

The focus of this study is to investigate whether or not there is a distinct relationship between a coastline's configuration (concavity and convexity) and its tendency toward either erosion or accretion. Several textbook authors (for example, ZENKOVICH, 1971; KOMAR, 1976; BLOOM, 1978; PETHICK, 1984; TRENHAILE, 1990) have claimed that headlands, where wave energy is generally concentrated, will tend to erode while embayments, which are often sites of low wave energy, will undergo accretion. The early work by ZENKOVICH (1971) states that areas of decreased wave energy, including bays and concavities, tend to be characterized by the formation of accumulation features (that is accretion is occurring). On the other hand, he mentions that depositional features may also occur on the leeside of headlands where waves approach the shoreline obliquely. In other words, he emphasizes the idea that where there is a decrease in wave energy, there is a decrease in the capacity of waves to carry sediment, resulting in the creation of depositional features. KOMAR (1976) links the process of energy concentration to increased erosion. He states that wave energy is concentrated on headlands and that this appears to be the cause of increased erosion of these features, resulting in a gradual straightening of the shoreline. Thus, it is not the shape of the shoreline itself that causes differences in accretion and erosion, but the influence of coastal shape on wave energy.

BLOOM (1978) asserts that the wave energy concentrated on coastal protrusions (headlands) leads directly to increased erosion at these sites as compared to adjacent bays or coves. In addition he states that longshore currents, which flow along the coast from headlands to the adjacent embayments, are generated as a result of these differences in the concentration of wave energy. This results in the transport of sediments eroded from the headlands to the embayments where they are deposited. Bloom concludes that wave refraction leads to the gradual straightening and simplification of the coastline due to the preferential erosion of headlands and the infilling of bays. Another study supporting Bloom's conclusion is that of PETHICK (1984), who states that wave refraction causes wave crests to bend until they match the submarine contours and therefore roughly match the shape of the shoreline. Wave rays which are perpendicular to the wave crest and represent the propagation of wave energy, converge on headlands and diverge at bays as a result of this process of refraction. TRENHAILE (1990) also discusses this process by which wave energy is concentrated on headlands and dissipated in bays.

PHILLIPS (1989), however, is reluctant to accept the idea of a gradual straightening of the shoreline due to the differential erosion of headlands and bays, despite the fact that he states that the concept is a "widely accepted principle of coastal geomorphology". He suggests that differences in material resistance along the coast, as well as the difficulties in meeting certain assumptions of the wave refraction model, provide severe limitations to it. In his work conducted in Delaware Bay, New Jersey, he found that the shoreline becomes more complex over an extended period of intense erosion. Further, he observes no systematic concentration of wave energy on protrusions or headlands, and states that, in some cases, concentration of wave energy occurs in embayments.

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Phillips (1989), however, does concede that increased erosion of headlands may occur on a broad scale due to a greater exposure to storm waves.

Given the fact that there is disagreement on how coastal configuration affects erosion and accretion, this study investigates whether or not there is a relationship between the shape of a coastline and its tendency to either erode or accrete. Empirical data are analyzed to determine whether concave coasts are the sites of least erosion (most accretion), convex coasts have the most erosion (least accretion), and straight coasts experience an intermediate amount of either erosion or accretion. The data utilized are measurements obtained along concave, convex and straight sections of the Guyana coast.

DATA ACQUISITION AND THE STUDY AREA

This study concentrates on the Guyana coast not only because there are episodic phases of erosion and accretion along its various coastal configurations, but also because the Government of Guyana is planning to initialize its Sea Defence Evaluation Model. This model, developed by the Dutch consulting company DHV Environment and Infrastructure (1992), has input parameters which show increased erosional rates along convex coasts and increased accretional rates along concave coasts. Since it is necessary to parameterize models with representative parameters and attributes (Lakhan, 1989), and because there is no consensus of opinion on how concave and convex coasts erode or accrete (see Phillips, 1989), then it becomes worthwhile to examine Guyana's coastal data to determine whether or not concave-shaped coasts are accretional sites, and convex-shaped coasts are sites of erosion.

The datasets analyzed were obtained from the Government of Guyana (1993) records stored at the Lands and Surveys Department and from the DHV Environment and Infrastructure Consulting Report (1992, Volume II). The datasets obtained pertain to the advance and retreat of Guyana's coast, especially the foreshore in front of the sea defence system. The report by S.R.K.N. Civil Engineering Consultants (1992) pointed out that the foreshore along Guyana's oceanic coast can be expected to be eroded in certain places to a level as low as 40.00 GD (Georgetown Datum). Although not entirely synonymous with erosion and accretion, shoreline retreat and advance are accurate indicators of the amount of material gained or lost by a coastline. Therefore, these terms will be used interchangeably for the purposes of this study. Advance or retreat were calculated by comparing the initial and finishing positions of two contour lines, the 46 + GD and the 54 + GD contours, which represent elevations along the coast. The 46 + GD contour approximates the position of the mean low water spring tide level while the 54 + GD contour represents the mean high water spring tide level. These contour data obtained from the Government of Guyana (1993) exist intermittently from the years 1941–1988 for cross-sections throughout the country. After examining the entire dataset for the 1941–1988 time period, this study excluded all intermittent data, and selected for analysis the most continuous and complete dataset which represents the period 1967–1977. The complete time series of data from 1967–1977 have been obtained from 86 cross-sections measured 300 m apart along straight, convex, and concave configurations of the Demerara coast.

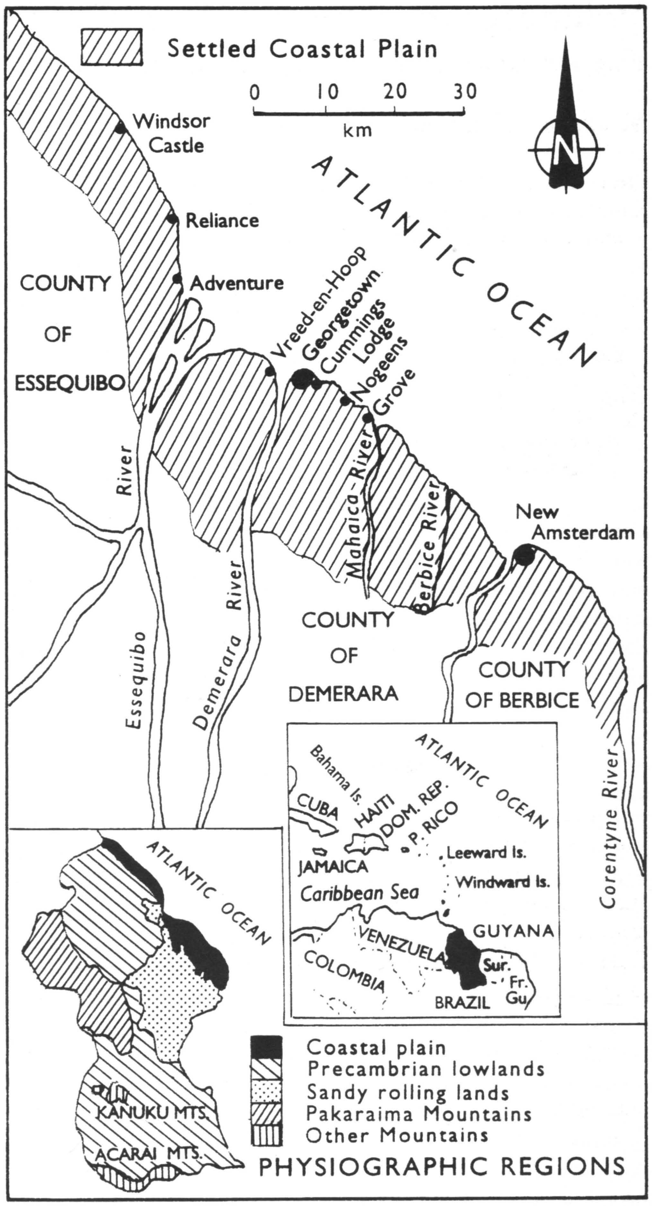


Figure 1. The study area showing the Demerara coast, Guyana.

The Demerara coast is fairly representative of the whole Guyana coast which extends a distance of about 435 km. The low lying coastal plain is generally flat and is about 0.5–1.0 m below the level of spring tides. With a width of 77 km in the west and 26 km in the east, the coastal zone is the smallest physiographic region. More than 90 percent of the country's population of about 900,000 live on the coast, with the majority living in the County of Demerara (Figure 1).

The inhabitants of the entire coastal zone of Guyana, especially those living on the heavily populated Demerara coast, are saddled with recurring erosional problems (LAKHAN, 1994). Several studies (ALLERSMA, 1971; NEDECO, 1972; and AUGUSTINUS, 1987) have described the essential hydrodynamics and sedimentological characteristics governing erosion of Guyana's coast. Other than the influence of moderately high waves and currents, the coast is affected by the continuous presence of massive loads of fine sediments. When the concentration of sediments exceeds a critical limit of about 450 kg m^{-3} it forms a coherent mass of viscous mud and settles under its own weight to form mud shoals (also referred to as mud banks) (ALLERSMA, 1971). The presence of mud shoals along the coast of Guyana have been attributed to erosional and accretional cycles (NEDECO, 1972).

METHODOLOGY

In the first stage of this study literature and data were examined to determine the occurrences of accretion and erosion along the Guyana coast. Topographic maps (1:50,000) were then used to demarcate and correlate coastline-advance and retreat data with measurable concave, convex and straight configurations. Next, a procedure outlined by DHV ENVIRONMENT AND INFRASTRUCTURE (1992, Volume II) was followed to precisely delineate the concavity, convexity and straightness of the coast. In this procedure, sections of the coasts that displayed a change in direction were isolated and centered around a straight 500 m length of line which connected the two adjacent, straight coastal sections (Figure 2). The directional change within the sections was then simplified to two lines of equal length, and the angular variation of these lines from the 500 m baseline was measured. Coasts which protruded seaward at an angle of greater than 5 degrees were classified as convex, while coasts that curved toward the land and displayed angles of greater than 5 degrees were classified as concave. All other coasts were considered straight. The measurements were then recorded to the nearest degree, with concavity considered positive and convexity considered negative.

In order to de-emphasize the importance of angular measurements, a second classification scheme was created as well. Measurements in degrees were rounded off to the nearest ten and then divided by ten resulting in classifications of −2, −1, 0, +1, and +2. Concavity and convexity measurements were, thus, determined in relation to the adjacent sections of straight coasts and thus rendered independent of the prevailing wind, wave, and current directions. The classification of concavity, convexity and straight coasts derived by utilizing the described procedures was then verified by field measurements done in Guyana in 1994.

After the coasts were classified, shoreline advance/retreat data were calculated for each section. Total erosion or accretion rates for the selected ten year period (1967–1977) were calculated by using the positions of the two contours in 1967 as a starting point, and subtracting the positions of the 1977 contours from them. The differences were then divided by 20 in order to calculate the mean rate of advance or retreat of the coastline per year. Twenty was used as the divisor because figures for two contour lines over a ten year period were used. The obtained results in meters per year were recorded as negative in the case of shoreline recession (erosion) and positive in the case of shoreline advance (accretion).

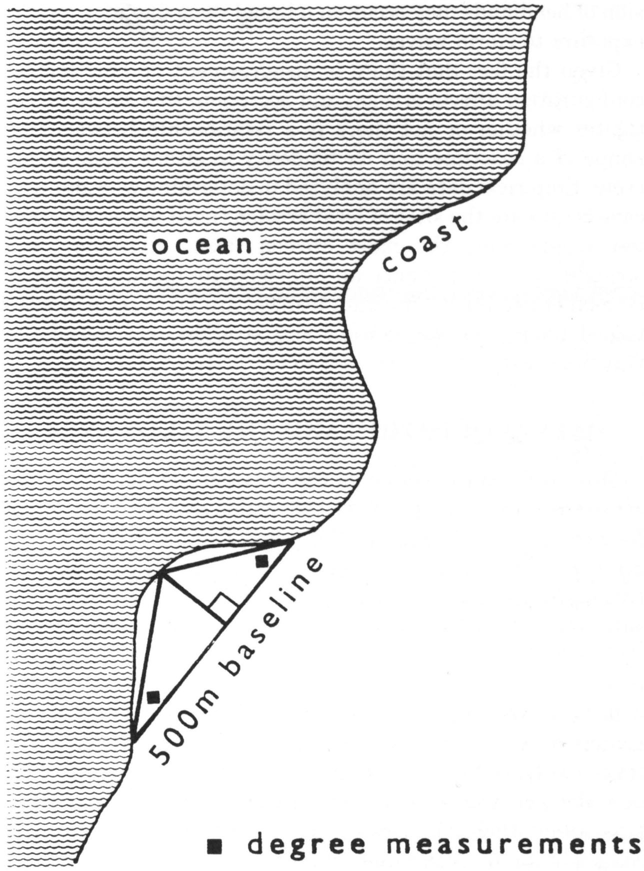
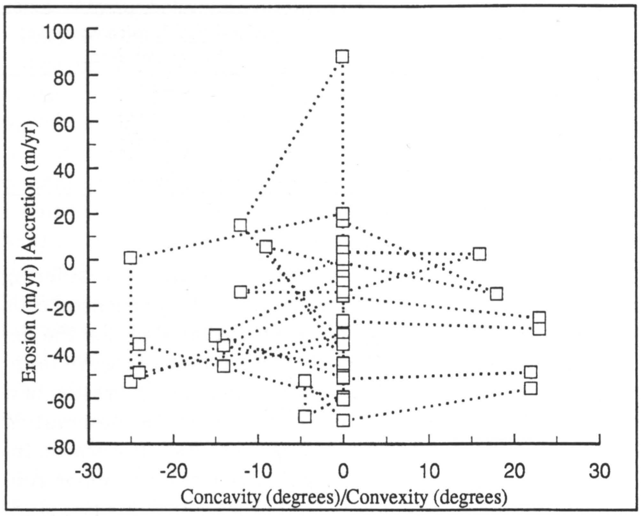


Figure 2. Illustration of technique used to measure concavity/convexity.

Following configuration classifications, angular measurements, and calculations of rates of shoreline advance or retreat, graphs were generated and statistical analyses were performed. Two scatter plots were generated. In the first, the exact angular concavity/convexity measurements were used as the independent variable (on the x-axis), and the annual rates of erosion or accretion for locations considered were used as the dependent variable (on the y-axis). In the second scatter plot, the generalized concavity/convexity classifications (−2 to +2) were used as the independent variable, and the annual erosion or accretion rates were used as the dependent variable. Linear regression was then performed twice, one on each dataset used in the scatter plots. Again, both the exact angular measurements and the generalized classification scheme measurements were used as the independent variables, and the annual rates of erosion or accretion as the dependent variables.

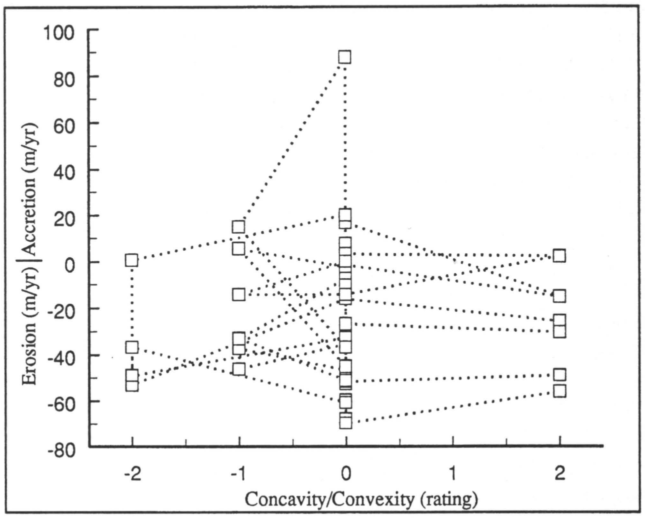
RESULTS

Calculations and classification scheme measurements reveal that most of the studied coastline (21.5 km or 72 percent)



Concave = +; Convex = -

Figure 3. Scatter plot of angular concavity/convexity measurements versus annual rates of erosion/accretion.



Concave = +; Convex = -

Figure 4. Scatter plot of concavity/convexity ratings versus annual rates of erosion/accretion.

is straight while convex coasts make up 5 km, or 17 percent, and concave areas make up only about 3.5 km, or 12 percent of the coast. Of the 86 sections within the study area 12 are classified as concave, 15 as convex and the remaining 59 are considered straight. Concave angles range as high as 23 degrees while the highest convex angle is 25 degrees.

Computations of shoreline advance and retreat demonstrated that the coast retreated an average of 26.3 m per year during the period 1967–1977. Of the 45 measured locations, 38 (80 percent) showed retreat over the study period, 8 showed advance and one showed almost no change. The greatest rate of calculated retreat, 69.66 m per year, was at Cummings Lodge while the greatest rate of advance was 27.02 m per year at Nogeens. Interestingly, both of these locations with the highest retreat and advance are on straight coastal sections and both are located within areas (groupings of several measured sections) that have similar erosional and accretional tendencies. Observations indicate that accretion or erosion varied both temporally and spatially; that is rates of advance or retreat varied widely from year to year at most locations and that a year of rapid erosion was often followed by a year of rapid accretion. Furthermore, the overall tendency of a location over the ten-year period did not necessarily preclude the occurrence of an event of the opposite nature within those ten years. For example, although Cummings Lodge had an erosion rate of 69.66 m per year throughout the study period, it actually had a net accretion rate of 49.85 m during 1971. Thus, the ten year average erosion or accretion should be considered a long term tendency of the coastal section rather than a definite indicator of what a particular coast may do on a different temporal scale. Overall, the Demerara coast tended to erode between 1967 and 1977, although the retreat was generally more episodic than uniform over time, and accretion was experienced at a few locations.

The configuration measurements together with the erosion/accretion measurements are represented graphically (Figure 3). Should the statement in the literature be accepted that concave-shaped coasts are accretional and convex-shaped coasts are erosional, then convex points should appear in the lowest range of the graph, concave points should appear highest, and points of zero curvature should appear somewhere in the middle. However, this pattern is not apparent in the distribution of points on the graph. Straight coasts, in fact, occupy the highest and lowest points on the graph, as well as virtually every other point in between, while concave and convex coasts show an apparently random scattering of erosion/accretion values. The second scatter plot (Figure 4) again places erosion/accretion on the y-axis as the dependent variable, but uses the rating system from -2 to $+2$ as the independent variable. As inferred in the literature, clusters of values should appear near the bottom left hand corner with each successive cluster to the right appearing higher up on the graph. However, this graph does not show any such pattern. Both plots demonstrate insignificant relationships between the independent and dependent variables.

Table 1 summarizes the linear regression results between

Table 1. *Output from regression of erosion / accretion rates against degree measurements of concavity / convexity.*

Constant	−85.501900
Standard Error of Y Estimate	82.919550
R	−0.017640
R Squared	0.000311
Number of Observations	45
Degrees of Freedom	43
X Coefficient(s)	0.1224709
Standard Error of Coefficient	1.0584008

Table 2. *Output from regression of erosion/accretion rates against concavity/convexity ratings.*

Constant	−85.745300
Standard Error of *Y* Estimate	82.931770
R	−0.004062
R Squared	1.65×10^{-5}
Number of Observations	45
Degrees of Freedom	43
X Coefficient(s)	−0.3152962
Standard Error of Coefficient	11.8232911

Table 3. *Mean erosion/accretion rates.*

Class	Total Average Erosion/Accretion Metres Per Year
Straight	−27.05
Concave	−28.66
Convex	−22.37
Total	−26.12

the independent variable of actual degree measurements of concavity or convexity and the dependent variable of measurements of shoreline advance or retreat. No meaningful relationship can be observed. The results of the second test (Table 2) use the generalized concavity/convexity ratings as the independent variable and the erosion/accretion measurements as the dependent variable. The results from the regression analyses indicate no significant linear relationship between angular measurements of concavity/convexity and erosion/accretion rates.

Probably the most surprising results of the study are the comparative mean annual rates of erosion and accretion along concave, convex, and straight coasts (Table 3). The average rate of erosion for the entire coastline between 1967–1977 was approximately 26.12 m per year, while straight coasts had an average erosion rate of 27.05 m per year. Concave coasts, for which it was inferred that erosion would be the lowest, actually had the highest rate of erosion with an average of 28.66 m per year. Convex coastlines, although expected to erode the most, experienced noticeably less erosion than the other types of coast with an average rate of 22.37 m per year. The straight coasts and concave coasts do not differ a great deal in their average erosion rates, while the convex coastlines have measurably lower erosion rates than the other two.

DISCUSSION

"Widely accepted principles of coastal geomorphology," as PHILLIPS (1989, p. 60) states, "indicate that, over time, shorelines become straighter or less complex in planform as headlands erode and bays fill in with eroded sediment." This concept still holds a fairly prominent role in the thinking of some coastal geomorphologists. This study, however, does not find increased erosional tendencies of convex areas and increased accretional tendencies of concave areas. The Guyana coastal data demonstrates that convex coasts, on average, experienced less erosion than either the concave or straight coasts. The reasons for this are probably very complex, perhaps relating to log-spiral currents which operate in the long-term and result in the eventual establishment of equilibrium conditions along a coast. CARTER (1988) stresses the role of long-term equilibrium processes as major determinants of coastal shape. He states that logarithmic spiral circulatory cells may create coastal features such as zeta (crenulate) bays which in turn perpetuate the circulatory cell itself, leading to the long-term persistence of the landform. This would seem to suggest that in the long-run, many coastal features tend to retain their shape despite their potential for exposure to differing levels of wave energy. The extreme complexity of coastal cells and currents may serve as a partial explanation for the departure of Carter's idea from the notion that exposure to increasing direct wave energy leads to increasing erosion of a coast. Further, this discrepancy may relate to the observation of characteristics on different temporal and spatial scales. Indeed, PHILLIPS (1986, 1989) considered scale a major contributor to differences in erosional processes in his two studies of Delaware Bay. It is no doubt important, then, to define scale in a coastal geomorphological study (see CAMBERS, 1976). Another possible explanation relates to stability, in that the foreshore of concave coasts may tend to accumulate a more unstable base of sediments during periods of accretion, which would subsequently be more likely to wash away during periods of erosion; or perhaps, there exists a dynamic relationship between the evolution of nearshore submerged topography and coastal retreat and advancement, especially for the Guyana foreshore environment.

Ongoing nearshore morphological investigations of the Guyana coast by the University of Windsor supplemented by the work of previous investigators (for example, DELFT HYDRAULICS LABORATORY, 1962; ALLERSMA, 1971; NEDECO, 1972; ABERNATHY, 1980; DANIEL, 1981; AUGUSTINUS, 1987; LAKHAN and BOWES, 1992) provide a plausible explanation as to why Guyana's coast may not conform to the established concept relating to erosion of convex areas and accretion of concave areas. Essentially, the morphological stability of the foreshore exposed to the ocean is influenced by the constant movement of huge concentrations of fine sediments in the near and offshore areas. The early study by DELFT HYDRAULICS LABORATORY (1962) reported that the total annual transport of sediments from east to west along the Guyana coast is approximately 100 million tonnes. The estimates by NEDECO (1972) reported that volumes of sediment transported along the Guyana coast vary seasonally from lows of 2×10^6 metric tonnes per month between August and September to 25×10^6 metric tonnes per month between April and May. ALLERSMA (1971) who studied the Guyana coast found that when the fine sediments exceed a critical concentration they form a coherent mass of viscous mud and settle under their own weight to form mud shoals or mud banks in the offshore areas. Depending on the concentration of sediments, multiple mud banks can form along the coast. The typical mud bank is approximately 50 to 60 km long and 10 to 20 km wide (LAKHAN and BOWES, 1992). The volume of the mud banks, with respect to a plane connecting the troughs, varies between 2 and 6×10^9 m^3 around an average of 3×10^6 m^3. Each mud bank becomes oriented toward the coast with the angle between the crest of the shoals and the coast varying between 20 and 30 degrees, with an average of 24 degrees (ALLERSMA, 1971).

The mud banks migrate at a rate of about 1.3 km/year along the Guyana coast in a westerly direction, and their movement is accompanied by a pattern of erosion and accretion of the adjacent coast (DANIEL, 1981). As found in other coastal areas (for example, WELLS, 1978; AUGUSTINUS, 1987; FROIDEFOND *et al.*, 1988; MATHEW and BABA, 1995), the mud banks attenuate shoreward propagating waves, and at times the attenuation is high enough to completely dampen the waves by the time they reach the shore. Over time, this occurrence contributes to the accretion of the coast. When the mud banks move along the coast, the coastal section that is opposite the trough of two mud banks is subjected to severe erosion (NEDECO, 1972). On the other hand, the section of the coast that is protected by the mud banks experiences accretion. As the mud banks migrate erratically in the nearshore area various concave, convex, and straight sections of Guyana's coast become eroded or accreted. In addition, whenever the mud banks become stabilized and attach themselves onto the coast they protect several sections of the coast with straight, convex, and concave configurations from being eroded. It is, therefore, apparent that the repeated patterns of mud bank migration and stabilization affect the time when, and the locations where the Guyana coast is being eroded or accreted. Although this explanation seems plausible, it must be pointed out that far more research remains to be done not only on mud bank migration in both time and space, but also on the hydrodynamic forces which control sedimentation and the evolved morphodynamic features which eventually influence the hydrodynamic processes.

CONCLUSION

The literature in coastal geomorphology suggests that concave-shaped coastal features (bays) tend to be sites of accretion while convex-shaped coastal features (headlands) tend to be sites of erosion. Straight coasts could have an intermediate amount of either erosion or accretion. This study, however, does not support the claim of increased erosional tendencies of convex areas and increased accretional tendencies of concave areas. The analyzed data from Guyana's foreshore coastal environment demonstrate that convex coasts, on average, experience a great deal less erosion (or more accretion) than either the concave or straight coasts. Several reasons could be attributed to this occurrence; with one plausible explanation being the influence of migrating mud banks which affect the time when, and the locations where the Guyana coast is advancing and retreating.

Whatever the reason, the results of this study emphasize the fact that the coast is a large scale, dynamic supersystem which varies in morphological form, pattern and configuration at all scales. With its complexity, and vast differences in hydrodynamic and morphological states it is highly unlikely that traditional accretion/erosion principles will be applicable for all coastal locations. The large number of uncontrolled independent and interdependent processes which operate on the coast compel researchers to study a particular coast with a great deal of scrutiny before issuing predictions on where coastal retreat and advancement are likely to occur. A consequence of not making scientifically informed decisions on the accretion and erosion of a coast, especially the Demerara coast of Guyana, will be the design and implementation of ill-conceived and dysfunctional sea defense strategies.

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