The Development of Downdrift Erosion

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ABSTRACT


Downdrift erosion is a common feature of shores occurring where a headland, inlet, river, bay, canyon, reef or shoal blocks the natural longshore drift of materials, that is transport of sand and gravel by waves and currents. Sediment transport results in accumulations on updrift or receiving side and in the adjoining ocean. There is a corresponding depletion of materials on the downdrift side. The terminology “Littoral Drift Barrier” is accordingly developed. This paper is “an interim report” which reviews practical cases of leeside erosion and attempts to explain the development as a function of time.

ADDITIONAL INDEX WORDS: Leeside erosion, littoral drift barrier, migration of downdrift erosion.

NATURAL LITTORAL DRIFT BARRIERS

Natural littoral drift barriers are found everywhere in the world, and they have a determining influence on the development of shoreline configurations. Barriers may be more or less effective. As they store material on their updrift side and as the storage capacity usually is limited, some material will finally bypass the barrier and may then resume migration downdrift. Part of it may then be lost to the offshore bottom or be deposited in offshore shoals. Complete littoral drift barriers on long uninterrupted shores are very rare, but they occur frequently as pocketed headland-shores, where the available materials are trapped between two headlands extending to greater depths making escape of materials from the pocket beach very difficult or impossible.

Man’s influence on natural shores first started in rivers when, a few thousand years ago, he began developing ocean-going vessels. At the beginning they were based in river entrances, bays and other sheltered areas, but such favorable conditions were not always available. About 3,000 to 4,000 years ago the Phoenicians built an open sea port at Tyre in the Eastern Mediterranean. Located on an open exposed littoral drift shore, it was protected by breakwaters consisting of heavy concrete blocks. The Cretes and the Greeks followed the Phoenicians but their ports were situated on rocky shores with little littoral drift. Two-thousand years ago the Romans built a large naval port at Ostia, near Rome. Situated in a river mouth it was an unfortunate choice for a port site because the harbor silted up rapidly.

Ancient Chinese and European ports were all situated in rivers or in protected bays which undoubtedly experienced similar siltation problems. The Danish Viking ports were placed in river entrances or protected fjords, but there is some evidence that the Vikings also started constructing rock breakwaters, and we know that they established wooden piers of almost modern design (BRUUN, 1990).

MAN-MADE LITTORAL DRIFT BARRIERS

Man’s intervention of coastal processes started when he erected shore-perpendicular or parallel breakwaters for protecting ports against waves and sediments and groins for coastal protection on open littoral drift shores. This type of construction began in the 19th Century in the Mediterranean and on the shores of the British Isles (BRUUN, 1990). The problem of man-induced erosion was magnified when the Dutch invented dredging in an effort to provide greater channel depths for navigation. It was by hard and very expensive experience that man learned that when he puts something out in the sea, “something is going to happen”. Commonly, shoaling occurs on one side and erosion on the other side of an obstruction. In most instances this probably came as a surprise and often initiated “desperate efforts” in order to maintain depths at an entrance.
(e.g., by extending updrift breakwaters or jetties or by dredging operations with available equipment or by both). This provided only a temporary relief for navigation and usually the greater the efforts to maintain depths, the more severe the erosion on the downdrift side. In its full perspective the combined problem was not realized, until the damaged parties finally became aware of the nature of the problem and requested remedial steps. This raised technical as well as legal problems.

The first technical counter-measures were the construction of groins and/or seawalls. While both mitigated the nearshore or onshore erosion problem, they also aggravated the downdrift erosion. Not until the late 1930’s was it realized that the only practical solution to the problem was the elimination of the barrier effect. This was done by establishing sand bypassing whereby material is pumped or trucked across the barrier to the downdrift beaches.

The need for bypassing was supported by legislation such as the Florida law (1987) which reads as follows (Section 161.142, Declaration of Public Policy Relating to Improved Navigation inlets):

“(1) All construction and maintenance dredgings of beach-quality sand should be placed on the downdrift beaches; or, if placed elsewhere, an equivalent quality and quantity of sand from an alternate location should be placed on the downdrift beaches.

(2) On an average annual basis, a quantity of sand should be placed on the downdrift beaches equal to the natural net annual longshore sediment transport.”

However, the intention of this paper is not to discuss the development of bypassing techniques, which is thoroughly described in other documents (e.g., Bruun, 1990, Chapter 9). Rather, it is to explore the coastal geomorphological development downdrift of littoral barriers, specifically erosional modes and patterns.

**QUANTITATIVE CONSIDERATIONS**

The qualitative aspect of longshore drift blocking by barriers is very simple. If the barrier causes the loss of a certain quantity of material which was “locked up” by the barrier, this quantity is unavailable to downdrift beaches which consequently will suffer erosion of that magnitude. The more difficult question is: how is erosion, due to loss of sand, distributed downdrift as a function of time.

**COASTAL GEOMORPHOLOGICAL CONSIDERATIONS**

Three parameters are important in this context: the length of the adversely affected shore, the cross-sectional retreat of the erosion cut and the rate of expansion of erosion, and its distribution downdrift as functions of time. Length and cross-sectional evolution of the erosion cut give the geometric development as a function of time. The corresponding development in the offshore bottom follows the same general pattern, but there is usually a material change in the configuration of the offshore profiles, which tends to flatten in the downdrift area (Bruun, 1990, Chapters 7 and 8). Figure 1a shows a typical longshore shoreline development trend, Figure 1b (Bruun, 1990) shows the offshore development as well. The following refers to the shoreline development.

Fields et al. (1989), for example, analyze the relative shoreline development before and after stabilization of St. Augustine, Port Canaveral and St. Lucie inlets on the Florida east coast. Their conclusions read as follows:

This study addresses the effects of three Florida tidal inlet systems on their adjacent shores. The Bruun and Gerritsen (1959) bypassing classification scheme was combined with a series of shoreline response parameters to evaluate the updrift and downdrift effects of the tidal inlets. The authors realize that this extends beyond the original intent of this classification scheme. However, any classification scheme is an attempt to arrive at broad groupings about which generalized statements can be made. The relative “good” or “bad” effects of tidal inlets have been debated for 10 to 15 years. This study has shown that an adequate classification system which permits broad statements about the “good” or “bad” effects of tidal inlets on adjacent shorelines does not presently exist.

The results of this study support the following conclusions for the tidal inlets studied: (1) “there is no single tidal inlet classification system or parameter which classifies the effects of inlets on adjacent shorelines as a function of available sediment transport and physical processes, (2) the dominant sediment bypassing mechanism at a tidal inlet affects the extent and magnitude of the downdrift shoreline response, (3) the updrift shoreline response to the introduction of a jetty is fairly localized and not dependent upon the
sediment bypassing mechanisms active at the tidal inlet, (4) tidal inlets which are predominantly tidal-flow bypassers have more severe downdrift effects on shoreline response than tidal inlets which bypass sediment through bar bypassing, (5) tidal inlets which are combined tidal flow and bar bypassers have relatively constant downdrift effects (magnitude and rate of change) through time, and (6) significantly deepening the channel through the bar can alter the dominant sediment bypassing mechanism.

"These conclusions are based on three cases located on the east coast of Florida. While three tidal inlets, with only several data points each, cannot be used as conclusive evidence of a relationship, the data can suggest trends. The authors have attempted to show trends in shoreline evolution, and to point out that a global statement about tidal inlets cannot be made with existing parametric analyses. Improved systems which relate the effects of tidal inlets to incident processes are required. This study is only a brief beginning.
in the effort to quantify the response of adjacent shores to the effects of tidal inlets and the introduction of stabilization structures."

The authors plotted time history diagrams for the shoreline development on either side of the inlets. The St. Augustine case considers jointly the development at the old, now closed inlet and the existing inlet, and is therefore due to interferences atypical for a single inlet channel. The development at the two others is summarized below.

It has been difficult to find good examples. Many were observed but not many were recorded by surveys. New entrances are not plentiful; and at the time they were established, the subject of downdrift erosion was of little concern. From this follows that the literature only mentions few examples where the downdrift long distance development was recorded as function of time to obtain a rate. Examples in the literature include FIELDS et al. (1989) and BODGE (1993). Theoretical approaches are available, but they concentrate on immediate downdrift reactions. Although admittedly, the effects continue to expand downdrift "infinitely" as indicated by PELNARD-CONSIDÈRE (1956).

Obviously, the migration rate of the downdrift erosion depends upon the quantitative magnitude of the barrier effect, e.g., the loss of material to inlet shoals. A large loss will expand faster than a small loss. As an example, the old natural Jupiter Inlet on the Florida southeastern coast was first re-opened in 1922, stabilized by jetties in 1929, and then improved several times by dredging and bypassing (GRELLA, 1993). In its unimproved state as a natural bar bypasser, the material lost in shoals was a relatively small quantity, a few ten thousands of cubic meters per year out of a net drift on the order of about 140,000 cubic meters per year. The downcoast loss increased after the construction of jetties (North Jetty, 1929). Now, as a result of a fairly regular bypassing by dredging, it is probably less than 20,000 cubic meters per year. The adverse effect of the inlet on the downdrift shores is difficult to trace, but seems to expand 10 or 20 km downdrift (MANN, 1993), with reference to MEHTA, 1993). For comparison Lagos, mentioned in the following, presents a huge barrier of more than one million cubic meters per year and has a corresponding severe effect downdrift, apparently extending 40–50 kilometers.

"Beach/Inlet Processes and Management", Special Issue No. 18, by the Journal of Coastal Research (1993, A.J. MEHTA, Editor) has a great number of examples on the influence of coastal inlets on the littoral drift system. The short distance effect of the inlet on the downdrift erosion is shown in several figures, but the development downdrift is cut short by only examining the development for a limited distance downdrift.

**EXAMPLES OF DOWNDRIFT SHORELINE DEVELOPMENTS**

**Port Canaveral, Florida East Coast** (Figure 2a, b, c) (FIELDS et al. 1989)

It is apparent that the downdrift development of shorelines can be separated in two parts: those which occur at a shorter distance from the barrier and those that occur at some longer distances. While the former may be explained as a coastal geomorphological development associated with changes in directional wave pattern, the latter seems mainly to be related to imbalances in the littoral drift budget caused by the littoral drift barrier. The entrance to the port was cut in 1951 and improved by jetties and a dredged channel in 1953–1956. The subsequent development of downdrift shoreline erosion is shown in Figure 2a, b, c. The "short" and "long" distance terminologies used in the following are explained in Figures 2c and 3c. It should be noted that the short distance influence by 1965 extended about 5 km downdrift, giving a migration rate of 0.6–0.7 km/year. By 1965 the long distance effect had reached about 18 km from the entrance, an erosional front migration rate of 1.5 km/year. The latest research explained by BODGE (1992, 1993) suggests that the erosion front now extends 30 to 40 km downdrift, a migration rate of 0.8 to 1.2 km/year. The small accretional peak located about 5 km downdrift is probably a result of a rock out-cropping.

**Port St. Lucie, Florida East Coast** (Figure 3a, b, c) (FIELDS et al. 1989)

St. Lucie Inlet was constructed by local interests in 1892 by dredging a channel 9.0 m wide and 1.5 m deep through the coastal barrier. Between 1892 and 1922 the inlet entrance continued to enlarge naturally until it reached a width of 800 m and a depth of 2 m. During this period, the updrift shoreline retreated at a rate of ~ 18 m/year and the downdrift side eroded at an even greater rate. Between 1926 and 1929 a jetty was con-

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structured from the northern barrier to a rock reef, located approximately 1,015 m offshore. During this same period, local interests dredged a 1,370 m long channel 5.5 m deep and 60 m wide from the ocean, through the offshore bar and rock reef system to the inlet throat. The dredged sediments were deposited in the back-bay region and on the south side of the inlet. In 1948, a 3 m deep by 61 m wide channel was dredged across the seaward bar and reef, approximately 229 m in length.

Referring to notations in Figure 3 it is apparent that the downdrift erosion since the completion of the North Jetty in 1929 has extended: short
distance 12 km during 1929–1962 = 33 years, or a migration rate of 0.4 km/year. The long distance rate has similarly been 24 km/33 = 0.7 km/year. Based on Figure 3c date, the rate for rapid increase during 1946–1962 = 16 years has been 24/16 = 1.5 km/year. The small accretional area located about 12 km downdrift is caused by a 200–300 m long reef outcropping.

Lagos, Nigeria (Bruun, 1990 and Communications)

Victoria Beach near Lagos has been the site of rapid erosion accentuated by the trapping of longshore drift at Lighthouse Beach. The beach has retreated by up to 1,300 m, of which 378 m eroded between 1966 and 1975 and 102 m from 1972 to 1975. Beach nourishment with sand pumped from the sea floor began in February 1976 and built up the beach profile, but renewed erosion in 1980 denuded the entire sea front up to the edge of the first row of houses on Victoria Island.

There have been substantial changes in this area since the coastline was first mapped at the beginning of this century. Lighthouse beach, for example, has prograded rapidly since the breakwater was built in 1912 to maintain a navigable entrance to Lagos Lagoon: between 1924 and 1972, the shore advanced 1,200 m seaward, and between 1972 and 1975, it advanced a further 100 m alongside the breakwater, widening a foreland on which numerous successive beach ridges have formed. By 1985 the sand had built out to not far from the end of the breakwater (Awosika, 1993). It has not been possible to obtain data on the downdrift erosion migration rate, but based on personal communication it has been very fast, exceeding 1 km per year or more.

Hirtshals, Denmark

The development at Hirtshals (North Sea Coast) is described by Bruun (1990, Chapter 7). It appears that the erosion at the 30–35 km distance downdrift at the Old Skagen picked up considerably 20 to 25 years after the completion of harbor works including breakwaters and a navigation channel. That indicates a migration rate of 1.2 to 1.5 km/year for that period. It happens that during this particular period of time weather conditions were less severe than during the adjoining periods. This may be taken as proof for the adverse effect and its cause. We are probably facing a short-range coastal geomorphological effect and a long-range imbalance in the littoral drift budget which is partly a result of the short-range development and partly is caused by deep water deflection of littoral drift materials as discussed in principle later in this paper.

Indian River, Delaware

Watson et al. (1993) examined the beach response to sand bypassing. Their figures reveal that the deepest cut north of the inlet migrated 3,800 m in 8 years, or 0.45 km/year. The surveys were not extended to measure the movement of the erosional front of the affected area. Davison et al. (1993) investigated “the Rhythmic Longshore Variability of Shoreline Change” for a distance of about 1,500 m north (downdrift) of the inlet. No migration rates are reported for the two classes of rhythmic forms: L < 1,500 m and L > 2,000 m. See also Bruun (1954) on migrating sand waves.

Southwest Coast of France

Migniot and Granbaulan (1985) studied shoreline developments at river entrances on the SW coast of France. From their figures, it appears that the downdrift erosion of the greatest point of erosion downdrift migrated downdrift (south) at a rate of 0.5 km/year (1875–1978) and 0.7–1 km/year (1867–1982).

Nile Delta

The situation at the Nile Delta shores, as described by Fanos et al. (1995), is very complex. The source of supply of beach material was gradually decreased by dams and almost cut off in 1964 by the Aswan Dam which barred 20 million m³/year river material from reaching the shore. The stabilization of river or canal outlets like Damietta, Port Said and El-Arish contributed severely to the erosion by their leeside (east) effects. Little information on migration rates of erosion is available, but in the case of El-Arish, the short-range downdrift erosion caused by breakwaters and next by groins apparently migrated eastward at about 0.2 km/year.

Skagen, Denmark

This site is located on the tip of Jutland separating the North Sea from the Baltic. Skagen Harbor, with its 500 m long jetties, is on the Baltic side. The net drift along the coast is fairly small or less than 50,000 m³/year. After the construction of the harbor, the erosion moved downdrift (southwest) at about 0.5 km/year. Later it slowed to about 0.2–0.3 km/year; the shoreline is re-orin-
enting slightly into the dominant wave approach during the most severe storms.

Rollover Pass, Texas

Conditions at Rollover Pass on the Texas Gulf, 31 km northeast of the Galveston Inlet, are described by Bales and Holley (1989). The pass is a man-made artificially stabilized inlet on the Bolivar Peninsula. Improvements of the pass were completed in 1959. Figure 4 compares shoreline rates of change near Rollover Pass. Referring to the period 1957–1974 in the figure, it may be seen that the downdrift effect extended at least 40,000 ft. or 13 km and probably more. Based on 1957–1974, one arrives at a migration rate of erosion of 13/17 = 0.8 km/year. The rate is 0.9 km/year if 1959, the completion year for the improvements, is used.

Cape May Inlet to Cape May Point, New Jersey, Atlantic Coast

Everts (1979) describes “Beach Behavior in the Vicinity of Groins”. Figure 5 shows mean rate of shoreline position change calculated for the Cape May beaches for the period 1949–1978. Everts explains how volume increased at depths from 4 to 6 m off the groins. The volume increase was greatest at the downdrift end of the groin system. Downdrift past the groins, a large volume of sand was deposited in water depths of 6 to 9 m (MLW). It is suggested that this material came from the updrift and the seaward side of the groins and also from the eroding shore downdrift of the groins. Figure 5, however, shows the characteristic feature of a short near-barrier effect and the start of the longshore effect which was interrupted by the Cape May Point. Even the small “0-area of erosion” exists. This is discussed with reference to Figure 9.

Sebastian Inlet, Florida East Coast

Sebastian Inlet was reopened in 1948 and jetty modifications were undertaken in 1952, 1955, and 1968–1970. The long distance effect according to Coastal Tech, Vero Beach extends about 22 km downdrift. With 1948 as a base, the expansion rate has been ~0.5 km/year.

Ft. Pierce Inlet, Florida East Coast

Ft. Pierce Inlet was cut in 1921 a few miles south of the old Indian River Inlet which had shoaled and ultimately closed. According to Coastal Tech, Vero Beach, the downdrift effects appear to extend nearly to St. Lucie Inlet or about 34 km to the south. Based on this information, a long distance erosion front migration rate of at least 0.5 km/year has taken place.

South Lake Worth Inlet, Florida Atlantic Coast

The inlet was cut in 1927 and provided with two jetties. A sand bypassing plant was built near the end of the north jetty in 1937 but bypassed only about 35,000 m³/year for five years, until the
plant was shut down in 1942. By 1945, after World War II, the plant resumed operation. Numerous reports have been written on its operation. Report by Olsen Associates, 1990 (Bodge, 1993) gives some information on shoreline movements. The best data are for 1927–1944 and show that the adverse effect has reached about 6,000 m towards the south or a migration rate of approximately 0.4 km/year. As the area has many rock reefs, it is difficult to evaluate causes and effects and to distinguish between short and long range migrations.

Regarding the Lake Worth Inlet, see, e.g., Walker and Dunham (1977). The situation is so complex that no definite conclusion can be drawn. Presently the plant is shut down. Improvements are being looked into (1993).

Iioka Port and Beach, Japan

Uda et al. (1991) discuss “Field Experiments on Sand Bypass off the Iioka Coast”. For a relatively short distance downdrift of the Ryuo-Zaki harbor, the deepest erosion cut migrated 6 km during 1977–1984. The total length of the affected shore was minimum 9 km and probably more (Figure 6). Using 9 km, one gets $9/7 = 1.3$ km/year for the front movement but it was possibly higher. Note the first up then down movement of shorelines at kilometers 6–9. During the middle part of the period, 1970–1984, detached breakwaters were built to counteract erosion.

Oarai Port and Beach, Japan

Oarai Beach is located just south of Cape Oarai. Shiraishi et al. (1977), describe how the construction of a breakwater for the port and a large groin immediately downdrift of the breakwater was investigated by a movable bed model properly field calibrated. It was found that the adverse effect of the two littoral barriers during the period 1973–1977 extended about 5,000 m downdrift or a migration rate of about 1.3 km/year.

Jarrett (1977) analyzes sediment budgets for Wrightsville Beach to Kure Beach. In his section on “the effect of Carolina Beach Inlet on Masonboro Island” he writes:

“Following the opening of Carolina Beach Inlet, Masonboro Island began to erode at a rapid rate. Estimates based on a comparison of aerial photographs made in 1956 and 1966 indicated an erosion rate of 59,000 cy/yr (45,000 m³/yr) along the northern 6,000 feet (1,830 m) of the island and

195,000 cy/yr (149,000 m³/yr) from the southern 32,000 lineal feet (9,750 m).”

Using the 1956 improvement date and the 1966 survey (10 years) and the 9,750 m figure for the influence of the inlet, one arrives at an about 1 km/year rate for the migration of erosion downdrift.

Ocean City Inlet, Maryland

Shoreline evolution on either side of the inlet is dealt with by Leatherman (1984). Historical shoreline changes on the downdrift side of the inlet on Assateague Island is shown in Figure 6. Construction of the Ocean City Inlet jetties, in combination with a net southerly longshore littoral drift, has resulted in severe erosion along north Assateague Island. It appears that none of
moving offshore to build a huge ebb tidal delta that is detectable from space through analysis of Landsat imagery. A comparison of the 1942 and 1962 shorelines clearly shows the trend since the jetty construction. The arc of erosion south of the inlet is clearly evident when considering historical changes 1950–1980 in Figure 6. The historical shoreline’s changes tend to converge further downdrift. This artificially induced erosion continues to impinge further downdrift through time.

Figure 6 does not extend far enough downdrift to indicate the front of the jetty-induced erosion. By a slight extrapolation, it was found that it is most likely that in 1962 it had reached 10 km south. That is a front movement of 10 km/20 years = 0.5 km/year.

**Charleston Harbor**

The geomorphological development in the area around the Charleston Harbor is described by Hayes et al. (1976). In citation:

“Construction was begun on the Charleston Harbor jetties in the late 1870’s. These jetties were designed to reroute the main harbor channel to the southeast and prevent shifting sand shoals from obstructing navigation. The harbor project was completed in 1896. Before construction of the jetties, the ebb-tidal delta was asymmetric toward the southwest, as is shown on the 1779 chart (Figure 7). The immediate effects of the jetty construction and dredging were:

1. Sediment normally supplied to adjacent beaches and shoals from the main ebb channel was either deposited into deeper waters as a result of the greater length and depth of the jettiéd channel, or it was removed by dredging.
(2) Without continued nourishment, the shoals and beaches on the downdrift side or the jetties began to diminish in size, as the normal process of south-westerly sediment transport, driven by dominant northeasterly waves, removed the sediment.

(3) The shoals paralleling the old main channel disappeared, leaving Morris Island open to wave attack.

(4) The shoals trending almost perpendicular to Folly Island (Figure 7) also disappeared, leaving Folly Island and Morris Island more exposed.”

The condition on the Folly Island deteriorated, until a comprehensive nourishment project was undertaken in 1992–1993 following Hurricane Hugo (1989), largely financed by the federal government which realized its responsibility.

GROINS, GROIN FIELDS

Groins have a similar adverse effect which has been demonstrated in many examples all over the world. The migration rate of the leeside erosion has the same order of magnitude as with other littoral drift barriers. Truitt et al. (1993) recommended in one specific case that a sand volume equal to 15% of the total fill should be placed downdrift to balance leeside erosion. This needs to be a continuous process because the groins will continue to bar the free drift as long as they are not kept fully filled, an impossible task.

SUMMARY OF SHORT AND LONG DISTANCE INFLUENCE OF THE LITTORAL DRIFT BARRIER

Examining the results from these cases of barrier effects on downdrift erosion, one may note the following points:

(1) The short distance influence occurs first (Figures 2 and 3). When it has developed to a certain extent, a long distance effect may appear, gradually moving downdrift faster than the short distance cut but fading out with distance.

(2) The short distance peak of the erosion occurs rather close to the littoral drift barrier, and only moves downdrift at a rate of about 0.3 to 0.5 km/year compared to a rate of 1–1.5 km/year for the long distance erosional front. In most cases it is difficult or impossible to observe both movements, short and long, as it may be seen from Table 1. This table compares the rate of movements for the cases mentioned in the examples. From a coastal geomorphological point of view, it is obvious that the combined short and long range development is most likely to occur for conditions of a very predominant drift indicated by an < in Table 1. See later under “The Zero or Slow Down Area”.

The examples of Table 1 are to be considered only as “indications”. Actual rates depend upon exposures, coastal topographies, bathymetries in the offshore and of materials in the drift-gravel or sand and their size.

THE CONNECTION BETWEEN SHORT AND LONG DISTANCE DEVELOPMENT

There appears to be a casual connection between the short and the long distance development of erosion downdrift, which are sometimes, but not always, separated by an area with about 0-erosion (Figures 2c and 3c). Consider the littoral drift budget combined with the movement of the front of the long distance effect:

Applying the littoral drift formula (U.S. Army Corps of Engineers, WES, Technical Note, 1990) one has:

\[ Q = \text{magnitude of drift} = KP/\omega (\rho_s - \rho)g \]  

(1)

where \( K \) = a dimensionless empirical sand transport coefficient (\( k = 0.39 \) if significant breaking wave height is used to calculate \( P_s \))

\( \rho_s \) = density of sand (quartz, \( \rho_s = 2,650 \text{ kg/m}^3 \))

Table 1. Dates of short and long term disturbance effects.

<table>
<thead>
<tr>
<th>Geographical Location</th>
<th>Short Distance (km/year)</th>
<th>Long Distance (km/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Port Canaveral, Florida, L (BODGE, 1993)</td>
<td>0.6–0.7</td>
<td>1.2</td>
</tr>
<tr>
<td>Port St. Lucie, Florida, L (BODGE, 1992)</td>
<td>0.4</td>
<td>0.7 (first), 1.5 (later)</td>
</tr>
<tr>
<td>Ft. Pierce, Florida</td>
<td>&gt;0.5</td>
<td></td>
</tr>
<tr>
<td>Sebastian Inlet, Florida</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>South Lake Worth Inlet, Florida</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>Carolina Beach Inlet, North Carolina</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Indian River, Delaware</td>
<td>0.45</td>
<td></td>
</tr>
<tr>
<td>Ocean City, Maryland</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Rollover Pass, Texas</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>Masonboro Inlet, North Carolina, L</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Hirtshals, Denmark, L</td>
<td>0.2–0.3</td>
<td>1.2–1.5 (front phase)</td>
</tr>
<tr>
<td>Skagen, Denmark</td>
<td>(0.5–1.0)</td>
<td></td>
</tr>
<tr>
<td>SW Coast of France, L</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>El Arish, Egypt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iioka, Japan, L</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>Oarai, Japan, L</td>
<td>1.3</td>
<td></td>
</tr>
</tbody>
</table>

1. Indicates large predominant drift
Figure 9. Bump in shoreline about 1,000 meters south of Port Everglades, SE Florida (circa 1936).

\[
\rho = \text{the density of water (seawater at } 20\, ^\circ\text{C, } \rho = 1,025 \text{ kg/m}^3) \]
\[
g = \text{acceleration due to gravity (} g = 9.81 \text{ m/sec}^2) \]
\[
a' = \text{ratio of the volume of solids to total volume, accounting for sand porosity (} a' = 0.6) \]
\[
P_{ls} = \text{longshore wave energy flux factor} \]
\[
P_{ls} \text{ depends on wave conditions at breaking (SPM, 1984 Equation 4-39).} \]
\[
P_{ls} = \frac{\rho E}{1\sigma} H_{sb}^2 C_{gb} \sin 2\theta_b \quad (2) \]

where

- \( H_{sb} \) = significant wave height at breaking
- \( C_{gb} \) = wave group speed at breaking
- \( \theta_b \) = angle breaking wave crest makes relative to the shoreline

In shallow water,
\[
C_{gb} = \sqrt{g d_b} \quad (3) \]

where \( d_b \) is the depth at breaking usually assumed to be linearly related to the wave height at breaking.

\[
H_b = \gamma d_b \quad (4) \]

in which \( \gamma = 0.78 \) is the wave breaking index.

As explained in the above technical note, “Wave measurements and observations have associated uncertainties, based instrumentation accuracy, and observer bias. Given that there are breaking wave height and wave angle uncertainty values, \( \Delta H_{sb} \) and \( \Delta \theta_b \), respectively.” An associated longshore transport uncertainty \( \Delta Q \) can be calculated. Combining equations (1), (2), (3) and (4)

\[
Q \sim (H_{sb})^{5/2} \sin 2\theta_b \quad (9) \]

An estimate of the uncertainty in the longshore transport rate can be evaluated by including the uncertainties in breaking wave height and angles

\[
Q \pm \Delta Q \sim (H_{sb} \pm \Delta H_{sb})^{5/2} \sin 2(\theta_b \pm \Delta \theta_b) \quad (10) \]

Assuming that the wave angle at breaking is small, and using the first two terms of a Taylor series expansion of Equation (10), the uncertainty in the longshore transport rate is estimated as

\[
\Delta Q \sim Q (\pm \Delta \theta_b / \theta_b \pm 5/2 \Delta H_{sb} / H_{sb}) \quad (11) \]

“The uncertainty in wave height is greatly amplified compared to the uncertainty in wave angle. For example, a 15% accuracy in wave height and
15% inaccuracy in wave angle result in 37.5 and 15% uncertainty contributions for height and angle, respectively, totalling a 52.5% uncertainty in Q. The uncertainties involved in the determination of littoral drift quantities and their variations are treated in detail in paper by Thieke and Harris (1993).

Consider now a development of downdrift erosion as shown schematically in Figure 8. Using realistic values for horizontal depth of cut and length of the short distance erosion cut as shown in Figure 8, one arrives at the angular values for the change in direction of the shoreline indicated in Figure 8. The wave fronts will turn correspondingly, as the depth contours also change orientation but more slowly and later than the shoreline (Figure 1b). That means a change in wave heights, $H_{sb}$, and in breakwater angle $\theta_b$, thereby also in $Q_b$, compared to the initial shoreline. Both will tend to slow down the longshore drift, which may or will be reversed just downdrift of the barrier as indicated in Figure 8. The quantity of material moving downdrift is going to decrease for a certain distance downdrift. This will result in erosion, thereby in an expansion of the downdrift zone influenced by the barrier.

Example

Assume that wave heights decrease from $H_{sb} = 1$ m to $H_{sb} = 0.9$ m, while $\theta_b$ due to turning of the wave crests, next turning of the shoreline, decreased about 2 degrees. Using Eq. (11) one arrives at a total change in littoral drift quantity $Q$ of $\sim 35\%$. For $Q = 200,000$ m$^3$ $Q$ is then about 70,000 m$^3$. This is the quantity which, in the start, must be subtracted from the drift, which gradually builds up again downdrift of the barrier reestablishing the normal drift quantity.

Let us look at the consequences of this development by assuming an expansion rate of 1.5 km/year (Table 1) and that the profile affected by this development is 8 meters high from +3 to -5 meters or from +2 to -6 meters. To balance the deficit in supply of material downdrift, one has to gain 70,000 m$^3$ where $x$ is the average shoreline and nearshore depth contour recession. This gives $x = 5$ to 6 meters annual recession, which is a practical figure recorded in many high exposure cases. There is, of course, a rather wide variance and erosion also continued behind the front.

The above is only given as an example indicating “a relationship”. It does provide an explanation of recorded facts which may be elaborated considerably by records and by models like, e.g., Hanson (1987) and others. The example also reveals the adverse effect of a littoral drift barrier which will gradually extend a considerable distance downdrift approaching an “asymptotic limit”, which may be called “infinite”. The “infinite” will never be reached, however. Another barrier will probably take over and make its own contribution to the continuation of the short and long distance adverse effect.

Model Result

Perlín and Dean (1978) developed a model for the prediction of initial planform with littoral controls. They compared models of an “explicit” and an “implicit” model. In citation:

“To evaluate the implicit scheme, comparisons were carried out with results obtained from the explicit model. The wave conditions used in both models were a breaking wave height of 5 ft., an angle of wave approach of 45 from the north, and duration of 1.39 days. The jetties were 1,500 ft. long, and both the north jetty and the south jetty were oriented at angles of 20 to the shoreline. The time step in the explicit and implicit models are 600 and 6,000 seconds, respectively. Because the differences between predicted shoreline changes by the two methods are small, rather than presenting plots, the results are tabulated in Table 2. The accretion is represented as a position change and the erosion as negative. Both the $x$-distances (distance from the shore end of the jetty at the baseline) and the $y$-coordinates have been rounded to the nearest tenth of a foot. Also, $y$-coordinates which did not change due to being outside of the region of jetty influence are not presented in Table 2(1).

“The distances proceed outwards in both directions from the jetty. Note that grid point 50 has a value of 176.2 ft. which is less than the value at grid 48. The explanation is simply that 176.2 ft. is the distance from the baseline to the jetty at grid 50 (i.e., the jetty is impounded with sand at this point). It is also worth noting that the south beach is affected for a larger distance from the jetty because the diffraction changes the wave heights along this stretch of beach and, therefore, the transport rate is not uniform even for the straight beach condition until the beach is out of the diffraction shadow zone.”

Referring to Tables from their articles, not noted by the authors, is the development of a “bump” like Figure 8 at a distance of 1,880–2,000 ft.
Table 2. Comparison of explicit and implicit one-line models shoreline changes adjacent to jetties at an inlet (Perlin and Dean, 1978).

<table>
<thead>
<tr>
<th>Grid Point</th>
<th>Distance from Base of Respective Jetty (ft.)</th>
<th>Explicit (ft.)</th>
<th>Implicit (ft.)</th>
<th>Percent Difference (explicit vs. implicit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Jetty</td>
<td>50</td>
<td>64.1</td>
<td>176.2</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>48</td>
<td>192.4</td>
<td>276.4</td>
<td>3.9</td>
</tr>
<tr>
<td></td>
<td>46</td>
<td>320.6</td>
<td>182.2</td>
<td>5.7</td>
</tr>
<tr>
<td></td>
<td>44</td>
<td>448.9</td>
<td>114.2</td>
<td>6.7</td>
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<tr>
<td></td>
<td>42</td>
<td>632</td>
<td>47</td>
<td>9.8</td>
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<tr>
<td></td>
<td>40</td>
<td>870.1</td>
<td>12</td>
<td>9.2</td>
</tr>
<tr>
<td></td>
<td>38</td>
<td>1,108</td>
<td>2.4</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td>36</td>
<td>1,346.3</td>
<td>0.4</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>34</td>
<td>1,158.4</td>
<td>0.1</td>
<td>0</td>
</tr>
<tr>
<td>South Jetty</td>
<td>62</td>
<td>119</td>
<td>-16.8</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>64</td>
<td>357.1</td>
<td>-13.7</td>
<td>2.4</td>
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<td>66</td>
<td>595.2</td>
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<td>1.4</td>
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<td></td>
<td>68</td>
<td>833.3</td>
<td>-55.6</td>
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<td>72</td>
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<td></td>
<td>76</td>
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<td>5</td>
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<td></td>
<td>78</td>
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<td>-8.5</td>
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<td>80</td>
<td>2,261.8</td>
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<td></td>
<td>88</td>
<td>3,214.1</td>
<td>0.1</td>
<td>0</td>
</tr>
</tbody>
</table>

approximately 2,500 ft. downdrift. This is the implicit model and almost alike in the explicit. This is what we find in many cases in the field, see Figures 8 and 9 where Figure 9 is an aerial photo from Port Everglades, SE Florida. A “bump” or outward curved shoreline is seen about 1 km from the entrance of the port.

THE ZERO OR SLOW DOWN AREA

The peculiar “zero-area” which sometimes appears downdrift at a rather short distance from the barrier (Figures 2c, 5 and 6) is a coastal geomorphological feature which does not necessarily indicate the extreme limit of leeside erosion. Obviously, the shoreline has to resume its initial direction following its change of direction on the downdrift side of the barrier. This can only be accomplished by an S-curve, which in turn develops a kind of a “corner” at point “a” as seen in Figure 8. This makes the local following section of the shore resemble “a groin” with some (minor) stabilizing effects updrift, but at the same time aggravating the large scale erosion downdrift caused by the littoral drift barrier. A consequence of that is that the bump is most developed when the drift is very predominant and less visible for a more neutral situation.

The above-mentioned effect does not always appear in the form shown in Figure 8 by a “zero-area”, but it may be observed as a (temporary) slow down of erosion at a certain distance without changing the general mode and pattern of the development of erosion downdrift (See Figures 2c, 5 and 6 and Table 2). Figure 9 is an aerial photo from Port Everglades, SE Florida. A “bump” or outward curved shoreline is, as mentioned above, visible about 1 km south of the entrance.

The small pointed accretion which occurs a short distance downdrift at Port Canaveral as well as at Port St. Lucie is not explained or discussed by Fields et al. (1989). As mentioned above, it probably is a result of a small rock-outcropping which became exposed by the downdrift erosion. The erosive development, however, passes right over its head downdrift. Foster (1992) includes a similar case in his mathematical modeling of downdrift erosion. His attempts to develop a small accretion on an uninterrupted rock-free shore downdrift of a barrier have not been successful to date. However, he indicates that for one almost neutral drift condition on a relatively curved (convex) regional shoreline, a larger area with stable or mildly accretionary tendency was developed, followed by mild erosion further away from the inlet. This came about in preliminary modeling of the erosion pattern on the north (updrift) side of Ponce de Leon Inlet. Foster expects that a similar situation may exist on the downdrift side (personal communication). A discontinuity developing downdrift of a very predominant drift is no surprise, simply due to the development of the wave pattern downdrift of a littoral drift barrier. Reference is made to Table 2 by Perlin and Dean (1978) who obtained the same result in a model with 45 degrees wave incidence of 1.5 m height (See Figure 8). In a groin field like Figure 5 from Cape May in North Carolina, the downdrift development showed a limited size accretion downdrift. (See also Figure 6, Iioka Coast in Japan.)

THEORETICAL APPROACH

Paper by Hanson and Kraus (1993) addresses in particular the erosion which occurs at “Beach Transitions”, such as those that take place at
abrupt lateral transitions of beach fills. Based on an assumption of two different wave directions, one causing drift to the left, the other towards the right the following expression was developed:

\[ Q = \text{increase in erosion} = 2\phi Q_1^* \]

where \( \phi \) is the change in shoreline directions, when the general fill orientation is compared to the orientation of the transition shore, and \( Q_1^* \) is the additional annual erosion angular gradient related to the transition. The quantity of drift is very sensitive to the change in wave height \( H_{bs} \) as well as to a change \( \Delta H_b \) in the breaker angle, \( \theta_b \).

Consider a very simplified case: an \( H_{bs} \) of 2 m occurring 5% of the year from a direction which only changed \( \theta_b \) from 5 degrees to 4 degrees. The quantity of drift outside the transition in the general fill is \( Q = 2.87 \times 10^6 \times 2^{5/2} \times \sin 2 \times 5 = 3,700,000 \text{ m}^3/\text{year} \) for continued wave action. With 5% it becomes 185,000 m³. No drift in the opposite direction is assumed.

If \( \theta_b \) changes from 5 degrees to 4 degrees on average the drift changes from 185,000 m³/year to 185,000 \times \sin 2 \times 4/\sin 2 \times 5 = 150,000 \text{ m}^3/\text{year} \) without consideration to \( H_b \) decreases 10% an additional \( \sim 40,000 \text{ m}^3 \) is lost. This is a total difference of about 75,000 m³, which must then be replaced by erosion downdrift similar to the above example. Of course, this is only "a demonstration" of the importance of small changes in \( \theta_b \) and \( H_b \) which shows how very small changes in \( H_b \) and \( \theta_b \) may have considerable influence on drift quantities. Like most of the examples given, it refers to shores where the net drift has a relatively strong predominance in one direction.

Theoretically and under idealized assumptions, the effect of a littoral barrier on the downdrift shoreline extends infinitely downdrift. To this may be added, "if this is possible and occurs on a shore which is uninterrupted by any other barrier and infinitely long" (PELNARD-CONSIDÈRE, 1956).

**RELATION BETWEEN THE HORIZONTAL DEPTH OF CUT AND THE LENGTH OF THE LONG DISTANCE EROSION AS A FUNCTION OF TIME**

The horizontal depth of cut and the length of the shore influenced by leeside erosion has been researched by many, e.g., by HANSON (1987). Obviously the peak of the cut in the shore first accelerates, next decelerates at the same time as the peak point migrates downdrift (Figure 1, BRUUN, 1990, Chapter 8). The ultimate result of this development may be observed at some rocky headland shores as a jigsaw shoreline configuration like the Southern California headland shores. This condition is explained by BRUUN (1954–1990) as a result of equal longshore drift on both sides of the maximum. This condition operating along shores with coarser materials may develop "giant cuspate forelands" as, e.g., found at Dungeness on the English Channel coast. (Reference to figures in BRUUN, 1990, Chapter 8.)

While the length of the erosion cut may be defined as "infinite", the horizontal cut in the shoreline and its movements depends upon physical factors like waves, sediment and geological characteristics. The maximum cut in the shoreline may be hundreds of meters in extreme cases, like Lagos, Nigeria, and the rate of recession could, e.g., be of the order of 10 m per year, as it actually was for a shorter period of time downdrift of a group of groins at Bovbjerg on the Danish North Sea coast during the 1940's (BRUUN, 1954). CHARLIER and DEMEYER (1989) report annual recession rates up to 35 m/year (Victoria Beach, Lagos, Nigeria). No shoreline configuration is stationary in detail. They all move! Often in cyclic patterns, in and out.

**NATURAL VS. LEESIDE EROSION**

It is sometimes difficult to distinguish natural erosion from downdrift erosion and to assess their relative magnitude. Based on observations in the field, "Model One" the following may be concluded.

1. If the erosion increases downdrift of an established littoral drift barrier and the weather climate worsens simultaneously, there is a combined effect on erosion downdrift.
2. If, however, the weather climate did not change and erosion increased, this is an indication of an adverse effect of the littoral drift barrier.
3. If the weather climate improved while erosion increased, this is or may be taken as a proof of the adverse effect of the barrier. Such cases exist.

**CONCLUSION**

The downdrift shoreline development at a littoral drift barrier may in some cases, but not always, be described by a short (local) as well as a long distance effect which both move downdrift at various rates; the long distance movement being 2–3 times faster than the short distance, or about \( \sim 0.5 \text{ km/year} \) versus \( \sim 1–1.5 \text{ km/year} \).
figures may be subject to considerable variances depending upon wave intensities, barrier morphologies and littoral drift magnitudes as well as upon the relative predominance of the drift. The short distance effect is a coastal geomorphological feature, the long distance a materials deficit feature.

To clarify all details of littoral barrier effects with respect to the fate of materials which were pushed seaward by the barrier would require comprehensive tracer and/or beach drifter tests, the results of which would be highly weather dependent. Also the conclusions of such tests would be mainly qualitative. However, they would give information on the gradual fading out of the leeside effect along the downdrift shore, still realizing that some material may be lost to deeper sections of the bottom profile and thereby be lost to the beaches downdrift causing erosion.

The need for effective bypassing procedures to balance the downdrift erosion is obvious and should never be ignored, although it has been in the past sometimes for face-saving reasons! Some states and/or countries have by law taken firm action against the continuation of littoral barrier effects. Others are still in limbo. The problem is that many inlets and entrances were established or approved by public agencies. Not all of them are willing or ready to accept their “guilt”. New laws are necessary to establish firm “coastal ethics”.

ACKNOWLEDGEMENTS

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LITERATURE CITED


