

# Assessment of the Hydraulics and Longevity of Wood End Cut (Inlet), Cape Cod, Massachusetts, USA<sup>1</sup>

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## ABSTRACT

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The terminus of Cape Cod, Massachusetts, consists of a recurved barrier spit, Wood End—Long Point, which protects an extensive salt marsh-tidal flat (2.5 km<sup>2</sup>). A 1,875-m permeable stone-dike connects the dune-covered barrier with high land of the Cape, completing the enclosure of the tidal flat. The barrier was breached during an unusually high spring tide (4 m) by a 1-m storm surge during the Blizzard of '78 (Feb. 7) and has remained open by natural processes. A physical process study utilizing velocity, discharge, tidal stage, hydraulic head, vibra-core and dye circulation data was carried out to: (1) determine the effect of the dike on inlet processes, (2) quantify sediment transport through the inlet, and (3) estimate longevity of the inlet. Water floods onto the tidal flats through the inlet (42%) and the dike (58%), and ebbs through inlet (21%) and dike (79%) creating a residual current drift entering the inlet and exiting the dike. There is net landward movement of sediment through the inlet. The back-barrier tidal flat is a sediment sink. A coarse sand and gravel flood tidal delta (area = 90,000 m<sup>2</sup>; vol. = 75,000 m<sup>3</sup>) has accumulated on the tidal flats during the 7½ year period following the breach.

**ADDITIONAL INDEX WORDS:** *Inlet, hydraulics, sedimentation, flood tidal delta, dike, tidal flat, vibra-core, tidal prism, velocity, bedforms.*

## INTRODUCTION

The geomorphology of Cape Cod, Massachusetts (USA), reflects both its glacial origin and subsequent modification by coastal and eolian processes. Glacial outwash sand and gravel deposited between two lobes of the Wisconsinan continental ice sheet were reworked by waves and tidal currents during Holocene sea level rise (ZIEGLER *et al.*, 1965) (Figure 1). The cliffs of the Outer Cape are retreating at a rate of 0.8 m/year (GEISE and GEISE, 1974). The tip of the Cape consists of a recurved spit (Wood End—Long Point) which acts as a barrier protecting an extensive salt marsh-tidal flat area (2.5 km<sup>2</sup>) (U.S.A.C.E., 1876). The coast is under the domain of the National Park Service (Cape Cod National Seashore). It is mesotidal with a semi-diurnal tidal range varying from 3.5 m (springs) to 1.7 m (neaps) (Figure 2).

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Storms in February 1885 and February 1940 breached Wood End Barrier, however these inlets were closed artificially with timber brush bulkheads. In 1914, a permeable stone-dike was constructed across the tidal flats by the Army Corps of Engineers connecting high land near Provincetown to the barrier, thus completely enclosing the flats (Figure 3). The purpose of the dike was to break the tidal flow across the flats and eliminate sand transport into the Harbor, as well as to protect the Harbor in case the barrier was overtopped again. During the blizzard of Feb. 7-8, 1978, a low stretch of the barrier was breached by a storm surge when water levels were elevated 1 meter above an unusually high 4-m spring high tide. The inlet has remained open since the storm and migrated 250 m towards the southeast.

The transfer of sediment from eroding beaches to the back-barrier environment via inlets is considered an important mechanism in the landward migration of barrier coastlands. The present Wood End Barrier Inlet (called "The Cut" locally) is protected by National Park Service regulations

from being closed artificially and thus provides an opportunity to study the evolution of a tidal inlet, as well as to quantify the amount of sediment moving through the inlet. The goals of this study are to: (1) determine the relationship of the permeable stone-dike to inlet processes, (2) estimate magnitude of sediment transport through the inlet, and (3) assess longevity of the inlet.

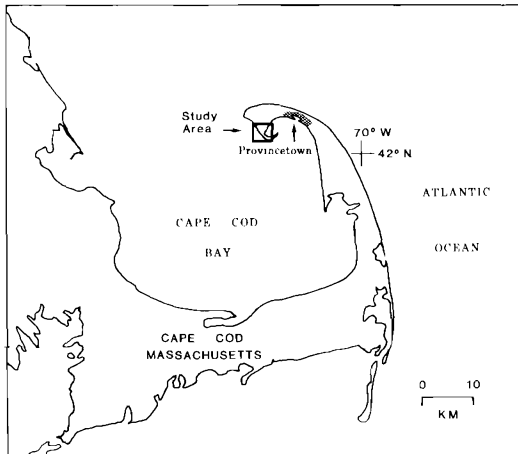


Figure 1. Location of Wood End Inlet study site, Cape Cod, Massachusetts.

## FIELD METHODS

### Water levels

Tidal staffs were erected on both sides of the stone dike during a spring tide. Water levels were read visually every 15 minutes for a complete tidal cycle (7/23/85 and 8/22/85) and a portion of a tidal cycle (8/21/85). On two of those days (8/21, 8/22) a third tidal staff was erected in the ocean (Cape Cod Bay) adjacent to Wood End Inlet, thus obtaining water level data simultaneously in the three water bodies: Provincetown Harbor, Wood End tidal flats, and Cape Cod Bay proper. A topographic profile surveyed by transit and stadia rod from dike to inlet was conducted to connect the water level staffs.

### Vibra-coring

A total of eight cores ranging in length from 62 to 108 cm were collected from the flood tidal delta in the tidal flat area by a custom-made vibra-coring unit. Compaction averaged 50%.

### Velocity

Velocity was measured in the deepest portion of the inlet channel on a spring tide (3.2 m) by two Marsh McBirney EM(511) 2-component current meters mounted on a stake. Probes were mounted

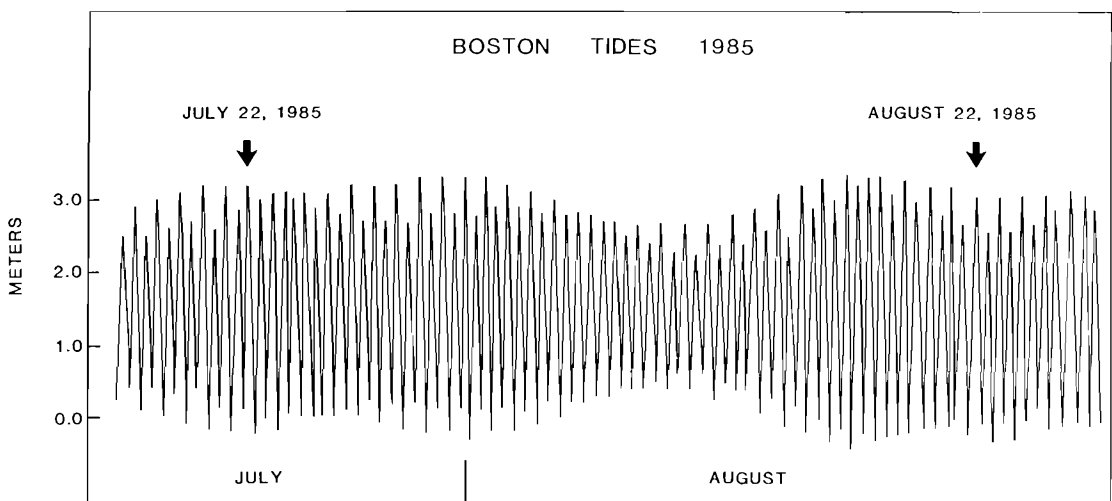


Figure 2. Tidal curve (predicted times and water levels at Boston, MA) during period of study (7/15/85—9/1/85)

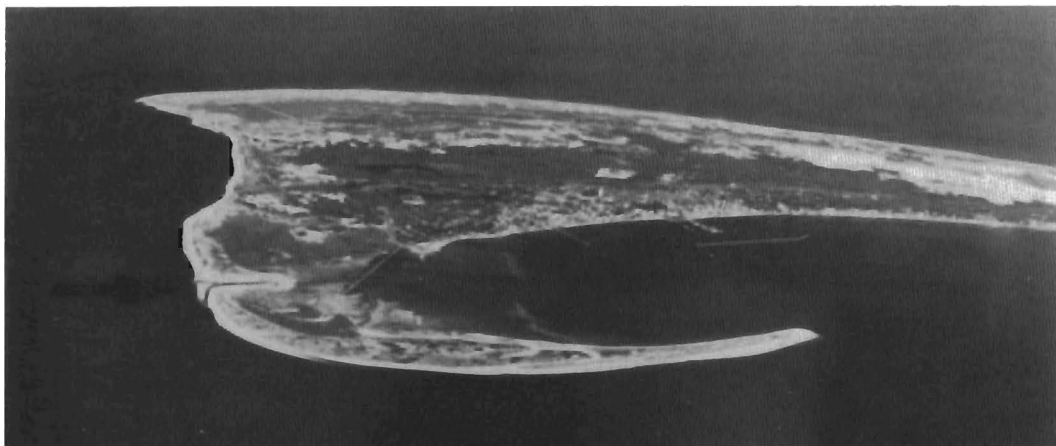


Figure 3. Aerial view of the outer tip of Cape Cod (10/15/80) at low tide. Arrow indicates Wood End Inlet. Photo by Richard Kelsey, Chatham, Massachusetts.

at 20 cm from bed and 80 cm (0.4 depth) from bed on 7/22/85. Auxiliary velocity data were collected by clocking surface drogues over a known distance and then corrected to mean velocity by multiplying by 0.8.

### Circulation (dye) studies

Red fluorescent dye in bricks of corn starch tied to a buoys were anchored in the inlet channel. Liquid dye was also poured directly into the water. The dye was released (8/23/85) during peak flood, flow which occurs 1.5-2 hours before high tide. Ebb circulation was monitored by 5 anchored buoys (approximately 200 m apart) placed by boat in a transect across the tidal flat area. The dye was emplaced during expected peak ebb flows (2.5-3 hours before low tide) on 10/21/85. Dye movements were recorded by aerial photography.

## RESULTS

### Wood End Cut (Inlet)

#### Physical Characteristics

The inlet is 105 m wide and 2.35 m deep at spring high tide. Cross-sectional area at maximum spring tide is 84 m<sup>2</sup>. The cross-sectional profile consists of a 25 m wide "channel" flanked by swash platforms. The profile is asymmetric with a narrow (20 m), shallow (0.50 m) swash platform on the eroding south side and a wide (60 m), deeper, gradually



Figure 4. Aerial view of Long Point barrier (toward southeast) taken at low tide reveals several recurved spits formed during inlet migration. Ebb tidal delta is a very small bulge on the shoreline.

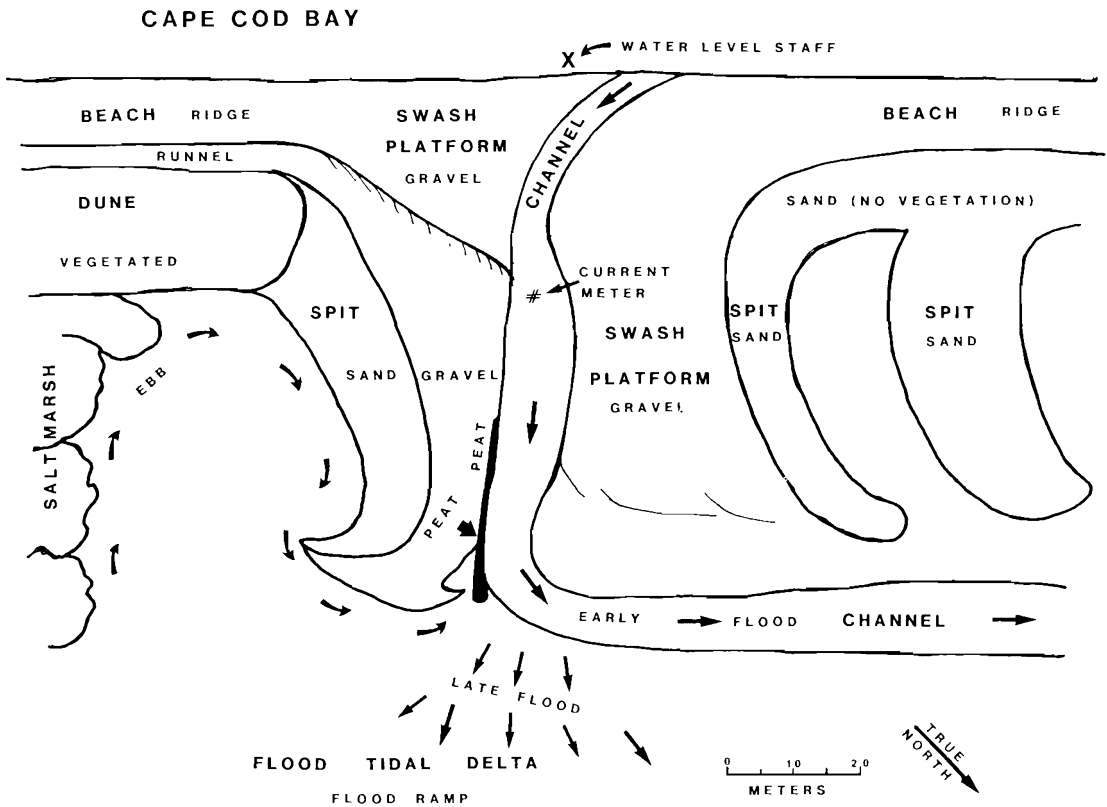


Figure 5. A geomorphic sketch map of Wood End Inlet. Arrows indicate flow directions during early and late portions of the flood cycle.

sloping (mean depth = 1.0 m) swash platform on the depositional north side. The asymmetry of the profile reflects the history of inlet migration from north to south. Several recurved spits have been left as a record of migration (Figure 4). The inlet is now apparently hung up on a resistant, salt marsh peat bed exposed on the south side of the inlet channel (Figure 5). At low tide, the inlet is completely drained and a pebble-cobble lag gravel armors the bed. The ebb tidal delta is very small and appears as only a small bulge on the shoreline (Figure 4).

#### Flow Characteristics

A graph of mean velocity *vs.* time reveals peak flood flow of 1.9 m/sec and a corresponding peak ebb of 0.95 m/sec (Figure 6A); the discharge plot also shows flood dominance (Figure 6B). Peak flood discharges are nearly 94 m<sup>3</sup>/sec, whereas peak ebb discharges are only 40 m<sup>3</sup>/sec. The sum of the dis-

charge for the flood tide entering the inlet is 489,000 m<sup>3</sup>, and the sum of the ebb tide exiting is 246,000 m<sup>3</sup>. The water volume excess (243,000 m<sup>3</sup>) must pass out through the dike on the ebb.

The tidal prism, the total volume of water exchanged on a tidal cycle, (1,160,000 m<sup>3</sup>) was determined by computing storage volume of the tidal flat area at spring high tide (3.1 m). Of this, only 42% passes through the inlet on the flood tide, the remaining 58% of the tidal prism must enter through the dike. During ebb, only 21% of tidal prism exits through the inlet, the balance (79%) passes out through the dike. Thus, approximately 1/3 of the tidal prism passes through the inlet, the rest moves through the dike.

#### Provincetown Dike

The rubblestone dike constructed on the sandy tidal flats in 1911-1914 is 1875 m long and is orien-

ted approximately north-south (Figures 3, 7). A thin veneer (15 cm) of crushed rock separates the tidal flats from the overlying stones (U.S.A.C.E., 1983). Individual blocks of the dike weigh from 0.5 to 4 tonnes each. The dike was designed to be 1.5 m wide at top and 15-20 m at the base and is 4.5 m high (above m.l.w.). Flow through and under the dike has eroded sections of the tidal flats causing settling of the overlying stones. Large, gaping holes have developed periodically in the dike, forcing maintenance repairs by the Corps of Engineers in 1940, 1957, 1971 and 1984.

**Hydraulic Head**

Water passes back and forth through the dike as the water level rises and falls in Provincetown Harbor. The dike inhibits flow and thus a head develops. Figure 8A depicts water level *vs.* time on the two sides of the dike. The flat section on the Harbor side stage curve is due to partially impounded water draining slowly off the tidal flats into Provincetown Harbor. Water level on the Wood End tidal flat side consistently lags behind the water level changes in the Harbor. The dike is built on intertidal flats and thus in this perched position the lowest water level that can be measured at the dike is not low water reached in Cape Cod Bay (near the inlet) or in Provincetown Harbor. Consequently, when water level is rising in the Harbor and Bay (*i.e.* flood tide) the water behind the dike is still draining out (ebbing). Duration of ebb flow from the Wood End tidal flats is longer (7 hrs, 12 min) than the flood flow (5 hrs, 12 min). Maximum difference in water level (head) is 56 cm on flood and 100 cm on ebb (Figure 8B).

Flows greater than 1m/sec were measured at spot locations passing through the dike on both flood and ebb tide. Coarse sand (in suspension) was collected with a hand-held Helley-Smith Sampler, from flows passing through the dike in ebb direction.

**Tidal Discharge**

The volume of water moving through the dike at any given time during the tidal cycle is a function of: (1) the area (A) of dike covered by water, (2) the head (h) difference across the dike and (3) gravity (g), and (4) the permeability of the dike (CX).

$$Q = CX A \sqrt{2gh} \quad (1) \text{ (KING, 1954)}$$

This equation for flow through an orifice was chosen to compute discharge because the dike is composed of a network of orifices which act as con-

duits for tidal flow. The dike can be considered a mosaic of stacked pipes that fill and empty as the tide rises and falls. The pipes convey water though thousands of tortuous paths. The size and effectiveness of the pipes in passing water is highly variable both vertically and laterally; therefore CX represents the effective permeability and is the average permeability for the entire length and height of dike. X is a measure of % voids in the dike and C is a measure of the "ease" in which water can move through the voids. The source of data for each variable is discussed below.

**Discharge (Q)**

The total volume of water passing through the dike on the flood tide and the total volume of water passing out through the dike on the ebb tide cannot be measured directly and must be computed from inlet flow and tidal prism data. Knowing that

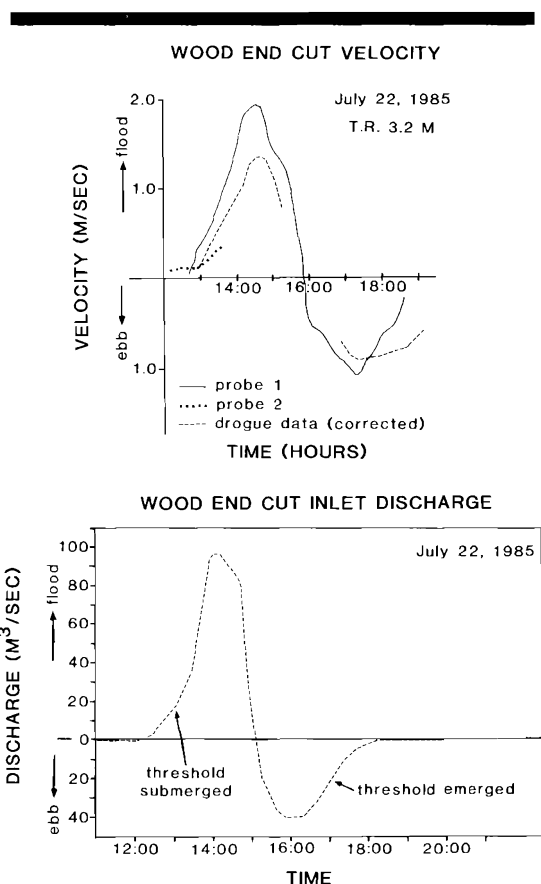


Figure 6. (A) Inlet velocity through a complete tidal cycle. (B) Inlet discharge. Times when the threshold located in the inlet channel is submerged and emerged are indicated.

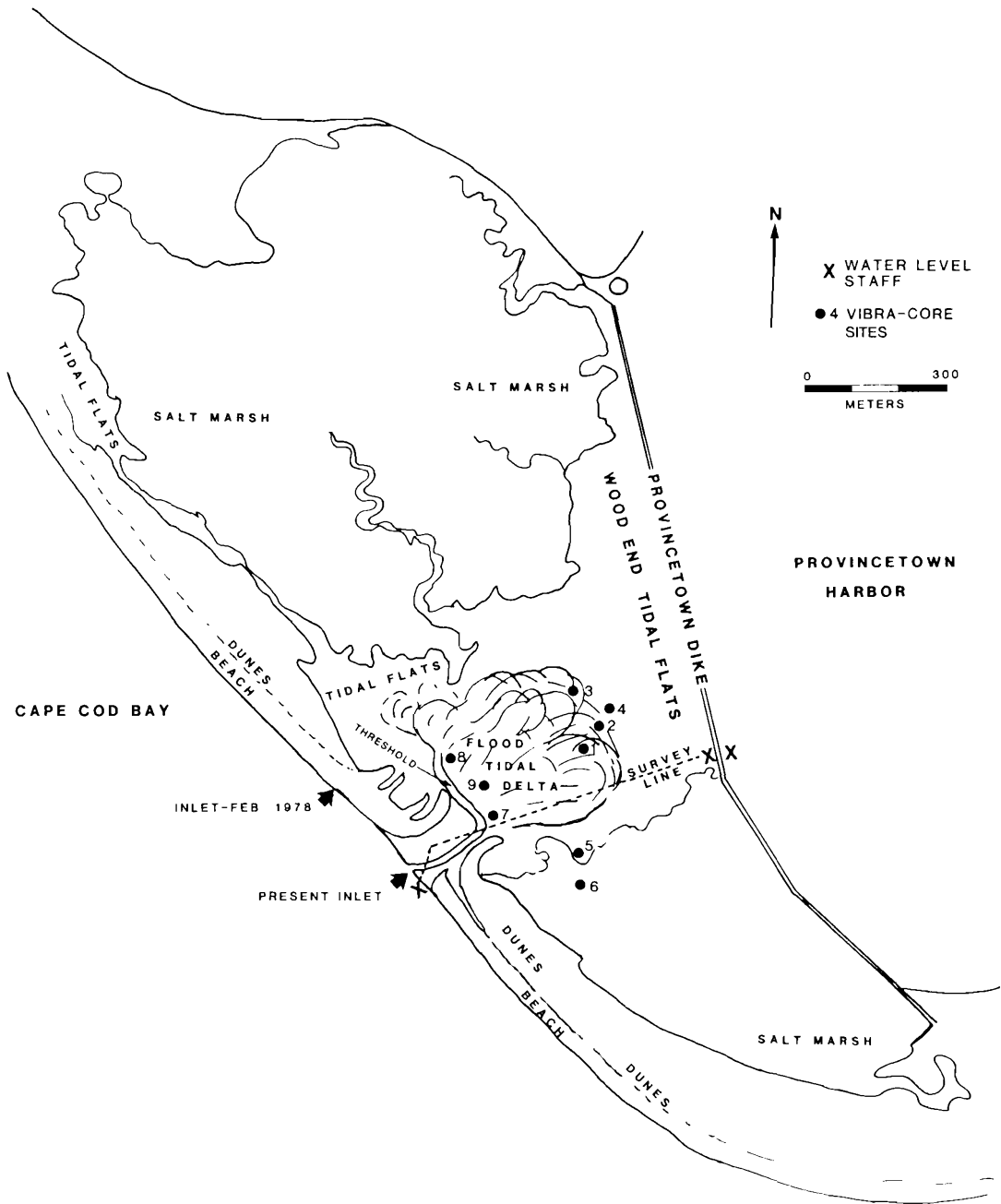


Figure 7. Geomorphic map of study area with location of original inlet breach, water level staffs, survey line and vibra-cores.

243,000 m<sup>3</sup> more water came through the inlet on the flood than flowed out on the ebb, the total dike discharge could be calculated by subtracting total inlet discharge from the tidal prism (Table 1).

Table 1. Hydraulic characteristics of inlet

	Peak Q (Flood)	Peak Q (Ebb)
Inlet	94 m <sup>3</sup> /sec	40 m <sup>3</sup> /sec
Dike	75 m <sup>3</sup> /sec	99 m <sup>3</sup> /sec
Wood End Tidal Flat (tidal prism)	Total Dike Discharge Flood 671,000 m <sup>3</sup>	Total Inlet Discharge Flood 489,000 m <sup>3</sup>
1,160,000 m <sup>3</sup>	Ebb 914,000 m <sup>3</sup>	Ebb 246,000 m <sup>3</sup>
1,160,000 m <sup>3</sup>		

**Area (A)**

Dike area (length times depth) covered by water was determined for each 15 minute period during the 12 hr, 25 min tidal cycles. The dike length affected by the tide is 1100 m. Mean depth (d) of water against the dike (for each 15 min period) was obtained from the tidal stage data (Figure 8A).

**Hydraulic Head (h)**

The hydraulic head value representing each 15 min time period was computed directly from the stage data (Figure 8B). Positive values indicate water levels are higher in Provincetown Harbor than in Wood End tidal flats (*i.e.* during flood).

**Gravity (g)**

9.8 m/sec<sup>2</sup> was used for gravity.

**Effective Permeability (CX)**

Equation 1 was used to solve for the "unknown" CX, by substituting the total discharge (Q) passing through the dike on a tidal cycle and the total of the "area-head" values (sum of 50 individual  $A\sqrt{2gh}$  calculations) for the same time period. There are approximately 50 15-min intervals in a tidal cycle. The effective permeability (CX) of the Provincetown rubblestone dike during August 1985 was 0.015723. Porosity (X) is percent voids in the dike. Permeability (C) is the interconnectedness of these voids, or how easily flow is transmitted.

C ranges from 0.5 to 0.8 in turbulent flows through orifices. However, because of the convoluted nature of the water pathways through the dike, C is likely to be reduced and be on the order of 0.2 - 0.3. Porosity (void space) of the dike is estimated to be on the order of 5% - 6%. With these limits, a reasonable value expected for CX is be-

tween 0.01000 and 0.018000. The value calculated in this study from field data (0.015723) lies within this range.

Equation 1 was then used again to calculate the discharge passing through the dike for each 15-min period by using the computed CX value (0.015723) and the individual  $A\sqrt{2gh}$  values.

**The Hydraulic Model**

The hydraulic system is complex but can be represented by a graph depicting the relative contribution of water volume to the tidal flat area by (1) Wood End Cut (Inlet) and (2) Provincetown Dike. Figure 9 shows cumulative water volume contributed by inlet vs. cumulative water volume via dike against time. Also graphed is the total cumulative water volume on the tidal flats that entered via inlet and dike (combined). Another way to express the physical relationship between the dike and the

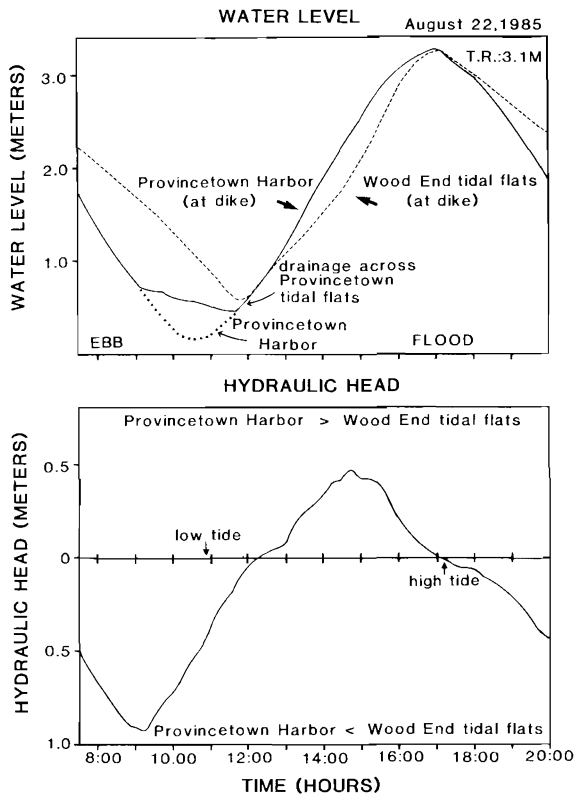


Figure 8. (A) Simultaneous water levels on both sides of the dike: Wood End tidal flats and Provincetown Harbor. (B) Hydraulic head developed across the dike calculated from the water level data.

inlet is by a series of diagrams representing discreet intervals of time during the tidal cycle (Figure 10A, B, C).

### Stage 1 (0-1.25 hr) Low Tide

When low water occurs in the ocean (Cape Cod Bay and Provincetown Harbor), water is still impounded behind dike and continues to ebb after the flood cycle has begun in the ocean. Lowest water on Wood End tidal flats occurs at 1 hour.

### Stage 2 (1.25-2 hr)

Water from Cape Cod Bay floods into the inlet channel, however, a high point in the channel (the "threshold") prevents water from flooding onto the tidal flats. Water level in Provincetown Harbor rises and water floods slowly through the dike. However, as the dike retards flow a head develops between the Harbor and the tidal flats.

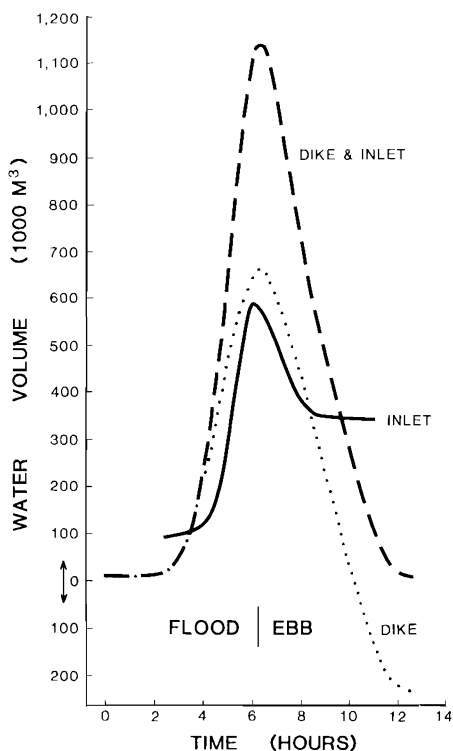


Figure 9. A summary of water volumes contributed to the Wood End tidal flat area via the inlet and the dike.

### Stage 3 (2-4.2 hr)

Water level on the tidal flats lags behind both "ocean" water levels (Cape Cod Bay and Provincetown Harbor). Water is still prevented from entering the flats through the inlet because of the "threshold." The semi-permeable dike retards flow from Provincetown Harbor onto the flats and thus the head across the dike continues to increase.

### Stage 4 (4.2 hr)

Maximum head (0.56 m) across the dike occurs and calculated discharge is  $75 \text{ m}^3/\text{sec}$ . This is peak flood discharge through the dike. At this time the high point ("threshold") in the inlet channel is reached and water from Cape Cod Bay begins to flow onto the tidal flat area. This increase in discharge raises the water level on the tidal flats, decreases head across the dike and decreases discharge through the dike.

### Stage 5 (4.2-6.2 hr)

The tidal flat area continues to fill up with water flooding through the dike and through the inlet. The highest discharges through the inlet occur between (4.75-5.5 hr); peak flood flow ( $94 \text{ m}^3/\text{sec}$ ) is at +5.2 hr or 1 hour before high tide.

### Stage 6 (6.2 hr) High Tide

High tide is reached in Cape Cod Bay and Provincetown Harbor. However, water level on the Wood End tidal flats is lower as it has lagged behind and is still rising after the "ocean" levels have crested.

### Stage 7 (0-2 hrs after high tide)

Stage falls in Cape Cod Bay and Provincetown Harbor leaving water dammed behind the dike and a hydraulic divide ("watershed") develops near the dike. Water near the dike exits to Provincetown Harbor. However, the dike inhibits flow and a more efficient route is through the inlet. Thus, initially, most of the water on the tidal flats drains out to Cape Cod Bay. Peak ebb discharge in the inlet ( $40 \text{ m}^3/\text{sec}$ ) is reached by 1 hour after high tide, with generally high discharges occurring from 0.5-2.0 hr.

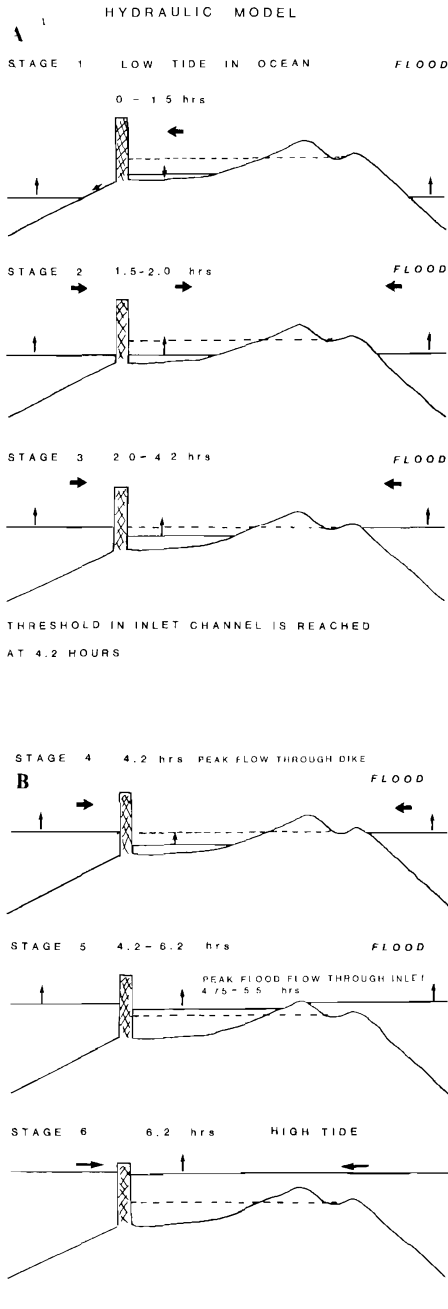
### Stage 8 (2-4 hrs after high tide)

Stage continues to drop in Cape Cod Bay and Provincetown Harbor. As head across the dike in-



creases and emerging topography (flood tidal delta) makes flow through the inlet less efficient, the "watershed" shifts toward the dike. Thus during the early part of the ebb the predominant direction

of drainage shifts gradually from being towards the inlet to being towards the dike. The high topographic point, the threshold, in the inlet channel emerges at approximately 4 hours, thus separating the hydraulic system into two parts: (1) water draining out of the inlet into Cape Cod Bay and (2) water draining off Wood End tidal flats into Provincetown Harbor via the dike.



**Stage 9 (5 hours after high tide)**

The inlet channel is completely drained and all water impounded behind the dike drains eastward into Provincetown Harbor. Maximum head (1 meter) across the dike occurs at this time, as well as maximum computed discharge (99 m<sup>3</sup>/sec).

**Stage 10 (5-6.2 hrs after high tide)**

Water levels continue to fall and as a consequence the head across the dike decreases gradually. Low tide in Provincetown Harbor and Cape Cod Bay (6.2 hr) starts the cycle again with Stage 1. Water is still ebbing from the Wood End tidal flats into Provincetown Harbor.

In summary, the inlet is flood dominant and the dike is ebb dominant (Table 1). A greater volume floods through the inlet (489,000 m<sup>3</sup>) than ebbs through the inlet (246,000 m<sup>3</sup>); whereas more water

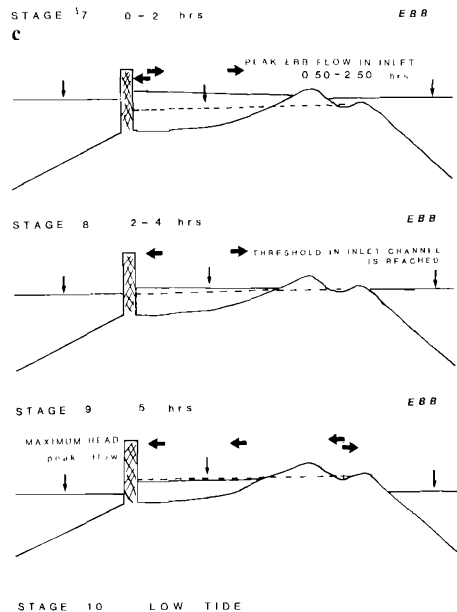


Figure 10. The Hydraulic Model in 10 stages summarizing the water levels and water movement between Wood End Inlet (east) and Provincetown Dike (west). Threshold level in inlet channel shown as dashed line.

ebbs through the dike ( $914,000 \text{ m}^3$ ) than flooded in ( $671,000 \text{ m}^3$ ).

### Wood End Tidal Flats

Wood End tidal flats were formed in the protected bight of the Long Point spit recurve (Figures 3, 7) and are "perched" on the spit platform which is nearly covered at spring high tide and nearly drained at spring low tide. These intertidal flats cover  $2.5 \text{ km}^2$  and are composed of gravelly coarse to medium sand. The flats are fringed with salt marsh vegetation (*Salicornia*, *Spartina patens* and *Spartina alterniflora*) dissected by small tidal creeks (MALCHMAN, 1979; SMITH and MELLO, 1985). The tidal flats slope gently from the barrier toward Provincetown Harbor. A well-integrated ebb drainage system on the tidal flats carries water and some sediment through and under the dike. A prominent flood tidal delta has developed on the tidal flats from sediments transported through the inlet (Figures 7, 11). Following the birth of the inlet, the channel migrated southeastward 250 m to its present position. The flood tidal delta deposits consist of overlapping lobes which become progressive younger from north to south. The progressive migration of the inlet can be seen by the recurved spits marking former inlet positions (Figure 4). It appears that the present inlet position is being controlled by a resistant salt marsh layer exposed on the south side of the channel. A pace-and-compass sketch map depicts the important geomorphic components of the tidal flat area (Figure 7).

The channel in the inlet throat is oriented NE-SW, perpendicular to the shoreline (Figures 3, 5, 7). Once behind the barrier, the channel makes a right-angle bend and flows northwest parallel to the barrier and around the highest part of the flood tidal delta. The elevation of the channel bottom gradually rises to an apex, then decreases again. This high point in the channel (marked with an arrow on Figure 11A) is the "threshold" separating water derived from Cape Cod Bay and water entering via the dike (Figures 10, 12).

The flood tidal delta crest is just barely covered with water at neap high tide, however during spring tide the delta crest is covered with 0.5 m of water. Flood-oriented coarse sand 2-D bedforms (wavelength = 2 m, height = 0.20 m) on the flood ramp indicate that active bed load transport occurs during flooding. Peak velocities ( $1.9 = \text{m/sec}$ ) and peak discharge ( $94 \text{ m}^3/\text{sec}$ ) occur at about the time the

crest of the flood tidal delta is covered with water (1 hour before high tide). This relationship coupled with the fact that the delta crest consists of a cobble gravel lag, indicates that the crest is a zone of through transport and that sand is transported up the ramp and over the delta during peak flood flows. During peak discharges the water depth over the delta would be shallow (0.5 m) and thus bed shear likely high. It appears that the flood tidal delta has accreted to as high an elevation as possible (Figure 12). The height is controlled by spring high tide.

Sediment is also transported in the delta channel along the inside of the barrier and out onto the flats. Fresh lobes of sand were observed after each tidal cycle, indicating an active sediment transport system. Eight cores were collected from the flood tidal delta with a vibra-corer in an attempt to determine the depth of the tidal flat-tidal delta contact to calculate volume of sediment deposited since breaching of Wood End Barrier. Location of cores are shown in Figure 7.

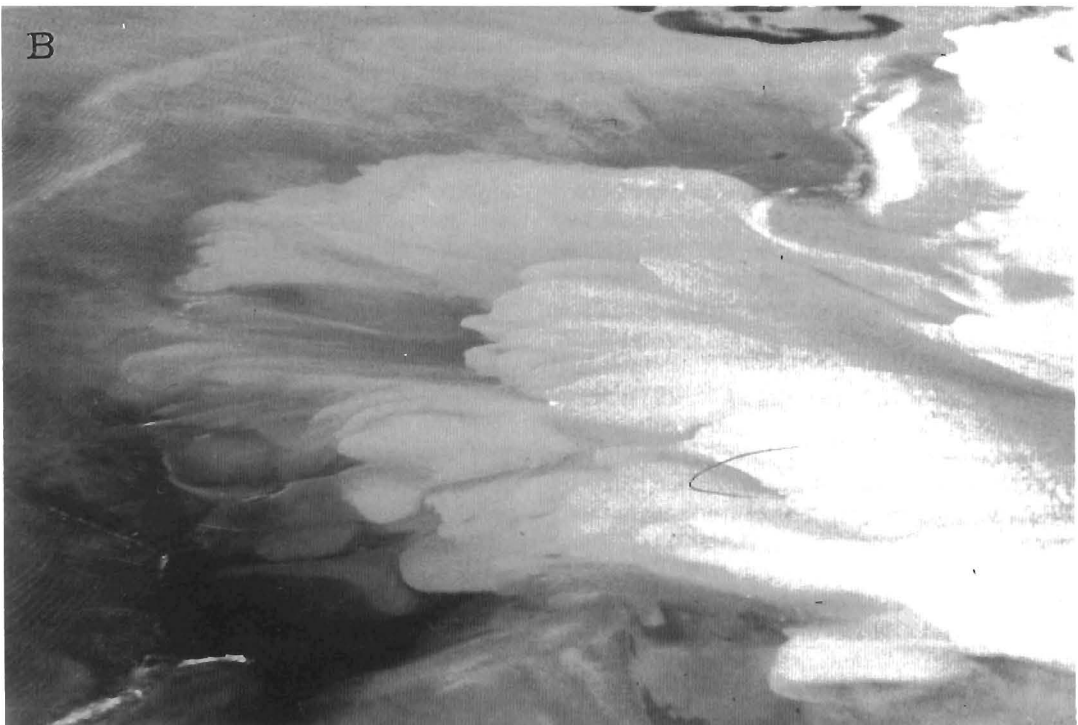
In general the tidal flats proper are finer (Median =  $+0.25\phi$ , coarse sand) than the delta sediments (Median =  $+0.4\phi$ , very coarse sand). Delta sediments contain pebbles and are more poorly sorted compared to the underlying better sorted tidal flats sediment. The thickness of tidal delta sediments ranges from 1.5 m near the inlet to 0.10 m thick where the delta pinches out on the flats. Total area of the delta is  $90,000 \text{ m}^2$ . Based on the area of the tidal delta complex and the varying thickness of the sediment wedge determined from the core data (uncompacted), a volume of  $75,000 \text{ m}^3$  of sand and gravel was deposited on Wood End tidal flats during the 7.5 years following the opening of the inlet.

## DISCUSSION

### Dike-Inlet Relationship

#### Inlets: general

Tidal inlets are short, narrow waterways that connect a bay or lagoon with the ocean and are maintained by tidal flow. They occur almost exclusively on micro- and mesotidal (tidal range  $<4 \text{ m}$ ) coastlines. However, no generalities can be made on inlet longevity (HAYES, 1979). Inlets may open during a storm and close within a few days, or may stay open for many years (JOHNSON, 1919; HITE, 1924; FISHER, 1962; GREENWOOD and KEAY, 1979). Historical maps indicate that some inlets may persist in the same general location of the coast for several



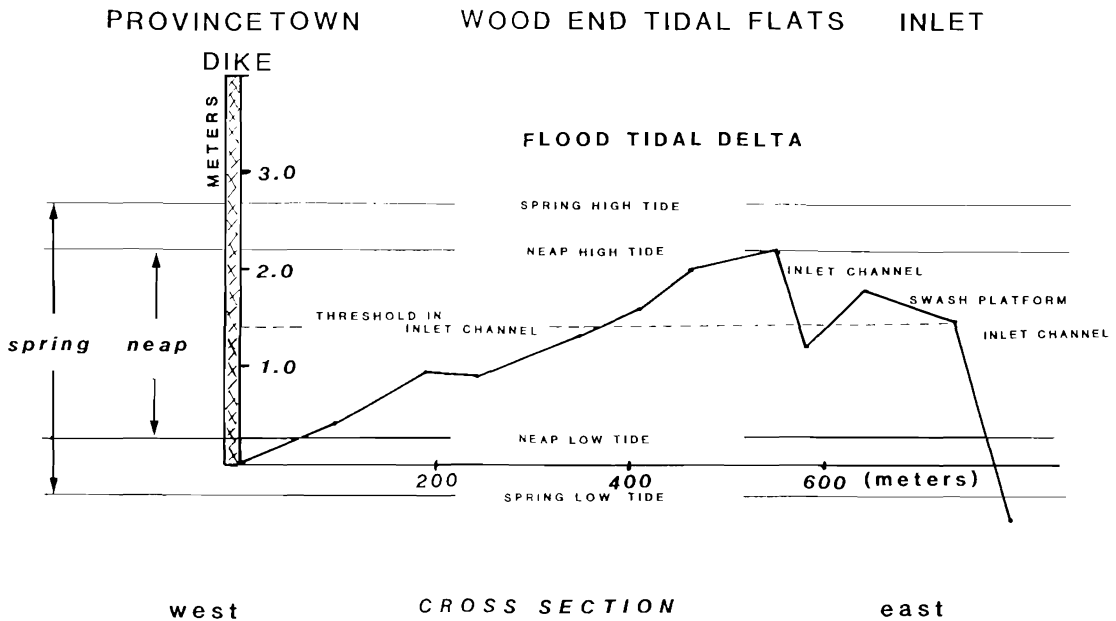


Figure 12. A west-east cross section of the Wood End tidal flats showing elevations of spring and neap tides and the threshold in inlet channel.

hundreds of years (FISHER, 1962, North Carolina; HALSEY, 1978, Delaware; FERLAND, 1985, New Jersey).

In order to stay open, inlet tidal flow velocities must be of sufficient magnitude to transport the sediment carried to the inlet channel by waves and tidal currents, either landward into the bay or seaward. Current velocities are a function of several factors: (1) hydraulic head differences between ocean and bay (KEULEGAN, 1967; MASON, 1973; U.S.A.C.E., 1979), (2) tidal prism (O'BRIEN, 1931, 1969) and (3) whether or not the backbarrier area is an open water body of a salt marsh and tidal channel system (MOTOLIVEIRA, 1970; HUBBARD, 1977; NUMMEDAL and HUMPHRIES, 1977; NUMMEDAL *et al.*, 1977; BOON and BYRNE, 1981; FITZGERALD and NUMMEDAL, 1983).

A considerable amount of information exists on the geomorphology and physical processes in sandy micro- and mesotidal inlets (CALDWELL, 1955; PRICE, 1963; BOOTHROYD and HUBBARD, 1975; HAYES, 1979; MASTERSON *et al.*, 1973; FINLEY, 1975; BYRNE *et al.*, 1975; HUBBARD and BARWIS, 1976;

Figure 11 (*preceding page*): (A) Aerial view looking northwest; inlet is in lower left corner. Inlet channel makes a right angle bend to flow around the flood tidal delta. The "threshold" is indicated by arrow. (B) Aerial close-up showing complex lobe system of flood tidal delta. Inlet is the the right (view towards south), 9/22/85.

and BOOTHROYD, 1978). Work done on Cape Cod includes that by HINE, 1975; HAMILTON and LEATHERMAN, 1979; MALCHMAN, 1979; WRIGHT and BRENNINKMEYER, 1979; and FITZGERALD and LEVIN, 1981).

### Wood End Cut

Wood End Cut is relatively small inlet; the channel "proper" is only 25 m wide. The inlet is elevated, or perched, so that it drains completely at low tide. This is unusual, as most natural inlets in micro- and mesotidal environments have channel bed elevations below spring low tide.

Inlets are commonly classified by the dominant current (*i.e.*, flood-dominant *vs.* ebb-dominant). However the weaker current is generally within 10-15% of the strength of the dominant current. Wood End ebb current is less than 50% of the flood. Approximately 1/3 of the tidal prism (1,160,000 m<sup>3</sup>) passes through the inlet, the other 2/3 "leaks" through the dike. The proportion is different on flood and ebb. Water floods onto the tidal flats through the inlet (42%) and the dike (58%), and ebbs through the inlet (21%) and dike (79%) creating a residual current drift entering the inlet and exiting the dike.

It is clear from these facts that Wood End Cut is a dike-dominated inlet rather than the more tradi-

tional ebb-dominated or flood-dominated inlet. The Provincetown Dike temporarily traps the water that floods onto the tidal flats from both east and west. The impounded water provides the head necessary to generate an ebb current through the inlet. If the dike were absent, water would flood onto the tidal flats from Provincetown Harbor and drain off in the same direction, as it did prior to 1914. The gentle eastward dip of the tidal flat area towards Provincetown, as well as the ebb tidal drainage system developed on this flat, reflect the geomorphic history of the study site; that water flooded from and ebbed to Provincetown Harbor, exclusively.

### Sedimentation on Wood End Tidal Flats

The deposition of sand and gravel on the tidal flat surface began when the Cut opened during the Blizzard of 1978. The locus of deposition moved from north to south as the inlet migrated. Sedimentation is now occurring back near the site of the original breach, as sediment is carried northward along the inside of the barrier, around the flood-tidal delta, and out onto the flats (Figure 5). The dye study carried out 4.5-5 hours after low tide showed this pathway of water motion, and presumably the path of sediment. The evidence of active sediment transport and deposition is abundant. Fresh lobes of sand deposited on tidal flats (covered with an algal mat) have been observed during several days prior to and following spring tide. Bedforms, which indicate active bed-load transport, are ubiquitous on the tidal delta.

The tidal delta is a distinctive geomorphic feature with an area of 90,000 m<sup>2</sup> and consists of multiple overlapping lobes which pinch out away from the inlet source, in the direction of the dike. The furthest lobe reaches nearly 550 m of the total 750 m distance between inlet and dike. However, the bulk of the delta is located between 200 - 400 m from the inlet (Figures 7, 12). Average sedimentation rate of the tidal delta is 15 cm a year over the 90,000 m<sup>2</sup>.

Estimates of delta thickness from the cores multiplied times areas of each thickness yield a total volume of 75,000 m<sup>3</sup> which is only 6% of the initial tidal prism (which existed when the inlet was opened in 1978). Assuming a steady rate of sedimentation, it would take nearly 100 years for the tidal flat area to "fill up." However, continued sedimentation will likely trigger a negative feedback mechanism eventually closing the inlet by increasing the size of the tidal delta, decreasing the efficiency of flow onto the flats, and reducing the tidal prism.

### Longevity of the Inlet

Inlets are dynamic environments. Their geographic position, their cross-sectional area and flow characteristics reflect a balance between several, often opposing, parameters:

(1) tidal prism—

(a) magnitude of tidal flow (flow strength), and

(b) relative strength of flood vs. ebb currents;

(2) efficiency of the flow path and sediment transport system on both flood-and ebb-oriented flows. Hydraulic efficiency is affected by length, sinuosity and roughness of the inlet channel and the position of flood tidal delta with respect to the inlet throat.

(3) volume of sediment delivered to the inlet by the littoral drift system.

In order to evaluate the likelihood of future change in any of the above factors, some of the specific results of the Wood End Cut study are summarized below:

(1) the dike is semi-permeable with a CX of 0.015723;

(2) water impounded by the dike reaches a maximum head of 0.54 m on flood and 1.0 m on ebb;

(3) heads created on both flood and ebb support flows of sufficient strength to maintain the inlet channel cross section of 84 m<sup>2</sup>;

(4) mean flood flows in the inlet reach nearly 2 m/sec; mean ebb flows are less than 1 m/sec;

(5) sedimentation is actively taking place on the tidal flat, reducing the tidal prism about 1% each year; and

(6) sedimentation of the flood tidal delta is also creating topography which has the potential of reducing efficiency of flow in and out of the tidal flat area.

Three scenarios involving a different set of physical conditions seem plausible:

*Scenario 1:* The dike develops large holes from settling blocks. An increase in permeability (i.e. an increase in CX) will decrease the head on both flood and ebb, decrease flow strength through the inlet on both flood and ebb, encouraging sedimentation. The larger the holes, the quicker the inlet will close.

*Scenario 2:* A major storm or several closely spaced storms approaching from the W or SW hit the coast. Storms tend to increase sediment transport in the littoral drift system. A large slug of sediment could close the inlet, particularly if it occurred during neaps (T.R. = 1.7 m) when flow strength is significantly reduced.

*Scenario 3:* Sedimentation continues at the present rate with no major storm activity and the dike remains intact. As sedimentation proceeds, the tidal prism will gradually decrease because of a reduction of available space and the reduction of dike permeability as sediment builds up against the dike. As the tidal prism decreases, the hydraulic heads developed during both flood and ebb will decrease. As sedimentation proceeds the efficiency of the sediment transport system onto the flats will decrease. The channel is likely to become longer and more sinuous and eventually close. A computer based analysis is necessary to simulate and evaluate the cumulative effect of the series of negative feed back mechanisms set off by this scenario.

### CONCLUSIONS

Given the present hydraulic relationships between the Provincetown Dike and Wood End Cut:

(1) Sand is moving "landward" through the inlet at a rate of 10,000 m<sup>3</sup>/year.

(2) The tidal flat area is a sink for sediments transported through the inlet.

(3) The inlet could close in a matter of days if hit by a series of storms from W or SW that placed a significant increase of sediment in the littoral drift system, particularly if the storm hit at neap tide.

(4) The inlet could close within several months to a few years if large holes (thereby increasing permeability) were allowed to develop in the dike.

(5) The inlet will likely close within two to three decades if left in its present natural state. The littoral drift system is forcing the inlet to the south, where it appears to be "hung-up" on resistant salt marsh sediment. Flow through the inlet and onto the flats is constrained by a topographic high, the gravel-capped flood tidal delta. This has created a system which can only become less efficient with time. Increasing hydraulic inefficiency will increase sedimentation, decrease the tidal prism and decrease tidal flow strength which keeps the inlet open.

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#### □ ZUSAMMENFASSUNG □

Der Endpunkt Cape Cods, Massachusetts, besteht aus ein weidengekrümmte Barriere-Landzunge (Wood End-Long Point), die ein geräumige (2,5 km<sup>2</sup>) Meeressumpf schützt. Ein 1.875-m durchlässiger Steindeich verbindet die dünenbedeckte Barriere mit dem hohen Land der Cape, und vervollständigt die Einfassung des Sumpfes dadurch. Während eines Schneegestöbers im Jahrgang 1978, im Lauf einer ungewöhnlich hohen (4 m) Frühlingsflut, wurde die Barriere durch eine 1 m Sturmwege durchgebrochen; durch Naturvorgänge bleibt der Bruch geöffnet. Eine physikalische-Vorgangsversuch, die schliesst Geschwindigkeits-, Abfluss-, Flutstufen-, hydraulische, Vibracore- und Farbstoff-Kreislaufdaten ein, wurde durchgeführt, um die Folgende festzustellen: (1) die Einwirkung des Deiches auf die Vorgänge des Bruches, (2) die durch den Bruch fließende Sedimentmenge, und (3) die Langlebigkeit des Bruches. Wasser ergeisst sich auf der Sumpfen durch den Bruch (42%) und den Deich (58%), und ebbt durch den Bruch (21%) und den Deich (79%); auf diese Weise ist ein Reststrom erzeugt, der die Sumpfen durch den Bruch hineinfließt, und durch den Deich herausfließt. Es gibt eine netto Landwärtsbewegung des Sediments durch den Bruch. Das hintere Flachland der Sumpfen ist einer Sedimentabfluss. Im Lauf der 7,5 Jahre nach dem Bruch hat sich ein Flutdelta (Grundfläche=90.000 m<sup>2</sup>, Rauminhalt=75.000 m<sup>3</sup>) auf der Sumpfen gehäuft.--Stephen A. Murdock, CERF, Charlottesville, Virginia, USA

