SAFE HARBOR
ENVIRONMENTAL MANAGEMENT
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# The Synergistic Elements of Anomalous Coastal Erosion

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*Figure 1. Limited width breach, overwash fan and remnant sand bar rip channel*

***Anomalous Coastal Erosion*** events provide an opportunity to study synergistic energy interactions within ***Linked Coastal Resource Systems***. Historical studies of "resource areas" have shifted to the ***Systems Approach,*** incorporating the various forms of energy moving through each system. Natural forms of energy, such as tide and wind, act as external links between adjacent resource systems, creating ***Linked Coastal Resource Systems.***

***Linked Coastal Resource Systems*** incorporate the bathymetry of underwater sand bars and intertidal beaches with topography of upper beach and coastal banks. When resource system energy interacts with linked bathymetry and topography, a distinctive ***Coastal Profile*** is formed. We will explore this interactive complexity.

***Coastal Bank Landforms:*** toe; face (scarp); and bluff, were created by deposition from glacial meltwater. Varying layers of: clay; fine sand; coarse sand; and stones, were deposited and consolidated during thousands of years of melt water running beneath the ice sheet. These deposits were consolidated by the weight of glacial ice. This varied composition contribute to variable Coastal Bank erosion rates.

***Figure 2. Varying rates illustrate the non-linear nature of anomalous erosion events.***

***Coastal erosion events incorporate uncertainty***. They cannot be attributed to a single cause or explained in a linear, cause-and-effect manner. Figure 2 illustrates this particular uncertainty principle, showing three very different rates of erosion along a limited area of Coastal Bank. Using the "Systems Approach" we identify the elements: topography; bathymetry; water, and the energy: wind; tide currents. These factors interact to create varied rates of erosion.

***Coastal profiles are linked together.*** A variety of profiles are linked: offshore and intertidal bathymetry; elevations on the lower- and upper-beach; and adjacent topographic landforms.

***Tidal flow is the "sleeping giant" we often forget*** in Coastal Resource Systems. We can quantify this overlooked tidal energy potential using a basic model:

Cape Cod Bay (CCB) can be viewed as a 20-mile diameter bowl with a representative tidal depth of 10 feet. Every six hours, the entire bay fills up or empties by ten feet.

1. Area of CCB surface = (3.14 x 10-mile radius)$^2$ ≈ 300 mi$^2$
2. We then convert sq miles to sq feet: 300 mi$^2$ = 1,584,000 ft$^2$
3. Tidal volume = 1,584,000 ft$^2$ x 10 ft tidal depth = 15,840,000 ft$^3$

15,840,000 cubic feet of water enter CCB on this 10-foot tide. This translates to 118,800,000 gallons of water, weighing approximately 986,040,000 pounds.

Thus, nearly half a million tons of water are moving around the arm of Cape Cod and into the Bay within the six hour time period we are measuring.

**Coastal Topography and Bathymetry may alter tidal energy**. Tidal currents encountering resistance, move parallel to land and accelerate, moving water faster through a smaller space. There can be significant differences in tidal velocities within the same Coastal Resource System. Figure 3 on the right, illustrates this variance, showing an anomalous acceleration node between Cape Cod and Stellwagon Bank. The bathymetric image of the same area in Figure 4 next page, illustrates the linkage between the underwater contours of Stellwagon Bank and the topographic contour of Cape Cod. These two points restrict and accelerate incoming and outgoing tides.

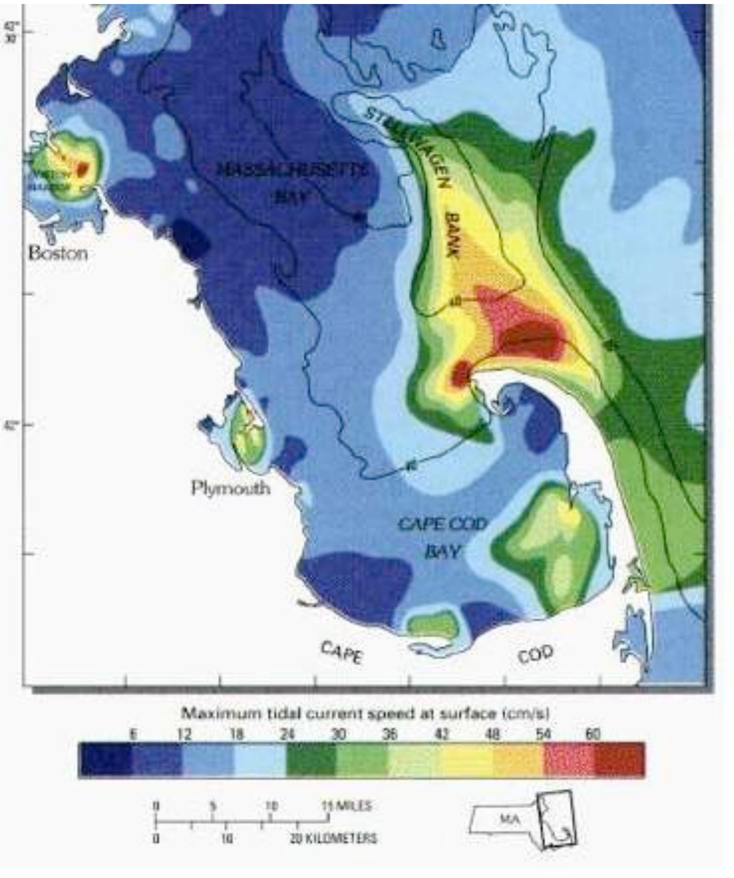

Figure 1. Tide currents demonstrate acceleration between two restricting points

***To complete our CCB tidal flow model over a 24-hour time period***, we begin with the approximate volume of 118,800,000 gallons that entered CCB over a six hour period, which represents only 25 % of the daily volume of 2 incoming and 2 outgoing (diurnal) tides per day. Total daily volume of tidal water moving into and out of CCB is approximately 475 million gallons, or nearly two million tons. This weight of water, energized by tide currents and constrained by geology, has the power to reshape landforms.

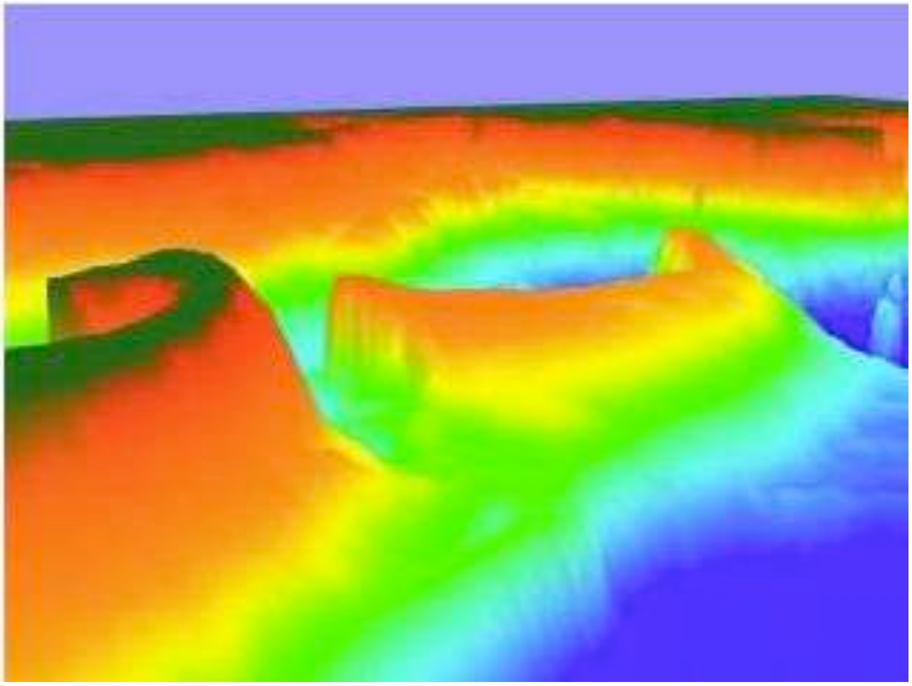

Figure 3. Bathymetric image of Stellwagon Bank (at center) and the tip of Cape Cod (at left). The avenue created between the two landforms creates a bottleneck effect, accelerating tidal flow.

**Wind energy is restricted by Coastal Bank topography**. Wind energy has characteristic, seasonal patterns. Summer patterns are predominantly low velocity south winds; winter patterns are predominantly high velocity, north winds. After crossing open water, surface level, onshore winds experience significant restrictions from Coastal Banks. Topography reduces the cross sectional wind flow area, increasing velocity along the beach, face, and bluff of the bank. It is possible to have significant differences in wind velocity within Coastal Bank Systems.

Wind energy, variable in direction, intensity and duration, generates direct material transport through erosion and deposition. Materials are transported from higher velocity areas to low velocity areas. Material deposition zones can be the upper beach, dune or toe of the bank. Transport also occurs laterally, parallel to the beach and face of the bank. Under intense, onshore wind conditions, accelerating wind blows beach materials against the bank, removing material from the bank face. Wind drives this mix up and over the top of the bluff, velocity is reduced and the sand deposited. Safe Harbor has documented the collection of a half million pounds of sand on a 10,000 sq ft (50 lbs per sq ft) area at the top of an ocean front bluff. Wind energy can transport sand horizontally, laterally or vertically.

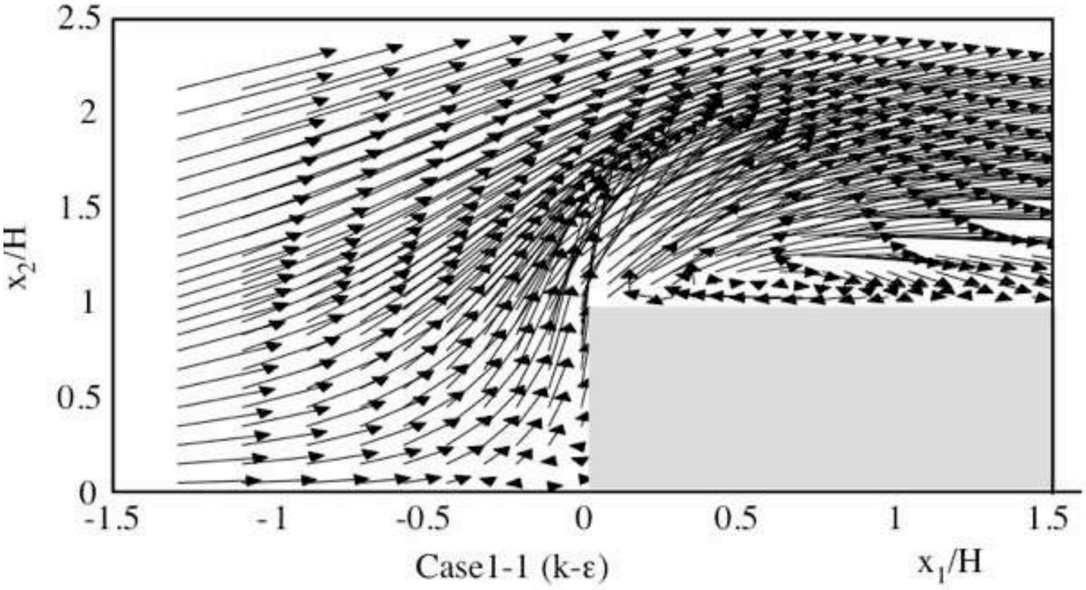

Figure 4. Onshore winds are restricted by Coastal Banks. This increases wind velocity, transporting sand up the bluff, where velocity decreases, depositing sand.

Wind energy blows against the fluid surface of the sea, creating uneven ripples known as capillaries or “cat’s paws”. Continued wind pressure against capillaries generates increasingly larger waves, which move with the wind direction. Wave size is determined by three primary variables: wind speed, wind duration, and wind direction. Speed describes the potential energy available for creating waves. Duration describes the amount of time available for energy exchange. Direction is defined as open water distance (or “fetch”). Greater fetch will create larger waves.

**Wave energy is redirected by coastal bathymetry**. The cross section of a wave is only partially seen at the surface. Most of the circular wave form is moving under water. As waves cross the near shore coastal profile, energy is reduced through bathymetric friction. Bathymetric friction may also reshape waves, with energy transfer contributing to shoreward movement of sand across sandbars. These bars also create barriers trapping incoming tidewater against the beach. When the tide reverses, this water creates huge “rip channels” to drain. Sandbars absorb wave energy, reducing wave size. This provides a degree of protection for beaches and Coastal Banks. Inshore waves transfer energy directly through impact.

Energy is also transferred less directly, by sand erosion, transport and deposition. Beaches have patterns of eroding in winter and building in summer. The degree of wave intensity (frequency) contributes to deposition or removal of beach sand. Low frequency waves contribute to deposition of sand, increasing beach elevation. High frequency waves contribute to removal of sand, decreasing beach elevation. **<u>Conclusions</u>: linked synergistic factors contribute to Coastal Erosion on Cape Cod. Generalized erosion events over continuous lengths of beach, will only be briefly discussed. Anomalous Coastal Bank erosion is discussed in detail.**

1. **Tidal Cycle alone:** A synchronous low tide may limit storm damage. A synchronous high tide may amplify storm damage. Low tide exposes miles of open area to absorb wave energy. High tide provides a platform for wave propagation to reach the upper beach.

2. **Tide Currents, wind and wave energy:** Tidal currents interrupted by coastal landforms accelerate and move parallel (lateral) to the shoreline. Lateral currents are referred to as “alongshore” and are bidirectional, depending on the state of the tide. ***Onshore wind***, generating high frequency wave energy, erodes beach sand, which is transported laterally, in the direction of the tide current. ***Sideshore (angled) wind,*** generating high frequency wave energy, erodes beach sand. ***When sideshore wind and waves are synchronous*** with lateral tidal current, there is an exponential potential for sand erosion and transport. ***When sideshore wind, waves and tidal current are not synchronous***, there may be minimal lateral transport.

Figure 6. When sideshore wind and waves are synchronous (align) with lateral tide currents, the resultant synergy has the potential for exponential erosion rates during a single tidal cycle. Ocean beach, Cape Cod. Image by G. Peabody

3. **Sand Bars, Beaches and Coastal Banks:**
   ***Sand bars*** exhibit significant, time- and tide-sensitive linkages in their ability to protect beaches and Coastal Banks. Beaches and sandbar profiles are linked by energy transfer during wave events and tide cycles. Sand removed by wave erosion is transported through backwash currents away from the beach. Beyond the surf-zone, reduced turbulence reduces transport and sand is deposited as sand bars. Changes in rates of deposition create changes in bathymetric friction. Variable rates of bathymetric friction contribute to variable rates of sand transport from bars to beaches and during Ocean Storms, from beaches to bars. During onshore winds, waves will push incoming tidewater inshore, over sandbars. Once the tide reverses, this trapped water drains by creating deep, perpendicular "Rip Channels" in the sandbar. Storm waves are reduced by sand bars, except where temporary or chronic "Rip Channels" exist. Rip Channels are linked to erosion anomalies.

Figure 7. The satellite image above shows the link between sandbars, rip channels and beach erosion. The areas protected by sandbars demonstrate significantly less erosion.

***Beaches*** with angled (perched) profiles are best able to absorb wave energy. When the magnitude or duration of wave energy erodes excessive sand, the beach profile transitions reshaping the beach from angled (perched) to horizontal. Horizontal profile beaches allow waves access to the upper beach, transitioning that profile from angled to horizontal, to renourish the beach, protecting the Coastal Bank.

***Coastal Banks*** are linked to the coastal process through the above links and their own structure (bluff, face, toe). When erosion events transition lower and upper beach profiles, waves have access to the toe of the Coastal Bank. The toe now absorbs wave energy and erodes. Materials from the toe move seaward to replace upper beach materials. Once the toe profile has transitioned to horizontal, the bank will absorb wave energy and a section will collapse, creating a new toe to restore the profile.

***<u>Findings:</u> Anomalous Coastal Bank Erosion*** can be linked to many of the above processes. Our study of localized, anomalous Coastal Bank erosion events on Cape Cod, suggests possibly significant linkages to sand bars and rip channels. Where rip channels remain in place temporarily or chronically, anomalous, onshore erosion events seem to occur more frequently. During an Ocean Storm, with onshore winds and a rising tide, full size storm waves can freely access unprotected areas of beach through open rip channels. Waves on either side of the rip channel would be reduced by sand bars. The beaches and coastal banks aligned with the rip channel, could experience significant (anomalous) erosion while protected beaches on either side of the rip channel might show less significant erosion by comparison.

Figure 9. The image above shows a rip channel adjacent to a Coastal Bank. During the Next Ocean Storm, waves pushed by storm winds and the incoming tide, could come ashore onto an unprotected section of beach at full strength. This could provide a possible case study for an anomalous erosion event. If the lower and upper beach and the toe of the bank were eroded by this event, a partial collapse of the section of bank directly in line with the rip channel could be compared with erosion rates on adjacent beaches and banks.

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