Woods Hole Sea Grant Program
Cape Cod Cooperative Extension

# *Longshore Sediment Transport*

## *Cape Cod, Massachusetts*

April 2011

**Disclaimer**

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## Introduction

The purpose of this report is to provide a qualitative understanding of the net motion of sediment along the beaches of Cape Cod, Massachusetts, which are such an important resource to the region. Longshore transport of sediment along the coast becomes an issue when an existing (or proposed) structure interferes with the natural movement of sediment. Many coastal structures on Cape Cod act as dams to sediment transport, impounding material on the updrift side and concurrently inducing erosion on the downdrift side. The intended goal of slowing net sediment transport is, in some cases, completely obstructing it - which leads to sediment starvation in many of Cape Cod's coastal systems. Any future human interventions should be well planned. Progressively less material will be available to sustain the beaches of Cape Cod, due to portions of the shoreline armored against erosion, which deprives the system of sediment, coupled with rising sea level. Multiple stakeholders across Barnstable County, as well as the U.S. Army Corps of Engineers (2002), have indicated that knowing the direction of longshore sediment transport is central to successful studies of coastal erosion and shore protection projects. Careful thought should be given to what direction sediment moves when planning a project in order to make sure that this limited resource isn't deprived from an area that needs it (property/resource/storm protection) or squandered on an area that may be harmed by excess sediment (bury a marsh, fill a navigable waterway, etc.). Accelerating relative sea-level rise has been well documented (Fletcher and Merrifield, 2009; Bindoff, 2007; Zervas, 2001; etc.,) and the associated increase in shoreline retreat rates will be exacerbated by this issue in the future. Longshore sediment transport, one of Cape Cod's most important nearshore processes, affects beach morphology and directly influences the shoreline's tendency to accrete, erode, or remain stable. It is hoped that this document, derived from a synthesis of historic sediment transport and an in depth analysis of transport inhibitors, will provide valuable qualitative resource for understanding Cape Cod's dynamic shoreline.

## Background

Cape Cod's beaches are dynamic systems, constantly altered by wind and waves. As wind is most often not perfectly perpendicular to the shoreline, wind-generated waves usually run up the beach at an oblique angle, with a portion of the energy parallel to the shoreline. At the maximum wave run-up, gravity takes over and pulls the water downslope in a parabolic pattern. This component of longshore transport is located within the swash zone with sediments transported directly by oscillatory wave action (**Figure 1**) for a net movement in a single shore-parallel direction. The other component entails transport by currents generated from this wave action. In this way, sediments are transported parallel to the shoreline, so erosion at one spot provides material for beaches and dunes downdrift of that position. These longshore currents act like a shallow river flowing parallel to the shoreline, with speeds

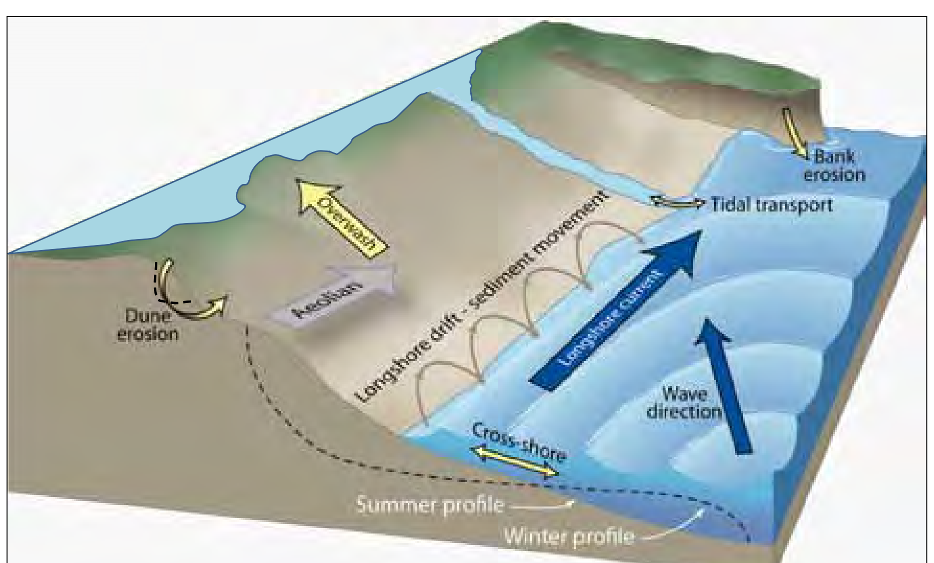



Figure 1. Multiple coastal processes along a simplified beach. Longshore transport is derived by a combination of direct oscillatory wave action (parabolic pattern) and wave-generated currents for a net movement in a single shore-parallel direction.



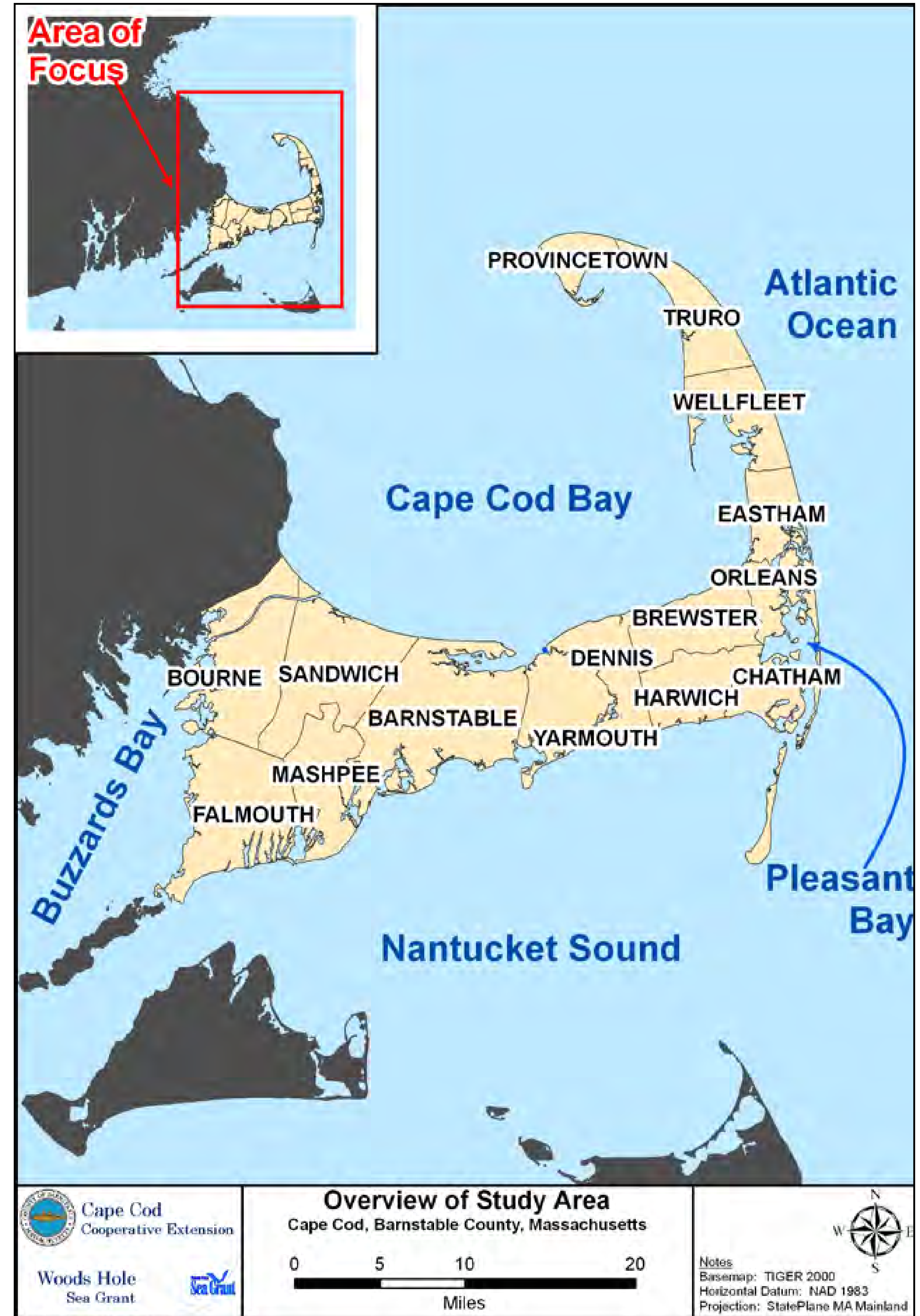



Figure 2. Overview map showing the location of Cape Cod in relation to the adjacent water bodies. Town boundaries are also indicated.

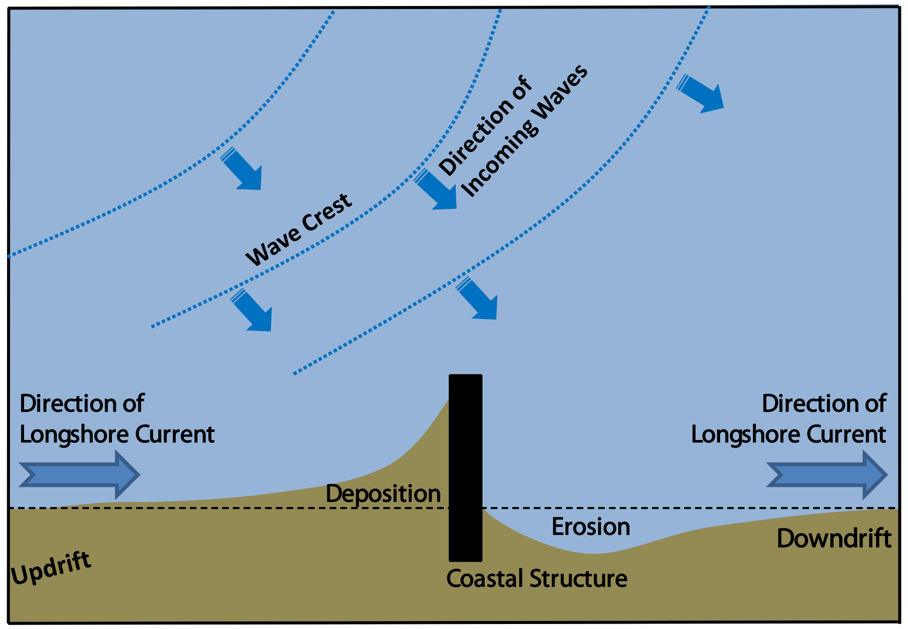



Figure 3. Simplified illustration showing longshore transport being slowed/interrupted by a structure. Note the impoundment of sediment on the updrift side of the structure and the "depositional shadow" effect downdrift.

varying with typical currents at 10-20 cm/s and some storm driven flows in the 1 m/s range (Davis, 1994). Longshore currents affect most of Cape Cod, including the larger estuaries (**Figure 2**), but have the most significant impact on open ocean beaches of the Outer Cape, where the large-scale sand spits and islands demonstrate the role of increased fetch to subsequent transport. Longshore currents mobilize sediments in what is known as longshore sediment transport (longshore drift). Water serves as a media to transport sediment, while the wind provides energy for transport. At any given point on the beach, both erosion and accretion is occurring, transporting sediment into and out of the area parallel to the shoreline.

The magnitude and direction of longshore sediment transport along the Massachusetts coast is highly variable (FitzGerald, 1993). Longshore transport can be slowed, or interrupted, by inlets, groins, jetties and breakwaters. Shore-perpendicular structures (e.g., groins and jetties) tend to get a buildup of sediment on the updrift side of the structure and erosion downdrift (**Figure 3**). In this way the structures impacting the natural longshore transport may have a "depositional shadow" effect on downdrift beaches, channels, harbors, etc.

Longshore sediment transport is typically qualitatively measured in several ways: examining the impoundments of littoral drift at the updrift side of a jetty, breakwater, spit, or deposition basin; bypassing impounded material (e.g., at an inlet); or measuring tracer transport rates. Quantitative measurements (not collected for this report) are much more involved, involving sediment budgets, modeling, suspension and bedload transport, etc. Vector diagrams in Cape Cod Bay depicting maximum potential transport, derived from wave height and wind speed, did not always correctly predict the dominant direction of longshore sediment transport (Giese, 1964). The Coastal Engineering Research Center (CERC) formula (Shore Protection Manual 1984), which is based on quantitative field studies, is often used to calculate the total longshore sand transport rate. Accuracy of the CERC formula is believed to be ± 30-50%, however some parameters that might influence transport are not incorporated, such as breaker type and grain size (Wang, et al., 2002). Of course, not all material eroded from coastal banks is transported by longshore currents. In a study by Zeigler et al (1964) it was determined that the material eroded from the Outer Cape coastal banks was distributed in the following ratios: beaches and nearshore bars (43%), offshore bars (36%), and lost offshore (21%).

Littoral cells are, in the most basic sense, a way to divide geographic regions for sediment budgets. More specifically, they consist of a section of coastline that contains sediment sources, transport paths, and sinks. While there is no universally accepted set of standards for defining a littoral cell, some widely accepted criteria used in this study include: minimal sediment exchange with other cells, a distinct change in transport rate, typically bounded by areas of transport convergence/divergence. Cell boundaries defined for this report may not be appropriate for other studies due to differing scale, data sets, project boundaries, etc. Littoral cells boundaries are highly dependent on project scale, there may be nested cells, or sub-cell within cells. Large littoral cells may have smaller sub-cells that have behavior deviating for the larger cell. The cells identified in this report might be subcells or larger-scale cells, depending on the scale of a particular project. Coastal management analysis and decisions should scale with the cells. State and county issues may apply to larger cells with local decisions focusing on sub-cells. However, all management decisions should keep in mind that subcells may exchange sediment, as will larger cells under certain scenarios. At the smallest scale every inlet, groin, etc. could act as a littoral cell boundary under certain wind/wave conditions. These inhibitors, typically inlets, large groins, or headlands, may not inhibit transport in all wind/wave conditions. Sources and sinks can affect the transport during "normal conditions" and then be bypassed during larger storm events. For example, during a large storm event sediment can be transported through an inlet or overtop a groin. Additionally, some sources and sinks can reach a tipping point during day-to-day conditions after impounding a large quantity of sediment, such as redirected inlet flow allowing a large ebb tidal delta to bypass an inlet. This emphasizes the need to appreciate how cumulative impacts have an effect on cell and subcell sediment exchange. Therefore, the littoral cells, mapped in this report, can only be used to determine the impact area of a coastal project during certain wind/wave conditions. Smaller-scale sub-cells may be required for a focused sediment budget of a small scale area. It can be complicated to define littoral cell boundaries using airphoto analysis in certain areas of the Cape, particularly in areas where there is minimal drift and variable direction. Development of littoral cell boundaries as well as an estimate of net longshore sediment transport direction, as shown on the map series, was based on a thorough review of available data. This was in no small part augmented by the review panel's local and regional knowledge, gained from many years of working on coastal-related issues on Cape Cod.

## Historic Sediment Transport Mapping

Five key reports have characterized sediment transport over most of Cape Cod (Woodworth and Wigglesworth, 1934, Geise, Strahler, 1966, Fisher, 1979, and FitzGerald, 1993). Sediment transport in these studies was determined by a combination of map interpretation, spit growth, beach and sandbar orientation, and erosional-depositional trends in the vicinity of coastal structures and features. From these studies a composite historic transport map was generated showing transport of sediment throughout the Cape Cod region (**Figure 4**). Each of the component maps was georeferenced in GIS and the arrows converted to scaled vectors. The arrow length and position is depicted in a similar fashion to the original study map, except in cases where overlap made the arrows illegible. Three areas on the composite map (red circles on Figure 4) show a conflict between studies. The conflict on the Outer Cape has to do with the specific placement of the diverging sediment transport, made vague by lack of coastal structures and seasonality of the transport. In general, more material is being transported southwards along the Cape to the sandbars of Chatham and Monomoy than northward to Provincetown due to the greater influence of nor'easters (Woodworth and Wigglesworth, 1936). The conflicts in Cape Cod Bay and Nantucket Sound are likely due to a larger scale study not indicating a smaller scale direction change picked up by a smaller scale study. The relatively recent availability of multiple years of high quality aerial photography spanning the entire Cape allows for the in-depth small scale (1:2,000) study of sediment transport in this report.

## Changes Over Time

On Cape Cod, as on most coastlines, the wind and wave directions are variable day-to-day and have seasonal trends (i.e., winter storms and summer calm). While longshore currents act like a shallow river flowing parallel, the flow of sediment is not always steady and can be highly punctuated. Little sediment may be transported over weeks or months of low wave energy followed by relatively large volumes of sediment being moved during a storm event. However, depending on the number and intensity of storm events, more common conditions of low wave energy may move more material over the course of a year. Currents and associated transport can go north one day and south the next if the wave conditions reverse. It is the transport over a long period (typically annually) that gives us a net transport to base coastal projects upon. Net longshore transport is defined by Komar (1998) as the summation of the movement under all wave trains arriving at the shore from countless wave-generation areas, and accounting for the different transport directions. The gross longshore transport is the total transport up and down the beach. Some beaches may have a large gross transport and a minimal net transport if there is not a dominant wind/wave direction. These two different temporal scales may have different coastal project applications. Gross transport might be more effective in examining shoaling rates in channels and inlets, while net transport might be more useful in longer term analyses of deposition/erosion rates at engineered structures. The methods in this study are most applicable to an analysis of net longshore transport. An example of the common seasonal variability in the direction of longshore transport (**Figure 5**) was documented from the pattern of sand entrapment along Falmouth groins from 1951 to 1980 (Aubrey & Gaines, 1982). Areas with relatively weak longshore transport can show little net change with a significant amount of variability.

In addition to seasonal wind patterns, longshore transport can reverse directions through time at varying scales due to other factors (geomorphology, sea-level rise, etc). An example of a very long term reversal is the role an exposed Georges Bank served as protection from waves traveling southeast to northwest. Since its submersion due to melting glaciers and associated sea-level rise approximately 6,000 years ago, littoral drift shifted toward the north, leading to the building of the Provincetown Hook (Uchupi et al., 1996). Short term longshore transport reversal can occur due to inlet bars and

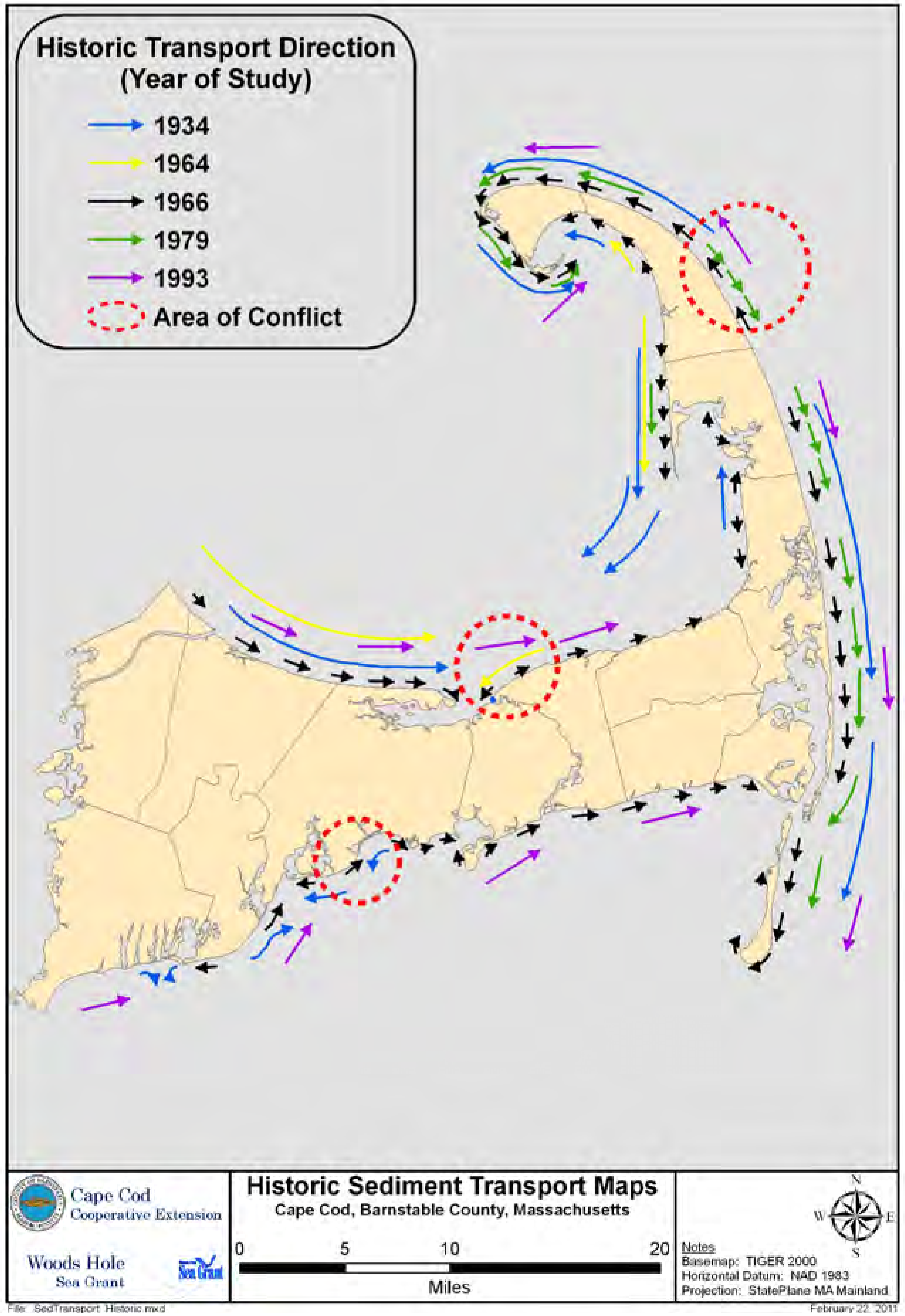



Figure 4. Composite historic transport map showing transport of sediment throughout the Cape Cod region. Each of the component maps was georeferenced and the arrows converted to vectors. The arrow length and position is depicted similarly to the original study map, except in cases where overlaps made the arrows illegible. Each study is color-coded according to the legend (Woodworth and Wigglesworth, 1934. Giese, 1964, Strahler, 1966. Fisher, 1979. FitzGerald, 1993.) Giese (1964 data) analysis based in part on previous studies (U.S. Congress, 1959 & 1960).



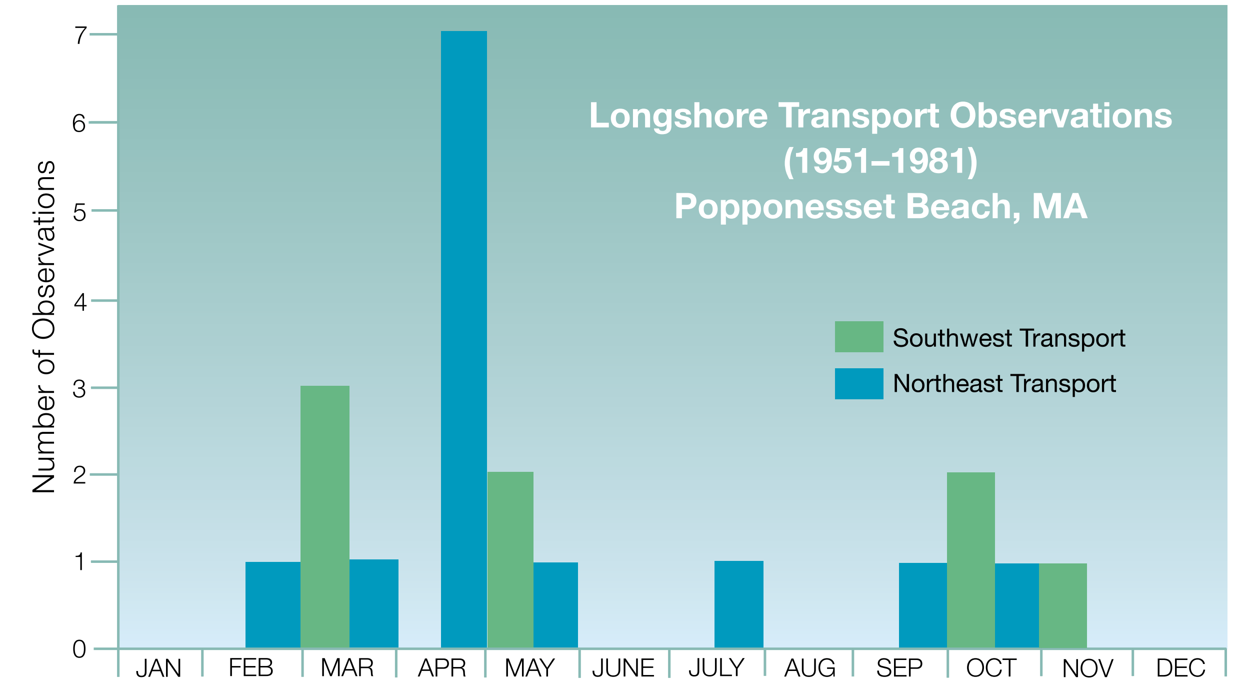



Figure 5. Seasonal variability in the direction of longshore transport was documented from the pattern of sand entrapment along the groins from 1951 to 1981 (from Aubrey & Gaines, 1982).

deltas blocking wind and waves from their average direction. An inlet in Sandwich shows east to west transport adjacent to a jetty, however the accretion that identifies this trend is only present when there is a significant delta/bar system (Figure 6). As there is not a significant offset between the updrift and downdrift beaches, it is likely that the sediment in the delta/bar system naturally bypasses the inlet to provide material for the downdrift beaches. Relatively small structures (jetties/groins) can rapidly illustrate the seasonal effects of longshore reversals. Larger structures will impound more sediment and so take longer to display a perturbation in a trend.

## Updrift Migration

Typically, inlet migration indicates the direction of net sediment transport, however there are mechanisms that can cause inlets to migrate counter to the net longshore transport (i.e., updrift transport). These processes include: attachment of ebb tidal deltas to the downdrift barrier spit; storm-induced breaching forming a new inlet updrift of the original inlet; tidal flow around a bend in the inlet, eroding the outer channel bank and accreting the inner channel bank (Aubrey and Speer, 1984). These means of updrift migration all exist on Cape Cod, and a single inlet, Nauset Inlet on the Eastham/Orleans border, has documented all three.

## Methods

Since direct, quantitative field measurements of longshore transport have not been made across all of Cape Cod, this study depends heavily upon indirect lines of evidence. Net transport was qualitatively measured by examining multiple years of high quality aerial photography for impoundments of littoral drift in order to determine direction of longshore sediment transport. Secondary parameters included: qualitative degree of transport (high, medium, low), source (airphoto year, publications, local knowledge, etc.), type (groin, jetty, inlet, etc.), and seasonality (potential for short-term reversals). This data was interpreted at 1:2,000 resolution (1:1,000 resolution when required) and then repeated at 1:5,000 to determine if larger trends were present or contradicted the fine scale interpretation. Longshore drift direction was predominantly observed at locations where transport was impeded, such as jetties, revetment, and groins. In natural systems, there are far fewer indicators of direction, typically only sediment morphology near inlets, and hooked sand bars. As other studies (USACE, 2002) have indicated, blockage by major structures such as jetties provide the clearest indication of the long-term net transport direction. Sand entrapment by groins was of similar importance but generally involved smaller volumes and can more rapidly be affected by short-term reversals. This potential for error was at least partially mitigated by viewing multiple seasons and years of aerial photographs (Fall/1994 MassGIS, Spring/2001 MassGIS, Spring/2005 MassGIS, Summer/2007 USACE, Summer/2008 NAIP, and Spring/2009 MassGIS) along with communication with local experts. Other geomorphic indicators included deflection of tidal inlets, shoreline displacements at headlands, and the longshore growth of sand spit and barrier islands. This study only qualitatively measured the direction of transport. The aerial

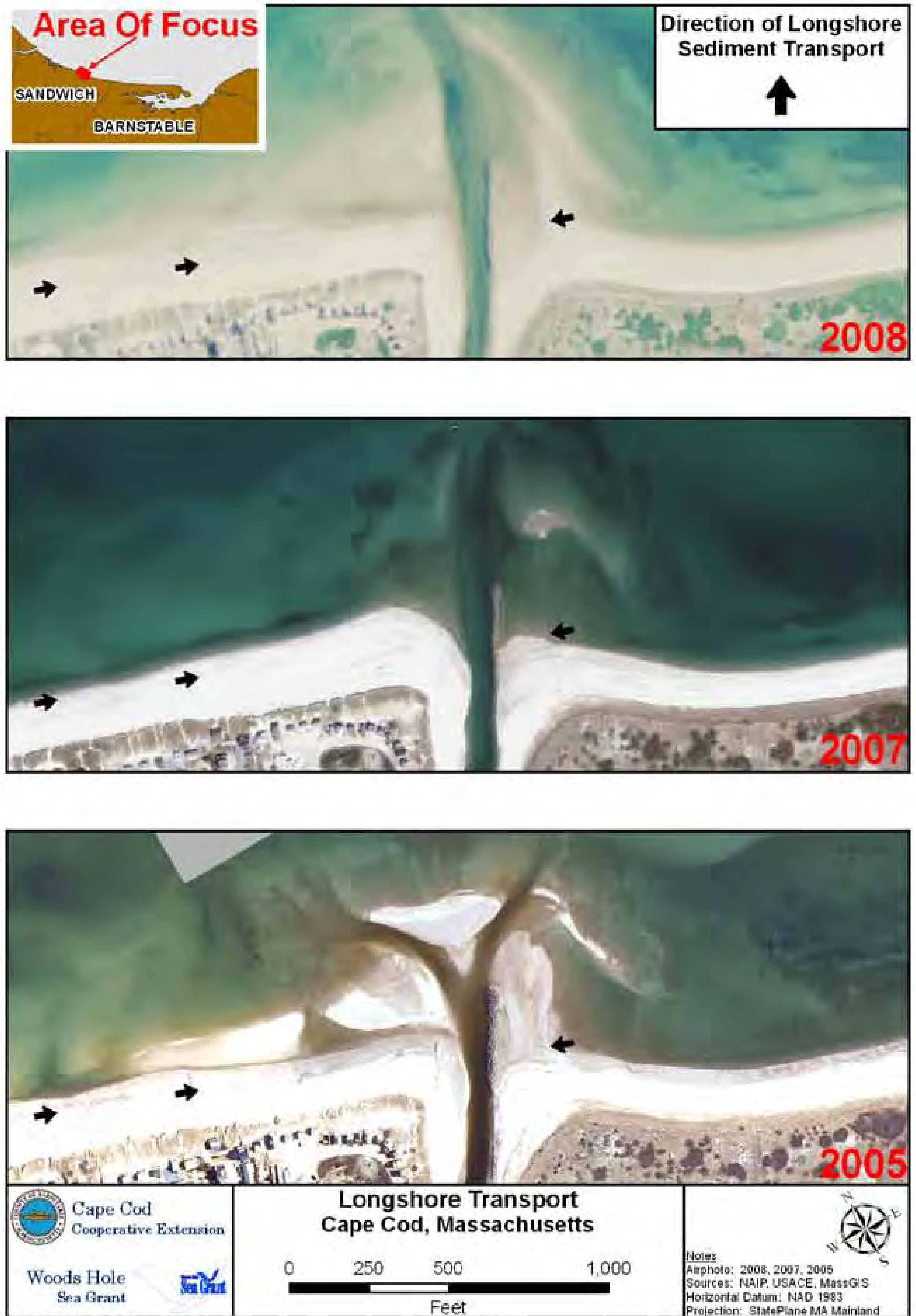



Figure 6. An inlet in Sandwich that shows east to west transport adjacent to a jetty. However the accretion that identifies this trend is only present when there is a significant delta/bar system. The red numbers in the lower right hand corners refer to the year the aerial image was acquired.

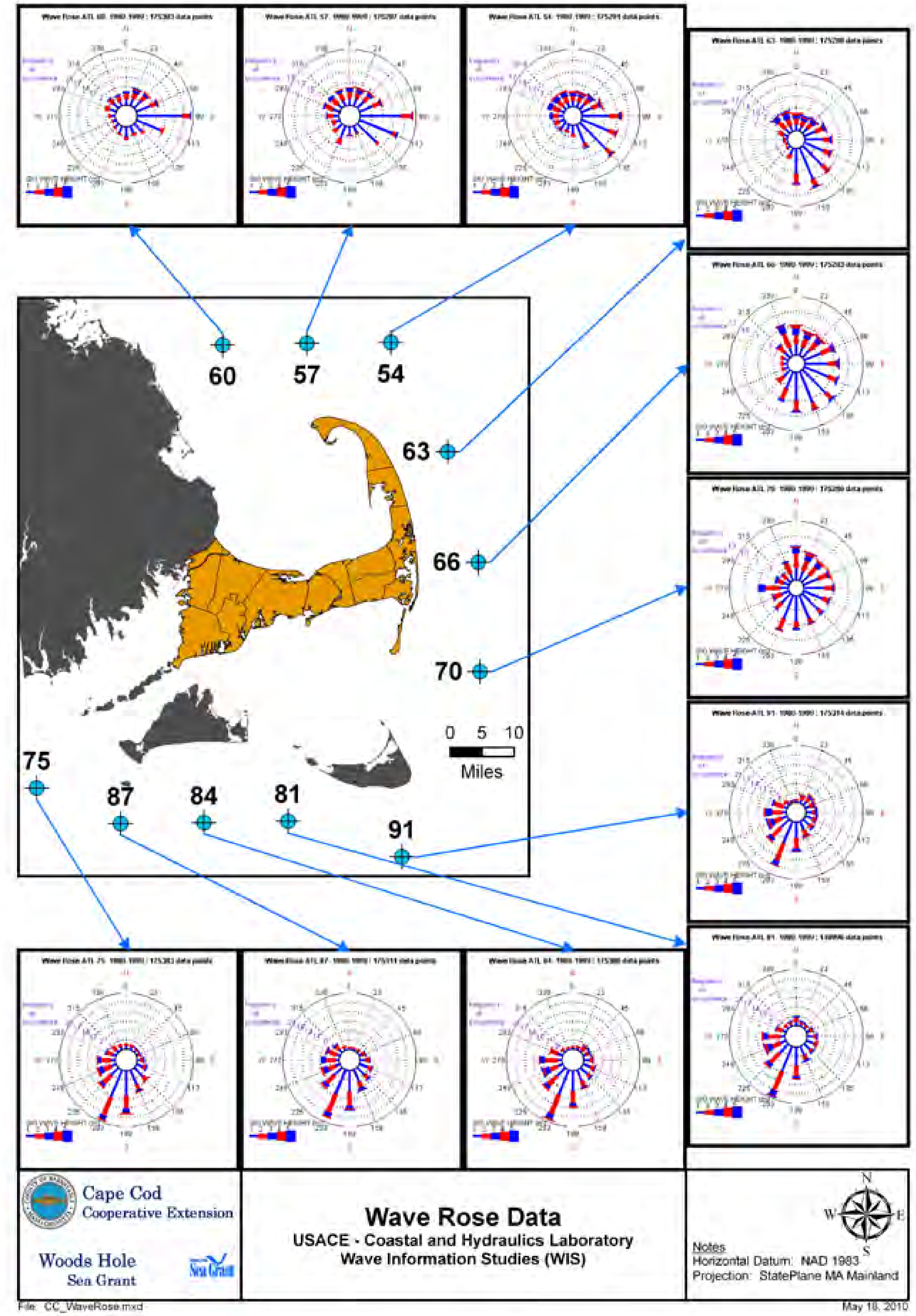



Figure 7. Wave Climate - Wave roses for 11 offshore WIS wave hindcast stations showing the regional wave conditions for the open ocean. The wave roses divide wave data into direction bands and color code by wave height. The data is plotted for sixteen directions radially by percent occurrence, which is labeled (purple) in the left portion of the rose. A wave direction of 0° corresponds to a wave that is propagating from due north. The wave data is from all months during the period 1980-1999.

photographs are two dimensional images and do not provide data on the vertical differences on each side of groin that might provide the magnitude of transport. Grain size was not used to determine transport direction as it may be affected by factors unrelated to transport. This study attempted to examine all available potential evidence related to transport direction, while also considering the site history (through communication with town officials/local experts), indicator reliability, and other relevant studies in order to determine the best available data regarding net sediment transport.

Wave roses (graphics summarizing wave height, frequency, and direction) derived from offshore Wave Information Studies (WIS) hindcast stations were used to aid aerial interpretation, especially with regard to potential seasonal trends. The wave roses in Figure 7 illustrate the percentage of waves that arrive from a given directional band and the distribution of wave height within that direction band. It should be noted that these roses are for an area greater than 10 miles offshore and do not take into consideration fine-scale geometry that can have a significant local impact on wind and waves. A relatively small change in wave direction could correlate to a major impact on storm damage for a portion shoreline protected by headlands. An open stretch of barrier beach (e.g., Nauset) is much less sensitive to small changes in the angle of wave attack. This data was utilized to illustrate the general wind and wave patterns for portions of the coastline exposed to ocean waves. WIS stations 54, 57, and 60 illustrate dominant wave energy from the east, representing conditions north of Cape Cod, however being removed from the protection of the Outer Cape they do not represent conditions within Cape Cod Bay. Station 63 shows more energy from the south, station 66 has relatively even distribution of wave energy between 330 and 210 degrees. Both 63 and 66 show a higher quantity of waves from the south, but a larger significant wave height from the north as well as relatively weak westerly wave conditions for the open ocean due to the shadowing effect of the Outer Cape. Station 70 is similar to 66, save additional wave energy from the west, through Nantucket Sound. Stations 75, 81, 84, 87, and 91 all illustrate dominant wave energy from the south-southwest. These offshore stations are more heavily influenced by conditions in the Atlantic Ocean than nearby land-derived winds. As such, the waves likely do not represent conditions within Cape Cod estuaries, but instead provide insight as to the energy impacting the outer coastlines of the barrier beaches.

Littoral drift is caused by wind and wave action. Some portions of the coast are dominated by other processes (such as tidal currents) which can make a littoral transport determination impracticable. Additionally, there are many coastal areas fronted by marsh. While marsh serves a myriad of desirable purposes (shoreline stabilization, habitat, etc) it also makes the area unsuitable for determination of littoral drift. These areas do not have the direction of net sediment transport indicated on the included map series.

## How To Read The Maps

The series of numbered red rectangles in **Figure 8** correlate to the following series of 16 maps indicating longshore sediment transport and littoral cell boundaries. The numbers indicated on Figure 8 are represented in the lower right hand corner of each of the subsequent maps. Areas not covered by the aerial basemap have been shaded light blue. A legend has been included on each map in the series, to specify what the colored symbols represent. Please note that the maps may be rotated in order to best fit the layout, resulting in north not being "up". North is indicated by the compass arrow above the scale bar. The *Net Transport Indicator* represented by an arrow in the center of a circle, shows the direction of net transport at a single location. Six hundred forty-five transport direction indicators were interpreted from predominantly shore perpendicular structures such as jetties/groins (>75%), with the rest determined from inlets, sand bars and spits, published studies, and local knowledge. A *Littoral Cell Boundary* represented by a dashed line, shows breaks in the longshore sediment transport. The size of the arrows and the length of the cell boundaries were determined for the scale of the map and are not intended to be representative of the relative strength of transport. However, areas between loosely spaced *Net Transport Indicators* can be interpreted as zones of relatively higher uncertainty, while more closely spaced indicators suggest relatively lower uncertainty. Additionally areas of high seasonal variability have been indicated in red. While these areas many have varying degrees of gross transport the annual net transport is likely minimal.

## Findings

For purposes of this discussion of sediment transport, the shoreline of Cape Cod was divided into several coastal regions defined by contiguous water bodies: *Cape Cod Bay, Atlantic Ocean, Nantucket Sound, Buzzards Bay, and Pleasant Bay* (Figure 8).

### Cape Cod Bay

Consisting of the northern shorelines of the towns of *Bourne, Sandwich, Barnstable, Yarmouth, Dennis*, and *Brewster* and the western shorelines of the towns of *Orleans, Eastham, Wellfleet, Truro*, and *Provincetown* (Map Series 1-4 & 13-16).

- The Cape Cod Bay shoreline of **Bourne** is approximately 1.5 miles in length and has a consistent transport towards the southeast.
- The Cape Cod Bay shoreline of **Sandwich** has consistent transport towards the east. Transport is effectively



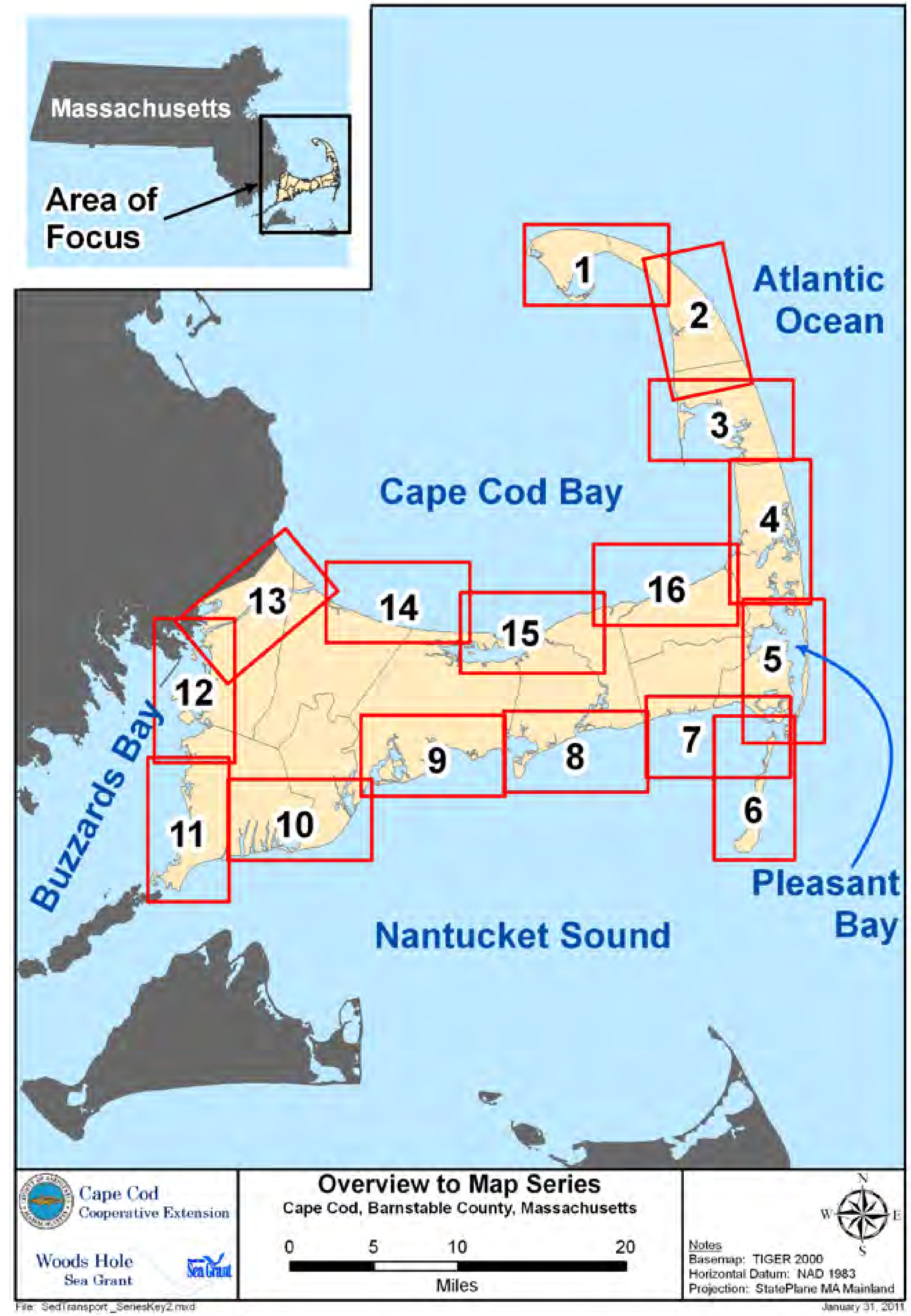



Figure 8. This series of numbered red rectangles correlates to the extents of the following series of maps indicating longshore sediment transport and littoral cell boundaries. The numbers indicated on this figure are represented inthe lower right hand corner of each of the following maps.

blocked by the Cape Cod Canal which acts as a littoral cell boundary. Whatever material was historically transported eastward is now being impounded at the jetty or transported offshore. Scorton Inlet shows localized east to west transport adjacent to a jetty, however the accretion that identifies this trend is only present when there is a significant delta/bar system (**Figure 6**). Local reversals in sediment transport occur (e.g. Town Neck Hill region of Town Beach) due to a perturbation in the shoreline orientation and indicate an alignment of waves to local depth contours (Woods Hole Group, 2004).

- The Cape Cod Bay shoreline of **Barnstable** includes Sandy Neck, a feature that has extended approximately five miles during the past 3,000 years, primarily due to the consistent eastward flow of sand due to longshore transport. Barnstable Harbor inlet acts as a littoral cell boundary, with tidal forces dominating transport within majority of the estuary.
- The Cape Cod Bay shoreline of **Yarmouth** is characterized by a fronting marsh, instead of a barrier beach, which does not allow for a "river of sand" surf zone and littoral transport.
- The Cape Cod Bay shoreline of **Dennis** experiences a node in the longshore transport. From Corporation Beach westward to Chase Garden Creek, sediment travels towards the west. Despite some small scale reversals due to the Sesuit Harbor jetties, it is likely that material from Crowes Pasture to Sesuit Harbor is still moving towards the west, however at a much reduced rate as this section of shoreline has seen minimal retreat over the last 15 years.
- The Cape Cod Bay shoreline boundaries of **Dennis** and **Brewster** experiences both eastward and westward longshore transport. Paines Creek geometry shows a movement of sediment towards the west, while the series of groins eastward of the creek and extending to the Brewster's eastern border indicate an eastward flow of sediment.
- The southern portion of the Cape Cod Bay shoreline of **Eastham** is characterized by minimal impoundment of material along the barrier beach. The maximum fetch directions of ~325° and ~240° create approximately equal energy from each direction likely yielding a minimal net transport. However shorter term gross transport after a storm may be significant. The portion of the Cape Cod Bay shoreline north of Great Pond experiences south to north net transport.
- The northern Cape Cod Bay shoreline of **Wellfleet** experiences southward longshore transport. This material extends the sand spit north of Billingsgate Shoal. North of the harbor the sheltering affect of the Provincetown Hook causes a reversal of the transport direction, likely with more material moving northward near the Wellfleet-Truro border. Wellfleet Harbor sediment transport has sand moving along the bayside beaches and into the harbor via two routes terminating at the northeast corner of the harbor (Dougherty, A.J. 2008). Lieutenant Island has undergone erosion at its central headland, with corresponding accretion to the north and south. Transport vectors in this location were mapped from Dougherty's intertidal bedform study (2008).
- The Cape Cod Bay shoreline of **Truro** experiences northward longshore transport. However the sheltering affect of the Provincetown Hook causes a reversal of the transport direction, with more material likely moving southward near the Wellfleet-Truro border.
- The net transport of sediment is from the Atlantic Ocean beaches north, then west, then southward into Cape Cod Bay and around the **Provincetown** Hook. Sediment on the southwest side of Provincetown Harbor tends to be transported towards the Dike, while the northeast portion of the harbor experiences frequent seasonal reversals, with interruptions due to the Ryder Street parking lot and the offshore breakwater.

## Atlantic Ocean

- Consisting of the eastern shorelines of the towns of *Provincetown, Truro, Wellfleet, Eastham, Orleans, and Chatham* (Map Series 1-6).
- The net transport of sediment from the Atlantic Ocean beaches of Provincetown is north.
- The relatively uninterrupted ocean shoreline of **Truro** and **Wellfleet** contains no clear indicators of longshore transport, just a few small scale and short-lived sand spits, however the indicated northward transport direction agrees with previous studies and analysis of the fetch and wind patterns.
- The ocean shoreline of **Eastham** is broken by Nauset Inlet (previously mentioned in the updrift migration section) which has been recorded (Aubrey & Speer, 1984) to migrate northward counter to the net longshore transport of approximately 250,000 cubed/yr to the south (USACE, 1969). While the exact position of the nodal point, at which the net longshore transport changes from north to south, likely changing year to year it is expected to be located near the Eastham-Wellfleet border. Close to this node there will be relatively large gross transport and little net transport, while the further away you get from this point there will be increasing net transport.
- The ocean shoreline of **Orleans** and **Chatham** has consistent transport towards the south. Recent examples of interrupted transport are the new inlet formation that occurred across from Chatham Light in 1987, and again across from Minister's Point in 2007. Under Giese's (2009) scenario, after formation the inlet may stabilize within 20 years and then begin a southward migration in 30 years, potentially ending up somewhere between Minister's Point and Chatham Light in 50 years. Ultimately, the Outer Cape's ocean longshore sediment transport is the major contributor to the terminal sand spit that makes up Monomy.

## Pleasant Bay

Including the estuarine shorelines of the towns of *Orleans, Brewster, Harwich,* and *Chatham* (Map Series 4 & 5). Along most areas of the Pleasant Bay shoreline, tides and waves comprise the primary forces for reshaping the shoreline. Sediment transport was only delineated in areas where sediment movement is significant, i.e., shorelines exhibiting active movement of nearshore sediments. The estuarine sediments do not form a straight smooth shoreline, but rather a crenulated coast with multiple islands to break up the wind, waves and currents. Additionally, large portions of shoreline (e.g., bayside of the northern barrier beach system) are fronted by marsh which dissipates wave energy by friction and drag, thereby reducing erosion further inland. The natural variability in shoreline type influences the coastal processes that dominate how a particular shoreline stretch responds to the long-term effects of waves and tides, as well as the infrequent short-term influence of storm waves and surge. Based on the regional geomorphology and exposure of the coast to wave conditions (i.e., fetch, the distance over which wind can travel over water unimpeded by dry land), it was possible to assess the dominant coastal processes governing the various shoreline regions of Pleasant Bay. The lack of observable longshore sediment transport indicators in areas with fetch less than a half mile likely indicates that other coastal processes are more significant in these areas. Sediment transport in estuarine systems (due to estuarine circulation, tidal currents, etc) is more complex to map than open coast environments, which is one of the reasons not all estuaries were analyzed. Multiple inlets, new inlet formation, islands, and deltas all add to a shifting fetch environment for portions of Pleasant Bay.

## Nantucket Sound

Consisting of the southern shorelines of the towns of *Chatham, Harwich, Dennis, Yarmouth, Barnstable, Mashpee,* and *Falmouth*. The Nantucket Sound shoreline of all of these towns is characterized by numerous indicators of north and eastward transport in the form of the many groins and jetties attempting to slow longshore transport and stabilize inlets (Map Series 6-11).

- **Chatham**, **Harwich**, and **Dennis** exhibit some small-scale reversals in the shadow of large jetties. Sediments would be ultimately transported to Monomy if allowed to follow the natural flow of material.
- In **Yarmouth**, transport is northward on both sides of Great Island with some material moving towards Lewis Bay. Transport within the bay is affected by fine-scale geometry that can have a significant local impact fetch and therefore wind and waves, as well as tidal forces.
- **Barnstable** contains some notable exceptions to this north and eastward transport direction, typically the areas protected by headlands and affected by inlets (Sampsons Island, Cotuit and West Bay, and the north side of Popponesset Bay inlet) and some headland areas.
- One example in **Mashpee** of westward transport is the eroded sand from Washburn Island providing material to the spit that is ultimately dumping sand into Eel Pond Inlet. The jettied inlet at Waquoit Bay has been relatively stable over the last 70 years due to the set of hydrodynamic conditions that balance the east-west net sediment transport conditions existing along this more eastward stretch of shoreline (Weidman, 2009).
- Some **Falmouth** inlets have a buildup of sediment on their eastern sides, typically indicating westward transport. This impoundment is likely due to the excavation activities attempting to keep the tidal flow active. The excavators dump the material on whichever side the machine is located. Additionally, some material is being transported offshore into deep water by jetties at pond inlets (CRWG, 2003). Significant seasonal variability in the direction of longshore transport was documented, by Aubrey and Gaines (1982), from the pattern of sand entrapment along the groins from 1951 to 1980 (Figure 5).

## Buzzards Bay

Consisting of the western shorelines of the towns of **Falmouth** and **Bourne** (Map Series 11-13). A crenulated shoreline due to the moraine deposits left behind after the last glacial event, forming numerous headlands, and consequently multiple small-scale littoral cells with minor fluctuations for small harbors, embayments, and, marshes. Additionally, the strong seasonality of the wind/wave conditions within the bay leads to predominantly northward transport during summer months and southward transport during the winter (CRWG, 2010). The greater southwest fetch provides the potential for a greater net northward transport, especially if a tropical storm affects the area, however this is likely different on an annual basis. This propensity towards northward transport is indicated by the airphoto analysis, excluding areas protected by headlands, but may be biased due to time of year the photo was acquired (winter photos are underrepresented). Falmouth harbors along this coast act as traps for sediment transported from adjacent headlands, however due to general lack of sediment in this system most harbors are infilling relatively slowly (CRWG, 2010). The Buzzards Bay shoreline of Bourne is characterized by transport on both sides of a "neck" (i.e., Scraggy Neck, Wings Neck, Mashnee) that extends into Buzzards Bay and acts as a littoral cell boundary. Transport is effectively blocked by the Cape Cod Canal (also a littoral cell boundary), with whatever material historically transported now being temporarily captured within the canal and transported offshore. This is all to a lesser degree than what occurs on the Cape Cod Bay side of the canal, since there is relatively less material being transported on the Buzzards Bay side of the Canal.

PROVINCETOWN
TRURO
Longshore Sediment Transport
Barnstable County, Massachusetts
Notes
Basemap: MassGIS 2009
Horizontal Datum: NAD 1983
Projection: StatePlane MA Mainland
0 0.5 1
Miles
Net Transport Indicator
High Seasonal Variability
Littoral Cell Boundary
Cape Cod Cooperative Extension
Woods Hole Sea Grant
Map #01


# Longshore Sediment Transport

Barnstable County, Massachusetts

Notes
Basemap: MassGIS 2009
Horizontal Datum: NAD 1983
Projection: StatePlane MA Mainland

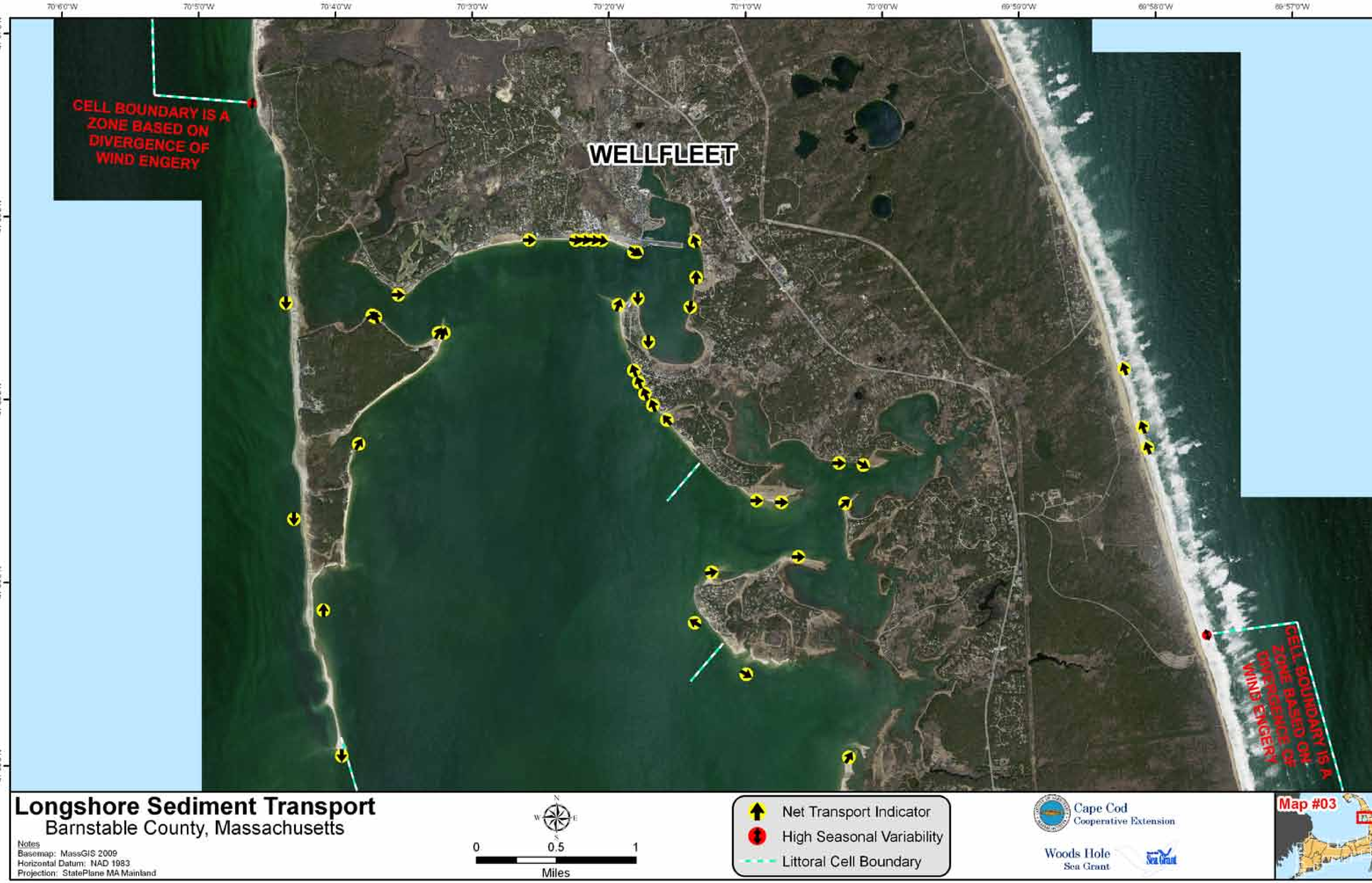
0 0.5 1
Miles

Net Transport Indicator
High Seasonal Variability
Littoral Cell Boundary

Cape Cod Cooperative Extension

Woods Hole Sea Grant

Map #02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41°53'0"N
CELL BOUNDARY IS A ZONE BASED ON DIVERGENCE OF WIND ENGERY
WELLFLEET
CELL BOUNDARY IS A ZONE BASED ON DIVERGENCE OF WIND ENGERY
Longshore Sediment Transport
Barnstable County, Massachusetts
Notes
Basemap: MassGIS 2009
Horizontal Datum: NAD 1983
Projection: StatePlane MA Mainland
0
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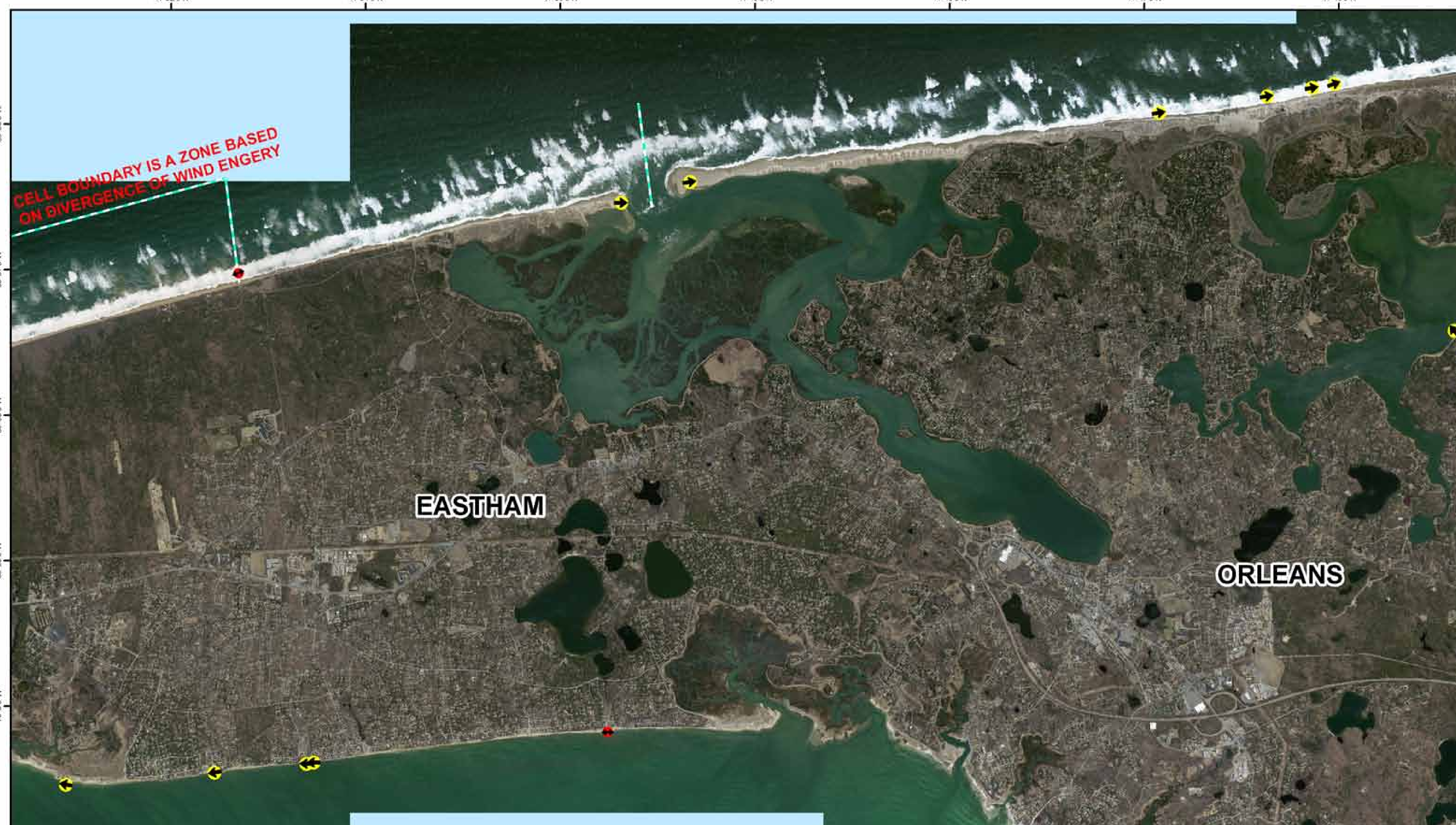
Miles
Net Transport Indicator
High Seasonal Variability
Littoral Cell Boundary
Cape Cod Cooperative Extension
Woods Hole Sea Grant
Map #03




# Longshore Sediment Transport

Barnstable County, Massachusetts

Notes
Basemap: MassGIS 2009
Horizontal Datum: NAD 1983
Projection: StatePlane MA Mainland

0 0.5 1
Miles

Net Transport Indicator
High Seasonal Variability
Littoral Cell Boundary

Cape Cod Cooperative Extension

Woods Hole Sea Grant

Map #04


# Longshore Sediment Transport

Barnstable County, Massachusetts

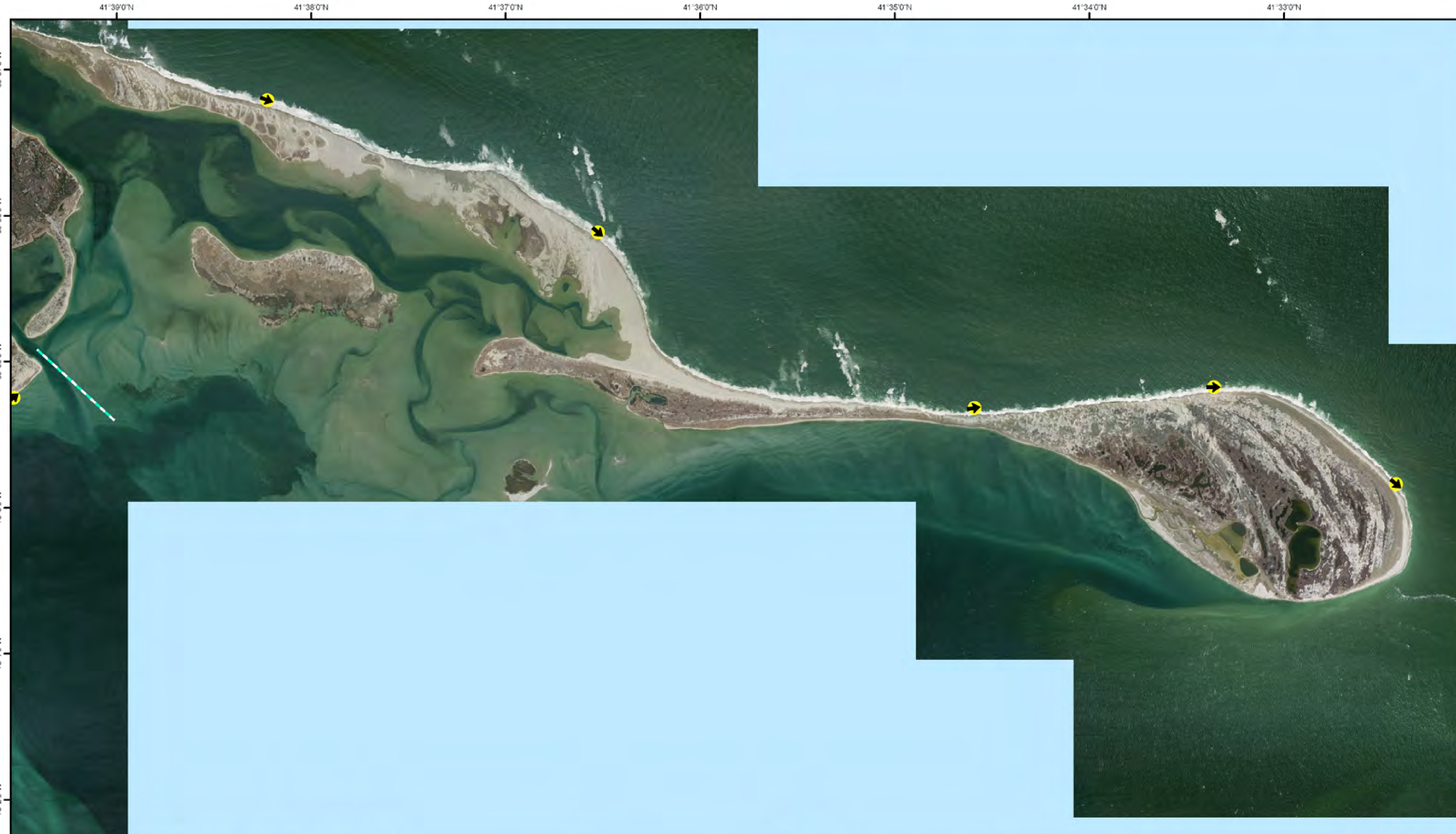
Notes
Basemap: MassGIS 2009
Horizontal Datum: NAD 1983
Projection: StatePlane MA Mainland

0 0.5 1
Miles

Net Transport Indicator
High Seasonal Variability
Littoral Cell Boundary

Cape Cod
Cooperative Extension

Woods Hole
Sea Grant




# Longshore Sediment Transport
Barnstable County, Massachusetts

Notes
Basemap: MassGIS 2009
Horizontal Datum: NAD 1983
Projection: StatePlane MA Mainland

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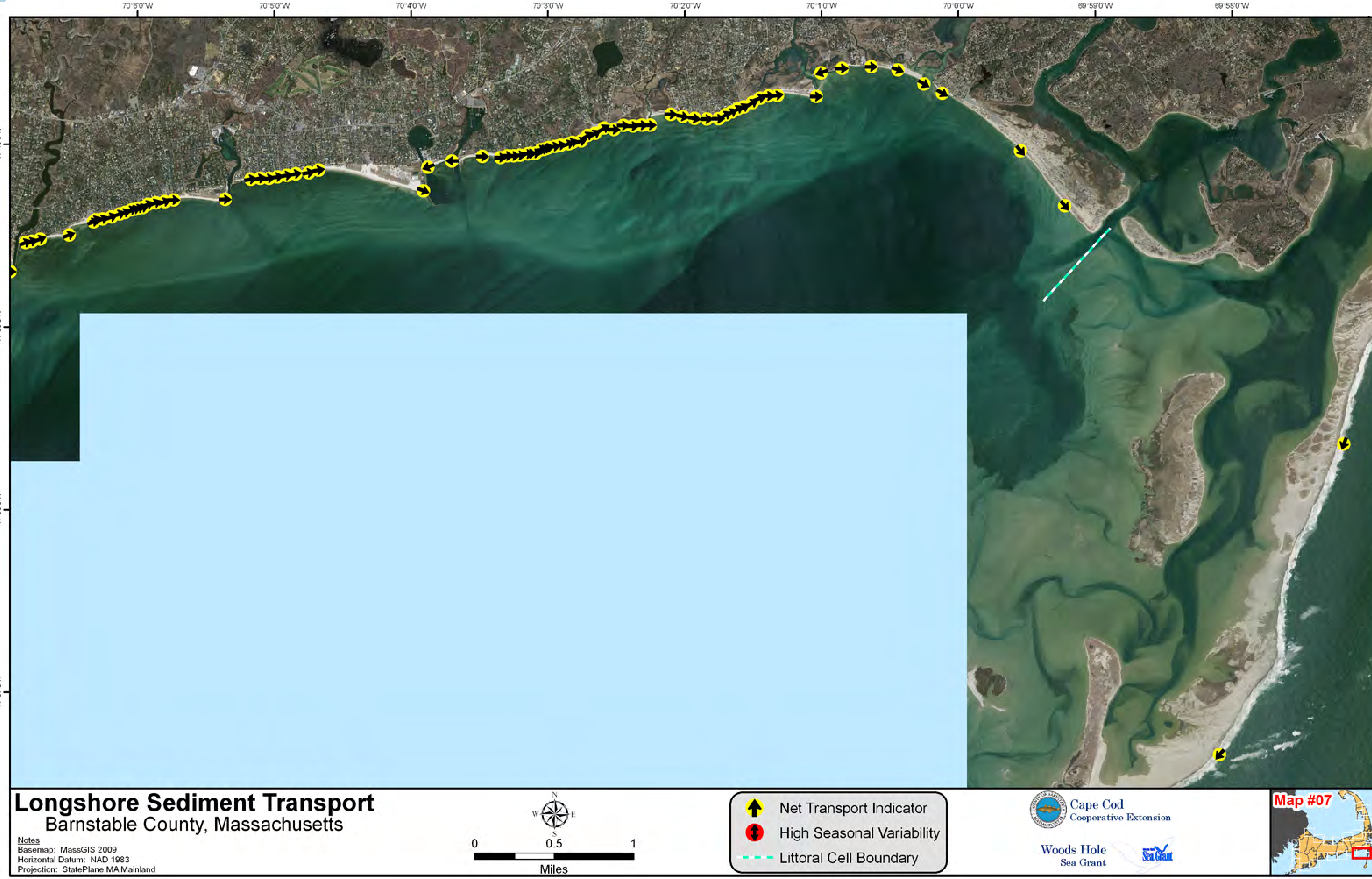
Miles

Net Transport Indicator
High Seasonal Variability
Littoral Cell Boundary

Cape Cod Cooperative Extension
Woods Hole Sea Grant

Map #06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41°40'0"N
41°39'0"N
41°38'0"N
41°37'0"N
Longshore Sediment Transport
Barnstable County, Massachusetts
Notes
Basemap: MassGIS 2009
Horizontal Datum: NAD 1983
Projection: StatePlane MA Mainland
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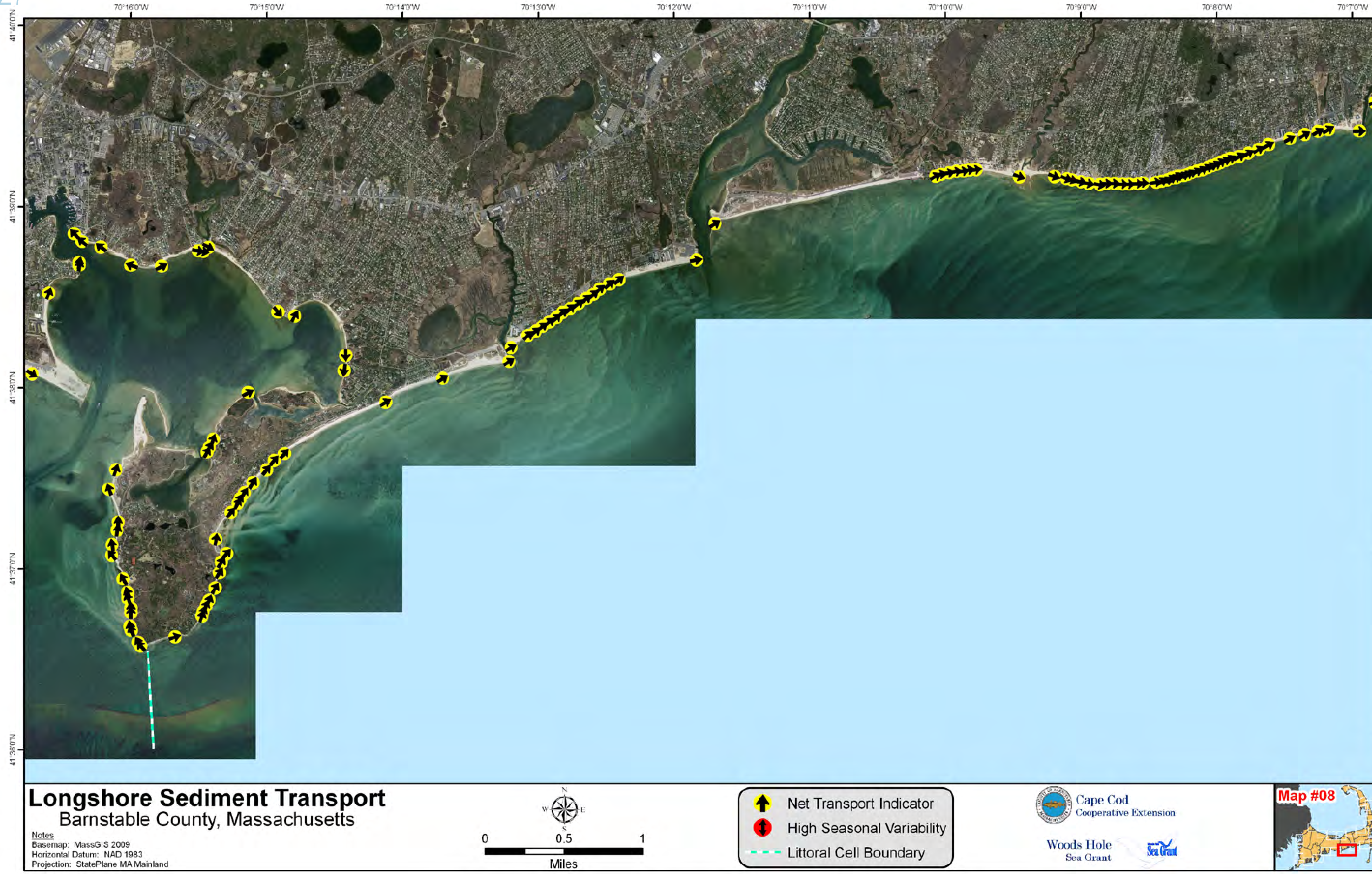
Miles
Net Transport Indicator
High Seasonal Variability
Littoral Cell Boundary
Cape Cod Cooperative Extension
Woods Hole Sea Grant
Map #07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70°9'0"W
70°8'0"W
70°7'0"W
41°40'0"N
41°39'0"N
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41°37'0"N
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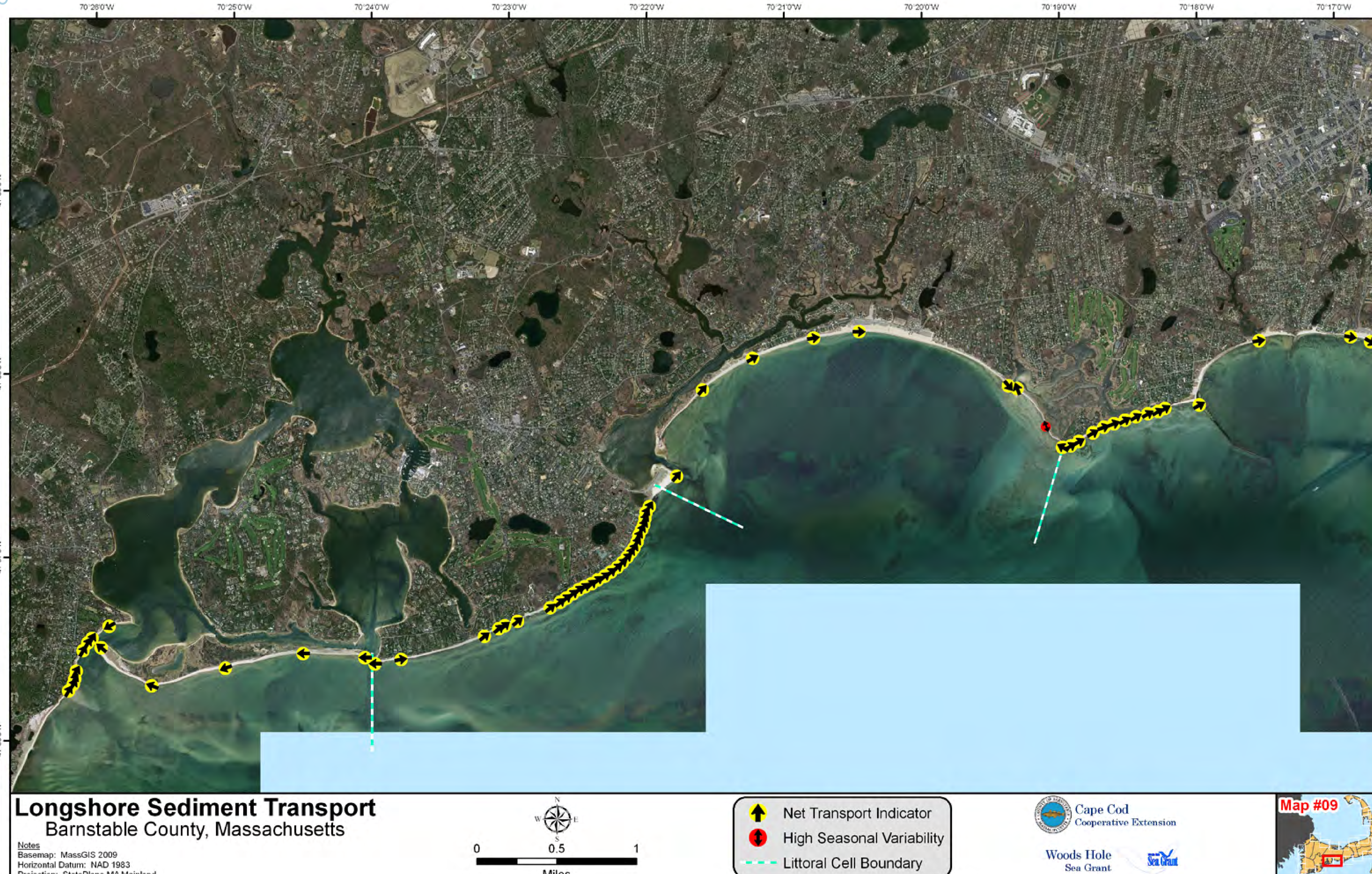
Longshore Sediment Transport
Barnstable County, Massachusetts
Notes
Basemap: MassGIS 2009
Horizontal Datum: NAD 1983
Projection: StatePlane MA Mainland
0 0.5 1
Miles
Net Transport Indicator
High Seasonal Variability
Littoral Cell Boundary
Cape Cod Cooperative Extension
Woods Hole Sea Grant
Map #08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70°18'0"W
70°17'0"W
41°39'0"N
41°38'0"N
41°37'0"N
41°36'0"N
Longshore Sediment Transport
Barnstable County, Massachusetts
Notes
Basemap: MassGIS 2009
Horizontal Datum: NAD 1983
Projection: StatePlane MA Mainland
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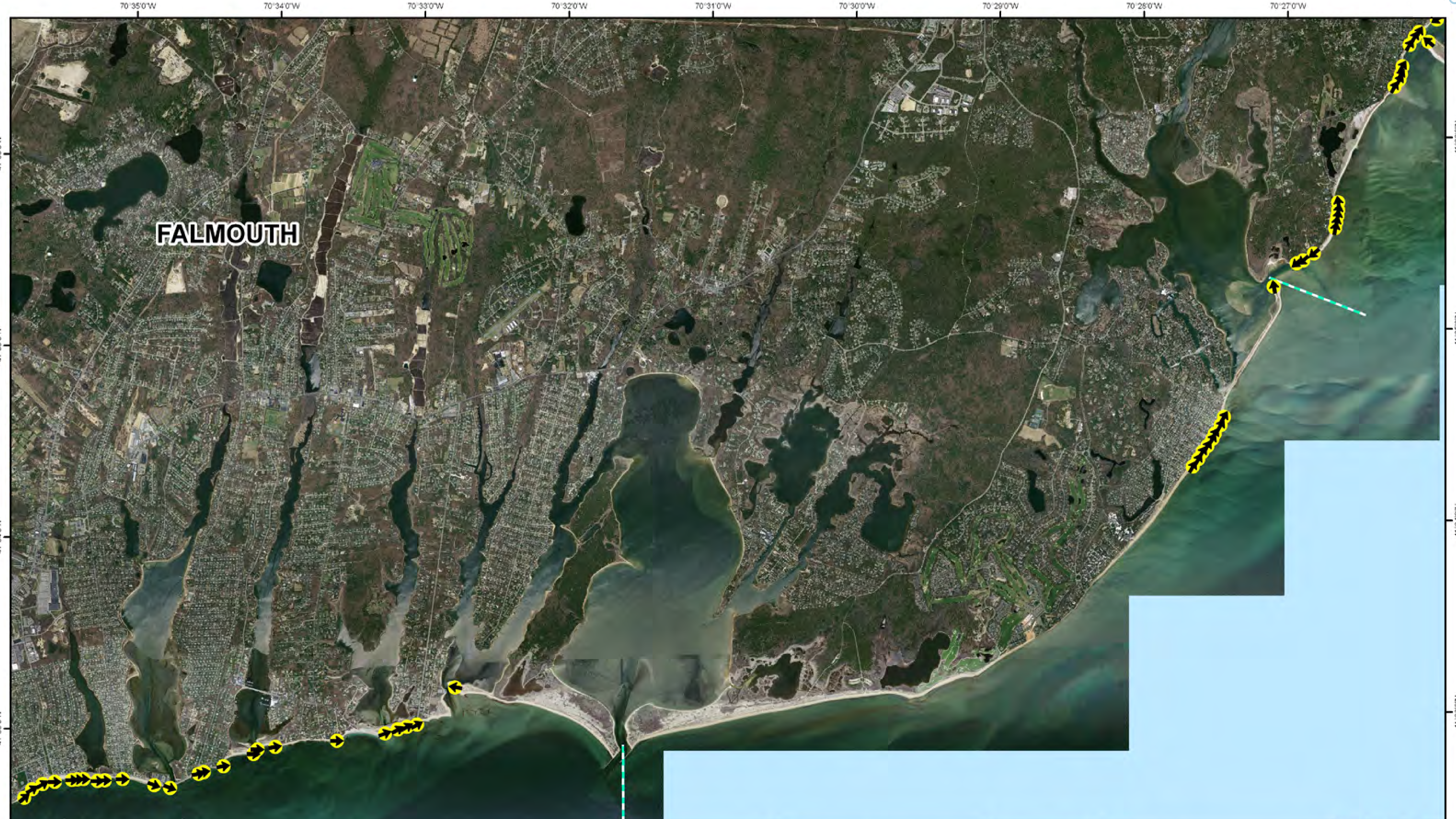
Miles
Net Transport Indicator
High Seasonal Variability
Littoral Cell Boundary
Cape Cod Cooperative Extension
Woods Hole Sea Grant
Map #09




# Longshore Sediment Transport

Barnstable County, Massachusetts

Notes
Basemap: MassGIS 2009
Horizontal Datum: NAD 1983
Projection: StatePlane MA Mainland

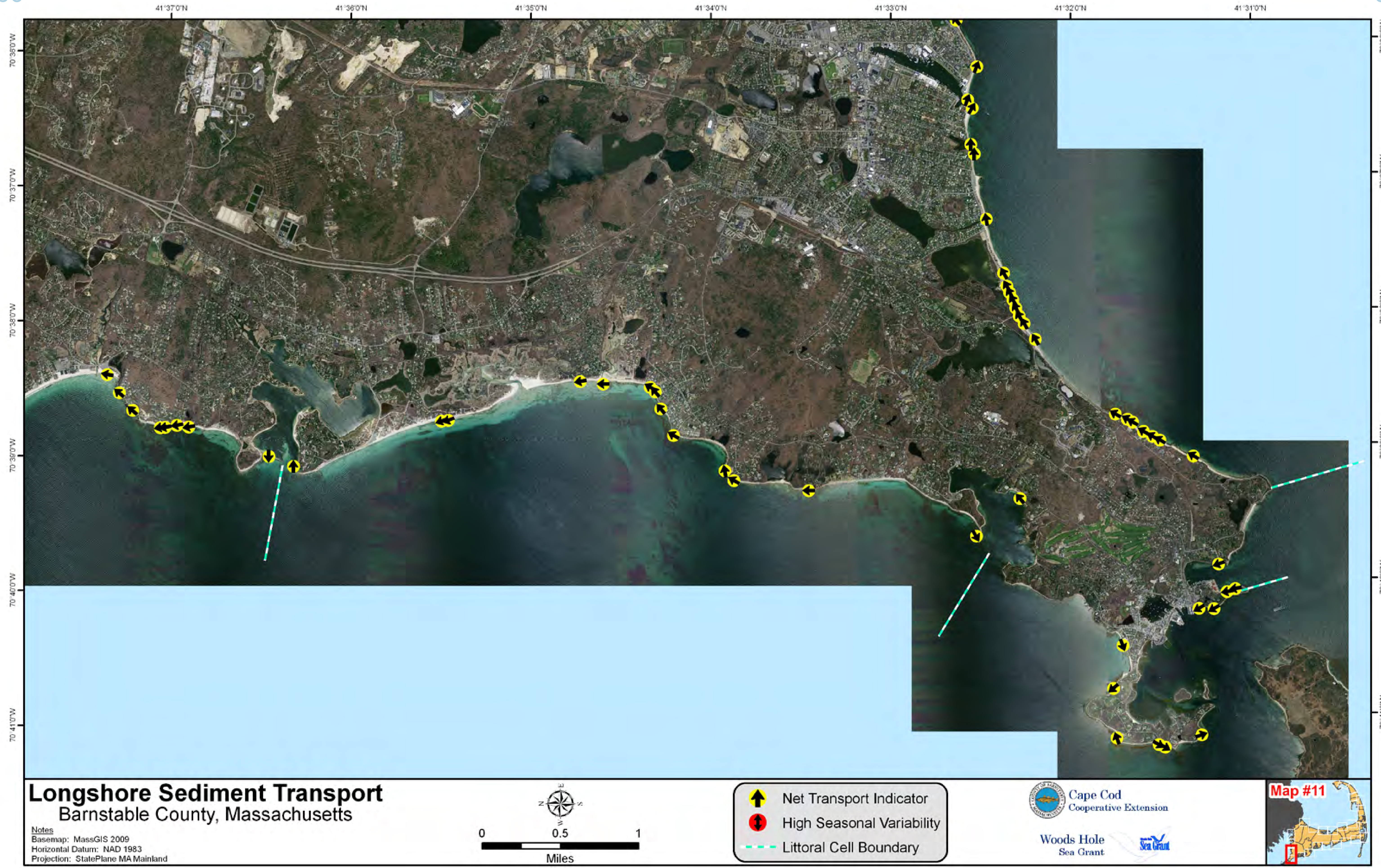
0 0.5 1
Miles

- Net Transport Indicator
- High Seasonal Variability
- Littoral Cell Boundary

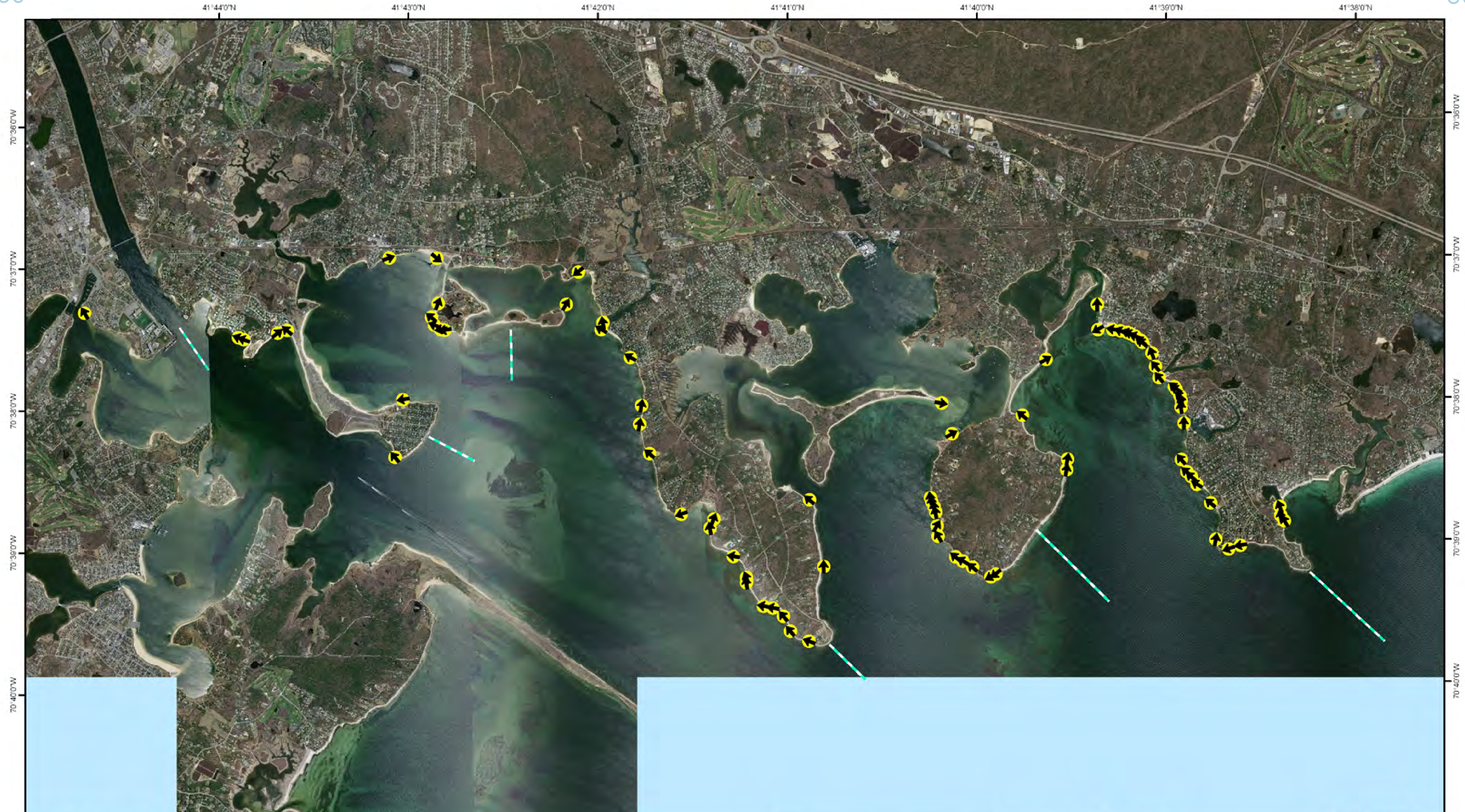
Cape Cod Cooperative Extension

Woods Hole Sea Grant

Map #10



Longshore Sediment Transport
Barnstable County, Massachusetts
Notes
Basemap: MassGIS 2009
Horizontal Datum: NAD 1983
Projection: StatePlane MA Mainland
0 0.5 1
Miles
Net Transport Indicator
High Seasonal Variability
Littoral Cell Boundary
Cape Cod Cooperative Extension
Woods Hole Sea Grant
Map #11




# Longshore Sediment Transport

Barnstable County, Massachusetts

Notes
Basemap: MassGIS 2009
Horizontal Datum: NAD 1983
Projection: StatePlane MA Mainland

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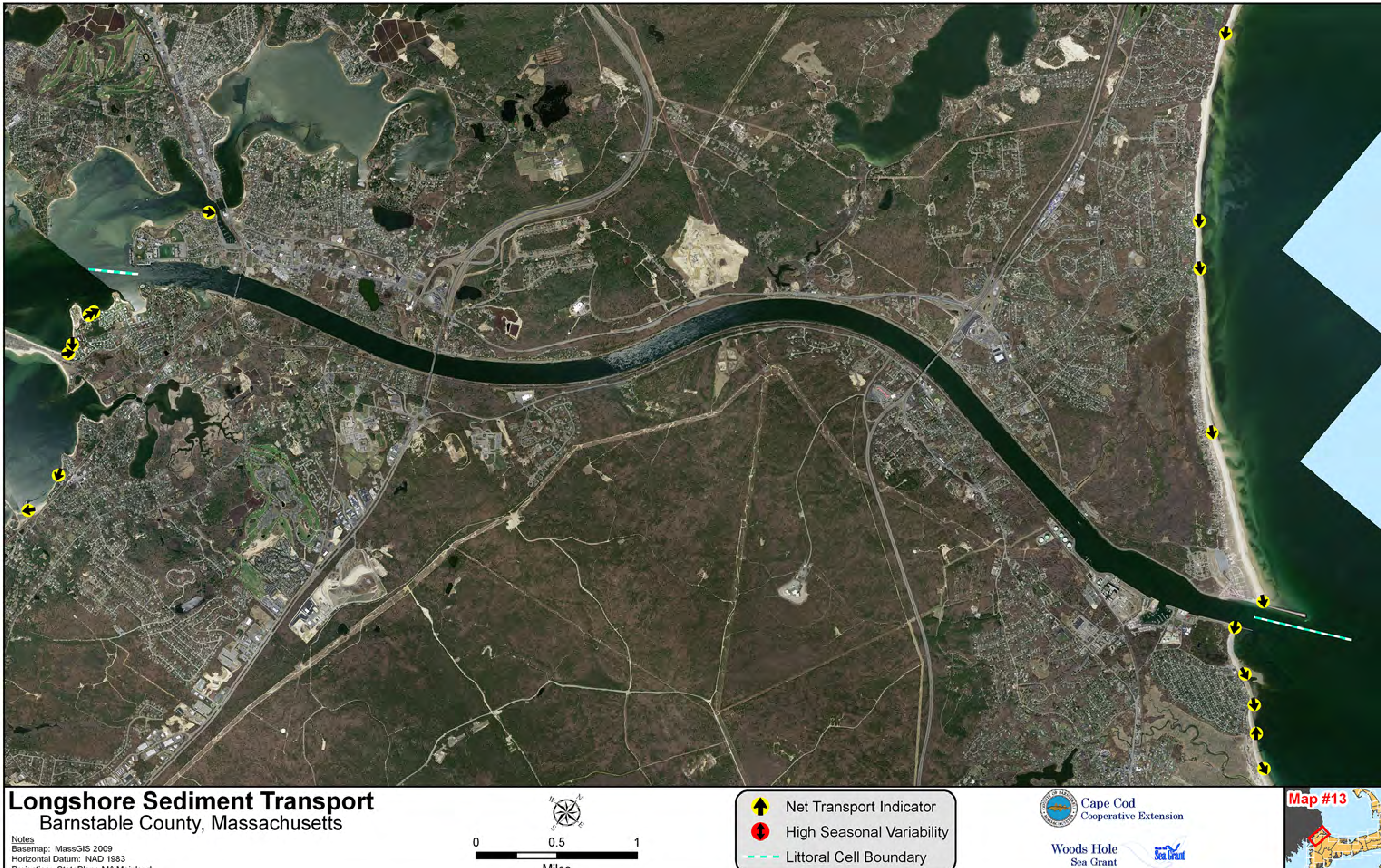
Miles

Net Transport Indicator
High Seasonal Variability
Littoral Cell Boundary

Cape Cod Cooperative Extension

Woods Hole Sea Grant

Map #12



Longshore Sediment Transport
Barnstable County, Massachusetts
Notes
Basemap: MassGIS 2009
Horizontal Datum: NAD 1983
Projection: StatePlane MA Mainland
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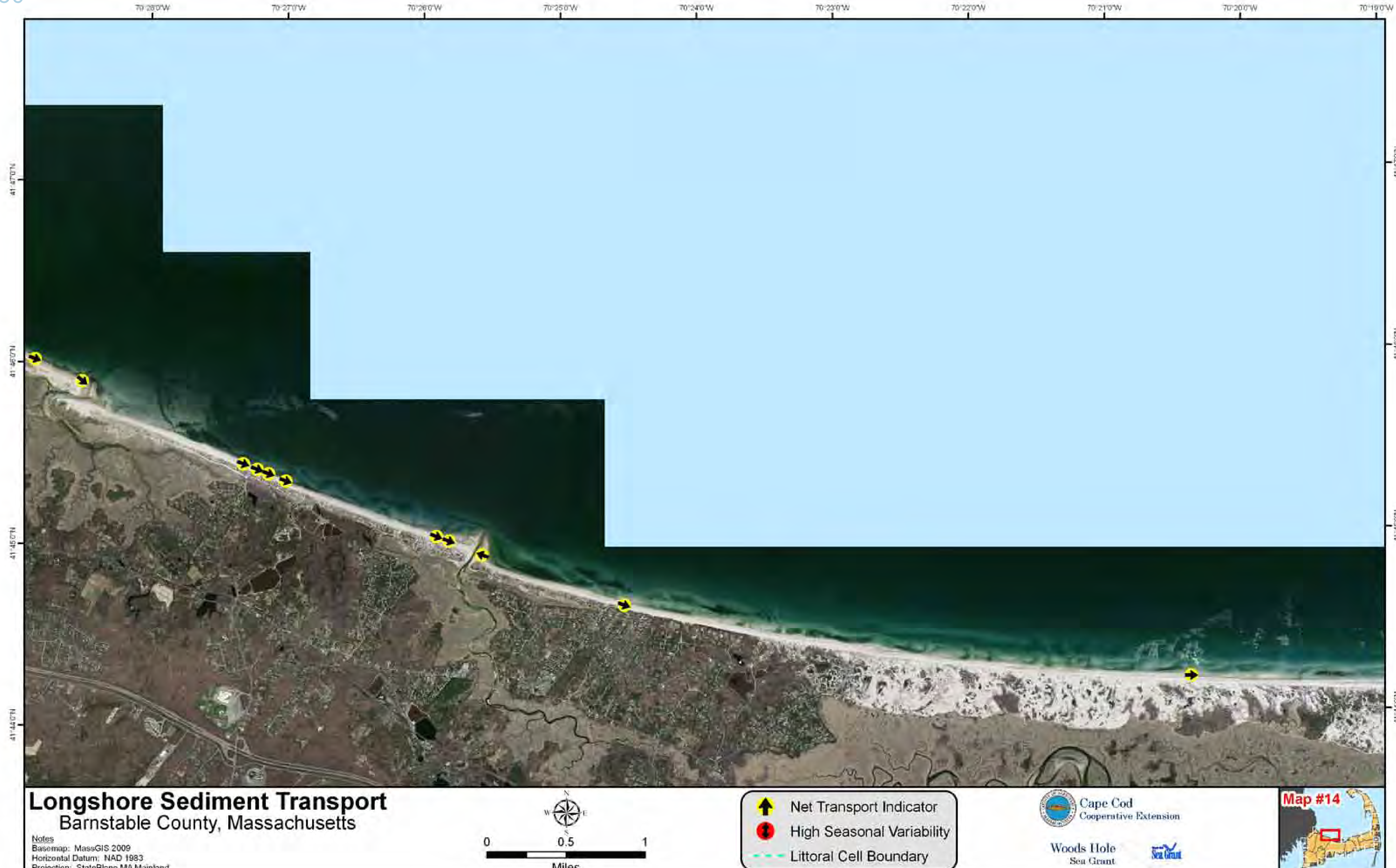
Net Transport Indicator
High Seasonal Variability
Littoral Cell Boundary
Cape Cod
Cooperative Extension
Woods Hole
Sea Grant
Map #13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70°20'0"W
70°19'0"W
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Longshore Sediment Transport
Barnstable County, Massachusetts
Notes
Basemap: MassGIS 2009
Horizontal Datum: NAD 1983
Projection: StatePlane MA Mainland
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Net Transport Indicator
High Seasonal Variability
Littoral Cell Boundary
Cape Cod
Cooperative Extension
Woods Hole
Sea Grant
Sea Grant
Map #14


CELL BOUNDARY IS A ZONE BASED ON DIVERGENCE OF WIND ENGERY
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Longshore Sediment Transport
Barnstable County, Massachusetts
Notes
Basemap: MassGIS 2009
Horizontal Datum: NAD 1983
Projection: StatePlane MA Mainland
0 0.5 1
Miles
Net Transport Indicator
High Seasonal Variability
Littoral Cell Boundary
Cape Cod Cooperative Extension
Woods Hole Sea Grant
Map #15


**Longshore Sediment Transport**
Barnstable County, Massachusetts

Notes
Basemap: MassGIS 2009
Horizontal Datum: NAD 1983
Projection: StatePlane MA Mainland

0 0.5 1
Miles

Net Transport Indicator
High Seasonal Variability
Littoral Cell Boundary

Cape Cod Cooperative Extension
Woods Hole Sea Grant

Map #16

## Summary

Structures interfere with the natural movement of sediment on Cape Cod, acting as dams to sediment transport. The original goal of slowing net sediment transport may be leading to sediment starvation in many of Cape Cod's coastal systems. Exacerbating this are portions of the shoreline armored against erosion, coupled with rising sea level, providing less material than historically available to sustain the beaches of Cape Cod. The longshore sediment transport direction mapped in this report can fluctuate at various time scales. The direction and cell boundaries indicated on the map series are best estimates of the conditions represented in the data sources. As weather patterns vary annually there is the potential for reversals from indicated trends, especially at areas identified as an open coast littoral cell boundary, identified by prevailing wind and wave direction. It is hoped that this document will provide a resource for those wishing to understand a bit more about Cape Cod's dynamic shoreline.

## Acknowledgements

This extension bulletin could not have been accomplished without the ideas and experience that so many people were willing to share. The following individuals are thanked for contributing to this bulletin: Amy Usowski (Town of Eastham); Andrew Ashton (Woods Hole Oceanographic Institution); Bill Clark (Cape Cod Cooperative Extension); Chris Weidmen (Waquoit Bay National Estuarine Research Reserve); David Deconto (Town of Sandwich); Ellen Jedrey (Mass Audubon); Graham Giese (Provincetown Center for Coastal Studies); Hillary Greenburg (Town of Wellfleet); Jeffrey Brodeur (Woods Hole Sea Grant); Judy McDowell (Woods Hole Sea Grant); Kirk Bosma (Woods Hole Group); Kristin Andres (Town of Chatham); Lindsey Counsell (ThreeBays Preservation, Inc.); Peter Sullivan (Sullivan Engineering, Inc.); Rob Gatewood (Town of Barnstable); Rob Thieler (U.S. Geological Survey); and Ted Keon (Town of Chatham). My sincere apologies if I have unintentionally omitted anyone who was supportive of this endeavor. Source credit for aerial photography is Office of Geographic Information (MassGIS), Commonwealth of Massachusetts Information Technology Division.

Graham Giese is particularly acknowledged for providing technical advice, sharing his extensive knowledge of Cape Cod sediment transport, and being so willing to answer my numerous questions.

## Glossary

**Accretion:** A gradual or intermittent natural process of deposition of sediment by wind, wave or current action … resulting in the natural raising or extension of a land area.*

**Aerial Photography:** A photograph of the earth's surface taken from the air.**

**(Beach) Morphology:** The shape of the earths' surface; the properties and distribution patterns of layers in a sedimentary profile.**

**Depositional Shadow:** An area that is denied natural depositional processes occurring in adjacent areas. (See Figure 3).

**Downdrift:** The direction sediment is transported along the shore. (See Figure 3).

**Beach Erosion:** A process whereby a beach loses its sediment, resulting in a depletion of its sediment budget … an imbalance between energy inputs and the resistance of the sediment to mobilization.*

**Estuarine:** Pertaining to an estuary – the seaward end of a river, opening toward the sea … subject to tidal movements and incursion of salt water from the sea.*

**Geomorphic:** Pertaining to the form of the earth or of its surface features.**

**Groin:** A wall built out at right angles from the coastline, intended to intercept drifting beach material.*

**Impoundment:** A term often used to describe the river sediment captured by dams. This also describes the sediment being transported by littoral drift being captured and accumulated (See Figure 3).

**Jetty:** A solid structure built out more or less at right angles to the coastline or on either side of a river mouth or lagoon entrance.*

**Littoral:** Pertaining to the zone between high water and low water.*

**Littoral Cell:** A coastal compartment that contains a complete cycle of sedimentation including sources, transport paths, and sinks. The cell boundaries delineate the geographical area with which the budget of sediment is balanced, providing the framework for the quantitative analysis of coastal erosion and accretion.*

**Littoral Current:** See Longshore Current

**Littoral Drift:** See Longshore Drift

**Littoral Transport:** See Longshore Drift

**Longshore:** Parallel to and near to shore.

**Longshore Current:** The flow of water along the shore or nearshore as result of oblique waves, often augmented by wind-driven and tidal currents.*

**Longshore Drift:** See Longshore Sediment Transport

**Longshore Sediment Transport:** The cumulative movement of beach sediment along the shore (and nearshore) by waves arriving at an angle to the coastline and by currents generated by such waves.*

**Nodal Point:** The point at which longshore sediment transport diverges or converges due to wind/wave action as opposed to shoreline geometry or structures.

**Nor'easter:** A strong storm characterized by a low pressure system with winds rotating onto land from the northeast. They can cause erosion and flooding with hurricane force winds and heavy precipitation (rain/snow) and are predominantly a winter storm.

**Revetment:** Sloping coastal engineering structures constructed on banks or cliffs in order to absorb the energy of incoming waves and thus defend against erosion.

**Sediment:** Solid fragmental material transported and deposited by wind or water, and that forms in layers in loose unconsolidated form.** Here on the Cape our sediments are glacially derived, and as such, a large spectrum of grain sizes are present, from mud to sand to gravel.

**Sediment Sink:** An area where sediment is removed (temporarily or longer-term) from a littoral cell.

**Sediment Source:** An area where sediment is acquired (temporarily or longer-term) into a littoral cell.

**Spit:** A finger-like ridge … of beach material built up above high tide level and diverging from the land at one end to terminate … curving landward.*

The definitions marked by asterisk are verbatim, or with minimal adaptation, from the following sources:

* *"Encyclopedia of Coastal Science." Encyclopedia of Earth Sciences Series, M.L. Schwartz (ed.). 2005.*

** *"Dictionary of Geological Terms (3rd edition)." The American Geological Institute, R.L. Bates and J.A. Jackson (eds.). 1984.*



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