Coastal Engineering 125 (2017) 23–27

Contents lists available at ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng

Flow separation effects on shoreline sediment transport

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ARTICLE INFO

Keywords:
Flow separation
Inlet hydrodynamics
Numerical modeling
Coastal evolution
Delft3D

ABSTRACT

Field-tested numerical model simulations are used to estimate the effects of an inlet, ebb shoal, wave height, wave direction, and shoreline geometry on the variability of bathymetric change on a curved coast with a migrating inlet and strong nearshore currents. The model uses bathymetry measured along the southern shoreline of Martha's Vineyard, MA, and was validated with waves and currents observed from the shoreline to ~10-m water depth. Between 2007 and 2014, the inlet was open and the shoreline along the southeast corner of the island eroded ~200 m and became sharper. Between 2014 and 2015, the corner accreted and became smoother as the inlet closed. Numerical simulations indicate that variability of sediment transport near the corner shoreline depends more strongly on its radius of curvature (a proxy for the separation of tidal flows from the coast) than on the presence of the inlet, the ebb shoal, or wave height and direction. As the radius of curvature decreases (as the corner sharpens), tidal asymmetry of nearshore currents is enhanced, leading to more sediment transport near the shoreline over several tidal cycles. The results suggest that feedbacks between shoreline geometry and inner-shelf flows can be important to coastal erosion and accretion in the vicinity of an inlet.

1. Introduction

Sediment transport on shorelines is affected by wave-orbital velocities, breaking-wave-driven currents, tidal currents, and inlet flows. In particular, inlet flows can interrupt alongshore sediment transport, resulting in sediment deposition inside the bay (flood tide delta), in the ocean near the inlet mouth (ebb-tide delta or shoal) or farther offshore [1–4], references therein and many others]. Erosion downstream of the inlet is possible owing to inlet-induced reduction in alongshore sediment supply. The inlet influence can extend for more than 10 km along the coast [5], although it often extends less than 4 km [4–7]. The inlet region of influence depends on many factors, including the geometry of the ebb shoal and main inlet channel [8], the offshore bathymetry [9,10], wave climate [11,12], tidal prism [4,13], and the presence of headlands [14,15].

Traditional knowledge associates increased sediment transport around the shoreline at Wasque Point on the southeast corner of Martha's Vineyard, MA, USA (Fig. 1) with the opening of the nearby Katama Inlet [16]. Katama Inlet breached in 2007 near the middle of Norton Point (Fig. 1c) and migrated east until it closed in 2015 (Fig. 1d). While the inlet was open, the shoreline near the corner of Wasque Point eroded ~200 m [Fig. 1d, compare the purple curve (2014) with the blue curve (2008, similar to 2007)]. Once Norton Point extended eastward and wrapped around Wasque Point, closing the inlet, the corner reverted toward its 2007 position [Fig. 1d, compare the yellow curve (2015) with the blue curve (2008)]. Here it is shown that although the erosion and subsequent accretion of the southeast corner of Martha's Vineyard is consistent with a potential reduction (increase) in alongshore transport when the inlet is open (closed), the variability of transport (magnitude of erosion plus magnitude of deposition) depends strongly on the radius of curvature of the corner, a proxy for flow separation, which also may impact the shoreline evolution.

Similar to the Martha's Vineyard coastline, many shorelines with inlets also have complex larger-scale bathymetry and strong inner-shelf currents, including inlets throughout New England [17], along the U.S. Atlantic Coast [18], and on sandy coasts around the world [12,19]. Strong currents near headlands or sharp shoreline transitions such as Wasque Point (Fig. 1) can impact sediment transport significantly. In particular, the separation of currents flowing around headlands or sharp corners can generate eddies that suspend, transport, and deposit sediment [18,20–23 and many others]. Flow separation and the generation of eddies depend on the radius of curvature of the corner (or aspect ratio of a headland) [24], the balance of bottom friction and current strength, and the ratio of flow strength to local acceleration [21]. Near Wasque Point, the strong ebb jet through Muskeget Channel

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http://dx.doi.org/10.1016/j.coastaleng.2017.04.007
Received 11 October 2016; Accepted 7 April 2017

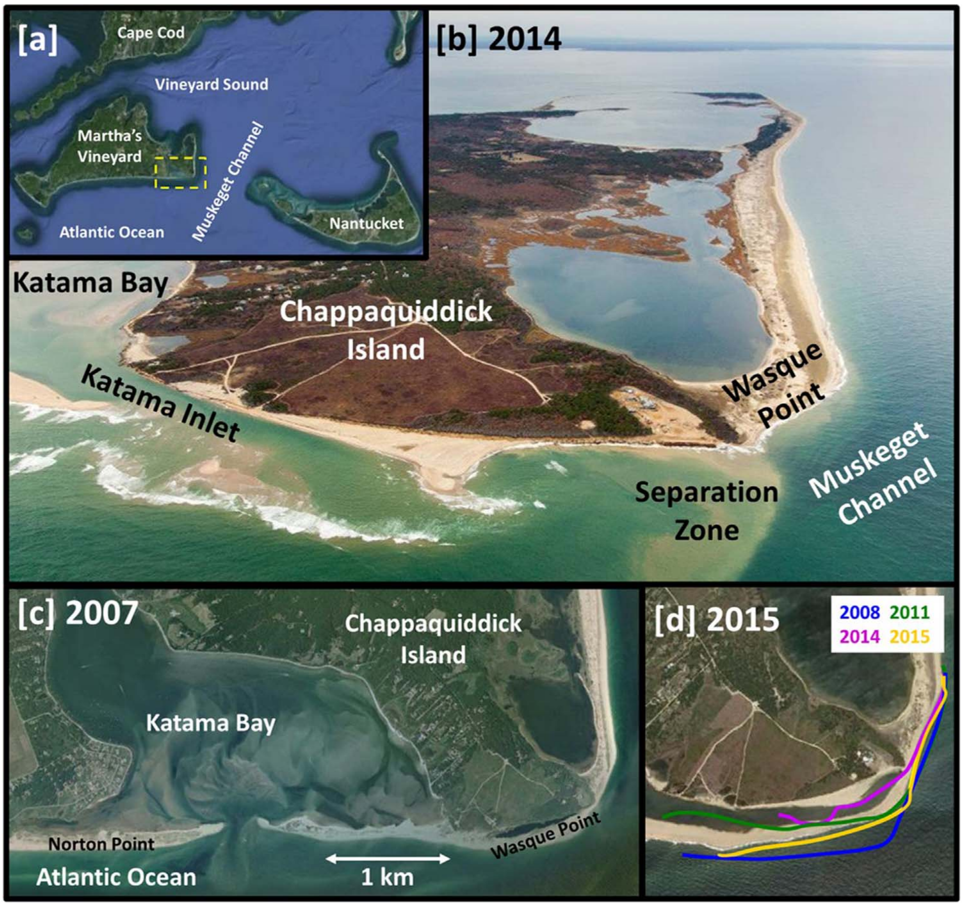

Fig. 1. (a) Location of Martha's Vineyard, MA, (b) photograph of Chappaquiddick Island, Katama Bay and Inlet, and Wasque Point in 2014 [within the yellow box in (a)], (c) Google Earth image of the Katama area 2 months after Norton Point was breached in Apr 2007, and (d) close up image of Wasque Point in 2015, with shorelines from 2008 (blue curve, similar to 2007), 2011 (green), 2014 (purple), and 2015 (yellow). Photograph in (b) by Bill Brine. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

separates from the shoreline, resulting in a quiescent zone at the southeastern corner of Chappaquiddick Island (Fig. 1a,b). The evolution of the radius of curvature of Wasque Point, a primary control of flow separation, over the lifetime of Katama Inlet (Fig. 1d) suggests that flow separation, in addition to the inlet, could impact sediment transport at nearby shorelines. Here, field-tested numerical model simulations are used to estimate the effects of an inlet, the ebb shoal, wave height, wave direction, and shoreline geometry on erosion and deposition along a curved coast with a migrating inlet.

2. Numerical simulations

Waves and currents were simulated with the numerical models SWAN (waves [25]) and Delft3D-FLOW (currents [26]). The wave model solves the spectral action balance and includes the effects of shoaling, refraction, and wave-current interaction. Similar to previous studies at this location [27], for the no-wind cases and relatively short evolution distances here, wind and nonlinear interactions were not included. The circulation model includes the effects of waves on currents through wave radiation-stress gradients, combined wave and current bed shear stress, and Stokes drift. The wave and flow models were coupled such that FLOW passes water levels and Eulerian depth-averaged velocities to SWAN and SWAN passes wave parameters to FLOW.

SWAN was run with 36 10°-wide directional bins and 37 frequency bands logarithmically spaced between 0.03 and 1.00 Hz. The model also used a depth-limited wave breaking formulation without rollers [28], with the default value $\gamma=H_{sig}/h=0.73$ (where the significant wave height H_{sig} is 4 times the standard deviation of sea-surface elevation fluctuations, and h is the water depth), and a JONSWAP bottom friction coefficient associated with wave-orbital motions set to 0.10 m^2/s^3 [27].

The circulation model was run using the 13 most energetic satellite-generated tidal constituents [29] along open boundaries, which were dominated by the M2 (~80% of the variance, with small variation along the boundary) and N2 (~10% of the variance) constituents. In addition, the model used a free slip condition at closed (land) side boundaries, a spatially uniform Chezy roughness of 65 $m^{0.5}/s$ (roughly equivalent to a drag coefficient of C_d=0.0023) at bottom boundaries, and default Delft3D parameters for coupling the FLOW and WAVE models [30]. Second-order differences were used with a time step of 0.15 s for numerical stability.

Sediment transport [31] was simulated using the modeled waves and currents. Model parameters were set to default values with a grain size of 300 μm, except for the reference height (0.5 m), the current-related reference concentration factor (0.25), and the wave-related suspended and bed-load transport factors (0.1), which were reduced from the default values (1) that smoothed all bedforms and produced unrealistic transport around the island. Transport was averaged over several tidal cycles to remove variability within ebb or flood flows. The divergence (convergence) of the transport vectors was used as a proxy for erosion (deposition), and the morphology was not updated during the model run. These proxies primarily are a function of the simulated hydrodynamics, which have been verified with field observations at this [27] and other [10,32–35] shallow-water locations.

SWAN and Delft3D-FLOW (in depth-averaged mode) were run over