

THE RESPONSE OF SPIT SHAPES TO WAVE-ANGLE CLIMATES

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Abstract: We investigate spit formation and evolution in light of the high-wave-angle instability in shoreline shape arising from a maximizing angle for wave-driven alongshore sediment transport. Single spits emerge in a simple one-contour line numerical model that evolves the coast using morphodynamic feedbacks and a ‘climate’ of waves approaching the shore from variable directions. Analysis of sediment transport and shoreline stability metrics illustrate how spits can be generated, demonstrating how waves from all angles can play a role in spit formation and evolution. Simulations suggest that regardless of whether high- or low-angle waves dominate relative to the general shoreline trend, as spits extend offshore, they tend to orient themselves such that most of their coast barely experiences low-angle waves and alongshore sediment transport to the spit end is maximized. This ‘graded’ spit shape minimizes gradients in sediment flux, while the recurve at the spit end experiences larger gradients and a region of high-angle instability. Examining hindcast wave data, similar trends are seen along the natural example of Long Point, Lake Erie, Canada.

INTRODUCTION

Discussion of the presence and the morphological importance of a maximizing angle for alongshore sediment transport is not new (e.g. Bruun 1954; Grijm 1960, 1964); however, interest in the importance of this maximum has recently been reinvigorated by studies of a high-wave-angle instability in shoreline shape (Ashton et al. 2001; Falqués and Calvete 2005). Numerical simulations have demonstrated how ‘high-angle’ waves, with angles

between deep-water wave crests and the shore greater than this transport-maximizing angle, could cause the self-organization of a coast into quasi-periodic fields of flying spits, cusped spits, and capes. Although many such series of capes and flying spits can be found in nature, frequently spits are found alone and in regions dominated by low-angle waves. Here, we extend recent developments in the understanding of shoreline evolution (Ashton and Murray 2006a) to study how the maximum in alongshore sediment transport affects the evolution of single spits. Using newly developed wave climate metrics (Ashton and Murray 2006b), numerical modeling results and comparisons with nature suggest that the transport maximum plays an important role in determining the orientation of spits.

BACKGROUND

Fed by an updrift source of littoral sediment, spits represent one of the most common depositional clastic coastal landforms. As the downdrift end of a spit is by definition untethered, primary driving forces, particularly alongshore sediment transport, help determine spit shape and orientation. Sometimes spits are considered to grow in the direction of the alongshore current; unfortunately, drift direction alone cannot be used to explain spit orientation as the alongshore current is by definition shore-parallel. Spits also recurve, or trend back towards the shore—even the high-energy, seaward-facing side of a spit faces many directions, experiencing waves from a variety of deep-water directions.

Spit Orientation

Bruun (1954), from quantitative and laboratory investigations, was one of the first to suggest that a maximizing angle for alongshore sediment may determine the angle of spit accumulation. Grijm (1960; 1964) theoretically explored the shoreline shapes that could result from waves approaching from any one angle greater or less than a suggested maximizing transport angle of 45° (not specifying whether this is a breaking or deeper-water angle). Zenkovich (1967) also studied the influence of wave angle on spit shapes, suggesting that for high-angle waves, spits should grow offshore at an angle of 45° to the shoreline trend.

More recently, Kraus (1999) developed a simple analytic mode of spit extension, although this model does not account for shoreline reorientation. Petersen et al. (2001) present a one-contour-line analytical model for spit accretion for an assumed ‘equilibrium’ spit shape, again emphasizing the importance of a maximizing angle in evolution. Results suggest that more detailed hydrodynamic models are required to give rise to recurved spit ends. Further laboratory experiments, similar to those of Bruun (1954), investigate the growth of a spit subjected to waves from a single high angle (Petersen et al. 2002). These investigations follow the research history of investigating the issue of spit orientation in terms of waves approaching from only one direction.

Other research, particularly studies focusing on the evolution of periglacial environments, suggests a distinction between ‘swash-aligned’ and ‘drift-aligned’ spits (Forbes et al. 1995). According to this distinction, ‘drift-aligned’ coasts tend to experience waves with oblique approach, with strong gradients in wave heights and

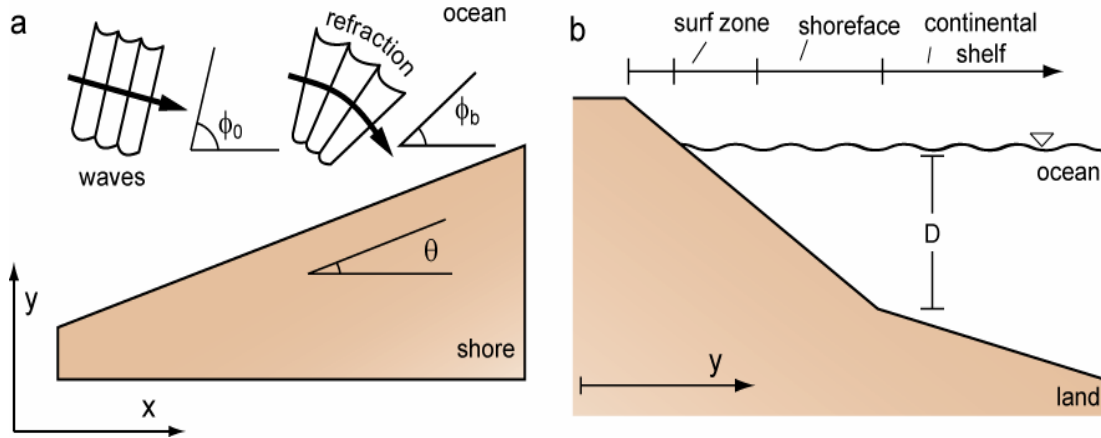


Fig. 1. a) Plan-view domain. b) Cross-shore profile.

angles, whereas wave approach tends to be shore-normal for ‘swash-aligned’ coasts (Orford et al. 1991). The results of numerical modeling experiments presented below raise the question of whether a process distinction must be evoked to explain these different modes of shoreline behavior.

Shoreline Instability

Because wave refraction changes both wave angle and height, common breaking-wave formulations for alongshore sediment transport, such as the CERC formula (Komar 1971), cannot be used to properly understand gradients in alongshore sediment transport along an undulating coast (Ashton and Murray 2006a; 2006b). Instead, a deeper water reference frame is required. The CERC formula can be recast for fully deepwater waves assuming refraction over shore-parallel contours,

$$Q_s = KT^{1/5} H_0^{12/5} \cos^{6/5}(\phi_0 - \theta) \sin(\phi_0 - \theta), \quad (1)$$

where Q_s is the alongshore sediment flux (m^3/s deposited volume), K typically equals $\sim 0.34 \text{ m}^{3/5} \text{ s}^{-6/5}$, T is the wave period (s), H_0 is the root-mean-squared deep-water wave height (m), and $(\phi_0 - \theta)$ is the relative wave angle (Fig. 1). This formula exhibits a maximum for a relative deep-water angle of 42° (Fig. 2a). Recasting the CERC formula for non-breaking waves suggests that the shoreline instability can frequently occur, and does not require that waves break at uncommonly large angles (as previously thought).

The standard one-contour-line approach (Pelnard-Consideré 1956), where local surf-zone gradients in Q_s are assumed to be spread over a shoreface of depth D (Fig. 1b), yields a diffusion-like equation for the plan-view evolution of the shoreline,

$$\frac{\partial y}{\partial t} = -\mu \frac{\partial^2 y}{\partial x^2}. \quad (2)$$

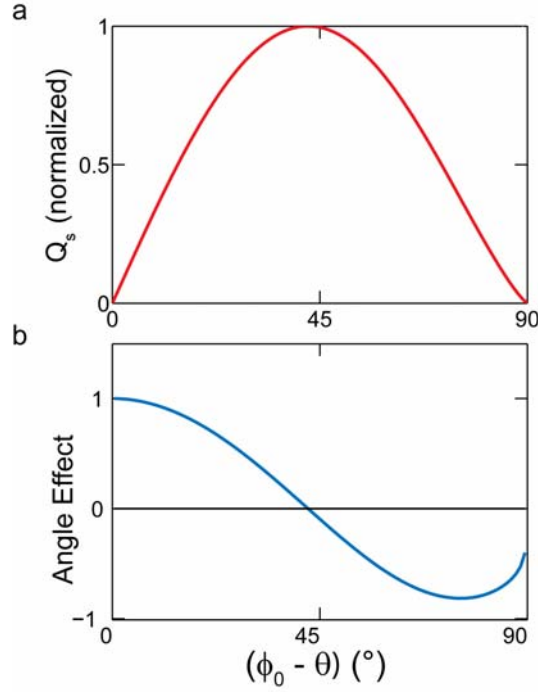


Fig. 2. a) Normalized alongshore sediment transport vs. deep-water angle.
b) The 'angle effect' upon diffusivity vs. deep-water angle.

For (1), the deep-water CERC formula, the diffusivity, μ (m/s^2), varies with the angle of wave approach,

$$\mu = \frac{K}{D} T^{1/5} H_0^{12/5} \left\{ \cos^{1/5}(\phi_0 - \theta) \left[\left(\frac{6}{5} \right) \sin^2(\phi_0 - \theta) - \cos^2(\phi_0 - \theta) \right] \right\}, \quad (3)$$

The term in the brackets $\{ \}$ represents the wave-angle dependence of the diffusivity. Fig. 2b shows a negative diffusivity for high-angle waves, representing the shoreline instability which causes perturbations to an otherwise straight coast to grow.

Recent research using more realistic treatments of wave refraction suggest that the growth of slight shoreline protuberances is damped at smaller alongshore scales (Falqués and Calvete 2005; List and Ashton 2007). However, the importance of the maximizing angle for Q_s extends far beyond initial instability. For example, simple analysis suggests that waves approaching from a single high angle will cause a finite-amplitude shoreline protuberance to eventually develop into an off-shore extending flying spit with an erosional updrift flank (Ashton and Murray 2006a). Numerical modeling shows that over time, morphodynamic feedbacks and finite-amplitude effects occurring well beyond initial instability play increasingly important roles in high-wave-angle shoreline evolution; these effects, for example, can lead to emergent behaviors, such as the self-

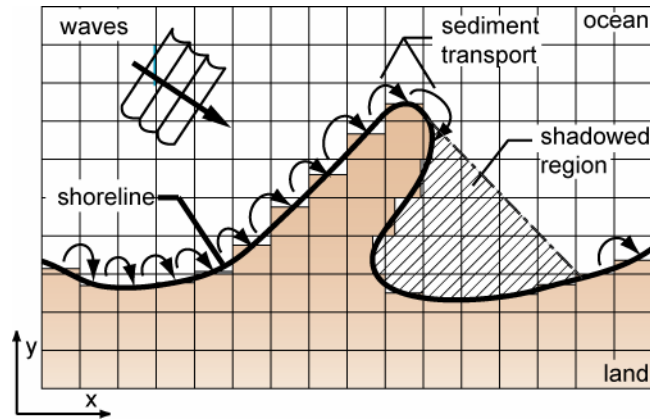


Fig. 3. Plan view model schematic

organization of alongshore sandwaves, flying spits, and capes (Ashton and Murray 2006a).

As terminal portions of littoral cells, spits elongate because of the gross alongshore delivery of sediment to the spit end (per (1)). Updrift of this point, evolution of the shoreline shape remains controlled by gradients in alongshore sediment transport (per (3)). Interestingly, the CERC formula predicts that such gradients in sediment transport are minimized when transport is at a maximum (diffusivity = 0 at the transport-maximizing angle, Fig. 2), suggesting that the waves that control spit elongation may be unimportant in the evolution of the spit shape, relative to other waves in the climate. Correspondingly, waves important in the evolution of the spit shape will not transport much sediment towards the spit end (large diffusivity when transport is small, Fig. 2). Therefore, it is unlikely that spit evolution can be sufficiently understood using waves approaching from just one presumed ‘dominant’ angle.

METHODS

Here we apply a previously developed numerical model that evolves the plan-view shape of the shoreline in response to gradients in alongshore sediment transport. Wave climate metrics, used to determine the long-term net, directional alongshore sediment transport and the long-term coastal stability are computed along the shore.

Numerical Modeling

Similar to other common ‘one-contour-line’ models (Hanson and Kraus 1989), we have developed a model evolving the shape of the shoreline due to gradients of alongshore sediment transport within the surf zone (assuming that the shoreface maintains a constant shape (Fig. 1b)). Discretizing the CERC formula, (1), the model contains a numerically stable solution scheme for the case of high-angle waves, and can accommodate a shoreline that becomes arbitrarily sinuous, even doubling back on itself (Fig. 3) (Ashton et al. 2001; Ashton and Murray 2006a). To simulate spit growth, the model contains a simplified representation of barrier overwash. Overwash is assumed to occur whenever a barrier is below a minimum critical width (Leatherman 1979), and it will widen a barrier whenever backbarrier depths are less than the shoreface depth (Jiménez and Sánchez-Arcilla). Waves (with $H_0 = 2$ m, $T = 8$ s) approach from a new angle every day, with a

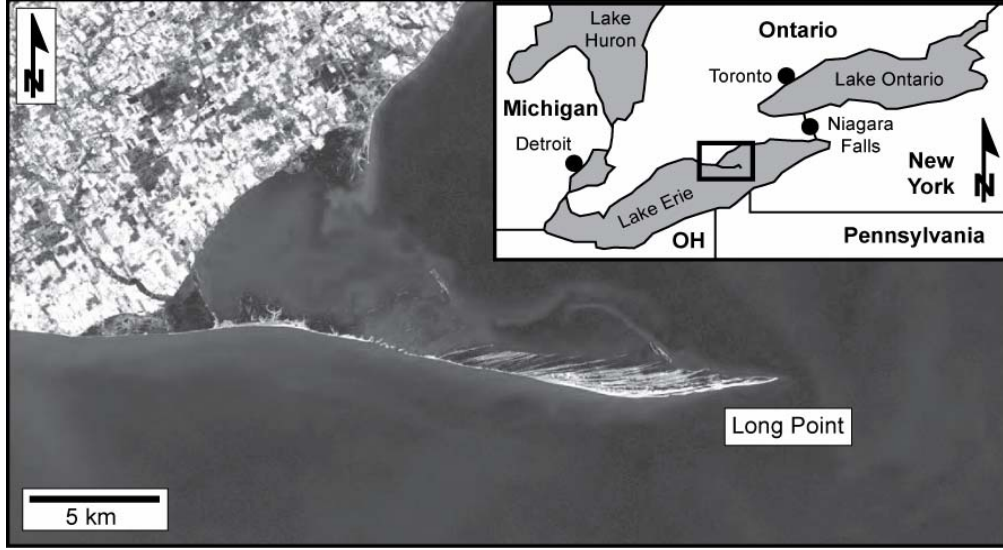


Fig. 4. Long Point, Lake Erie, Canada. Data are available from USGS/EROS (figure from Ashton and Murray 2006b).

direction selected from a probability distribution function determined by U , the fraction of unstable, high-angle waves, and A , the asymmetry, defined as the fraction of waves approaching from the left, looking offshore. Computations assume that all wave refraction occurs over shore-parallel contours.

Wave Climate Metrics

At a shore of a given orientation, the contributions to alongshore sediment transport from a long-term wave climate can be summed, leading to $Q_{S,net}$, the net alongshore sediment transport. Similarly, every approaching wave contributes to the evolution of the coastline, either diffusively or anti-diffusively. A dimensionless ‘instability index’, Γ , assesses the competition between diffusion and anti-diffusion,

$$\Gamma = \frac{\sum_{i=1}^n \mu_i \Delta t_i}{\sum_{i=1}^n |\mu_i| \Delta t_i}, \quad (4)$$

for each data point i , and data interval Δt . This normalized index, which represents the ‘competition’ between high- and low-angle waves, ranges between 1 for a wholly low-angle climate and -1 for a wholly high-angle climate. A Γ of zero would mean that a wave climate is on the verge of instability—low- and high-angle waves balance each other out. (Ashton and Murray 2006b)

RESULTS

First, the model and metrics will be used to build upon research into the effects of high-angle waves by studying in detail a single ‘flying’ spit, or ‘ness’. Further simulations

investigate spit growth in wave climates dominated by low-angle waves, and how spit reattachment to the mainland can result in dramatic shoreline reorientation.

Natural 'Flying' Spit: Long Point

Long Point is a large flying spit along the Canadian shore of Lake Erie (Figure 4). WIS hindcast covering 1956-1987 from Lake Erie WIS station 33 shows that the predominant westerly winds blowing along the long axis of the elongate lake result in a high-angle-dominated wave climate along the north and south shores of Lake Erie (Great Lakes WIS hindcast can be found at <ftp://ftp.erdc.usace.army.mil/pub/PERM/wisftp/>). Although there are other high-wave-angle features along these shores, such as Point Pelee, Rondeau Point, and Presque Isle, they are far from Long Point. This spit, which appears to have formed over the Holocene, is not part of an alongshore chain, likely because it began as a large glacial moraine perturbing to the shoreline trend (Coakley 1992).

Wave climate computations show although local wave climates are unstable at either end of Long Point, the spit is oriented such that the main stretch of the shore is marginally stable (Figure 5). Alongshore sediment transport is dominantly to the left (looking offshore), but it is slightly reduced along the middle of the spit, and maximized at the updrift and downdrift regions where the wave climate becomes unstable. Interestingly, another type of feature associated with high-angle waves, alongshore sand waves, appear along same portions of the spit that experience unstable wave climates (further discussed by Ashton and Murray (2006b)).

Modeled Single 'Flying' Spit

To determine if alongshore sediment transport and the high-angle instability can give rise to a feature similar to Long Point, the numerical model was run using a single initial shoreline protuberance added to an otherwise straight coast. Like the natural case, waves were high-angle ($U = 0.6$) and asymmetric (with more waves approaching from the right, looking offshore, $A = 0.2$). Not only does the simulated flying spit eventually attain a shape that generally resembles Long Point, perhaps more significantly, there are similar trends in wave metrics (Fig. 6). The simulated flying spit has reoriented itself such that the main stretch of the spit experiences predominantly low-angle waves, whereas predominantly high-angle waves affect the proximal and distal spit ends.

Modeled Headland-Extending Spits

As a corollary to the high-angle spit evolution, another simulation investigates how spits extend offshore even if the local wave climate is dominated by low-angle waves. Beginning with a large rectangular protuberance, waves that are regionally low-angle ($U = 0.2$) with an asymmetry (net drift to the right, looking offshore, $A = 0.7$) lead to the extension of spits in both the updrift and the downdrift direction (Fig. 7). As a result of the asymmetry in the wave climate, the spits attain different orientations on either side of the hump. In both cases the direction of spit growth is not parallel to the initial shoreline orientation.

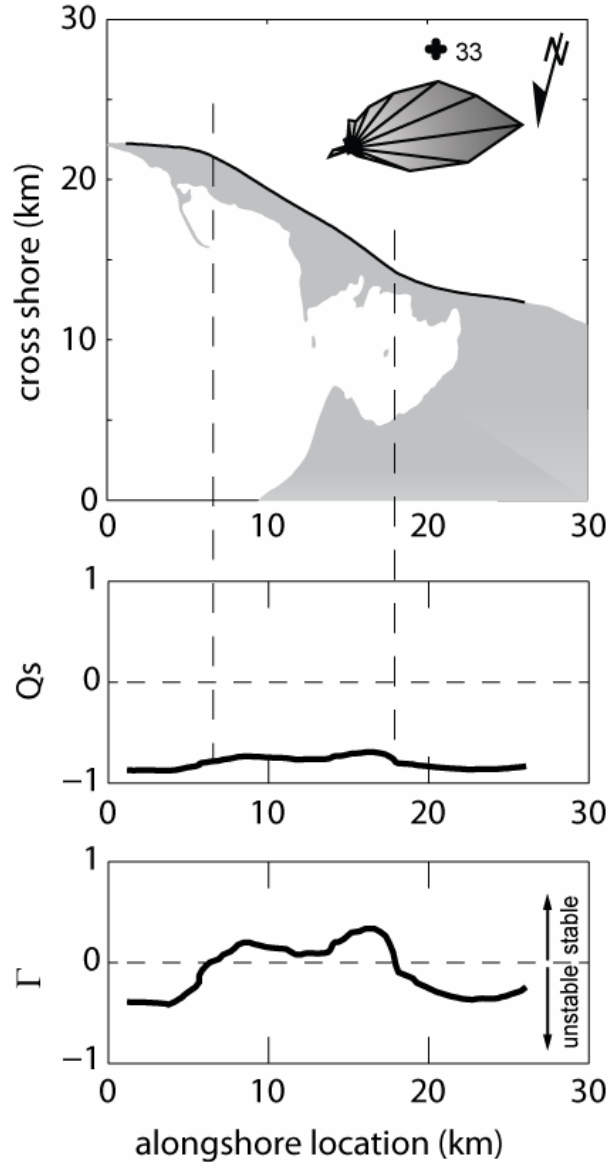


Figure 5. Long Pont rotated 195° clockwise, showing a) shoreline with b) relative Q_s and c) Γ along the shore. Inset rose of ‘wave energy’ and location of WIS station 33.

After the spits have extended offshore, wave climate metrics indicate that although the coast along most of the spit experiences a predominantly stable wave climate, there is a transition to instability at the end of the spit. For both spits, the transition to instability corresponds to the location of the maximum in net Q_s . This suggests that the instability and the maximizing angle for sediment transport play key roles in the orientation of the spit ends. Interestingly, spits extend in what would be described as a dynamically ‘equilibrium’ form even though the updrift shore is not dominated by high-angle waves as suggested by Petersen et al. (2001). Note that although for the updrift (left) spit, the maximum in Q_s and the transition to instability occurs at the spit end, for the downdrift

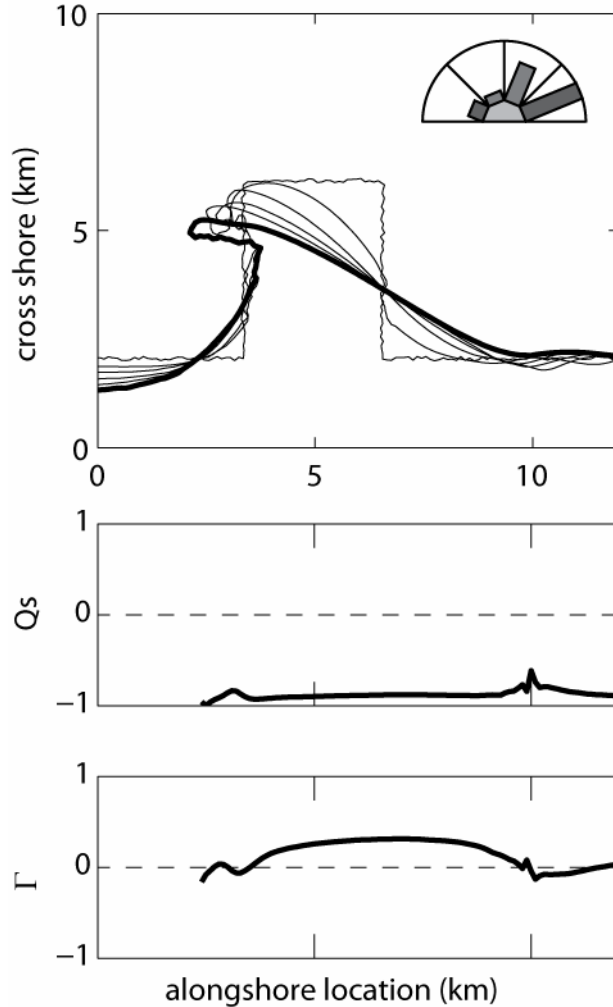


Figure 6. Simulated high-angle spit showing a) shoreline (analyzed shoreline in dark line with b) relative Q_s and c) Γ along the shore. Inset of PDF of wave-approach angle.

(right) spit, the Q_s maximum and instability transition occur updrift of the spit end. This effect is likely due to the wave ‘climate’ used to simulate shoreline evolution, such behavior would not be predicted by a one-contour-line model using only a single wave approach angle (Petersen et al. 2001).

As the spits continue to extend offshore, they eventually intersect the mainland coast (Fig. 8). After this intersection, shoreline orientation dramatically changes; new behavior occurs after the spit connects to the down drift beach. As the spit end extends offshore, the coastal changes at the spit end are controlled by the rate of sediment delivery, the alongshore flux to the tip. However, once the spit reconnects with the coast, sediment can be transported in both directions—like the rest of the coast, shoreline evolution is now controlled by gradients in alongshore sediment flux, not by the magnitude of flux.

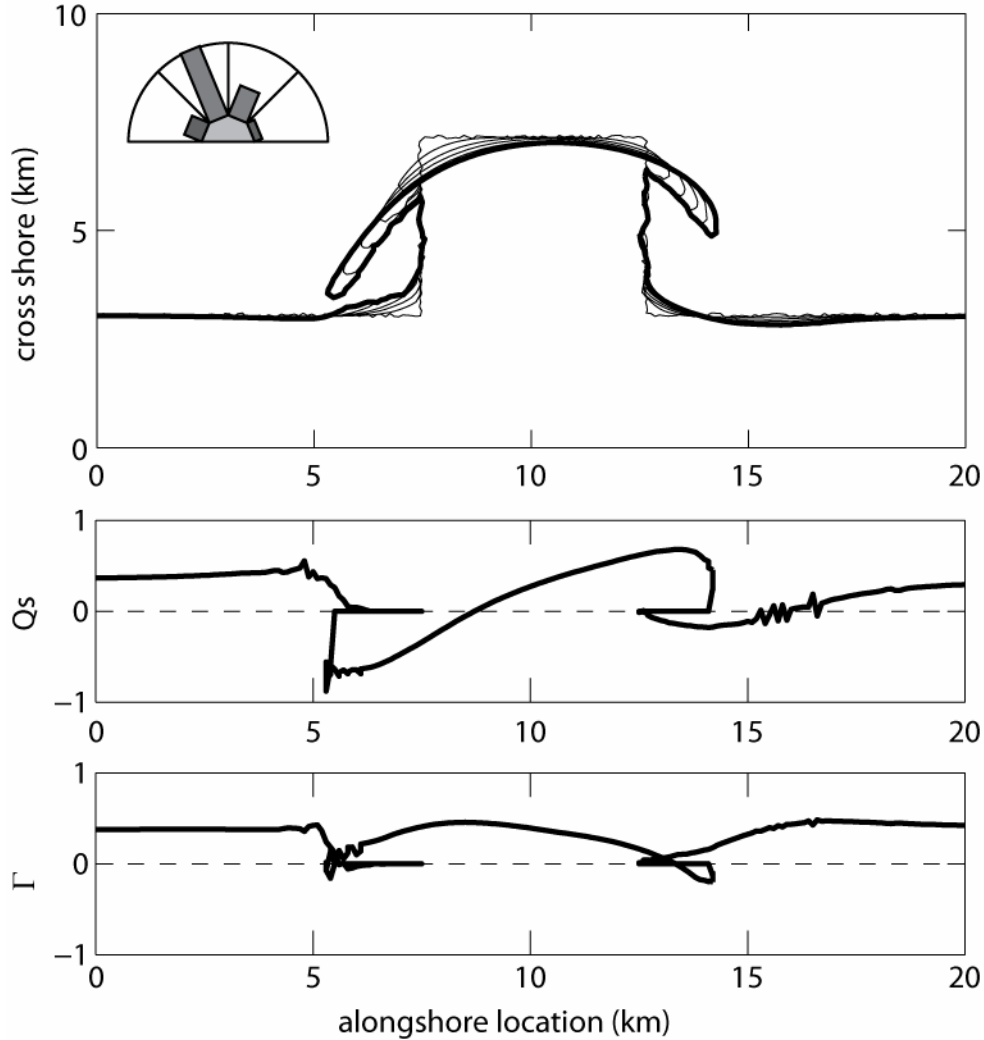


Fig.7. Low-angle spit simulation results showing a) shoreline (analyzed shoreline in dark line) with b) relative Q_s and c) Γ along the shore. Inset of PDF of wave-approach angle.

Because of the generally stable, diffusive wave climate, the simulated shore continues to smooth over time, eventually eliminating the initial hump.

DISCUSSION AND CONCLUSIONS

Although the exploratory model here appears to capture many essential elements of spit evolution, more attention should be paid to the controls upon the accretion rate of the spit end. For instance, if a spit is accreting into water significantly deeper than the shoreface depth, spit growth will be slowed dramatically, which would have a strong effect on spit shapes and orientation (the current numerical model assumes accretion onto a constant depth seabed). Also, the simple one-line approach assumes that a section of coast corresponds to a shoreface segment of the same alongshore width. Where the coastline curvature is extreme, such as at spit ends, this assumption breaks down, as a segment of the shore will correspond with a 'wedge' of shoreface of increasing width

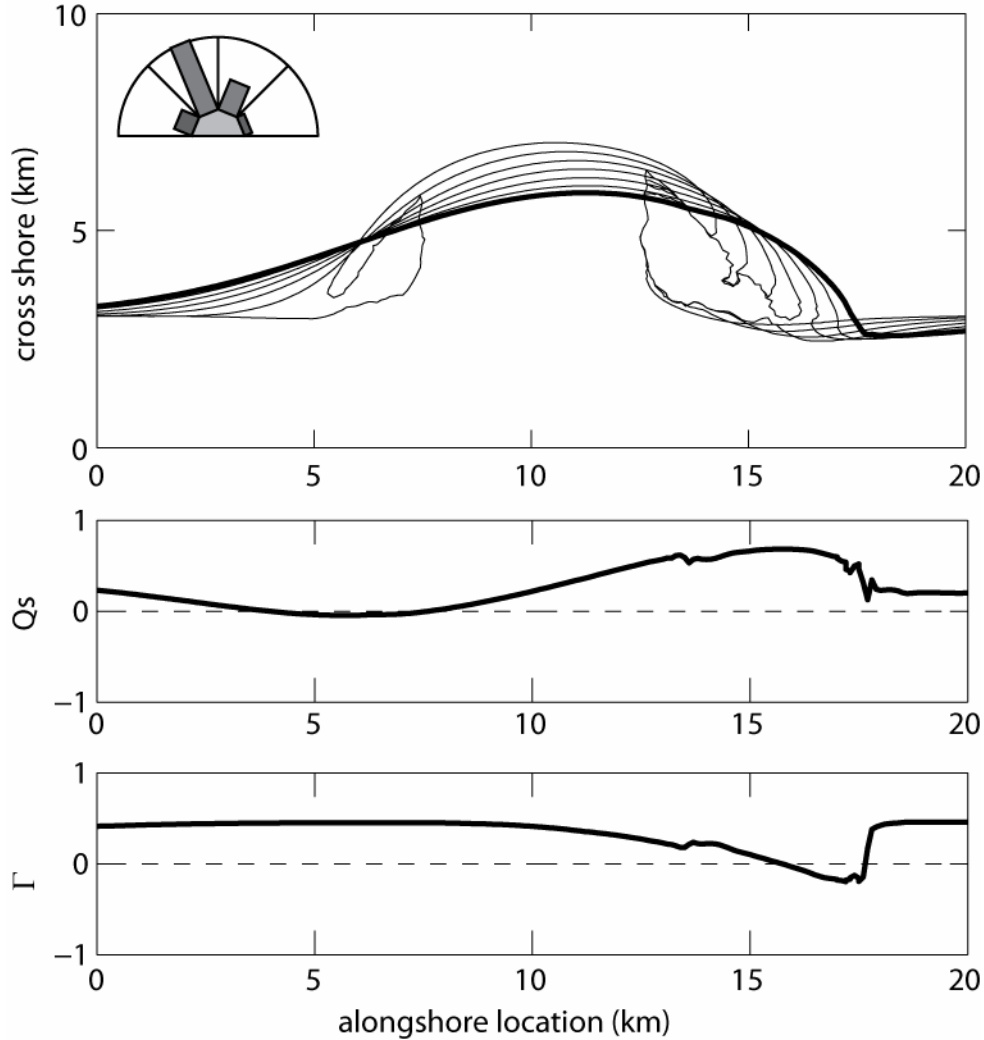


Fig.8. Low-angle spit simulation results showing a) shoreline (analyzed shoreline in dark line) with b) relative Q_s and c) Γ along the shore. Inset of PDF of wave-approach angle.

offshore. Rigorously studying spit-end phenomena would require a more spatially explicit model—a break from the one-contour-line approach. Although more explicit models may improve the numerical accuracy of simulations, they would likely be driven mainly by the same processes and feedbacks operating in the existing model.

We have studied shoreline evolution using a one-contour-line model, using sediment transport and stability metrics to better understand how spits can orient themselves in response to wave climates. In both high- and low-angle climates, simulations evolve a smooth spit shape, and along its flank: 1) gradients in net sediment flux are very low; 2) net alongshore sediment flux tends to be maximized; and 3) the effective local diffusivities are small but positive (stable). These three characteristics are intertwined. Net sediment flux for a given wave climate should be maximized when the shoreline orientation produces an effective diffusivity of 0 (Fig. 2). When the effective diffusivity becomes small, shoreline curvatures do not produce strong gradients in alongshore

flux—the shoreline will evolve slowly and its shape will persist. Although continued spit extension (caused by sediment delivery to the spit end) prevents a true static steady state from developing, evolution of the spit shape itself will be slow. In short, the orientation that produces the maximum sediment flux (for a give wave climate) along the flank dictates general spit orientation in this model. Trends along the Long Point coast are consistent with these model suggestions. (Future work should include more comparisons of the modeled wave climate trends with those found along natural coasts.)

These results present a unified model for spit extension, suggesting that distinctions such as ‘drift-’ and ‘swash-aligned’ may not be of fundamental importance. The results shown in Fig. 7 show that along a single coastline stretch, areas that would be called swash aligned (experiencing little to no net transport) grade into areas that would be called drift aligned (experiencing the maximum transport possible for the local wave climate). Fig. 8 further demonstrates that even in the same wave climate, alongshore sediment transport alone can result in a coast with spits to trend towards an orientation dramatically different than that of an open coast. These preliminary investigations suggest that the maximizing angle for alongshore sediment transport, combined with boundary conditions, may explain many observed spit behaviors.

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