Tidal Flat Morphodynamics: A Synthesis
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1. Introduction
Tidal flats commonly occur along coasts where the tidal range is large relative to typical wave height. They can be found where hydrodynamic energy is high or low, where sediments are sandy or muddy, and where shorelines are prograding, retreating, or stable. The study of the morphology and evolution of tidal flats is particularly well suited in the context of morphodynamics since characteristics such as profile shape, bed slope, and grain size clearly and systematically vary as a function of sediment supply and wave and tidal forcing, and the nature of wave- and tide-induced velocities across tidal flats is, in turn, a direct function of the flat morphology itself.

In this presentation, which summarizes and extends the findings of Friedrichs (2011), a tidal flat profile in dynamic equilibrium is defined as one where its shape remains more or less constant over some characteristic period of natural forcing. The concept of a dynamic equilibrium is a central point of this work. When considered as an average over a typical annual cycle (and when accounting for antecedent geology and anthropogenic effects), this paper argues that most tidal flats are characterized by predictable morphologies that are in an approximate dynamic equilibrium with their local climate of waves, tides, and sediment sources and sinks. This does not mean that they are static in space as they are more often than not in the process of advancing or retreating. Rather, it means that when averaged over annual timescales or longer, their characteristic shape and the spatial distribution of surficial grain sizes remain relatively fixed in the reference frame of the flat itself as it recedes or progrades.

2. Results
Some of the most important concepts, processes, and properties associated with a better understanding of the morphodynamics and dynamic equilibria of tidal flats include the following:

1. It is useful to divide the asymmetries, which drive net sediment transport across tidal flats, into local (Eulerian) asymmetries and spatial (Lagrangian) asymmetries. Eulerian asymmetries involve eb–flood or high–low water distortion of local tidal velocity. Lagrangian asymmetries follow a periodic excursion of water in space and require (a) horizontal gradients in suspended sediment concentration and (b) a lag in the response of the concentration to bed stress.

2. Simple theory and observations both support the conclusion that tide- and wave-induced bed stresses typically decrease and increase, respectively, with landward distance across tidal flats (Figure 1). These two opposite patterns of Lagrangian asymmetry, in turn, drive an analogous landward decrease or increase in peak suspended sediment concentration. Periodic advection then leads to net landward or seaward sediment transport, respectively.

3. Sediment sources and/or sinks can also drive spatial gradients in concentration, which ultimately lead to net sediment transport. Examples include a high sediment concentration boundary condition provided by a tidal river, spatial gradients in the critical stress necessary for sediment resuspension, and/or gradients in settling flux. Common causes of spatial gradients in erodibility and settling include biological activity and recent deposition of weakly consolidated mud.

4. For flats exhibiting minimal spatial gradients in velocity, stress, or concentration, net sediment transport can still occur over a tidal cycle in response to Eulerian (i.e., local, time-dependent) asymmetries. Coarser sediment is more sensitive to local asymmetries in maximum velocity, whereas fine sediment is more sensitive to local asymmetries in the duration of slack water. Eulerian asymmetries induced by local continuity effects cause tidal velocities, stresses, and concentrations to be greatest near the tidal front, and eb–flood asymmetry reflects whether the boundary tide is faster rising or faster falling.

5. Over an entire embayment, continuity and momentum, in the context of a finite channel depth, favor flood dominance, a longer high-water slack, and sediment import, whereas, in the context of intertidal storage, they favor eb dominance, a longer low-water slack, and sediment export. Locally, flood dominance over flats may be increased by bore-like distortion of the incoming tidal wave. Negative feedbacks at the scale of entire embayments may favor a balance between the
effects of finite channel depth and intertidal storage such that local tidal asymmetries are minimized.

6. The asymptote for an equilibrium tidal flat profile subject to symmetric forcing of tidal elevation and velocity in the absence of waves is one whose bathymetry minimizes spatial variations in tidal velocity, bed stress, and, therefore, concentration. Analytical solutions and numerical sediment-transport experiments with sinusoidal tidal forcing at the flat’s seaward edge produce convex-up equilibrium profiles of across-shore width \( L_x \approx (\cos \theta \omega_x^2 + 1) U_c/\omega_x \), where \( U_c \) is a spatially uniform critical stability velocity, \( \omega_x \) the tidal frequency, and \( \theta \) the angle between the maximum tidal velocity and the shoreline.

7. 1-D sediment-transport models predict the equilibrium width of tidally dominated flats to increase with increased offshore concentration, \( C \), because a higher value of \( U_c \) is then needed to maintain uniform \( C \) across the width of the flat. Assuming a higher tidal range, \( R_x \), leads to higher offshore \( C \), and then a higher \( R_x \) should also require higher \( U_c \) and lead to greater equilibrium flat widths under tidal dominance. For embayments as a whole, negative feedback mechanisms suggest that stability will be favored by a spatial extent of tidal flats which minimizes Eulerian asymmetries by balancing finite channel depth and intertidal storage effects.

8. The asymptote for an equilibrium flat subject only to dissipative shallow-water waves at high water, such that wave orbital velocities are uniform in space, is a concave-up profile. The depth of the profile is given theoretically by \( h = f_c U_c^2 (\pi g)^{2/3} R_x^{-1/3} x^{-1/3} \), where \( h \) is the depth below high water, \( f_c \) is the wave friction factor, \( x \) is the distance offshore, \( g \) is the acceleration due to gravity, and \( U_c \) is as defined above.

9. The theoretical width of a wave-dominated tidal flat depends on whether \( R_x \) is larger or smaller than \( h_0 = (h_0^2 g)/(4 U_c^2) \), where \( h_0 \) is the depth at which the offshore wave height \( H_0 \) is first able to mobilize sediment by producing an orbital velocity equal to \( U_c \). For small \( R_x \leq h_0 \), the width of the tidal flat, \( L_x \), is simply the distance offshore where \( h = R_x \), the width growing with tidal range as \( R_x \) moves further down the \( h \sim x^{-2/3} \) profile. For large \( R_x > h_0 \), \( L_x \) is controlled by the distance offshore where \( h = h_0 \), the width growing with \( H_0 \) in order to provide a longer distance over which to dissipate wave energy. For both cases, the wave height to depth ratio on the inner flats is given by \( H/h = (dh/dx)(9\pi)/4f_c \).

10. 1-D sediment-transport models and empirical engineering models that include both waves and tides predict that the equilibrium profile is initially convex-up in the absence of waves and becomes progressively more concave as wave energy increases. 1-D modeling also indicates that offshore transport by waves provides a mechanism that can potentially balance onshore transport by tides, leading to a profile that remains stationary in space.

11. Several authors have demonstrated observationally that the shape of tidal flats and macrotidal beaches tends to become more convex (or concave) as tidal range increases (or decreases) to wave height or in response to significant accretion (or erosion). Eigenfunction analysis can be used with observations of tidal flat morphology to assess the simultaneous affects of tides, waves, and sediment supply.

12. Observations suggest that tidally dominated flats become wider as tidal range increases, a result which is consistent with model predictions assuming that greater tidal range is associated with higher sediment concentrations. Observations of wave-impacted flats along estuaries suggest that wave-dominated flats widen with increased wave energy, implying that larger waves require a larger distance over which to dissipate energy. This trend and explanation are consistent with the wave-dominated analytical solution developed for \( R_x > h_0 \) (see point 9 above).

13. The magnitude of bed slope \((dh/dx)\) observed on erosional, concave-up mudflats is on the order of 0.01 to 0.001 and is generally consistent with predictions of the strongly dissipative, wave-dominated analytical solution. The maximum values of wave height relative to water depth \((H/h)\) on mudflats are observed to be about 0.15 to 0.3 and are also consistent with analytical predictions as a function of \( dh/dx \) and \( f_c \) (see point 9).

14. Because the time needed for the shape of a tidal flat profile to reach a near-static equilibrium in response to constant external forcing is typically of the order of several years, natural tidal flats rarely reach instantaneous equilibrium in response to seasonally varying tide and wave forcing. Yet, the net seasonal effects of tide- and wave-induced deviations from the long-term profile shape often nearly cancel out. Thus, we can still consider the annual average morphology to represent a type of dynamic equilibrium in response to the combined effects of both waves and tides. By contrast, the morphological response of most tidal flats is rapid relative to the decade-plus timescales of engineering works, climatic fluctuations, and sea-level rise.

15. Surficial grain size on tidal flats responds to gradients in energy much more quickly than the overall profile shape can respond. It therefore follows that the classic fining of grain size toward the high-water line on tidal flats may be usefully interpreted as a lowest-order response to persistent short-term morphologic disequilibrium.

16. Most of the time, tides in the absence of strong waves result in a decrease in energy toward shore, and the grain-size gradient generally reflects the competence of peak tidal flows at each location to remobilize the local sediment. In addition, the broader grain-size spectrum depends on the size and supply of the available source material. As surficial sediment can easily change from mud to sand in response to a single storm, strong temporal and spatial variations in grain size on tidal flats are common.

17. From the above insights, a conceptual model arises for the shape of tidal flat profiles (Figure 2), which is largely consistent with, but further extends previous conceptual profile diagrams presented by others (Dyer, 1998; Van Rijn, 1998; Kirby, 2000; Bearman et al., 2010). The end members for the two basic types of tidal flat profiles are convex- and concave-up. Although a tide- and wave-dominated static equilibrium theoretically exists at each of these
extremes, natural tidal flats over annual time-scales are typically at an intermediate dynamic equilibrium somewhere between these two extremes.

18. A more convex-up profile is favored in the presence of increased tidal range, decreased wave height, increased external sediment supply, increased bioaggregation/adhesion, forcing by a faster-rising tide, and/or external forcing by a tide with an extended period around high water. Processes and properties associated with evolution toward a convex-up tidal flat include net shoreward sediment transport, increased deposition, a local decrease in the duration of high-water slack, decreased grain size, and a profile form that progrades seaward.

19. A more concave-up profile is favored in the presence of decreased tidal range, increased wave height, decreased external sediment supply, bioturbation/human disturbance, forcing by a faster-falling tide, and/or external forcing by a tide with a shortened period around high water. Processes and properties associated with the evolution toward a concave-up tidal flat include net seaward sediment transport, increased erosion, increased grain size, a local increase in the duration of high-water slack, and a profile form that retreats landward.

References