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RESEARCH ARTICLE

10.1029/2019JC015492

Special Section:

Contributions from the
Physics of Estuaries and
Coastal Seas meeting, 2018

Key Points:

- Observed and modeled mudflat profiles are remarkably resilient to seasonal variations in wave and tidal forcing
- Confirming observations, Mflat reproduces seasonalmorphodynamic activity mainly around the mudflat-channel edge
- Three-monthly measurement intervals are probably too long to discriminate various morphodynamic processes on mudflats

Supporting Information:

- Supporting Information S1
- Supporting Information S2
- Table S1

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Morphodynamic Resilience of Intertidal Mudflats on a Seasonal Time Scale

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Abstract Intertidal mudflats are morphodynamic features present in many estuaries worldwide. Often located between vegetated shores and deep channels they comprise valuable ecosystems and serve to protect the hinterland by attenuating waves. Although mudflats are persistently present on yearly to decadal time scales, little is known on their morphodynamic adaptation to short-term variations in forcing such as storms, spring-neap tidal cycles, and sediment supply. This study aims to explore the morphodynamic resilience of mudflats to seasonal variations in forcing. First, we compare transects observed in South Bay, California, at 3- to 6-monthly intervals. Second, we present the results of a process-based, morphodynamic profile model (Mflat). Mflat is an open source, Matlab code that describes both cross-shore and alongshore tidal hydrodynamics as well as a stationary wave model. An advection-diffusion equation solves sediment transport while bed level changes occur by the divergence of the sediment transport field. Mflat reproduces the observed South San Francisco Bay profile in equilibrium with significant skill. Short-term variations in hydrodynamic forcing and sediment characteristics disturb the profile mainly at the channel-shoal edge. The modeled profile disturbance is consistent with observations. The modeled profile is remarkably resilient since it recovers to the equilibrium profile within weeks to months. The model results suggest that 3-monthly observation intervals are probably too long to discriminate processes responsible for the profile disturbance. These processes may include variations in sediment supply, mudflat erodibility, and wave action as well as the spring-neap tidal cycle.

Plain Language Summary Intertidal mudflats are morphodynamic features present in many estuaries worldwide. Often located between vegetated shores and deep channels, they comprise valuable ecosystems and serve to protect the hinterland by attenuating waves. Mudflats seem to be quite stable features, but their bed level may change due to variations in hydrodynamic forcing, like waves and tides. In this research we explore how a mudflat reacts to changes in forcing like high waves, changing sediment supply, or variations in tides. We first explored observed mudflat profile changes in South San Francisco Bay at 3- to 6-monthly intervals. Next, we developed a model (Mflat) to reproduce observed mudflat profiles. We then imposed varying forcing conditions on the equilibrium profile. Mflat skillfully reproduces observed mudflat profiles in equilibrium. Imposing variable forcing conditions such as storms or periods without waves leads to bed level changes that resemble observed changes. The main bed level changes occur at the channel-shoal edge, while the profiles restore their equilibrium once normal forcing conditions prevail again. Our validated model can be used in future studies to explore the impact of sea level rise and the management of shoals by extra sediment supply.

1. Introduction

Intertidal mudflats are muddy shoals that dry and flood during a tidal cycle. They form an essential part of many estuarine systems worldwide, provide unique estuarine ecosystem values (e.g., Allen, 2000; Day, 1989; Kennish, 1990), and protect onshore areas against direct high wave attack because waves attenuate as they travel across shallow mudflats and their adjacent marshes or mangrove belts (e.g., Borsje et al., 2011; Möller et al., 2014).

Mudflats are often found in estuarine areas sheltered from direct wave attack from the ocean. Suspended mud can settle in relatively low energy areas when there is limited tidal flow and wave action. Intertidal mudflats may be “free,” surrounded by channels, but most mudflats are attached to shorelines or fringed, being largely encapsulated by levees or other shoreline features (Allen, 2000; Friedrichs, 2011).

Tidal forcing and wave action have been long recognized as the main drivers for the mudflat's shape and morphodynamic evolution (e.g., Friedrichs & Aubrey, 1996; Bearman et al., 2010; Hunt et al., 2015; Mariotti & Fagherazzi, 2013a). Wind-driven flows (e.g., de Vet et al., 2018), human interventions (de Vet et al., 2017), and the amount of sediment transported into the system with either marine or fluvial origin play an important role as well.

Forcing conditions and associated morphodynamics of mudflats are not constant over time. Variations occur on time scales ranging from hourly storms, to intertidal dynamics, century varying sediment supply, and beyond (Friedrichs, 2011). Examples are wave action during storm conditions (e.g., Kohsiek et al., 1988; Zhu et al., 2017), changes in tidal difference due to damming (e.g., Louters et al., 1998; de Vet et al., 2017), neap-spring tidal oscillations (e.g., Kohsiek et al., 1988; Zhu et al., 2017), seasonal variations in presence of biofilms (e.g., Paarlberg et al., 2005), seasonally varying wave climate (Fan et al., 2006) or wind climate (e.g., De Vet et al., 2018), or yearly and decadal changes in sediment supply (e.g., Allison et al., 1995; Jaffe & Foxgrover, 2006). Belliard et al. (2019) further suggest that the relative importance of wave forcing compared to tidal forcing varies depending on the location on the flat. Finally, sediment properties can have a significant impact on the profile's shape by consolidation (e.g., Zhou et al., 2016) and grain sorting (e.g., Zhou et al., 2015).

Remarkably, many mudflats appear to be quite stable in the sense that they do not develop or vanish overnight. Equilibrium seems to be present on a yearly time scale, while the mudflats' profile varies seasonally (and on shorter time scales) from the yearly averaged equilibrium profile. Nevertheless, mudflats generally do slowly evolve over decades (De Vet et al., 2017; Jaffe & Foxgrover, 2006). One may argue that equilibrium in the strict sense cannot occur due to ever changing forcing conditions operating at multiple time scales (Zhou et al., 2017).

Numerical, process-based modeling has shown reproduction of observed mudflat profiles in equilibrium for various 1-D and 2-D case studies (e.g., Maan et al., 2015, 2018; Pritchard & Hogg, 2003; Roberts et al., 2000; Van der Wegen & Jaffe, 2014; Van der Wegen et al., 2017). In a 2-D setting Gong et al. (2012) and Wang et al. (2019) explored the impact of additional longshore currents on a prograding mud coast and recognized the considerable impact of the suspended sediment concentration boundary conditions on the profile development. Others show that also observed decadal time scale developments in various case studies can be modeled with significant skill (Ganju et al., 2009; Van der Wegen et al., 2011; Elmilady et al., 2019). More aggregated modeling efforts present migrating profiles on long, decadal time scales based on a moving equilibrium profile concept (Maan et al., 2015) or vulnerability against sea level rise, increased storminess, or enhanced sediment supply (Mariotti & Fagherazzi, 2013b).

Emphasis of modeling work has been on reproducing observed profiles or yearly to decadal time scale developments toward equilibrium conditions. Less attention has been paid to morphodynamic profile variations of days to months. One of the reasons may be that observations of short-term, full transect dynamics are scarce. For example, Zhu et al. (2017) observed significant dynamics on an intratidal time scale with erosion and subsequent recovery of 1–2 cm over 4 hr at a Yangtze mudflat but only at a limited number of locations along a transect. Belliard et al. (2019) report daily measurements during 18 months, albeit they only collected data at two locations along a transect.

This study aims to explore, in a fundamental way, the governing processes of intertidal mudflat morphodynamics on a short time scale, from days to seasons, in the presence of alongshore flow. We first present a new 1-D, process-based numerical model (Mflat) that allows for systematic sensitivity analysis of processes. We then compare Mflat results in equilibrium to an observed mudflat profile in South San Francisco Bay, California. An extensive sensitivity analysis shows the impact of variations in forcing. We finally compare model results to a unique data set of observed 3-monthly mudflat profiles and explore possible responsible processes.

This work differs from Van der Wegen et al. (2017) in the sense that we apply a newly developed open access Matlab code allowing us to explore possible model simplifications (e.g., replacing the cross-shore momentum equation by a cross-shore continuity equation) and more straightforward and flexible testing of alternative process descriptions (e.g., related to wave dissipation by friction, and the inclusion of alongshore tidal flow). We will show that the inclusion of the alongshore flow is a crucial factor for obtaining skillful model results under representative conditions.

The next section describes the setting, morphology, and seasonal changes of the mudflat in South San Francisco Bay, California, that is used as a test case for Mflat. The following section describes Mflat. The model results section describes the comparison of Mflat results to the observed mudflat profiles in South San Francisco Bay and an extensive sensitivity analysis of the model parameter space.

2. Test Case: A Mudflat in South San Francisco Bay

2.1. Setting

We test the Mflat model at a mudflat in San Francisco Estuary, one of the largest estuaries on the west coast of the United States. The Dumbarton mudflat is located on the western side of South San Francisco Bay just south of Dumbarton Bridge (Figures 1c and 1d). South San Francisco Bay is a relatively shallow subestuary in the San Francisco Estuary with an average depth of approximately 4 m at mean sea level and a surface area of about 400 km² (Figures 1a and 1b) (Foxgrover et al., 2004). The morphology of South San Francisco Bay is simple with a single main channel near its center flanked by broad shallows and intertidal flats (Figure 1b). The channel narrows (and shoals) from about 1 km (25 m depth) in the north to several hundred meters (5 m depth) in the south. The width of mudflats increases from 200 m in the north to 900 m in the south. Surface sediments in South San Francisco Bay are predominately silts with a mean grain size of approximately 50 μ m. Most of the sediment has a mud content greater than 75% mud, although some coarser sediments with higher sand and shell contents are found on the eastern shoals (Jones & Jaffe, 2013; Barnard et al., 2013).

The movement of water in South San Francisco Bay is driven by tides, winds, and freshwater flow from seasonal streams (Walters et al., 1985; Cheng et al., 1993). Fresh water enters the estuary primarily through the Sacramento-San Joaquin River Delta, a drainage basin that covers ~40% of the state of California, and mixes with saline waters entering from the Pacific Ocean beneath the Golden Gate Bridge (Conomos et al., 1985). San Francisco Bay experiences a Mediterranean climate with cool wet winters and relatively dry summers accompanied by persistent northerly to northwesterly winds. Wind-driven waves resulting from these persistent winds play a strong role in intertidal sediment transport (Lacy et al., 2014). During the winter, frequent storms (cyclonic low-pressure atmospheric systems) transit the region and cause strong, gusty southerly to southeasterly winds. These storms often bring substantial rainfall to local land areas with subsequent runoff into the bay (Conomos et al. 1985). Local streams and small creeks that enter South San Francisco Bay discharge varying amounts of sediment and freshwater during and after flooding (McKee et al., 2013). Winter runoff into North San Francisco Bay and Delta from the Sacramento and San Joaquin River systems influences water levels and flows in South San Francisco Bay. However, the exchange of water between North and South San Francisco Bays and the effects of this exchange on circulation and sediment transport are not well understood (Walters et al., 1985).

2.2. Morphology and Observed Seasonal Change

The morphology of Dumbarton mudflat was surveyed seven times from December 2008 to January 2011 using a 234-kHz interferometric sidescan (SWATHplus) sonar pole-mounted to the United States Geological Survey's research vessel *R/V Parke Snively* (see Foxgrover, Finlayson, et al., 2018 for a description of the data collection system). The SWATHplus is optimized for collecting high-resolution bathymetry in shallow water, with a beam width greater than 12 times the water depth. The system was able to document the morphology and seasonal changes of the Dumbarton mudflat to within 100–200 m from shore, where depths were too shallow to survey, even at high tide. The output is a continuous, 1-m horizontal resolution survey with an average density of 20 soundings per square meter. Although each individual sounding contains some error, because a large number of soundings were collected values that are randomly either above and below the actual mudflat surface will tend to cancel out, resulting in a true average depth in each 1-m² cell. Another source of error is systematic bias, which will not cancel out. Foxgrover, Marvin-DiPasquale, et al. (2018) assessed bias using the same data collection system in a nearby area by comparing repeat surveys collected within days of one another. The mean difference in areas of overlap from five separate repeat surveys represents the bias between individual surveys (range of 1–5 cm, mean = 2 cm).

The Dumbarton mudflat is approximately 800 m wide (Figure 1d) and has an average slope of 1:700 (Figure 2). Throughout the period of measurements there were significant (greater than the uncertainty in

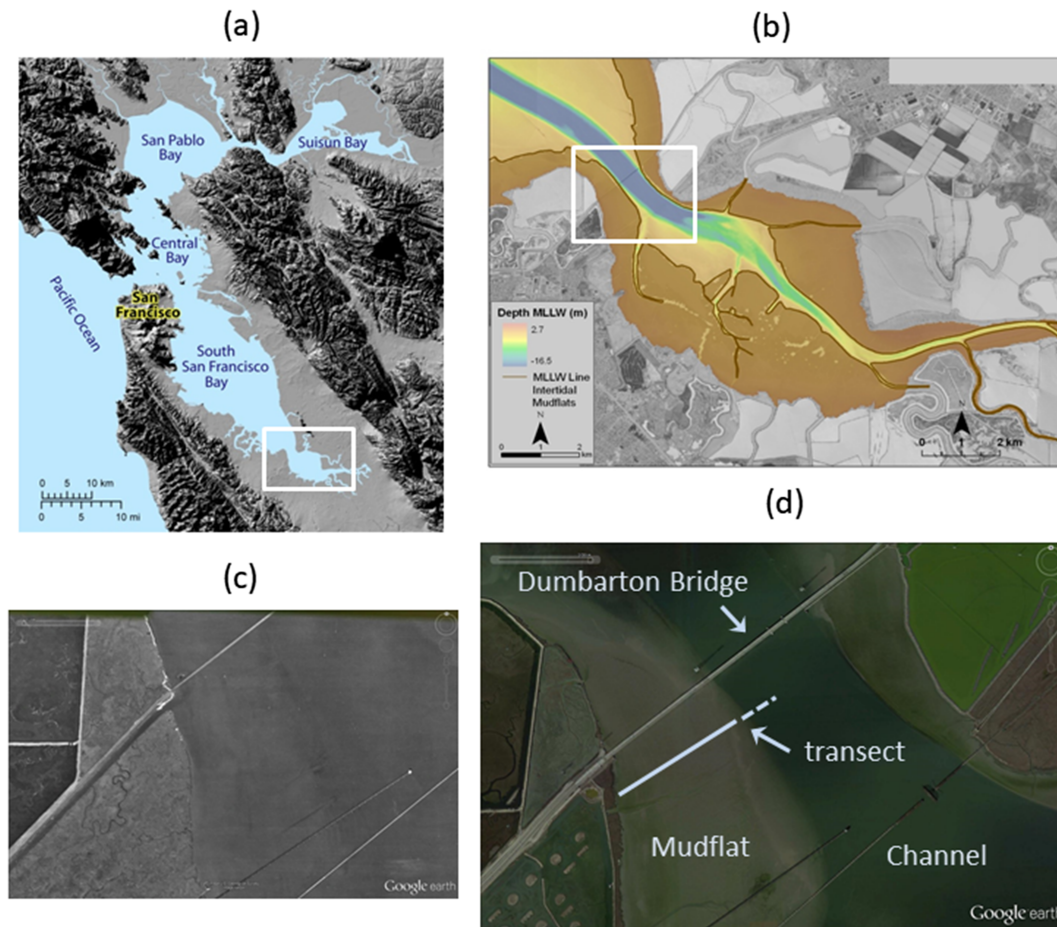


Figure 1. Location of Dumbarton mudflat (a) in San Francisco Bay and (b) in South Bay, (c) in 1948 and (d) in 2012. Line in (d) reflects transect analyzed in this study, with dashed part being the channel part. (c) and (d) are from Google Earth. Figure from Van der Wegen et al. (2017).

depths) changes in bathymetry for all surveys (Figure 2). The greatest changes, ~1 m in the vertical, occurred on channel slope, which tended to accrete Bayward resulting in a widening of the mudflat. Changes were also large, as much as ~0.5 m in the vertical, in the channel. The intertidal areas had the smallest, but still significant, changes, which were on the order of 0.1 to 0.2 m.

3. Model Description

The Mflat Matlab code is open source and attached to this work as supporting information. It is also available as part of the open source Open Earth Toolbox (<https://publicwiki.deltares.nl/display/OET/OpenEarth>).

Mflat applies a simplification of the shallow water equations resulting in a straightforward and fast numerical solution of governing processes. See Figure 3 for a schematic of the mudflat cross section and the definitions of the variables and coordinate system used in the model equations.

The cross-shore velocities are derived from the mass balance describing the cross-shore flow velocity as the result of tidal forcing. The cross-shore momentum equation is disregarded so that inertia and friction effects are neglected. This is justified under the assumption that the cross-shore velocity remains low. In the discussion of the results we will show that this is true for the short profiles considered in this study.

$$(hu)_i = \frac{dh_i}{dt} X_i \quad \leftrightarrow \quad u_i = \frac{dh_i}{dt} \frac{X_i}{h_i} \quad (1)$$

where

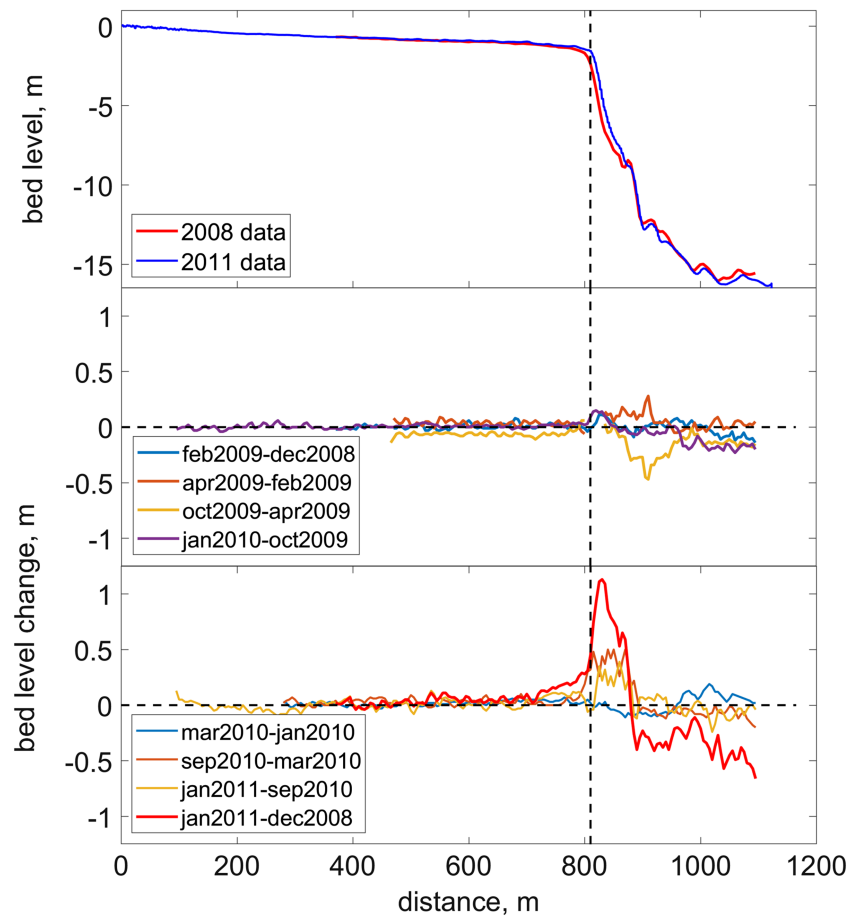


Figure 2. The 2008 and 2011 bed level and observed bed level changes over different periods. Dotted vertical line denotes shoal edge.

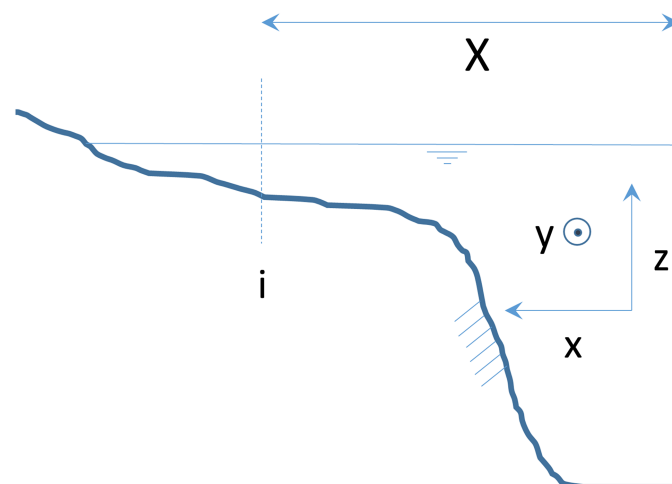


Figure 3. Schematics of mudflat cross section with relevant parameter definitions.

h = water depth, m

u = cross-shore velocity, m/s

X_i = distance from x_i to land boundary

The alongshore velocities are typically an order of magnitude larger than the cross-shore velocities. The alongshore velocity profile is derived from the alongshore momentum equation. A change in time of the alongshore velocity balances with the tidally driven, alongshore water level gradient (a so-called Neumann boundary) and bed friction by alongshore flow. The Neumann boundary condition is prescribed constant along the profile, but the alongshore velocities will vary depending on local water depth and friction.

$$\frac{\partial v}{\partial t} = -g \frac{\partial \eta}{\partial y} - \frac{\tau_{cv}}{\rho h} \quad (2)$$

with

$$\tau_{cv} = \rho C_d v |v| \quad (3)$$

and

$$C_d = \frac{g}{C^2} \quad (4)$$

where

v = alongshore velocity, m/s

g = gravitational acceleration, m/s²

η = water level, m

τ_{cy} = shear stress by alongshore flow, Pa

ρ = water density, kg/m³

C_d = drag coefficient, –

C = Chézy coefficient, m^{1/2}/s

We assumed that wave-driven alongshore flow as well as wave action impact on the alongshore shear stress could be neglected. Although these terms may be relevant at ocean beaches during high wind conditions or swell approaching the shore at an angle, waves and associated wave-driven flow in estuaries are typically much smaller. For example, this study applies wave heights of about 0.15 m.

Wave action is imposed by a stationary wave energy balance. Wind energy supply, wave breaking, and dissipation by friction determine the gradient of wave energy propagation across the mudflat.

$$\frac{dE_c}{dx} = S_w - D_b - D_f \quad (5)$$

with

$$E = \frac{1}{8} \rho g H_{rms}^2 \quad (6)$$

where

E = wave energy density per unit area, J/m²

S_w = wind-driven energy supply, J/m²/s

D_b = dissipation due to wave breaking, J/m²/s

D_f = dissipation due to bed friction, J/m²/s

H_{rms} = root-mean-square wave height, mand, after Van der Lugt (2017) based on Pierson and Moskowitz (1964), Breugem and Holthuijsen (2007) and Young and Verhagen (1996)

$$S_w = c_g \rho u_{10}^2 / \left[8a^2 b \left(\frac{16gE}{a^2 \rho u_{10}^4} \right)^{\frac{1}{2b}-1} \right] \quad (7)$$

with

$$a = 2.88e-3, b = 0.45,$$

u_{10} = wind velocity at 10 m elevation and with

$$c_g = \frac{1}{2} \left(1 + \frac{2kh}{\sinh(2kh)} \right) \sqrt{\frac{g}{k} \tanh(kh)} \quad (8)$$

where

$$k = \frac{2\pi}{l} \quad (9)$$

with k = wave number, m^{-1} , l = wave length, mand

$$D_b = 0.25 \frac{\rho g}{T_p} Q_b (H_{\text{max}}^2 + H_{\text{rms}}^2) \quad (10)$$

where T_p = peak wave period, s

and after Baldock et al. (1998),

$$Q_b = e^{-\left(H_{\text{max}} / H_{\text{rms}} \right)^2} \quad (11)$$

with

$$H_{\text{max}} = \frac{0.88}{k} \tanh \left(\frac{\gamma kh}{0.88} \right) \quad (12)$$

where

γ = breaker index (default 0.75), -and

$$D_f = \rho f_w |u_{\text{rms}}|^3 \quad (13)$$

with

$$u_{\text{rms}} = \frac{\pi H_{\text{rms}}}{\sqrt{2} T_p \sinh(kh)} \quad (14)$$

and

$$f_w = e^{5.213 \left(k_b / A \right)^{0.194} - 5.977} \quad (15)$$

and

$$A = u_{\text{orb}} \frac{T_p}{2\pi} \quad (16)$$

and

$$u_{\text{orb}} = \frac{0.5\pi^{1.5} H_{\text{rms}}}{\sinh(kh)} \quad (17)$$

where

f_w = wave friction factor, -

k_b = physical roughness length scale, m

A = wave excursion, m

u_{orb} = orbital wave velocity, m/s

The cross-shore sediment transport is modeled by an advection-diffusion equation in combination with bed interaction.

$$\frac{\partial hc}{\partial t} + \frac{\partial uhc}{\partial x} - D \frac{\partial^2 h}{\partial x^2} = \text{ero} - \text{depo} \quad (18)$$

where

c = concentration, g/m³

D = diffusion coefficient, m²/s

depo = deposition, g/m²s

ero = erosion, g/m²s

The numerical (first-order upwind) scheme allows for spatial steps of about 10 m with a time step of 5 s and a diffusion coefficient of 5 m²/s and is elaborated in the supporting information.

Erosion and deposition terms follow well-known cohesive sediment flux formulations by Partheniades-Krone (Ariathurai, 1974; Krone, 1962, 1993; Winterwerp & Van Kesteren, 2004)

$$\text{depo} = wc \quad (19)$$

and

$$\text{ero} = \begin{cases} M(\tau_{\text{tot}} - \tau_{e,cr}) & \text{for } \tau_{\text{tot}} \geq \tau_{e,cr} \\ 0 & \text{for } \tau_{\text{tot}} < \tau_{e,cr} \end{cases} \quad (20)$$

where

w = fall velocity, m/s

M = erosion factor, kg/m²/s

τ_{tot} = total shear stress, Pa

$\tau_{e,cr}$ = critical shear stress for erosion, Pa

Both wave action and current determine the shear stress for erosion, after Soulsby (1997),

$$\tau_{\text{tot}} = \tau_w + \tau_c \left[1 + 1.2 \left(\frac{\tau_w}{\tau_c + \tau_w} \right)^{3.2} \right] \quad (21)$$

and

$$\tau_w = 0.5 \rho f_w u_{\text{orb}}^2 \quad (22)$$

and

$$\tau_c = \sqrt{\tau_{cu}^2 + \tau_{cv}^2} \quad (23)$$

and

$$\tau_{ci} = \rho C_d U_i |U_i| \quad (24)$$

where

τ_w = wave induced shear stress, Pa

τ_c = current induced shear stress, Pa

$i = u, v, -$

The bed level is updated based on the net effect of the local sediment transport gradient as well as erosion and deposition terms enhanced by a morphological factor.

$$\frac{\partial z}{\partial t} = \text{MF} \left[\frac{\partial uhc}{\partial x} - D \frac{\partial h}{\partial x} + \frac{(\text{depo} - \text{ero})}{\rho_b} \right] \quad (25)$$

where

z = bed level, m

MF = morphological factor, –

ρ_b = bulk density of sediment, kg/m³

Channel depth is predefined and erosion below a predefined resistant channel bed is not allowed. The reason is that preliminary runs showed continuous channel erosion to unrealistically large depths. In reality, channel depth would be limited by compacted mud or coarser, sandy sediments. Slopes steeper than a threshold (1:10) are prevented every time step by a filter mimicking avalanching of the steep slopes until the slope threshold is met. The critical shear stress may vary with water depth to control lateral migration of the channel slope. For this model test case, critical shear stress is constant in intertidal areas, whereas the critical shear stress increases linearly toward a maximum value at channel depth, τ_d (see Figure 4). A physical reason to do this is that mud at deeper layers may be more consolidated and less prone to erosion than newly deposited sediment at the mudflat. Depth-dependent bed roughness for flow, equation (4), can be defined in a similar way. A depth-varying roughness would reflect a smooth bed on the muddy flat and a higher bed roughness in the channel because of sandy bedforms due to the prevailing high channel flow velocities.

4. Model Results

The following section presents model results of both a cross-shore only flow (CS) and a combined cross-shore and alongshore flow (CAS). Table 1 shows the applied model parameter settings. These values were derived by independent calibration of the CS and CAS models to match the observed mudflat profile. Both CS and CAS conditions describe a constant M_2 tidal forcing, constant wave action and constant sediment concentration at the sea ward boundary, a morphological factor of 100 and a roughness k_b of 0.004 m. Channel erosion deeper than the initial channel depth is not allowed. The channel and channel slope in the CS case are maintained by “dredging.” This implies that any deposition is removed from these sections, or else the channel would fill in completely. In contrast, the CAS case allows a dynamic landward or seaward migration of the channel slope and deposition in the channel. However, large tidal alongshore flows lead to high shear stresses at the toe of the channel slope. A low critical erosion shear stress (as prevails in the intertidal area) leads to erosion of the toe and a steepening of the channel slope. When the slope becomes too steep, avalanching takes place and the channel slope migrates landward eroding the entire mudflat. To keep the channel slope from moving landward, we applied a critical erosion shear stress in the channel (τ_d) of 6 Pa (according to Figure 4) and a linearly varying Chezy value from 85 at the intertidal area to 45 in the channel. This may somehow reflect lower roughness on the muddy flat compared to a higher roughness in the channel by sandy bedforms. These settings lead to very limited (<0.5 m) deposition in the channel after 100 years.

First, we present a calibration on the South San Francisco Bay mudflat profile in equilibrium and explore intratidal dynamics of water flow, waves and sediments on that profile. Next, we focus on the results of an extensive sensitivity analysis of model parameter values. Finally, we explore the impact of forcing disturbances on the equilibrium profile and compare these with observed profile variations.

4.1. Development Toward Equilibrium

The profile initially develops by the formation of a tidal levee close to the channel-shoal edge (Figure 5). This is where sediment deposits after entering the model domain at the seaward boundary during flood. As the levee accretes, waves at low water can suspend the sediments from the levee while flood flow transports the suspended sediments landward. These sediments deposit landward of the levee so that the levee extends landward and a smooth profile develops. The profile can be higher in landward direction because wave action suspending sediments reduces due to wave dissipation on the evolving profile or occurs at higher water levels

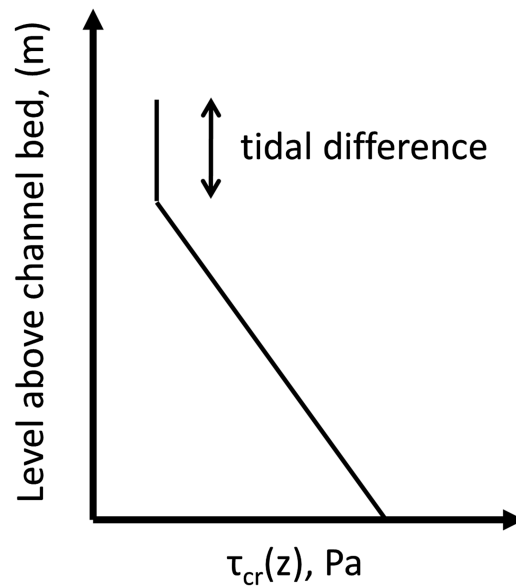


Figure 4. Schematization of depth-dependent critical shear stress.

in the tidal cycle. As the profile accretes more sediment is transported seaward during ebb. Morphodynamic equilibrium is reached when, along the profile, landward sediment transport during flood is balanced by seaward sediment transport during ebb. The equilibrium profile does not depend on the initial bed as long as the initial profile lies under the equilibrium profile. Calibration on the observed 2011 South San Francisco Bay mudflat profile was done by systematically varying wave forcing and sediment characteristics. The parameter values for the CAS equilibrium conditions require more “erosion-proof” sediments and less wave forcing, due to the increased prevailing shear stresses by the alongshore current. The CAS equilibrium profile is more concave than the CS profile. This fits the observed profile better near the channel edge but worse near the landward edge.

Figure 6 shows that the equilibrium profile allows for significant intratidal sediment dynamics. Maximum alongshore flow is largest in the channel (about 0.6 m/s) and is limited on the flat (about 0.25 m/s) due to a larger friction in shallower depths. This value range corresponds well with observations by Lacy et al. (2014) who report velocities of 0.4 m/s in the channel and 0.18 m/s at the adjacent flat about 15 km north of our case study. The CS and CAS cross-shore flow remains limited to 0.05 and 0.1 m/s, respectively, because of the different tidal ranges applied in each case. Waves attenuate considerably on the CS and CAS profiles although the CAS profile shows limited attenuation at high water. Wave-induced shear stresses are comparable for CS and CAS cases, but prevailing shear stresses are higher on the CAS profile due to the

Table 1
Model Parameter Settings and Ranges Used in the Sensitivity Analysis

Parameter	Standard value	
	CS	CAS
Wave height (H_{rms} , m)	0.12 ± 0.02	0.12 ± 0.02
Peak period (T_p , s)	1.25 ± 0.15	1.3 ± 0.2
Tidal amplitude (A , m)	0.5 (0.25,1)	1 ± 0.25
Critical shear stress (τ_{cr} , Pa)	0.3 ± 0.05	0.3 ± 0.1
Erosion factor ($\text{kg/m}^2/\text{s}$)	$5\text{e-}4 \pm 2.5\text{e-}4$	$5\text{e-}4$ (5e-5, 5e-3)
Fall velocity (mm/s)	1 (0.5,2)	0.6 (0.1,1)
Boundary sediment concentration (mg/L)	60 ± 10	50 ± 10

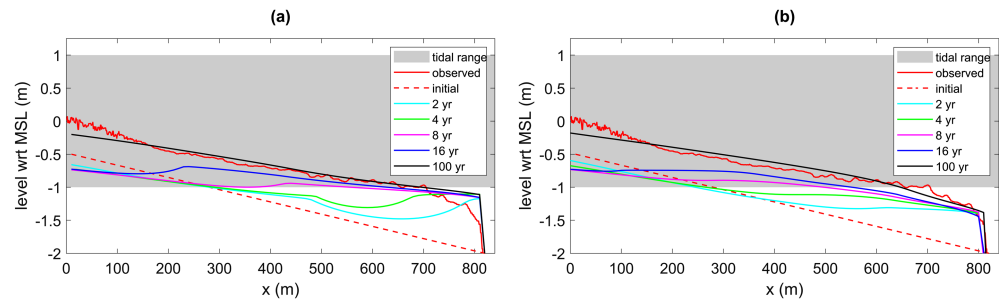


Figure 5. Profile evolution including (a) cross-shore flow and (b) cross-shore flow and alongshore flow.

presence of alongshore flow, which is highest near and in the channel. Maximum intratidal sediment concentrations exceed the sediment concentration prescribed at the boundary by a factor 5. This implies significant intratidal erosion and deposition at the equilibrium mudflat profile, albeit that the tide residual sediment transport and bed level change are 0. CS and CAS intratidal morphodynamic magnitudes are similar on the intertidal flat but CAS morphodynamics is an order of magnitude larger in the channel.

Profile evolution occurs because sediment deposits as a tidal levee near the channel. At a certain moment wave action at low water prevents further accretion of the levee. Sediment suspended at low water at the levee location is transported landward by subsequent flood flow. This sediment settles landward stimulating landward profile development. Equilibrium is reached when landward transport is eventually balanced by seaward transport due to increased sediment suspension and associated ebb transports on the accreting profile. Equilibrium occurs when the shear stress at higher water levels hardly exceed the critical erosion shear stress at the landward side. The profile at the channel edge is maintained by wave action at low water.

Comparing Mflat CS results of this study to Delft3D results by Van der Wegen et al. (2017), shows similar behavior but also small differences. Van der Wegen et al. (2017) applies a constant wave friction value of 0.02 whereas Mflat applies equation (15). Van der Wegen et al. (2017) did not consider alongshore flow, whereas Mflat (this study) shows that a similar profile in equilibrium can be generated in presence of alongshore flow. Also, Van der Wegen et al. (2017) and the CS case apply a M_2 tidal amplitude of 0.5 m, whereas the observed M_2 value is about 1 m. The CAS case applies a 1-m tidal amplitude and is thus closer to the observed parameter value. The possible impact of the very irregular tidal signal in South San Francisco Bay is discussed in a later section.

Inclusion of average wind conditions and associated wave growth via equation (7) showed very limited impact on the mudflat profile. This is due to the limited fetch in our model domain. Prevailing high wind conditions had some impact but coming sections will show that storms are short events disturbing the mudflat edge while equilibrium mudflat profile recovers within 100 days.

4.2. Sensitivity Analysis

Sensitivity analysis (Figure 7) shows qualitatively similar behavior for CS and CAS cases. Less wave action (lower H_{rms} and T_p) and prescribed higher sediment concentrations at the boundary lead to higher profiles. More “erosion-resistant” sediment (higher critical erosion shear stress, lower erosion factor, higher fall velocity) leads to steeper and higher profiles. A higher tidal amplitude leads to a lower, but steeper profile in the CS case. Mind that the profiles with migrating channel slopes under CAS conditions continue to show migrating channel slopes and are thus not in equilibrium after 100 years. A varying tidal amplitude leads to changing shear stresses at the channel slope toe and related sideward migration of the channel slope, even to the extent of a completely vanishing mudflat or a fully deposited channel. The same holds for changing sediment properties or changing sediment supply. Some of the profiles show a remarkable horizontal table (e.g., a low T_p under the CS conditions and a low tidal amplitude under the CAS conditions). These conditions develop in cases where wave action is most effective only at a certain limited stretch from the mudflat edge and during a certain part of the tide. During rising tide waves are able to erode sediments only at smaller water depths. At higher water levels the water becomes too deep for the waves to have erosive power so that associated landward sediment transport becomes limited. The shoal thus develops very slowly.

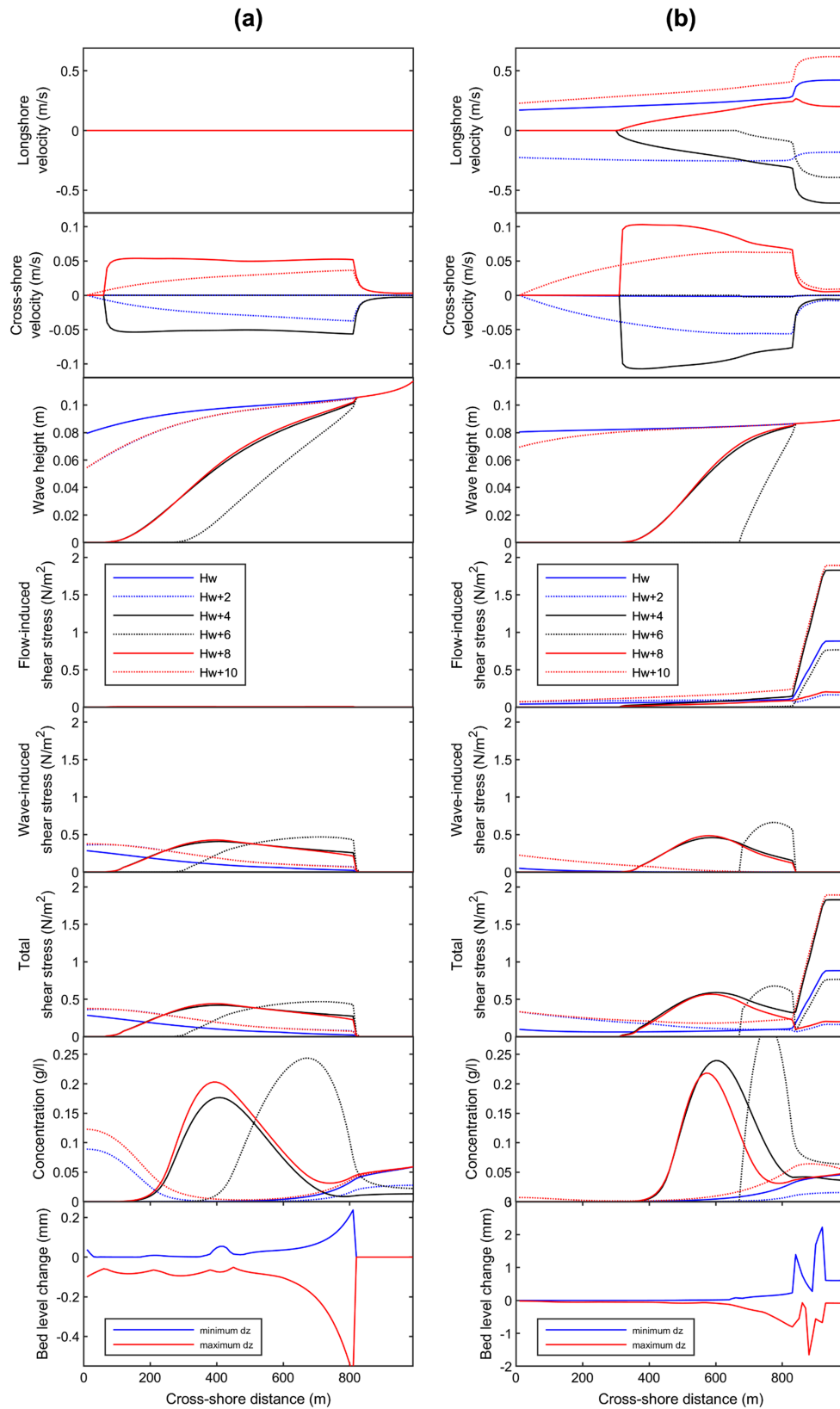


Figure 6. Intertidal dynamics on equilibrium bed profile at 2-hr intervals for (a) cross-shore and (b) cross-shore and alongshore flow. The bed level changes have a morphological factor of 1 to reflect actual bedlevel changes during a tide. Hw in the legend stands for high water.

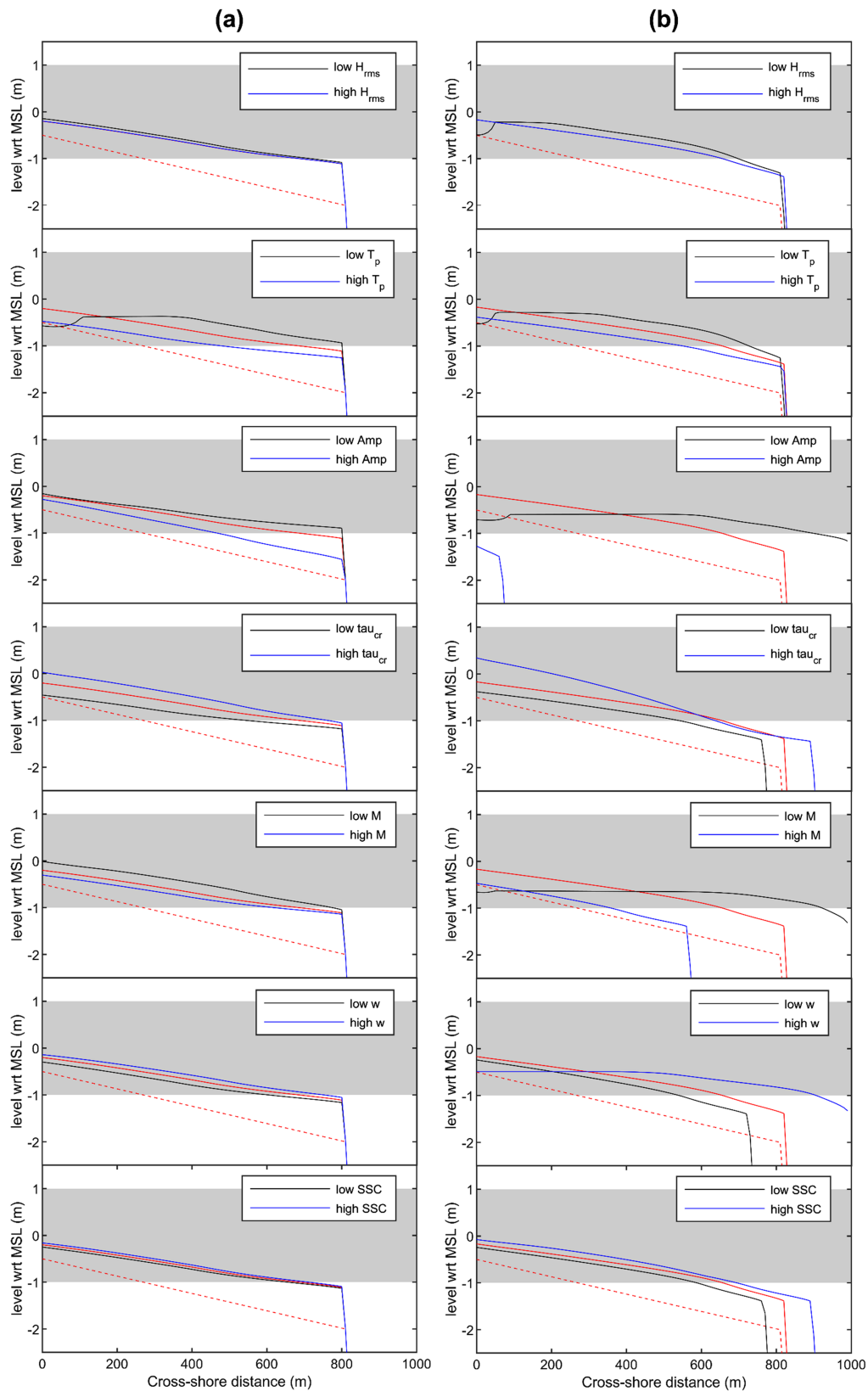


Figure 7. Sensitivity analysis for (a) cross-shore and (b) cross-shore and alongshore flow. Gray area denotes observed tidal range; red dotted line denotes initial bed profile; red solid line denotes equilibrium profile with standard settings. Results presented are after 100 years. The profiles with migrating channel slope and horizontal table are not in equilibrium.

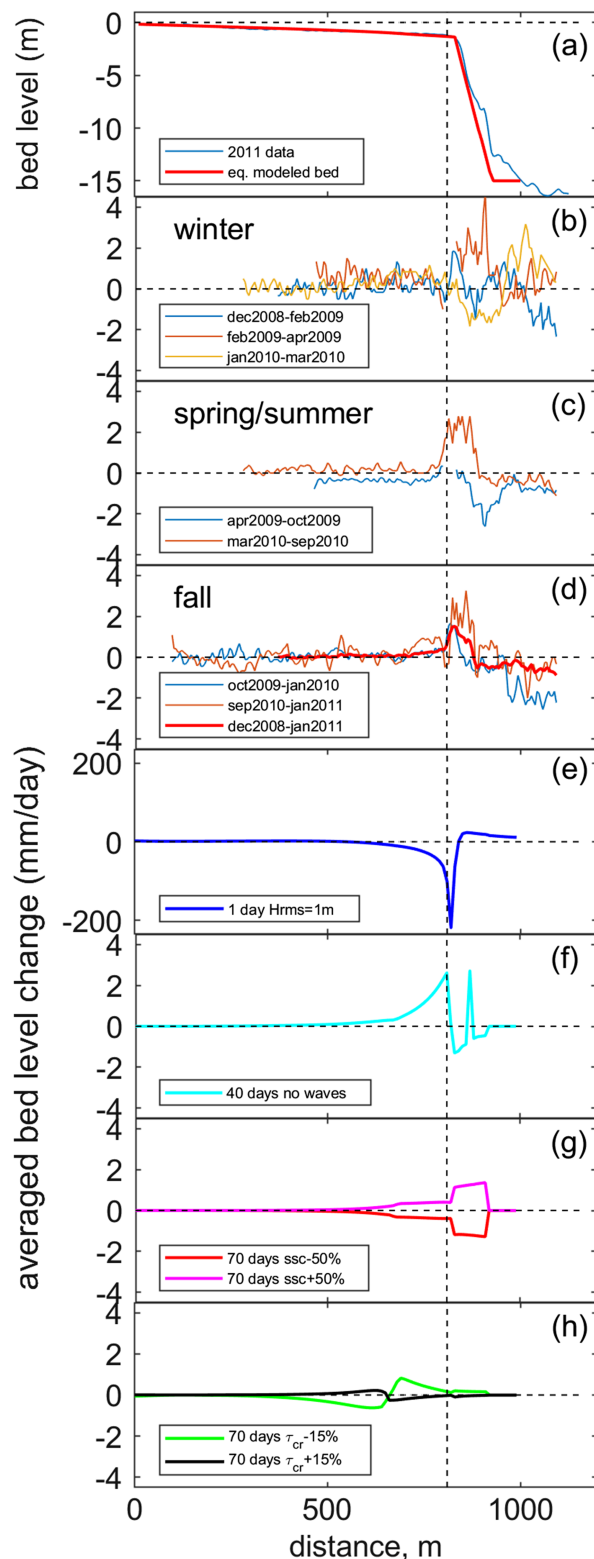


Figure 8. (a) Observed and modeled bed level, (b, c, d) observed bed level change in mm/day and modeled bed level change for (e) 1 day of high waves, (f) 40 days with no waves, (g) 70 days with 50% difference in suspended sediment concentration, and (h) 70 days with 15% critical shear stress change.

Sensitivity analysis (not fully shown) shows that important parameters are limited wave action, large wave attenuation by friction, “erosion-resistant” sediment, small tidal range and long mudflat width, suggesting the existence of a length scale of effective wave action. This concept needs further elaboration in future studies.

4.3. Comparison to Seasonal Changes

Model results show that a morphodynamic equilibrium can be obtained that is similar to an observed mudflat transect. To compare with observed seasonal bed level changes (Figure 2) we now expose this equilibrium profile to possible short-term natural variability of the forcing conditions. For these runs we used the standard CAS conditions (combined cross-shore and alongshore flow; Table 1) and varied wave height, suspended sediment concentration, and critical shear stress individually. Runs used a morphological factor of 1.

Figure 8 shows the observed bed level changes from Figure 2 grouped by season(s) and converted to rates of change in mm per day. Remarkably, seasonally observed morphodynamic rates can be larger than the net bed level changes over almost 3 years. The trend observed over three years is thus the result of seasonal variations larger than the trend. Bed level variations are largest in the channel and on the channel slope. On the mudflat itself bed level changes are largest at the mudflat edge, although there are seasonal changes of the entire mudflat profile. Clear seasonal trends or similarities between seasons over different years are not present, probably due to seasonally and yearly highly variable forcing conditions.

The lower panels show, also in millimeter per day, the impact of exposure of the equilibrium profile to a storm with one day of 0.5-m high waves, a 40-day period without waves, 70 days of 50% decreased/increased suspended sediment concentration at the boundary and 70 days of 15% increased/decreased critical erosion shear stress. The change in critical erosion shear stress mimics the influence of the presence or absence of diatoms on the intertidal area of the mudflat on erodibility. Austen et al. (1999) found that sediments were less erodible when diatoms were present. The sediment concentration variations in the channel are within the range of yearly observed average variations and can possibly be related to high Delta outflow during spring and seasonal diatom presence. The modeled disturbances of Figure 8 all recover to the equilibrium profile gradually when standard forcing conditions are restored. For example, following the greatest disturbances caused by 1-day high wave conditions, the equilibrium profile recovers in about 80 days.

The normalized seasonal observations are of similar magnitude as the modeled variations caused by changes in the forcing, except for the storm conditions, which have a higher magnitude, but may be of shorter duration. Like in the data, the mudflat changes are very limited near the landward edge. Variations in wave action have largest impact on the mudflat edge and channel slope. The sediment concentration variations have the largest effect in the channel, but also a significant effect at the edge and the outer third of the mudflat.

4.4. Impact of Tidal Variations

Another forcing mechanism responsible for profile variations is the highly irregular tide in South San Francisco Bay with different tidal constituents (Table 2) that cause not only spring-neap tidal variations but also

Table 2
Main Tidal Constituents at Coyote Creek Near Dumbarton Mudflat

Tidal constituent	Amplitude (m)	Phase (°)
M_2	0.953	18.1
S_2	0.213	33.8
N_2	0.191	5.1
K_1	0.397	126.5
M_4	0.049	257.8
O_1	0.225	121.2

Note. Source: <https://tidesandcurrents.noaa.gov/stationhome.html?id=9414575>

significant variations on longer, bi-monthly to monthly time scales (Figure 9c). If we would impose this tidal signal on a model with the standard parameter settings, the channel slope would continuously migrate landward. We thus had to increase the critical erosion shear stress to 0.33 Pa. We ran the model for 0.5 year with a morphological factor of 100 and derived the mean profile shown in Figure 9a, black line. After these 50 morphodynamic years the mean profile was fairly stable. Taking the mean profile as an initial bed, we then ran half a year with a morphological factor of 1 to reflect actual bed level changes during half a year.

The mean profile is remarkably similar to the observed profile, especially closer to the mudflat edge. In that area the fit seems better than the results by M_2 forcing only (Figure 5b). Figure 9b shows that the irregular tide causes maximum bed level changes over half a year varying between 0.2 and -0.2 m. Again, the variations are highest in the channel and channel slope, but variations toward the mudflat edge are considerable as well. Relating water level variations (Figure 9c) to bed level changes (Figure 9d) shows that daily bed level variations are small compared variations by a bi-monthly or monthly cycle. The mudflat level can decrease about 10 mm in 3 days (between Day 130 and Day 133). The bed level mainly decreases at lower daily tidal difference in the bi-monthly cycle. The profile restores partly at larger daily tidal difference with larger accretion for a larger daily tidal difference. A 10 mm decrease in 3 days is about 3.3 mm/day which compares well to the bed variations in Figure 8.

5. Discussion

5.1. Model Validation

We independently validated the standard CS and CAS cases by systematic parameter variations. The initial model parameter values were based on literature review and data analysis. We did not apply a predefined or automated methodology to optimize the search for the best fit, for example by varying wave parameters first and then sediment properties. It is possible that a better fit could be obtained by applying a different order in parameter variations leading to other model parameter settings. Optimization of (automated) validation can be subject of future research.

Fine tuning to the observed profile and the sensitivity analysis were done by varying the model parameter values (sediment properties, hydrodynamic forcing) within the range of observed values. An exception is that a reasonable fit for the CS case could only be obtained with a tidal amplitude of 0.5 m (similar to Van der Wegen et al., 2017), whereas the CAS case applied a value of 1 m which corresponds more to the prevailing tidal amplitude. This suggests that our approach of including alongshore flow is more appropriate.

5.2. Alongshore Dynamics

With respect to earlier 1-D profile models reported in literature, Mflat adds the opportunity to study the impact of alongshore tidal flow on mudflat profile morphodynamics. We neglected wave-driven alongshore flow (because of the small waves) and wind-driven flow which can be important in case of a persisting wind direction (de Vet et al., 2018). Also, this study considered only a cross-shore wave propagation direction, but along-shore wave propagation is possible when largest fetch is along the mudflat. This would lead to larger waves in landward direction. As a matter of fact, these conditions hold for many mudflats in South Bay since prevailing winds are along the main channel. The Dumbarton mudflat is somewhat sheltered from waves generated by North-westerly winds. Future research could explore the impact of these three terms by straightforward implementation in the code.

A more challenging task relates to the implementation of alongshore sediment transport gradients, which consist of alongshore velocity gradients and concentration gradients that vary along the profile. The current assumption is that there is no alongshore sediment transport gradient. Since Mflat is a line model, the possible effect of the transport gradient needs to be parametrized. An approach could be to derive alongshore flow gradients through the effect of friction while sediment concentration gradients could be kept constant in first approximation. Finally, there may be significant alongshore tide-residual transport gradients due to wind-driven circulation flows, density currents or tide asymmetry effects that can even lead to a different

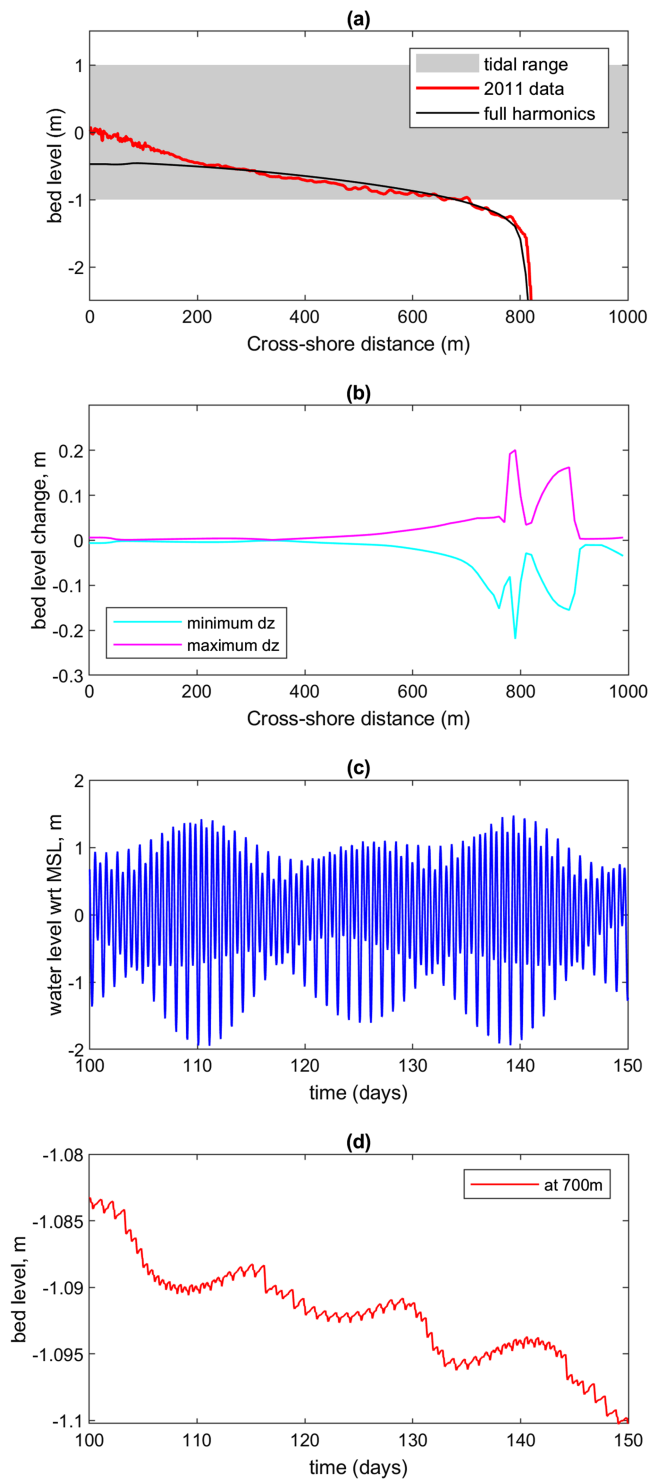


Figure 9. (a) Average bed level over 100 year morphodynamic run forced by full tidal harmonics, (b) minimum and maximum bed level over half a year with a morphological factor of 1, (c) tidal harmonics at Coyote Creek near Dumbarton mudflat, and (d) bed level at $x = 800$ m (mudflat edge) with a morphological factor of 1.

transport direction in the channel compared to the flat. For example, Lacy et al. (2014) describe these dynamics at a channel-flat system just north of our case study in San Francisco South Bay. To include these processes, a 2-D or even 3-D area model is required that then also includes the effect of the estuarine plan-form.

5.3. Significant Trend?

The seasonally varying observed bed level changes of the South San Francisco Bay mudflat profile and the modeled bed level changes as the result of small variations in the forcing are of a similar order of magnitude. Still, the comparison of model results and seasonal data remains quite qualitative. Like in the data analysis and confirming observations by Kohsiek et al. (1988), most morphodynamic behavior of the mudflat occurs at the mudflat-channel edge. Temporal strong wave action has largest effect on the mudflat edge, diatom presence varies the bed level only locally and variations in sediment supply and tidal behavior show largest variation of the channel bed. Although we were able to reproduce some of the tendencies in the observed bed level changes over 3 years, we were not able to reproduce all changes. No detailed, high resolution data on sediment properties, presence of diatoms and forcing conditions (channel sediment concentrations, wave action) were available to reproduce the observed bed changes. But even if they were available, Mflat could be missing processes like flocculation or consolidation significantly impacting the mudflat morphodynamics.

Mflat is able to evolve the general shape and elevation of the observed profile in equilibrium. It is even capable of reproducing observed seasonal bed level changes by varying a single forcing parameter. For example, the observed bed level changes in spring/summer of 2009 and 2010, are consistent with model predictions of deposition in the channel for low and high suspended sediment concentrations respectively.

However, during most observation periods it is not able to simulate the observed bed level changes for the entire profile by individually varying wave height, sediment concentration, or critical shear stress (Figure 8). A possible explanation is that the observed profile variations are not the result of variations in a single parameter, such as wave height, but a combination of variations in two or more parameters. Another possibility is that temporal variation in forcing during a season, such as a period of higher waves or diatom layers on the mudflat during only part of the season, and the associated restoration time scales cause the mismatch between model and observations. Also, the timing of forcing events is important. For example, Mflat predicts that a 1-day storm leads to a large 20 cm erosion at the mudflat edge and a mudflat profile recovery within the observation interval of 3–6 months. This implies that timing of the profile measurement (just before or after a storm) has a significant impact. The 3- to 6-monthly observation intervals are probably too long to discriminate different mechanisms of bed evolution.

The data seem to confirm that the timing of the profile measurements relative to the variations in forcing is important. They show that the bed level development on the channel slope between December 2008 and January 2011 is the result of considerably different profile variations in the 3- to 6-monthly intervals (Figures 2 and 8). In other words, it is tempting to consider it as a trend, but the bed level changes on the channel slope between December 2008 and January 2011 just may be governed by two

extreme, stochastic events occurring in the March 2010 to September 2010 and September 2010 to January 2011 periods.

On the other hand, Elmilady et al. (2019) shows that a similar, 2-D approach has significant skill in reproducing 150 years of observed morphodynamic developments of the San Pablo Bay mudflat on 30-year intervals under schematized forcing conditions and by slowly varying forcing conditions related to the sediment supply. They argue that the explanation for the skillful model performance lies in the fact that the 30-year period is long enough to capture trends in morphodynamic development. These trends are either not governed by (series of) forcing variations or the impact of these (series of) forcing variations events is captured implicitly in the model calibration and averages out over the 30-year period.

This raises questions on how long a series of measurements needs to be to expose a trend. The current study suggests that this should be longer than a 25-month period and probably shorter than a 30-year period, but this timeframe will be different for different case studies.

5.4. Channel Morphodynamics

This study has focused on reproducing an intertidal mudflat profile and exploring the dynamics resulting from seasonal variations in forcing. Still, both in the model and the observations, the largest bed level changes occur in the channel and on the channel slope, which is also the weakest link of Mflat. We had to impose a larger critical erosion shear stress in the channel and a variable roughness from channel to mudflat to prevent unwanted lateral migration of the channel slope. This implies that sediments settling on the channel bed will immediately obtain a high resistance against erosion. In reality, the high erosion resistance would only evolve through consolidation processes, not applied in the model. One could argue that the irregular tide could provide consolidation conditions during neap tides and that the Mflat approach could thus be valid when averaged over spring-neap tidal cycles or even longer periods. Another process enhancing a stable channel slope toe maybe that, in reality, sediment concentrations will be higher closer to the bed favoring deposition. Mflat applies a depth averaged concentration, whereas concentrations will be larger near the bed. Both processes may be parameterized in future Mflat versions and justify more detailed study and data collection.

5.5. Future Improvements to Mflat

The current study points to the potential of applying Mflat in future studies on intertidal flat morphodynamics. The open source context of Mflat explicitly stimulates further adaptations to the code, potentially by third parties. Future extensions could include validation studies against measured suspended sediment concentration (SSC) and wave heights, wind generated longshore currents, including alongshore generated waves, longitudinal gradients in sediment supply, vegetation dynamics, and sediment properties including sand dynamics. Future modeling studies could both focus on short, intratidal time scales as well as decades to centuries including climate change scenarios. Comparison studies with models solving the full Navier-Stokes equations (like Delft3D) will reveal where the assumption to neglect the cross-shore momentum balance is valid.

6. Conclusions

Mflat describes the prevailing processes governing the morphodynamics of intertidal mudflats. These include both cross-shore and alongshore tidal flow, wave action, sediment transport, and bed level changes on a high-resolution grid. Model results show significant skill in reproducing an observed mudflat profile in South San Francisco Bay in equilibrium.

By extensive sensitivity analysis we show that the mudflat is remarkably resilient against potential seasonally varying forcing conditions related to storms, waves, sediment supply, and sediment characteristics. Confirming 2-year profile observations at 3-monthly intervals, the largest morphodynamic activity occurs at the mudflat edge, channel slope, and channel. Model results suggest that 3-monthly observation intervals are probably too long to discriminate the morphodynamic impact of different forcing mechanisms.

Mflat provides a promising, open source tool to study intertidal flat morphodynamics across a range of process scales and time periods.

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