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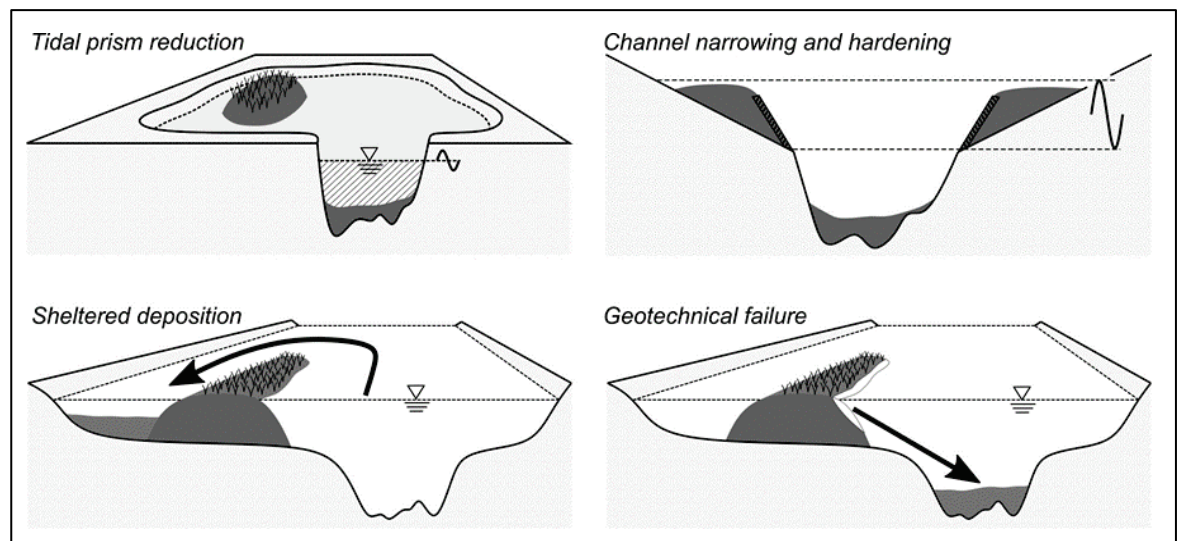


Coastal Inlets Research Program

A Review of Tidal Embayment Shoaling Mechanisms in the Context of Future Wetland Placement

Douglas Krafft, Rachel Bain, Jack A. Cadigan, and Richard Styles

November 2022



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Abstract

Wetland construction in tidally influenced embayments is a strategy for beneficial use of sediment dredged from nearby navigation channels. These projects have the potential to alter basin morphology, tidal hydrodynamics, and shoaling trends. This special report provides a broad review of the literature related to engineering-induced changes in tidal range, salinity, tidal prism, tidal asymmetry, and other known causes of shoaling. Each potential shoaling mechanism is then evaluated in the context of wetland placement to provide a foundation for future beneficial use research. Based on a compilation of worldwide examples, wetland placement may reduce tidal amplitude and enhance ebb current dominance, thus reducing shoaling rates in the channels. However, constructed wetlands could also reduce the embayment's tidal prism and cause accelerated shoaling relative to the pre-engineered rate. Because constructed wetlands are often created in conjunction with navigation channel dredging, the system's morphologic response to wetland construction is likely to be superimposed upon its response to channel deepening, and the net effect may vary depending on a variety of system-specific parameters. Planning for future wetland placements should include an evaluation of local hydrodynamic behavior considering these factors to predict site-specific response.

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Contents

Abstract.....	ii
Figures and Tables.....	v
Preface	vii
1 Introduction	1
1.1 Background	1
1.2 Objective(s)	1
1.3 Approach	1
2 Definition of symbols	3
3 Changes in Tidal Range	8
3.1 Physical mechanisms of tidal amplification and damping.....	8
3.2 Specific examples of tidal damping and amplification	12
3.2.1 Channel deepening.....	12
3.2.2 Flow connectivity and hydraulic conveyance changes	14
3.2.3 Interior shoreline changes and land reclamation	16
3.3 Implications for wetland placement	17
4 Changes in Salinity	21
4.1 Definition of estuarine circulation	21
4.2 Examples without amplification.....	24
4.3 Examples with amplification	26
4.4 Implications for wetland placement	28
5 Changes in Tidal Prism.....	29
5.1 Relationship between tidal prism and sediment transport	29
5.2 Examples of shoaling related to tidal prism.....	31
5.3 Examples of scouring related to tidal prism	33
5.4 Examples of tidal prism capture	34
5.5 Implications for wetland placement	36
6 Changes in tidal asymmetry.....	39
6.1 Relationship between tidal asymmetry and sediment transport.....	39
6.2 Examples of changes in tidal asymmetry.....	44
6.3 Implications for wetland placement	47
7 Other Causes of Shoaling with Possible Relevance to Wetland Placement	49
7.1 Deposition in sheltered areas of the basin	49
7.2 Hypsometric changes and effect on velocity surge	51
7.3 Geotechnical failure	52
7.4 Channel constrictions and expansions	54

8	Other Causes of Shoaling Not Directly Relevant to Wetland Placement.....	55
8.1	Channel avulsion.....	55
8.2	Migrating bedforms.....	55
8.3	Variations in sediment availability.....	56
9	Conclusions and Recommendations	59
9.1	Conclusions.....	59
9.2	Recommendations	59
	References.....	63
	Report Documentation Page	

Figures and Tables

Figures

Figure 1. Definition sketch of variables used throughout this report. Subplots (a), (c), and (e) show various embayment geometries, with the intertidal region shaded gray. The channel mouth is at the left boundary of the figure in all cases. Longitudinal cross sections (i.e., parallel to the x-axis) are shown in subplots (b) and (d) for the prismatic and convergent cases; note significant vertical exaggeration. Subplot (f) displays a transverse (i.e., perpendicular to the x-axis) cross section relevant to any of the embayment geometries..... 4

Figure 2. Generalized illustration of hypothetical tidal amplification effects in response to wetland construction with embayment narrowing and bank hardening. A navigation channel transect bordered by intertidal flats (subplot a) is modified by constructing wetlands with hardened edges and potentially increasing the local channel depth (subplot b). Embayment narrowing, hardening, and deepening may cause tidal amplification (subplot c), which may increase shoaling in the navigation channel by changing the system's salinity dynamics and/or delaying the propagation of low tide, favoring flood dominant sediment transport (subplot d)..... 19

Figure 3. Generalized illustration of tidal damping in response to wetland construction in the subtidal region of a wide bay. Subplot (a) shows a transverse section of a wide embayment (e.g., Galveston Bay) with a navigation channel. In (b), a wetland is constructed by placing dredged sediment in a subtidal area far from the channel. Frictional dissipation is enhanced due to the addition of vegetation in the intertidal region and may reduce the tidal amplitude. However, the effect on shoaling in the channel is likely to be site specific. Whereas the reduction in tidal prism may cause accelerated shoaling (subplot c), delaying the propagation of high water may also reduce flood dominance and promote sediment flushing. 20

Figure 4. Illustration of inlet shoaling in response to a reduction in tidal prism. The tidal prism, Ω , is defined as the volume of water required to fill the inlet between low tide (subplot a) and high tide (subplot b). Placing a wetland at any elevation above lowest lowwater reduces Ω (subplot c). Due to the relationship between Ω and the inlet's cross-sectional area at mean water level, A_{cross} , the inlet channel shoals in response to wetland construction (subplot d)..... 37

Figure 5. Hypothetical example of how wetland construction may drive shoaling and inlet closure in multi-inlet systems. In (a), an embayment is fed by two tidal inlets which each convey approximately equal tidal prisms Ω . Wetland construction then reduces the volume of water that must be conveyed by Inlet 2 (subplot b). Due to the relationship between tidal prism and inlet area, Inlet 2 begins to shoal and close in response to wetland construction (subplot c). This generates a positive feedback cycle in which Inlet 1 captures progressively more of the total basin volume..... 38

Figure 6. Channel geometries with contrasting tidal asymmetry based on parameters proposed by Fortunato and Oliveira (2005). With all other parameters held constant, channels with large values of $a/\langle hc \rangle$ (subplot a) are predicted to be more flood dominant than channels with small values of $a/\langle hc \rangle$

(subplot b). Channels with narrow tidal flats (small b_f/bc ; subplot c) are more likely to be flood dominant, while a reduction in flood dominance is predicted for channels with wide tidal flats (large b_f/bc ; subplot d). The greatest ebb dominance is predicted for tidal flats slightly above mean water level (MWL), which is represented by negative values of (hf) MWL (subplot e). Lower-elevation flats (subplot f) are predicted to be less ebb dominant relative to the scenario with flats slightly above MWL. 42

Figure 7. Possible effects of wetland construction on tidal current asymmetry. Beginning from a pre-engineered system comprised of a deep channel and a shoal (subplot a), wetlands are constructed near low water (subplot b), above mean water level (MWL; subplot c), and above high water (subplot d). Based on results from Fortunato and Oliveira (2005) and Stark et al. (2017), the predicted effect on tidal asymmetry varies with elevation. Wetlands constructed near low water may delay the propagation of the waveform trough and enhance flood current dominance, whereas wetlands constructed above MWL are predicted to enhance ebb current dominance. The vegetation is predicted to have minimal influence on tidal asymmetry when the wetland is above high water. Note that these predictions do not consider the potentially competing effects of tidal prism reduction, tidal amplification, or tidal damping 47

Figure 8. Illustration of possible sediment deposition in the low-energy area behind a constructed wetland. Although it is conceivable that enhanced deposition on the shoals could reduce the siltation rate in the navigation channel, data from Galveston Bay (Tate et al. 2014) indicate that sediment trapping effects were offset by enhanced shear and entrainment elsewhere within the system. 51

Figure 9. Illustration of wetland side-slope failure reintroducing sediment to the navigation channel. Oversteepening of the bank, vegetation die-off due to salinity stress, and underconsolidation of newly placed sediment enhance the likelihood of geotechnical failure. 53

Tables

Table 1. Variables and abbreviations used throughout this report. 5

Preface

This study was conducted for the US Army Engineer Research and Development Center (ERDC) under the Coastal Inlets Research Program (CIRP), Inlet Geomorphology Work Unit “Influences of Wetland Nourishment on Coastal Inlet Hydrodynamics”; Funding Account Code U4362900, AMSCO Code o60000.

The work was performed by the Coastal Engineering Branch of the Navigation Division, ERDC Coastal and Hydraulics Laboratory (CHL). At the time of publication of this report, Ms. Lauren M. Dunkin was chief, Coastal Engineering Branch; Ms. Ashley E. Frey was chief, Navigation Division; Dr. Tanya M. Beck was CIRP program manager; Ms. Tiffany Burroughs was chief, HQUSACE Navigation Branch and Navigation Business Line Manager; and Mr. Charles E. Wiggins, CHL, was ERDC technical director for Navigation. Dr. Ty V. Wamsley was director of CHL, and Mr. Keith Flowers was deputy director of CHL.

The commander of ERDC was COL Christian Patterson, and the director was Dr. David W. Pittman.

1 Introduction

1.1 Background

Wetland nourishments are an increasingly common strategy for new work conducted on navigation channels, as well as Operations and Maintenance (O&M) in dredged material management. This strategy can often serve as a beneficial-use option for the lifecycle management of sediment, and it also serves important storm risk reduction and habitat restoration/resilience functions. Extensive repeated application of in-bay placement strategies, such as wetland nourishment, may be an important part of planned beneficial use goals. However, it can be difficult to plan for the potential long-term impact of these large, cyclical wetland nourishments on tidal inlet systems and the associated O&M mission. It is possible that these changes could impact flow patterns and channel stability over time, but potential medium- to long-term impacts on navigation channels from different recurring beneficial use strategies appear to be largely under addressed or unaddressed. Hydrodynamic and morphologic changes in and around navigation channels have, however, been attributed to long histories of engineering modification. This special report reviews literature addressing these impacts and theories relating them to measurable quantities. Observations and theories are used to comment on possible similarities and differences between the engineering works in question and dredged sediment beneficial use options in tidally influenced bays and rivers.

1.2 Objective(s)

- Discuss potential impacts of wide-spread and recurring beneficial use strategies on navigation channels.
- Identify knowledge gaps and provide recommendations for future research.

1.3 Approach

This report reviews relevant literature to establish potential navigation impacts of long-term, large-scale beneficial use strategies for dredged sediment within tidally influenced bays and rivers. This is approached by summarizing key findings concerning the unintended hydrodynamic and morphologic impacts of engineering projects in tidal embayments and

providing a brief review of relevant channel shoaling processes. These findings address the capacity of anthropogenic modification to unintentionally alter tidal amplitude (Section 3), buoyancy-driven circulation (Section 4), tidal prism (Section 5), tidal asymmetry (Section 6), and other contributors to channel shoaling, which may or may not be directly relevant to beneficial use strategies (Sections 7 and 8). Concepts and variables common to a variety of topics are presented in Section 2 for clarity. Observations and theories on unintended impacts of other engineering works are compared to different beneficial use strategies to help establish the range of possible outcomes for ongoing widespread implementations.

Although the causes of shoaling are summarized separately in this report, it is necessary to emphasize that they are not mutually exclusive. For example, tidal amplification (Section 3) may delay the propagation of low tide and generate an enhanced flood current asymmetry (Section 6), with both mechanisms affecting sediment transport and deposition. Likewise, sediment deposition in a low-energy area of the basin (Section 7) may alter the tidal current asymmetry or the total tidal prism (Section 5), creating a feedback cycle. Many of the site examples presented in the following text appear within multiple sections due to the co-occurrence of multiple shoaling processes. The division of this report into sections was designed to improve clarity for the readers, but this organizational scheme does not imply that a single process was the exclusive cause of shoaling in any given example.

2 Definition of symbols

The remainder of the report considers tidally influenced coastal embayments of varying configurations ranging from idealized prismatic channels to arbitrarily shaped tidal basins with one or more entrances. Several examples are shown in Figure 1. For clarity, the variables used to describe these systems are defined in Table 1.

In all cases, the system's geometry is described with the x -coordinate oriented parallel to the channel's long axis and $x = 0$ at the entrance. The length of the system is described either by its total length L or, in the case of a convergent channel, by the e-folding lengths for cross-sectional area (L_A) or width (L_b) (see Figure 1a and 1c). Note that there is no requirement for $L_A = L_b$, although this scenario is depicted in Figure 1c for simplicity.

For arbitrarily shaped embayments, the system length may be alternately characterized by the length of the entrance channel, L_E (Figure 1e). The half-width of the channel is denoted by b_c , which is constant with respect to x for the prismatic case but varies with x in the convergent case. Using the rectangular cross section shown in Figure 1f, b_c is constant in time. However, in real systems b_c may vary throughout the tidal cycle if the sidewalls of the channel are nonvertical. The half-width of the tidal flats, b_f , may likewise vary in space and/or time depending on the geometry of the system.

The bed of the channel may be horizontal (Figure 1b) or sloped (Figure 1d), although in many natural systems the large convergence length for depth allows the bed slope to be neglected at first order (Savenije 2005). Depths above the channel bed are denoted $h_c(t, x)$. The time-averaged value $\langle h_c \rangle$ may vary with x even in the prismatic case due to the establishment of an along-channel setup (e.g., Friedrichs and Madsen 1992). Note that the angular brackets $\langle \cdot \rangle$ denote time-averaging over a tidal cycle. Tidal oscillations in water surface elevation have an amplitude $a(x)$ and are denoted ζ , such that instantaneous values of depth are given by $h_c(t, x) = \zeta(t, x) + \langle h_c(x) \rangle$. Inundation depths on the intertidal flats are denoted h_f .

Figure 1. Definition sketch of variables used throughout this report. Subplots (a), (c), and (e) show various embayment geometries, with the intertidal region shaded gray. The channel mouth is at the left boundary of the figure in all cases. Longitudinal cross sections (i.e., parallel to the x -axis) are shown in subplots (b) and (d) for the prismatic and convergent cases; note significant vertical exaggeration. Subplot (f) displays a transverse (i.e., perpendicular to the x -axis) cross section relevant to any of the embayment geometries.

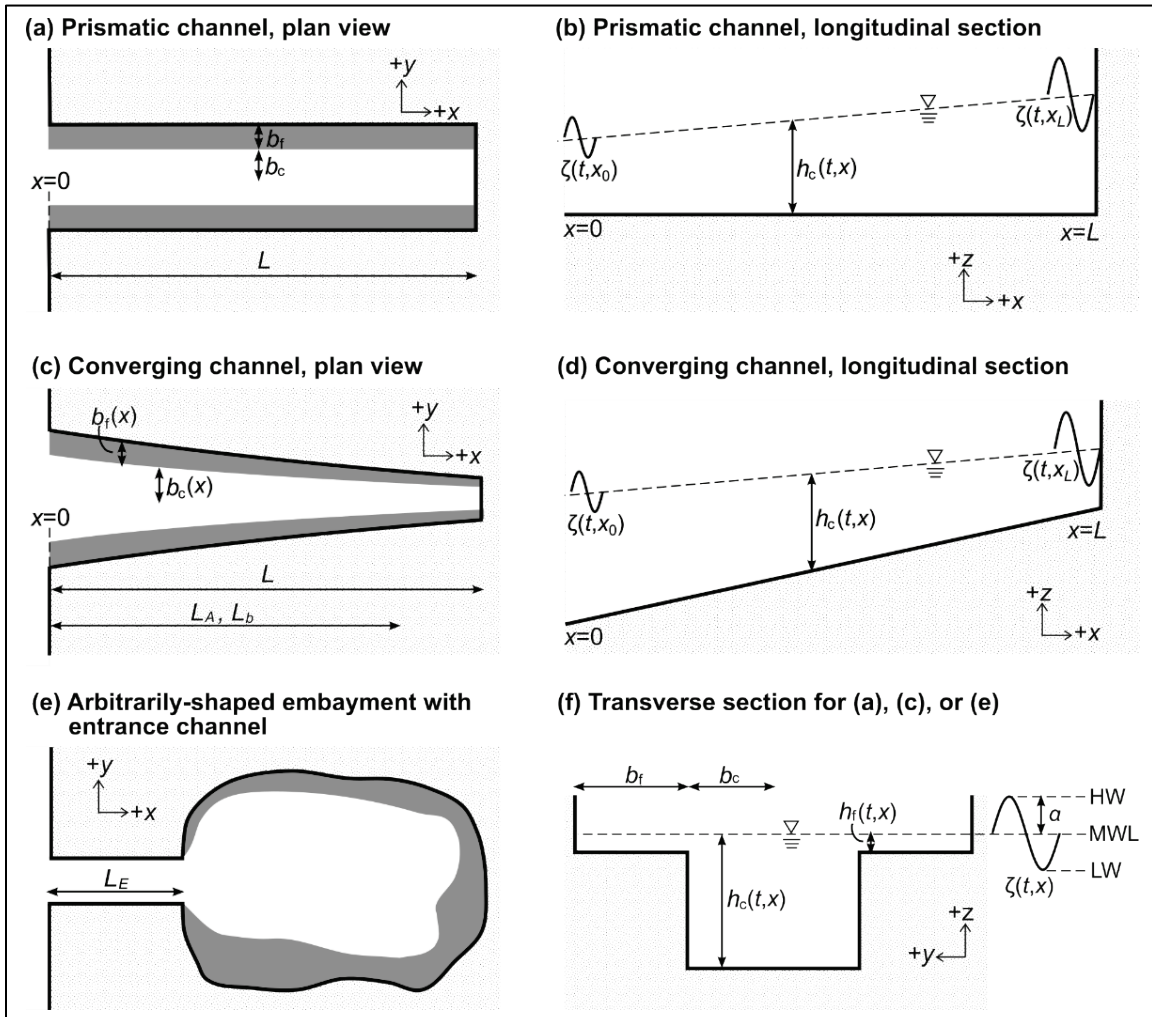


Table 1. Variables and abbreviations used throughout this report.

$A_{\text{cross}}(t, x)$	channel cross-sectional area at time t and position x
$A_{\text{plan}}(z)$	planform (hypsothetic) area of the basin at elevation z
A_v	vertical eddy diffusivity
$a(x)$	tidal amplitude at position x along a channel
$b(t, x)$	half-width of wetted cross-section at time t and position x
$b_c(x)$	half-width of the channel at position x
$b_f(x)$	half-width of the intertidal flats at position x
HW	high water level
C	Chezy coefficient
C_k	factor relating tidal prism and cross-sectional area
c_0	frictionless wave celerity
D_0	parameter related to tidal amplification in prismatic channels; see Equation 1
d_{50}	median grain size
Fr	Froude number
g	gravitational acceleration, 9.81 m/s^2
$h_c(t, x)$	water depth in channel at time t and position x
$h_f(t, x)$	water depth on intertidal flats at time t and position x
i	imaginary number, $\sqrt{-1}$
K_v	vertical exchange coefficient of salt
k	wave number
k_0	parameter related to tidal amplification in prismatic channels; see Equation 1

Table 1. (cont.) Variables and abbreviations used throughout this report.

k_s	bed roughness height
L	length of a channel or embayment along the primary axis
L_A	e-folding length of channel cross-sectional area
L_b	e-folding length of channel width
L_e	length of entrance channel
LW	low water level
MWL	mean water level
n	Manning's friction coefficient
$P(t, x)$	wetted perimeter
PSU	practical salinity units
$p(t, x, z)$	pressure
$Q(t, x)$	water discharge
$Q_L(t)$	water discharge at $x = L$ (i.e., the river discharge)
Q_ℓ	volumetric longshore sediment transport
R	hydraulic radius
Ra	Rayleigh number
Ri	Richardson number
r_*	Nondimensional friction parameter; see Equation 7
rms	root-mean square
S	slope
s	salinity
s_b	salinity at bed
s_s	salinity at water surface
SPM	suspended particulate matter

Table 1. (cont.) Variables and abbreviations used throughout this report.

SSC	suspended sediment concentration
T	tidal period
U_E	estuarine exchange flow
$u(t, x)$	representative flow velocity at time t and position x
u_s	velocity at water surface
V	volume
V_c	channelized volume of water at MWL
x	coordinate measured along primary axis of channel (note $x = 0$ at coast and $x = L$ at channel head)
y	transverse coordinate
z	vertical coordinate which increases upwards
α	empirical coefficient relating cross-sectional area to tidal prism
β	saline expansivity from equation of state
γ	parameter related to tidal asymmetry; see Equation 26
$\zeta(t, x)$	water surface elevation relative to local MWL
κ_r, κ_i	real and imaginary components of wavenumber κ ; see Equation 11
Λ_e	nondimensional convergence number; see Equation 8
λ	fitted power relating tidal prism and cross-sectional area
μ	amplitude growth factor for convergent channels; see Equation 4
ρ_w	density of water
ρ_s	density of sediment
Ω	tidal prism
ω	tidal frequency

Variables written with a superscript star (e.g., h^*) denote a spatially averaged value, which is treated as representative of the entire system.

The operator $\|\cdot\|$ returns the magnitude of a complex number.

Angular brackets $\langle \cdot \rangle$ indicate that the enclosed variable is time averaged over one tidal cycle.

3 Changes in Tidal Range

3.1 Physical mechanisms of tidal amplification and damping

Many authors have attempted to develop analytical solutions for tidal damping and amplification in coastal embayments (e.g., Hunt 1964; Dronkers 1964; LeBlond 1978; Prandle and Rahman 1980; Jay 1991; Friedrichs and Madsen 1992; Friedrichs and Aubrey 1994; Lanzoni and Seminara 1998; Savenije et al. 2008; Toffolon and Savenije 2011; Van Rijn 2011), with varying assumptions about frictional effects, estuarine geometry, and the retention of higher-order terms in the equations of motion. Tidal damping describes a decrease in tidal range, and tidal amplification describes an increase in tidal range. Notable for their conceptual simplicity are the analyses of Friedrichs and Madsen (1992) and Friedrichs and Aubrey (1994), which respectively consider tidal behavior in prismatic and convergent channels.

The major conclusions from these two papers are summarized in the following paragraphs.

Friedrichs and Madsen (1992) defined a frictionally dominated tidal system as an environment in which the friction term in the equations of motion is one to two orders of magnitude larger than the local and convective acceleration terms. These systems tend to be well mixed, with flow velocities of approximately 0.5 m/s ^(1,2) and an amplitude-to-depth ratio exceeding 0.1. Under such conditions, the propagation of the tide is governed by a nonlinear diffusion equation derived from balancing the friction term and the water surface gradient (e.g., LeBlond 1978). Analytical results for blind, prismatic channels (Figure 1a and 1b) forced at the mouth by the principle lunar semi-diurnal (M₂) constituent indicate that along-channel variations in M₂ amplitude are predominantly characterized by two non-dimensional parameters (Friedrichs and Madsen

¹ For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248-52, <https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf>.

² For a full list of the unit conversions used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 345-7, <https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf>.

1992). First, tidal damping is enhanced with increasing values of x/L , where x is distance from the mouth and L is the total length of the channel. The second key non-dimensional parameter is $||k_0||L$, where

$$k_0 = (i\omega/D_0)^{\frac{1}{2}} \quad (1)$$

$$D_0 = \frac{b_c^* (\langle h_c \rangle^*)^{\frac{5}{3}}}{n \langle b \rangle^* |\partial \zeta / \partial x|^{1/2}^*}$$

and

$$b(t, x) = \begin{cases} b_c(z), & z(t, x) \leq MWL(x) \\ b_c(z) + b_f(z) & z(t, x) > MWL(x) \end{cases}$$

In Equation 1, ω is the frequency of the forcing tide and n is Manning's friction coefficient; the remaining variables are as defined in Figure 1. Starred variables (*) indicate a spatially averaged value which is representative of the full system. The operator $|| \cdot ||$ returns the magnitude of a complex number. Tidal damping is enhanced for increasing values of $||k_0||L$, which is inversely related to D_0 (Equation 1). This implies that the tide should damp more strongly with higher friction (n). Damping should also be enhanced when the ratio of time-averaged total system width to channelized width ($\langle b \rangle^* / b_c^*$) is large. In contrast, a lower damping rate is expected as the depth h_c increases.

The analytical results of Friedrichs and Madsen (1992) assume a prismatic channel geometry (i.e., the cross section of the channel is unchanged along L). Other studies have evaluated how along-channel variations in geometry may change these results. For example, Friedrichs and Aubrey (1994) derived an analytical solution for strongly convergent, frictional tidal channels by assuming that channel width and cross-sectional area were exponential functions. Similar to the results for frictional prismatic channels (Friedrichs and Madsen 1992), the solution reduces to a balance between water surface gradient and friction provided that the observed waveform propagation speed c is similar in magnitude to the frictionless speed $c_o = \sqrt{gh_c}$. At first order, tidal elevations along the channel are given by

$$\zeta(t, x) = a_0 \cos(\omega t - kx) \quad (2)$$

where $a_0 = a|_{x=0}$ is the forcing amplitude at the mouth and k is the wave number. Specifically, Equation 2 implies that tidal amplitude will remain constant along the full length of the channel. At second order, local accelerations enter the solution, and the dominant tidal constituent becomes

$$\zeta(t, x) = a_0 e^{\mu k x} \cos(\omega t - kx) \quad (3)$$

Here, μ is an amplitude growth factor given by

$$\mu = k L_A \left[(c/c_0)^2 - 1 \right] \quad (4)$$

with L_A denoting the e -folding length of cross-sectional area. Note that when $c > c_0$, μ is positive, and Equation 3 predicts that the tide will amplify with distance inland. When $c < c_0$, the tide is predicted to damp. The rate of amplification or damping is further modulated by the convergence length of the system (L_A) relative to the tidal wavelength.

As several of the variables in Equations 1 through 4 can be anthropogenically changed, engineered modifications to a tidal system may alter natural patterns of damping or amplification. Winterwerp and Wang (2013) developed a similar semianalytical model to investigate the impacts of engineering modifications. Two of the key components are hydraulic drag and tidal amplification.

Winterwerp and Wang (2013) note that dredging affects hydraulic drag in three ways. First, given the Chezy relationship

$$u = C \sqrt{RS} \quad (5)$$

with

$$C = 18 \log_{10}(12h_c/k_s) \quad (6)$$

where u is flow velocity, R is hydraulic radius, S is slope, and k_s is the roughness height, it is seen that increasing h_c by dredging will lead to an increase in u due to lower hydraulic drag. Second, decreasing the roughness height k_s by the removal of bedforms will likewise generate higher flow velocities. Third, if dredging leads to an enhancement in suspended sediment concentration (SSC), the resulting flow stratification

will reduce dissipation at the bed (e.g., Soulsby and Wainwright 1987; Winterwerp et al. 2009). The increase in C due to enhanced SSC may be three to six times larger than the increase due to either a larger h_c or a smaller k_s (Winterwerp and Wang 2013).

Winterwerp and Wang (2013) relate differences in the Chezy coefficient C to tidal amplification through a dimensionless friction parameter r_* and a dimensionless convergence number Λ_e . The non-dimensional friction parameter, r_* , is related to C by

$$r_* = gu/(\omega h_c C^2) \quad (7)$$

where g is gravitational acceleration and u is characteristic depth averaged maximal velocity. The non-dimensional convergence number, Λ_e , is defined as

$$\Lambda_e = 4L_b^2 \omega^2 (2b_f + 2b_c)/(gA_{cross}) \quad (8)$$

where A_{cross} is the area of the flow-carrying cross section (the product of channel width, $2b_c$, and depth h_c), b_f is the intertidal half-width, and L_b is the convergence length. Convergence length, L_b , can be obtained from the assumed estuary shape of

$$b_c = b_0 e^{-x/L_b} \quad (9)$$

which becomes

$$L_b = x/[\ln(b_{c,0}) - \ln(b_c)] \quad (10)$$

where $b_{c,0} = b_c|_{x=0}$ is the flow carrying channel half-width at the mouth of the estuary.

Winterwerp and Wang (2013) develop a linearized analytical model for shallow water equations in exponentially converging estuaries. This model includes a real and imaginary wave number as functions of Λ_e and r_* (Winterwerp and Wang 2013), which are expressed nondimensionally as

$$\kappa_r = \pm \frac{1}{2} \left[2\sqrt{(\Lambda_e - 1)^2 + (\Lambda_e r_*)^2} + 2(\Lambda_e - 1) \right]^{\frac{1}{2}} \quad (11)$$

and

$$\kappa_i = \pm \frac{1}{2} \left[2\sqrt{(\Lambda_e - 1)^2 + (\Lambda_e r_*)^2} - 2(\Lambda_e - 1) \right]^{\frac{1}{2}} \quad (12)$$

where the non-dimensional κ_r and κ_i are related to k by

$$k = (\kappa_r + \kappa_i)/2L_b \quad (13)$$

which yields small values of k and tidal amplification for small values of r_* and Λ_e . The impact of small Λ_e values, from a decrease in A_c or b_f or an increase in h , can be offset by larger r_* values, such as the difference between mud ($r_* \approx 1$) and sand ($r_* \approx 6$; Winterwerp and Wang 2013). This interaction indicates that friction and bed composition are important factors in tidal propagation through estuaries. Winterwerp and Wang (2013) developed these equations assuming a small, narrow, exponentially converging estuary with a rectangular cross section, so they are not expected to apply directly to the wide variety of tidally influenced bays and rivers in which dredged sediment is placed, though general observations may be similar across many systems.

3.2 Specific examples of tidal damping and amplification

Engineering modifications have altered a number of characteristics relevant to tidal propagation in many estuaries. Many of these alterations can be grouped into three categories: channel deepening, flow connectivity or hydraulic conveyance changes, and interior shoreline changes. Tidal amplitude has been suggested to take varying amounts of time to respond to system modifications, with gradual changes over two decades not unheard of (Nestler and Long 1994; Winterwerp et al. 2013). Many of the modifications and characteristics which have altered tidal amplitudes can also impact estuarine circulation and salinity intrusion (Section 4).

3.2.1 Channel deepening

Channel deepening and widening have been observed in many systems to correspond with increased tidal ranges. Equation 1 represents channel deepening by an increase in h_o , which increases D_o and decreases k_o . Increased channel depths are represented in Equations 7 and 8 by

increases in h_c , which decreases r_* and Λ_e , resulting in decreased κ_r and κ_i values. Wave number (i.e., k , k_0 , κ_r , or κ_i ; see Equations 11 through 13) decreases are related to tidal amplification.

Reductions in tidal damping or transitions from tidal damping to amplification have been attributed to channel deepening in many estuaries. As examples, channel deepening and land reclamation appear to have increased tidal amplitudes in the Columbia River, Oregon/Washington, (Jay et al. 2011); the Coos Bay Estuary, Oregon (Eidam et al. 2020), the Cape Fear River Estuary, North Carolina, (Familkhalili and Talke 2016); the Thames, United Kingdom (Amin 1983; Prandle and Wolf 1978); the Ems, Germany (de Jonge et al. 2014); the Loire, France (Winterwerp et al. 2013); the Upper Sea Scheldt, Belgium (Winterwerp et al. 2013); the Rhine-Meuse, the Netherlands (Vellinga et al. 2014); and the Modaomen (Cai et al. 2012) and Lingdingyang (Zhang et al. 2021) of the Pearl River Estuary, China, among others. A similar effect on tidal amplitudes was observed in the Hudson, New York (Ralston et al. 2019), following the transition from a shallow, braided, multi-channel system with numerous islands to a deeper single channel.

Many authors relate channel deepening and land reclamation to increased depth and reduced frictional effects as part of the physical explanation for tidal amplification. Tidal amplitudes in Newark Bay, New Jersey, increased following channel deepening and widening and land reclamation throughout much of the twentieth century, but amplitudes had not changed within 3 yr of the 2005 deepening (Chant et al. 2018). This could be related to the delayed interaction between many engineering works and changes in tidal amplitudes described in Winterwerp et al. (2013), but estuarine exchange flow more than doubled in a similar timeframe (Chant et al. 2018) (see Section 4). Estuarine exchange flow generally responds relatively quickly to system changes. MacCready (1999) estimated a response time of fewer than 30 days in many estuaries. Tidal amplification has been observed to be most extreme in the upper estuary at a number of locations, including the Hudson (Ralston et al. 2019), the Ems (de Jonge et al. 2014), the Loire (Winterwerp et al. 2013), and the Modaomen (Cai et al. 2012).

An inverse relationship between tidal range and shoaling has also been observed. For example, tidal damping was enhanced after shoaling along the Passaic River in the upper reaches of Newark Bay (Chant et al. 2018). The tide also damped in the upper Mersey Estuary, United Kingdom, after

shoaling and bay volume reduction (Lane 2004), and in the Danshuei River estuary, Taiwan, after flood control structures reduced the channel cross section (Liu 2005).

3.2.2 Flow connectivity and hydraulic conveyance changes

Tidal amplitude can also be impacted by changes to flow connectivity and hydraulic conveyance. Flow connectivity is used here to describe the ability of tidal energy to propagate through the areas that it enters. Flow connectivity can increase as inlets are opened or both ends of waterways are opened where previously only one end had been open. Flow connectivity can decrease as one end of a waterway is closed off, or areas are added which are only open at one end. Generally, increasing flow connectivity appears to increase tidal amplification, and vice versa. Hydraulic conveyance is inversely proportional to the frictional forces influencing tidal propagation and increases as friction decreases. Increased hydraulic conveyance tends to increase tidal amplitude. Modifications to paths through which the tide propagates or the friction resisting that propagation can directly impact tidal amplitudes.

Waterway closures and openings in the Rhine-Meuse Delta provide one example of flow connectivity and tidal damping. Water level analyses by Vellinga et al. (2014) indicate that closing off the direct tidal flow into the Haringvliet Estuary and forcing more of the shared river discharge and tidal flow through the New Waterway decreased tidal amplitudes throughout the system. The connecting waterways between the New Waterway and the Haringvliet Estuary received tidal energy but did not transmit it upstream on the New Waterway, which Vellinga et al. (2014) describes as similar to adding large retention basins. Sluice gate removal on the Hartel Canal had a similar local effect, where tidal energy was allowed to enter the canal, but the other end remained closed, so this energy was not transmitted upstream (Vellinga et al. 2014). Restoring the hydraulic connectivity of the Hartel Canal increased nearby tidal ranges (Vellinga et al. 2014). This can be thought of as converting a retention basin into a side channel, allowing the Hartel Canal to transmit the tidal energy it receives. From a mass conservation perspective, fewer side basins can be expected to initially increase the volume of water in the main channel and amplify the tides. From a friction perspective, fewer side basins corresponds to lower frictional resistance, also contributing to tidal amplification.

As an example of increased hydraulic conveyance and decreased tidal damping, the addition of jetties and flow training structures along the eastern coast of Australia is correlated with increased spring tidal ranges by 1.8 mm/year since 1990 in Wallis Lake (for a total 55% increase), by 3.0 mm/yr since 1997 in Lake Wagonga, and 1.7 mm/yr since 1990 in Lake Macquarie (Nielsen and Gordon 2017). This response is partly attributed to increased hydraulic efficiency from the jetties and training structures hardening the shoreline, although increased hydraulic efficiency through the surf zone may have been a secondary contributor. The increased tidal prism has also scoured the channels (see Section 5), so channel depths have increased. This may favor further amplification (e.g., higher values of h_c in Equation 1).

Some of the training structure and hardened shoreline impact on hydraulic conveyance can be approximated with the Manning equation for open channel flow, following Nielsen and Gordon (2017), as

$$u = (A_c/P)^{\frac{2}{3}} S^{\frac{1}{2}} / n \quad (14)$$

where u is channel velocity, A_c is channel cross-sectional area, P is wetted perimeter, S is water slope, and n is Manning's roughness. As discussed in Nielsen and Gordon (2017), steepening side slopes from 1:10 to 1:2 and leaving the cross-sectional area the same has the direct impact of decreasing wetted perimeter P , and increasing u by 16% if only one side is steepened and 20% if both sides are steepened. Increased hydraulic efficiency can let the tide propagate past with more energy, increasing tidal range farther into the bay. Additionally, reduced frictional effects from channel deepening and straightening and the conversion from arrowhead to parallel jetties were suggested to decrease tidal damping in Barnegat Bay, New Jersey (Seabergh et al. 2003). Earlier channel cross-section reduction and tidal prism reduction at Barnegat Inlet was attributed to increased frictional effects of the sand dike rerouting flow to a longer, narrower secondary channel, but tidal amplitudes were not investigated directly (Seabergh et al. 2003).

Hydraulic conveyance is also related to the frictional effects that bed composition and suspended sediment can modulate. Anthropogenic changes to bed composition and suspended sediment are largely unintended consequences of other modifications but have been suggested to contribute to tidal amplification. Winterwerp and Wang (2013) argue

that river flushing capacity decreases with channel depth and that reduced flushing capacity can import and trap available fine sediment, lowering hydraulic drag and leading to tidal amplification. Winterwerp et al. (2013) argue that anthropogenic modification has reduced hydraulic drag in the Ems, the Loire, and the Upper Sea Scheldt, contributing to tidal amplification at each location. In the Ems and the Loire, hydraulic drag reduction, tidal amplification, and flood dominance (see Section 6) favor a transition into hyper-turbid conditions (Winterwerp et al. 2013). The opposite scenario has also been observed; for example, SSC reductions due to upstream dam construction between 1997 and 2000 coincided with a 2% reduction in tidal amplitude on the lower Yangtze (Li et al. 2012; Wang et al. 2015).

River discharge can also contribute to the frictional forces resisting to tidal propagation. As examples, tidal amplification appears to be offset by high river discharge in the Columbia River (Jay et al. 2011) and enhanced by reduced river discharge in the Modaomen (Cai et al. 2012). Similarly, Wang et al. (2019) found that greater river discharge corresponded with smaller tidal amplification in the Western Scheldt, and vice versa.

3.2.3 Interior shoreline changes and land reclamation

The interior shorelines along many rivers and estuaries have been heavily modified over the past few centuries. Shoreline changes have often involved intertidal area and wetland removal, which can impact multiple parameters in Equation 1. This narrowing leaves b_c largely unchanged, but reduces b_o , resulting in a larger D_o , smaller k_o , and larger tidal amplitude. Smoother, straighter shorelines with fewer shallow areas or vegetation can be represented by reduced friction (e.g., Jay et al. 2011; Nielsen and Gordon 2017; Ralston et al. 2019), such as a lower Manning's n , which also increases D_o and corresponds to larger tidal amplitudes. As an example, the spring tidal range has increased by up to 100% in the Pussur Estuary, Bangladesh, following severe channel constriction (approximately 1,000 km² intertidal area reduction and the removal of 2,000 km of secondary creeks and channels; Pethick and Orford [2013]).

Shoreline changes are often accompanied by channel deepening. This co-occurrence can complicate separating the impacts of each. In most examples discussed in Section 3.2.1, channels were both deepened and widened, and shallow channel adjacent areas were narrowed. Many authors do not specifically discuss differences between the effects of deepening and

shoreline change. Ralston et al. (2019) discuss shoreline hardening and wetland loss along the Hudson Estuary as factors that would reduce friction but apply the same drag coefficient for the historic and modern conditions. Prandle and Wolf (1978) found that observed tidal amplification and phase advance (tides arriving earlier over time) in the Thames could be reproduced by both increasing the estuary depth and decreasing the friction, which Amin (1983) ascribe to a combination of dredging, sea-level rise, and embankment hardening. Jay et al. (2011) suggest that the observed low and mean water level decreases and high water level increases in the Columbia were also likely the result of both channelization directing the flow into a narrower, deeper channel and drag reduction from diking, flow path straightening, and bank smoothing. The shorelines of the Loire were hardened in the early twentieth century, reducing convergence length (L_b) by 16%–30% and the intertidal area ratio (b_f/b_c) from 1 to 0.1 (Winterwerp et al. 2013). In combination with channel deepening, this shoreline hardening appears to have reduced tidal damping and initiated the shift towards amplification (Winterwerp et al. 2013).

Differences between the impacts of deepening and shoreline change on tidal amplification can be difficult to assess when these changes are concurrent. In two of the Section 3.2.1 examples, sensitivity analyses arrived at opposite conclusions for two different systems. Zhang et al. (2021) estimated that shoreline change had a larger impact on tidal amplification in Lingdingyang Bay. Zhou et al. (2016) also investigated tidal amplification in Lingdingyang Bay and found that shape index (the ratio of perimeter to the square root of area) and fractal index (a statistical index of complexity) changes associated with large-scale land reclamation projects correlated with the observed 23% increase in tidal range ($R^2 \approx 0.87$). In contrast, Familkhalili and Talke (2016) found that deepening had a larger impact on tidal amplification in the Cape Fear River Estuary.

3.3 Implications for wetland placement

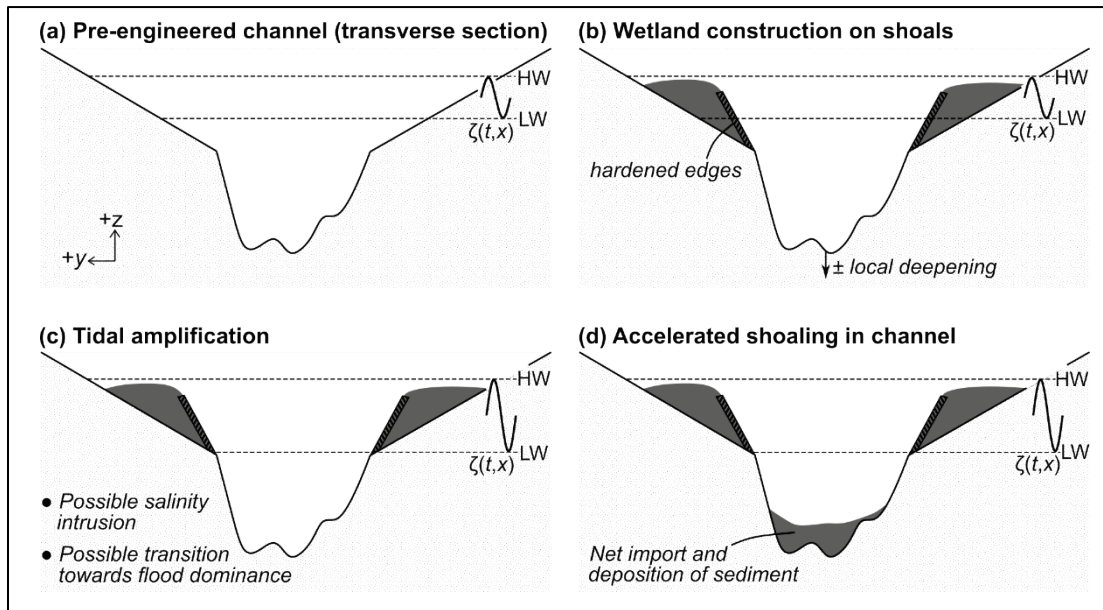
Tidal amplification is generally concurrent with additional tidal property changes. A variety of estuary modifications have been observed to alter tidal propagation in many locations (e.g., tidal phase changes) (Amin 1983; Cai et al. 2012). These engineering works have been implemented to serve other purposes, but tidal amplification or damping has been an unintended consequence. Tidal amplification can impact navigation in a variety of ways.

Many of the largest morphodynamic responses observed following tidal amplification have been related to estuarine circulation and salinity intrusion, which is described in detail in Section 4. Tidal amplification can also increase tidal prism, which can be related to net erosion. A detailed description of changes to tidal prism and morphologic responses is provided in Section 5. In addition to the variety of morphodynamic responses associated with tidal amplification, reduced depths at low water can also directly impact limiting navigation depths in some instances. Altered water levels have impacted low tide more than high tide on the Columbia River (Jay et al. 2011) and the Hudson (Ralston et al. 2019). The forces driving some of these tidal amplifications are also suggested to lower mean water levels (e.g., Lane [2004], in the Mersey; Ralston et al. [2019], in the Hudson; Jay et al. [2011], in the Columbia), exacerbating the impact of more extreme low tides on navigability.

The modifications associated with observed tidal amplitude changes have generally been larger than implemented or planned wetland nourishments, but large-scale wetland nourishment may have the potential to modify similar characteristics relevant to tidal amplification. Additionally, tidal amplitude responses likely vary between different wetland nourishment strategies. Tidal amplification largely follows convergence effects and is inversely related to frictional effects.

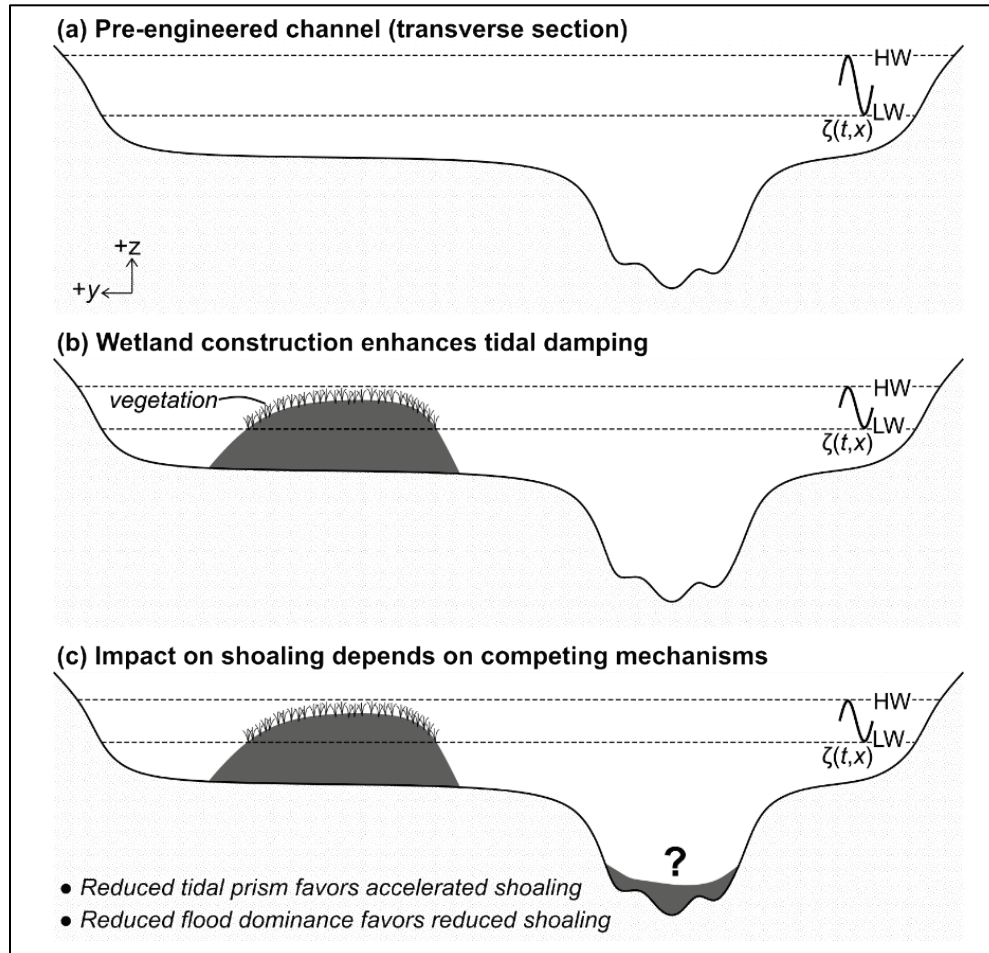
Figure 2 displays a hypothetical scenario in which wetland construction may lead to tidal amplification. In this example, a wetland is constructed on the shoals near a navigation channel, with hard retaining structures preventing downslope movement from the wetland into the channel (Figure 2b). Increasing the elevation of the shoals within the tidal reference frame reduces the ratio $\langle b \rangle^* / b_c^*$ in Equation 1, generating higher values of D_0 (Equation 1) and is predicted to reduce tidal damping (Figure 2c). If the sediment used for wetland construction were locally sourced, then the local deepening of the channel will increase $\langle h_c \rangle^*$ in Equation 1, further increasing D_0 and decreasing the damping rate. The consequent tidal amplification may increase the salinity intrusion or alter the estuarine circulation (Section 4), and a reduction in waveform celerity at low tide may enhance flood dominant sediment transport (Section 6). Any of these hydrodynamic changes may increase the net import of sediment into the channel and accelerate shoaling (Figure 2d).

Figure 2. Generalized illustration of hypothetical tidal amplification effects in response to wetland construction with embayment narrowing and bank hardening. A navigation channel transect bordered by intertidal flats (subplot a) is modified by constructing wetlands with hardened edges and potentially increasing the local channel depth (subplot b). Embayment narrowing, hardening, and deepening may cause tidal amplification (subplot c), which may increase shoaling in the navigation channel by changing the system's salinity dynamics and/or delaying the propagation of low tide, favoring flood dominant sediment transport (subplot d).



An alternative scenario may occur if the constructed wetland is positioned far from the channel in a wide embayment (e.g., Galveston Bay) and enhances frictional dissipation (Figure 3). In this configuration, the effects of channel constriction are largely avoided, and higher values of Manning's n due to intertidal vegetation favor tidal damping (Equation 1). However, the net effect of these changes is ambiguous and must be evaluated on a site-specific basis. The combination of smaller tidal amplitudes and delayed high-water propagation may promote a transition towards ebb dominance (Section 6), and it is possible that the net import of sediment into the channel will be reduced. Alternatively, the reduction in tidal prism may lead to lower flow velocities and higher shoaling rates. If the wetland is constructed using sediment dredged from the nearby navigation channel, these effects may also be superseded by the opposing influence of channel deepening.

Figure 3. Generalized illustration of tidal damping in response to wetland construction in the subtidal region of a wide bay. Subplot (a) shows a transverse section of a wide embayment (e.g., Galveston Bay) with a navigation channel. In (b), a wetland is constructed by placing dredged sediment in a subtidal area far from the channel. Frictional dissipation is enhanced due to the addition of vegetation in the intertidal region and may reduce the tidal amplitude. However, the effect on shoaling in the channel is likely to be site specific. Whereas the reduction in tidal prism may cause accelerated shoaling (subplot c), delaying the propagation of high water may also reduce flood dominance and promote sediment flushing.



4 Changes in Salinity

4.1 Definition of estuarine circulation

In coastal embayments receiving freshwater discharge from upstream, the mixing of fresh and saline water is a critical component of the sediment transport dynamics. Due to the density difference between river (fresh) and sea water, it is typical for density-driven convection to be established in such environments. This convection, commonly known as *estuarine circulation* or *exchange flow*, is characterized by residual inland-directed transport near the bed and residual seaward-directed transport near the surface of the channel (e.g., MacCready and Geyer 2010; Becherer 2013). MacCready and Geyer (2010) provide the following simple description of the underlying physics: the salinity-induced variation in water density between the mouth of the estuary and the head generates an along-channel pressure gradient $\langle \partial p / \partial x \rangle < 0$, with p denoting pressure and the coordinate system as defined in Figure 1. This pressure differential causes seawater to flow into the estuary; the seawater remains near the bed due to the buoyancy of freshwater. The density-driven flux of water into the channel raises the water level near $x = L$, i.e., $\langle \partial \zeta / \partial x \rangle > 0$. This head gradient in turn drives a seaward-directed surface flow (see also Pritchard [1952]).

The magnitude of estuarine circulation is a function of the embayment's geometry, freshwater input, and tidal energy (Hansen and Rattray 1966), which together control the mean horizontal advection and the vertical diffusion of saltwater (Pritchard 1954). The relative strength of these parameters determines the estuary classification. When tidal currents are weak, the fresh water floats atop the seawater and creates a highly stratified or *salt wedge* estuary. In this scenario, there is a sharp horizontal boundary between salt and fresh water along the full length of the estuary while horizontal salinity gradients are less significant (i.e., $\partial s / \partial x \ll \partial s / \partial z$, with s denoting the salinity). Systems with greater energy for mixing tend to be slightly stratified with non-negligible vertical and along-axis salinity gradients. When tidal energy is high and river input is low, systems tend to become well mixed in the vertical ($\partial s / \partial z \approx 0$), with $\partial s / \partial x$ becoming the dominant salinity gradient.

Hansen and Rattray (1966) proposed that all estuaries could be classified based on stratification and circulation. The circulation parameter was

defined as the ratio of the net surface current to the depth-averaged freshwater current:

$$\text{circulation parameter} = \langle u_s \rangle / (2Q_L \langle h_c \rangle \langle b_c \rangle) \quad (15)$$

where u_s is the velocity at the surface of the estuary and $Q_L = Q|_{x=L}$ is the river discharge. The stratification parameter was defined as the ratio of the top-to-bottom salinity difference to the cross-sectionally averaged salinity, or

$$\text{stratification parameter} = (s_b - s_s) / s_{\text{cross}} \quad (16)$$

The subscripts s and b respectively denote the surface and the bed of the estuary. This classification scheme emphasizes that the stratification and circulation are distinct features of estuarine behavior. For example, well-mixed estuaries have low stratification parameters, and the circulation parameter is also low because the net flow is seaward regardless of depth. However, certain natural systems such as the Columbia River mouth at high river discharge display a higher stratification parameter. Nevertheless, the circulation parameter remains low because the net flow is seaward at all depths.

Other authors have proposed alternative parameters for characterizing the relative strength of stratification and circulation. The baroclinic circulation in an embayment is represented by the densimetric Froude number, defined as

$$Fr = u_L (\rho_0)^{\frac{1}{2}} / \sqrt{g \langle h_c \rangle (\rho_{w,0} - \rho_{w,L})} \quad (17)$$

where $u_L = u|_{x=L}$ is the flow velocity of freshwater input, $\rho_{w,0} = \rho_w|_{x=0}$ is the density at the mouth ($\rho_{w,0} \approx 1025 \text{ kg/m}^3$ if the mouth is fully saline), and $\rho_{w,L} = \rho_w|_{x=L} \approx 1000 \text{ kg/m}^3$ is the density of water at the upstream limit of tidal intrusion. Equation 17 characterizes the relative importance of river flow versus the potential for density-induced gravitational circulation (Hansen and Rattray 1966; Fischer 1976; Díez-Minguito et al. 2013). Hansen and Rattray (1966) report a strong correlation between Fr and the Rayleigh number,

$$Ra = \beta g(s_0 - s_L)\langle h_c \rangle^3 / (A_v K_v) \quad (18)$$

where $s_0 = s|_{x=0}$ is the salinity at the mouth, $s_L = s|_{x=L}$ is the river salinity, β is the saline expansivity from the equation of state relating salinity and density, A_v is the vertical eddy diffusivity, and K_v is the vertical exchange coefficient of salt. A_v and K_v are both driven by tidal energy, which allows for turbulent mixing. Higher values of Ra correspond to a stronger estuarine circulation (Festa and Hansen 1976). The expression for estuarine exchange flow magnitude is similar in form to Equation 18:

$$U_E = \frac{g\beta \langle h \rangle^3}{48 A_v} \frac{\partial s}{\partial x} \quad (19)$$

(MacCready and Geyer 2010). However, Equation 19 explicitly accounts for the effect of estuary length via the ∂x term whereas Equation 18 does not consider the distance over which the salinity gradient extends.

As a substitute for Equation 16, stratification has also been characterized by the estuarine Richardson number,

$$Ri = (\rho_{w,0} - \rho_{w,L})gQ_L / (2\rho_{w,0}\langle b_c \rangle (u_{rms})^3) \quad (20a)$$

(Hansen and Rattray 1966; Fischer 1976), where u_{rms} is the root-mean-squared horizontal velocity. Equation 20a is based on a ratio of freshwater buoyancy to turbulent tidal mixing, with $Ri > 0.8$ corresponding to stratification and $Ri < 0.08$ corresponding to well-mixed systems. If $Q_L = 2u_{rms} \langle b_c \rangle \langle h_c \rangle$, then Equation 20a reduces to

$$Ri = (\rho_{w,0} - \rho_{w,L})g\langle h_c \rangle / (\rho_{w,0}(u_{rms})^2) \quad (20b)$$

which is the form used by King (1966).

Because suspended sediment concentrations tend to be greatest near the bed (e.g., Burchard et al. 2008), the net inland transport in the lowest layers of the estuary has significant implications for shoaling in navigation channels. In particular, engineering projects that increase the magnitude of estuarine circulation may cause an increase in the net volume of sediment transported into the system. Considering that Ri is directly proportional to the time-averaged depth $\langle h_c \rangle$ (Equation 20b), deepening the navigation channel is likely to enhance stratification because greater turbulent energy is required to homogenize the salinity gradient in deeper channels. If the

estuary's tidal prism remains constant after deepening, then the cross-sectionally averaged velocity u_{rms} will also decrease to conserve mass; this is predicted to generate an even larger increase in Ri . A similar conclusion may be drawn from Ra (Equation 18), which predicts a significant increase in estuarine circulation with increasing values of $\langle h_c \rangle$.

Note that channel deepening is frequently associated with tidal amplification (Section 3), which may lead to larger values of u_{rms} (e.g., Chant et al. 2018). Systems with higher tidal energy tend to be less stratified (i.e., lower values of Ri) because there is more energy available for vertical mixing. For example, many natural systems tend to display greater stratification and more significant circulation during neap tides due to the lower turbulence intensity (e.g., the Hudson River, Peters [1997]; the Chesapeake Bay, Haas [1997]; Li and Zhong 2009; and the Puget Sound entrance channel, Geyer and Cannon [1982]). However, in certain systems such as the Tees Estuary, the estuarine circulation increases during spring tides (Lewis and Lewis 1983).

Even if a system becomes better mixed in response to increasing tidal range, tidal amplification may cause a vertically homogenized plug of saline water to penetrate farther upchannel. This is significant for sediment transport due to the tendency for clay flocculation at the saltwater-freshwater interface. Floc size, and thereby settling velocity, increases with increased salinity (Kondo and Torrance 2005). For example, increasing the salinity from 0 to 30 PSU during laboratory experiments was found to increase the settling velocity by a factor of 6.5 (Portela et al. 2013). If tidal amplification shifts the freshwater-saltwater interface towards larger values of x , the depositional locus may shift farther inland and enhance local shoaling (e.g., Jiang et al. 2013; Sutherland et al. 2014), even in unstratified or non-circulating systems.

4.2 Examples without amplification

The Chesapeake Bay is considered the archetypal example of estuarine circulation and salinity dynamics following the classic papers of Pritchard (1952, 1954, 1956) and Cameron and Pritchard (1963). The Chesapeake Bay is partially mixed during most of the year, with a net inflow of saline water near the bed and a net outflow at the surface. Sedimentation in the Chesapeake is attributed to flocculation in the estuarine turbidity maximum, which spans a 32 km length of channel near the head of the bay (Schubel 1968; Sanford et al. 2001).

Salinity dynamics can vary widely both across and within systems. In the Lower Mississippi River, for example, channel deepening for navigation corresponds to an increased extent and duration of saltwater intrusion (i.e., the salt wedge) during periods of low river flow (Johnson et al. 1987). The upstream movement of the salt wedge can be drastic; during low river stages of the Mississippi River, salinities of approximately 27 PSU have been recorded in New Orleans, LA, which directly affects the city drinking water supply (Wright 1970). The mouth of the Mississippi River has the highest observed stratification parameter of any system considered by Hansen and Rattray (1966). The circulation parameter is low for high river discharge but increases by approximately an order of magnitude at low river discharge, emphasizing the importance of fluvial discharge for controlling estuarine circulation. This behavior is further modulated by relative channel depth. In the deeper Southwest Path distributary, which conveys a larger proportion of the freshwater input than the other passes, the salt plume behavior is controlled by river stage and discharge rather than by variations in tidal amplitude (Johnson et al. 1987). By comparison, Wright (1970) found that tidal oscillations more significantly influence salt wedge dynamics in the South Pass distributary, which conveys a smaller proportion of the fluvial discharge due to its shallower depth. From the perspective of sedimentation, flocculation near the boundary of saltwater intrusion has been observed as a major contributor to sediment transport in the lower Mississippi River (Parchure and Teeter 2002b). River-borne clays flocculate at the saltwater interface and ultimately form a *gel* mixture, which has been anecdotally noted by boat captains in the Mississippi River region to cause a strong draw on boat power due to the increased viscosity compared to seawater (Johnson et al. 1987; Kondo and Torrance 2005).

Another example of changing salinity and its effect on sedimentation occurred in Charleston Harbor, South Carolina. In 1942, freshwater discharge to the Cooper River estuary was increased by approximately 425 m³/s due to the diversion of the Santee River (Patterson 1983). The navigation channel was also deepened by 1.5 m between 1941 and 1943. Subsequently, shoaling rates in Charleston Harbor increased by two orders of magnitude, from 7×10^4 m³/year to 7.6×10^6 m³/year (Parchure and Teeter 2002a).

Patterson (1983) attributed the sudden acceleration in shoaling to the estuary's transition from well mixed to partially mixed, which was facilitated by the combination of deeper flow depths and excess fresh

water. The newly stratified flow in the channel caused the system to transition from net export to net import of sediment.

In Newark Bay, New Jersey, progressive deepening of the navigation channel correlates with changes in estuarine circulation. Between 1999 and 2008, the channel was deepened from 12 to 14 m, during which period the exchange flow was observed to double (Chant et al. 2018). The measured increase in exchange flow was larger than the value predicted by Equation 19. Chant et al. (2018) proposed that the greater-than-predicted increase in circulation was due to some combination of increasing the along-channel salinity gradient $\partial s / \partial x$ and decreasing the vertical eddy diffusivity A_v .

4.3 Examples with amplification

The Ems estuary, which drains into the North Sea at the German-Dutch border, is often cited as the archetypal example of hyperturbidity due to deepening. Between 1954 and 2005, sediment concentrations increased by a factor of 2 to 3 in the lower Ems estuary and a factor of 10 in the upper Ems. Modeling results from de Jonge et al. (2014) suggest that channel deepening reduced the hydraulic drag in the channel and shifted the turbidity maximum 25 km upstream from its pre-engineered location. Increasing turbidity levels further enhanced density-driven stratification. This shift in the locus of sedimentation occurred in association with significant tidal amplification, but a causal relationship between deepening, tidal range, and sedimentation is difficult to establish. The amplification may have been driven by reflections off the Herbrum weir (Schuttelaars et al. 2013) rather than being a direct consequence of deepening, and disturbance of the bed due to dredging may have contributed to higher sediment concentrations immediately after deepening (van Maren et al. 2015). However, it is generally accepted that the continuation of these hyperturbidity issues is related to salinity intrusion in the deepened channel.

Channels in the Mekong River Delta (Vietnam) have been scouring due to sediment starvation from upstream dams and sand mining, leading to M2 amplification a factor of 10 larger than that predicted from sea level rise alone (Eslami et al. 2019). While discharge rates have increased in the Mekong, salinity concentrations have also significantly increased as bed levels deepen and tidal amplitudes are magnified. The increased intrusion of salt water has led to severe degradation of agricultural soil quality and

fresh water supplies (Loc et al. 2021). This saline water has been associated with enhanced flocculation and high suspended sediment concentrations (Tien et al. 2020).

Correlations between channel depth, tidal amplification, and salinity have also been observed for harbors in the United States. Eidam et al. (2020) estimates that the channel at Coos Bay, Oregon, has been deepened by >4 m between 1865 and the present. In response, the tide has amplified, and salinity intrusion has increased. Sediment trapping in the bay during winter has more than doubled. Similarly, a numerical model of Tampa Bay, Florida, indicates that dredging the shipping channel increased in tidal range and led to a 4 PSU increase in salinity (Zhu et al. 2015). However, the authors of the Tampa Bay study did not directly model sediment transport, so it is unclear if salinity-induced circulation changes led to shoaling in this particular example.

However, note that dredging-induced changes in salinity do not always affect sediment transport and shoaling. In the Hudson River, dredging since the late 1800s has doubled the depth of the mouth, and the rest of the estuary has been deepened by 10% to 30% (Ralston and Geyer 2019). Tidal amplitude has more than doubled in the upper estuary in response to engineering, and both salinity and stratification have increased over the past century (Ralston et al. 2019). Interestingly, the estuarine circulation has not increased in response to enhanced stratification, and there have not been significant changes to the sediment concentration. Ralston and Geyer (2019) proposed that the absence of a circulation change was due to the simultaneous removal of shallow subtidal regions and overall narrowing of the system, where saltwater-freshwater mixing may have occurred in the pre-engineered configuration.

The Western Scheldt estuary is another example of a system in which sediment concentrations have not increased in response to deepening. Although tidal range along the Western Scheldt has increased over the past 50 yr (Wang et al. 2019) in association with deepening of the navigation channel, the system has not become hyperturbid. Numerical modeling of the system suggests that suspended sediment concentrations will not increase across a range of future dredging scenarios (Dijkstra et al. 2019); in fact, the deeper channel was predicted to have lower suspended sediment transport due to reduced bed shear and lower resuspension rates near the turbidity maximum. Because the Western Scheldt is vertically

well mixed (e.g., Baeyens et al. 1998), it is possible that the divergence in behavior between this location and the other examples discussed above may be related to differences in stratification and salinity dynamics.

4.4 Implications for wetland placement

Dredging and wetland placement within a coastal embayment have the potential to alter several terms in Equations 15 through 20b, influencing shoaling rates. If the wetland is constructed with locally dredged sediment, then the associated increase in channel depth h_c may generate a significant increase in estuarine circulation (e.g., Equation 18 or 19). A stronger net inland-directed flow near the bed may lead to higher shoaling rates after dredging.

The response of flow velocity to deepening and wetland construction is likely to be site specific. Holding all other parameters constant, an increase in cross-sectional area due to deepening the navigation channel should lead to lower flow velocities and stronger stratification (Equations 20a and 20b).

Conversely, wetland placement may constrict the flow and increase velocity, potentially reducing stratification.

Because channel deepening is often associated with tidal amplification (Section 3), the estuarine salinity profile may become less stratified due to greater turbulent mixing. This is predicted to reduce buoyancy-driven circulation within the estuary (e.g., Equation 19). In addition, greater inland penetration of the tide may reduce the along-axis salinity gradient $\partial s / \partial x$, further reducing estuarine circulation. However, due to the tendency for flocculation near the saltwater-freshwater interface, tidal amplification may also shift the estuarine turbidity maximum farther inland and lead to higher local shoaling rates at a new location.

The examples presented in this section emphasize the broad range of possible responses to changes in salinity. Although greater salinity penetration and/or circulation may occur in response to an engineered modification to the system, there are also examples (e.g., the Hudson River estuary and the Western Scheldt) in which these changes were not associated with a major change in salinity-driven sediment transport dynamics. Careful site-specific evaluation is therefore necessary to determine how future wetland placement projects may influence both circulation and post-placement sediment transport for a given embayment.

5 Changes in Tidal Prism

5.1 Relationship between tidal prism and sediment transport

In many tidal embayments, the inlet cross-sectional area and the tidal prism are related by a power law of the form

$$A_{cross} = \alpha \Omega^\lambda \quad (21)$$

where A_{cross} is the inlet cross-sectional area at mean water level, Ω is the tidal prism conveyed by A_{cross} during spring tides, α is a fitted dimensional coefficient, and λ is a fitted dimensionless power. Early studies from the United States found best-fit values of λ between 0.84 and 1.1 (LeConte 1905; O'Brien 1931, 1969; Jarrett 1976) whereas the theoretical derivation of Marchi (1990; see D'Alpaos et al. [2010], for English-language summary) suggested that λ should be exactly $6/7 \approx 0.86$ for small-scale embayments with negligible cross-system tidal phase lags.

Although use of Equation 21 was originally limited to embayment entrances, the relationship has been validated for arbitrary channel cross sections along the Western Scheldt estuary (de Jong and Gerritsen 1984; Eysink 1990) and the Venice Lagoon tidal channel network (D'Alpaos et al. 2010). This implies that any channel cross section (not just the mouth) may be treated as the *inlet* to the basin volume inland of that location and provides conceptual context for understanding siltation over a broader region of an embayment.

Local transport conditions may cause the parameters α and λ to vary between systems (e.g., Gao and Collins 1994). For example, given a fixed value of Ω , systems with high longshore transport will have smaller values of A_{cross} than systems with low littoral drift because longshore transport adds excess sediment to the inlet that must be removed during ebb (Kraus 1998). Balancing the transport capacity of the tidal current with the longshore-transported sediment volume led to an expanded expression of Equation 21 which incorporated more parameters:

$$A_{cross} = \left[\pi^3 C_k^3 n^2 (2b_c)^{\frac{4}{3}} / Q_\ell T^3 \right]^{0.3} \Omega^{0.9} \quad (22)$$

where n is Manning's friction factor, Q_ℓ is the longshore sediment transport rate, T is the tidal period of the dominant constituent, and C_k is a factor between 0.81 and 1.0 (Kraus 1998). In addition to implying that inlets with high Q_ℓ will have smaller values of A_{cross} , Equation 22 also implies that inlets with higher frictional dissipation (parameterized by a larger Manning's n) must have a larger cross-sectional area in which to convey the same tidal prism as a lower-friction inlet (cf. Petti et al. 2021).

After noting that existing relationships between A_{cross} and Ω systematically over predicted cross-sectional area in scale model experiments, Hughes (2002) considered the idea of a maximum equilibrium discharge per unit width, which was defined as the maximum discharge per unit width of channel that can be tolerated by a given channel depth before it begins to scour. This led to the derivation of the equation:

$$A_{\text{cross}} = 0.87 \left[(2b_c)^{\frac{1}{9}} / \left([g(\rho_s/\rho_w - 1)]^{\frac{4}{9}} (d_{50})^{\frac{1}{3}} T^{\frac{8}{9}} \right) \right] \Omega^{8/9} \quad (23)$$

where d_{50} is the median grain size, ρ_s is the sediment density, and ρ_w is the water density. A key implication of Equation 23 is that larger and/or denser sediment will lead to smaller values of A_{cross} because more tidal energy is required for transport. The new relationship generated a good fit to a large dataset containing both natural and scale-model measurements and has the added benefit of being dimensionally homogeneous, in contrast to Equation 21.

Implicit in Equations 21 and 22, and explicitly stated in the derivation of Equation 23, is a relationship between inlet area and flow speed. Given an inlet with fixed A_{cross} , increasing the tidal prism Ω (e.g., by increasing the volume of the inland tidal basin) necessitates an increase in current speeds through the inlet to conserve mass. The relationship between Ω and velocity is asymptotic, with its upper limit constrained by friction (currents cannot become indefinitely fast) and basin length (the tide can only propagate inland by some finite length during a 6 hr rising limb; see Petti et al. [2021]), but for reasonably small basins, it is expected that increasing the basin volume with A_{cross} constant will generate an increase in velocity.

However, in systems with a movable bed, A_{cross} is not artificially fixed, and greater velocities due to larger Ω will scour the bed until a new equilibrium value of A_{cross} is attained.

This relationship between inlet area and velocity was quantified by Escoffier (1940) and led to the development of the classic “Escoffier curve,” which has been analyzed extensively for its utility in predicting inlet stability (e.g., Keulegan 1967; O’Brien and Dean 1972; Van de Kreeke 1992; Escoffier 1977; Escoffier and Walton 1979; Walton and Escoffier 1988; DiLorenzo 1988; Walton Jr. 2004). Although the specific values vary depending on which calculation method is used, Escoffier curves always consists of a positively sloped left limb along which increasing A_{cross} generates an increase in maximum flow velocities. Inlets in this regime are predicted to be unstable because sediment deposited in the inlet cannot be flushed out by the current. The right limb of the Escoffier curve is negatively sloped such that increasing the value of A_{cross} leads to a decrease in peak flow velocity. In this regime, a decrease in inlet area due to sediment deposition will generate an increase in current speed, flushing the added sediment from the inlet until the original equilibrium value of A_{cross} is reattained. The intersection of the right Escoffier limb and the tidal prism-inlet area relationship corresponds to the predicted equilibrium value of A_{cross} and the equilibrium flow velocity for a given inlet (e.g., Nielsen and Gordon 2017).

5.2 Examples of shoaling related to tidal prism

There are several common scenarios in which shoaling is directly related to tidal prism effects. First, the tidal prism-inlet area relationship is relevant to the situation in which an embayment’s entrance channel is artificially deepened but the basin volume is otherwise unchanged. Because the tidal prism Ω remains constant, the entrance channel is expected to shoal after deepening in order to re-attain the equilibrium cross-sectional area predicted by Equation 21, 22, or 23 (see also Rosati and Kraus 2009). Matthew et al. (1997) found that deepening the Tauranga Harbor (New Zealand) entrance channel by 2.8 m caused the shoaling rate to increase from $7.0 \times 10^4 \text{ m}^3/\text{year}$ to $1.3 \times 10^5 \text{ m}^3/\text{year}$. Rosati (2005) compiled pre-deepening and post-deepening conditions from six entrance channels in the United States. The change in shoaling rate ranged between a 9% increase at Brazos Island Harbor, Texas, up to a 310% increase at Shinnecock Inlet, New York, following a similar pattern to changes in channel cross-sectional area. Based on these observations, Rosati (2005) proposed the following empirical relationship:

$$\text{volumetric dredging rate} = \Delta V / 16.3 \text{ years} \quad (24)$$

The volume change ΔV is defined as

$$\Delta V = (L_E \cdot A_{cross})_{post} - (L_E \cdot A_{cross})_{pre} \quad (25)$$

where L_E is the length of the entrance channel (see Figure 1e); the subscripts “pre” and “post” respectively denote the natural and engineered channel dimensions. Equation 24 was later used to predict a 15% increase in the shoaling rate after deepening the Houma, LA, navigation channel (Rosati and Lawton 2011).

Another scenario informed by the tidal prism-inlet area relationship occurs when formerly intertidal landscape is reclaimed for agriculture or industrial usage. As a direct consequence of the relationship between A_{cross} and Ω , this engineered reduction in Ω will lead to regional shoaling in tidally dominated coastal environments. For example, land-filling projects at Norfolk, VA, reduced the tidal prism by 24% between 1872 and 1982 and likely accelerated shoaling rates in the harbor (Nichols and Howard-Strobel 1991). Similarly, dike construction in the Skagit River Delta, Washington, led to sedimentation in the channels (Hood 2004). The shoaling occurred not only within the diked reaches but also in reaches downstream of the dikes due to the reduction in water volume conveyed by the local cross section. On a larger spatial scale, widespread embankment construction in the southwest Ganges-Brahmaputra-Meghna Delta eliminated 5,000 km² of intertidal area in the 1960s and 1970s. This caused over 600 km of formerly navigable waterways to fill with sediment during the subsequent half-century (Wilson et al. 2017).

Land reclamation in the Netherlands’ Eastern Scheldt (in Dutch, *Oosterschelde*) estuary occurred in conjunction with storm surge barrier construction. Because the barrier artificially reduced A_{cross} , frictional dissipation at the inlet was expected to increase, and coastal managers anticipated a corresponding reduction in Ω . To compensate for the predicted reduction in flow velocity, smaller basins within the estuary were artificially closed with the goal of maintaining the pre-engineered tidal range in the main estuary channel (Wang et al. 2015). Despite these interventions, the channels in the Eastern Scheldt have been shoaling. The remaining tidal flats are also eroding due to a loss of sediment input from the North Sea (Wang et al. 2015) and a lack of storm energy necessary to resuspend the sediment in the channels and move it to the flats (Mulder and Louters 1994; Borsje et al. 2012; van Wesenbeeck et al. 2014).

However, land reclamation does not always lead to shoaling. For example, the Western Scheldt (in Dutch, *Westerschelde*) estuary's intertidal area was reduced by 65% (from 295 km² to 104 km²) between 1650 CE and 1968 due to the embankment of tidal flats (Van der Spek 1997). Although the tidal prism-inlet area relationship predicts channel shoaling in response to the loss of intertidal volume, the channel was observed to scour instead. Van der Spek (1997) emphasizes that a satisfactory explanation of this behavior has not yet been attained, although later results from Stark et al. (2017) suggest post-embankment tidal range amplification (see Section 3.2) as a possible physical mechanism for the observed scouring.

Finally, an embayment's total tidal prism may be reduced by relocating sediment from one area of the system to another. In Spain's Oka Estuary, the tidal prism was reduced when dredged sediment from a shipyard was placed on the nearby shoals (Liria et al. 2009). Even though the total volume of sediment within the estuary remained unchanged, moving the sediment from below lowest low water to an emergent position reduced the volume of water required to fill the estuary.

5.3 Examples of scouring related to tidal prism

Under certain conditions, tidal amplification (Section 3) may increase an embayment's total tidal prism and lead to scouring. Nielsen and Gordon (2017) note that jetty or training wall construction at the entrance to an embayment reduces the frictional impedance to flow, enabling higher flow velocities and a larger tidal range. The consequent scouring of the channel introduces a positive feedback loop in which frictional impedance is further reduced by scouring the channel to progressively greater depths. This process has been observed at several estuaries in New South Wales, Australia, including the Wallis Lake estuary, the Lake Macquarie-Swansea Channel system, and Lake Wagonga. For these three sites, the increase in tidal range was between 1.7 and 3.0 mm/yr, and A_{cross} was predicted to increase by a factor of 2 to 10 (Nielsen and Gordon 2017).

Marsh restoration projects that increase an embayment's total volume likewise affect flow velocity. In San Francisco Bay, managed dike breaches to restore inundation caused a tripling of A_{cross} for the Sonoma Baylands inlet channel over a 14 yr period while the Coyote Slough channel doubled its cross-sectional area over 13 yr (Williams et al. 2002). Similarly, Stark et al. (2017) describes ongoing efforts to restore formerly embanked

marshland along the Western Scheldt estuary via embankment breaching or removal. Numerical modeling results for several hypothetical marsh reconstruction scenarios suggest that the tidal prism generally increases downstream of newly constructed marshland, with a corresponding increase in peak velocity. However, in most simulations the tidal prism upstream of the constructed marsh was predicted to decrease relative to the scenario with no marsh restoration. This suggests that intertidal restoration may reduce shoaling rates downstream, but these benefits may be counteracted by higher shoaling rates upstream of the restored area. In addition, marshes that were constructed far inland had the effect of reducing the tidal range, and therefore the tidal prism, in a localized area near the estuary mouth.

Shoreline erosion may also increase an embayment's tidal prism and cause scouring at the inlet. In Barataria Bay, Louisiana, 775 km² of wetlands have been converted to open water. The resulting increase in the bay's tidal prism led to a 44% increase in the inlet's A_{cross} between 1880 and 1980 (FitzGerald et al. 2003; Sánchez 2008; Howes et al. 2013). In contrast to San Francisco Bay and the Western Scheldt, wetland restoration in Barataria Bay has been proposed as a method of intentionally decreasing the bay's total tidal prism to prevent further inlet scouring (FitzGerald et al. 2003).

5.4 Examples of tidal prism capture

In embayments with multiple entrances, an imbalance in the entrances' tidal prisms may initiate a positive feedback cycle in which the dominant entrance captures progressively more of the non-dominant entrances' flow. The dominant entrance then scours to accommodate its augmented flow volume while the non-dominant entrances are partly or fully abandoned. This is particularly common for barrier inlet systems, where lateral channel migration due to littoral drift may catalyze the formation of a new channel. Tung et al. (2009) described the following simple conceptual model of migration-induced channel abandonment based on the earlier work of FitzGerald (1988). As a barrier inlet migrates in the longshore direction, the entrance narrows and lengthens due to spit growth and/or detached subtidal bar formation (see also FitzGerald et al. [2000]). As a result of this narrowing and lengthening, frictional resistance to flow is enhanced, and the tidal range decreases in the back-barrier basin. Depending on basin size, non-negligible tidal phase lags may also develop between the basin and the open water. The resulting

differential in tidal elevation and phase may cause a breach in the barrier island, leading to the formation of a new inlet. Due to its more favorable hydraulic position, the new inlet captures most or all of the basin's tidal prism, and the old inlet closes.

Barrier inlet abandonment due to prism capture is a natural phenomenon that may occur cyclically at the same location. The inlet migration rate depends on parameters including the longshore sediment transport rate, tidal flow velocities through the inlet, and the erodability of the inlet banks and substrate (Bruun and Gerritsen 1959; De Alteris and Byrne 1975; FitzGerald 1988; FitzGerald et al. 2000). These parameters consequently affect the rate of barrier island elongation and critical head generation. Friedrichs et al. (1993) found that the Monmoy Island barrier inlet in Massachusetts is abandoned on a 150 yr cycle. This is the timespan required for sufficient elongation of the barrier island such that a critical head difference can be established between the bay and the ocean, leading to breach formation.

Artificially opening a new inlet or enlarging an existing non-dominant inlet may lead to an imbalance in tidal prisms. This was observed when an artificial cut for the Matagorda Ship Channel (Texas) captured the tidal prism from the natural inlet, leading to rapid sedimentation at Pass Cavallo (Ward 1982; Batten et al. 2007). Pacheco et al. (2011) similarly measured a 75% reduction in flow volumes through a Portuguese barrier inlet after the artificial opening of a new channel nearby. Along the Pacific Coast of Guatemala, jetty construction at the seasonally closed Iztapa Inlet to maintain the channel year round led to flow reductions through nearby San Marino Inlet (Seabergh 2007). Two additional notable examples occur on the Gulf Coast of Florida. First, the 1848 creation of John's Pass near St. Petersburg, FL, captured 70% to 80% of the tidal prism from nearby Blind Pass (Mehta et al. 1976). When this prism capture is combined with the construction of man-made islands in the back-barrier area, the tidal prism at Blind Pass has reduced to a degree that it now remains open only due to artificial maintenance (Becker and Ross 2001; Wang and Beck 2012). Second, the 1934 opening of the St. Andrew Bay entrance channel near Panama City, FL, caused the naturally occurring East Pass inlet to close completely in 1992 (Jain 2002).

Although tidal prism capture is most commonly referenced in the context of barrier inlets, this process may also be relevant for understanding

channel abandonment in other tidal environments. In multi-channel tidal flat systems, small perturbations may lead to a positive feedback cycle in which one channel expands by capturing an increasingly larger portion of the tidal prism. This leads to the closure of other channels within a threshold distance (Toffolon and Todeschini 2006). On a larger spatial scale, competition for flow volume may also occur in multi-channel estuaries and tidal river deltas. For example, the Western Scheldt estuary is naturally divided into cells containing parallel ebb and flood channels. Dredging the ebb channels and depositing the sediment in the flood channels destabilizes the system as the deeper channel becomes increasingly dominant (Wang and Winterwerp 2001; Jeuken and Wang 2010; Wang et al. 2015; Van Dijk et al. 2021). Likewise, Bain et al. (2019) concluded that siltation of a major estuarine navigation channel in Bangladesh was largely a consequence of tidal prism capture by an adjacent channel following anthropogenic perturbation.

5.5 Implications for wetland placement

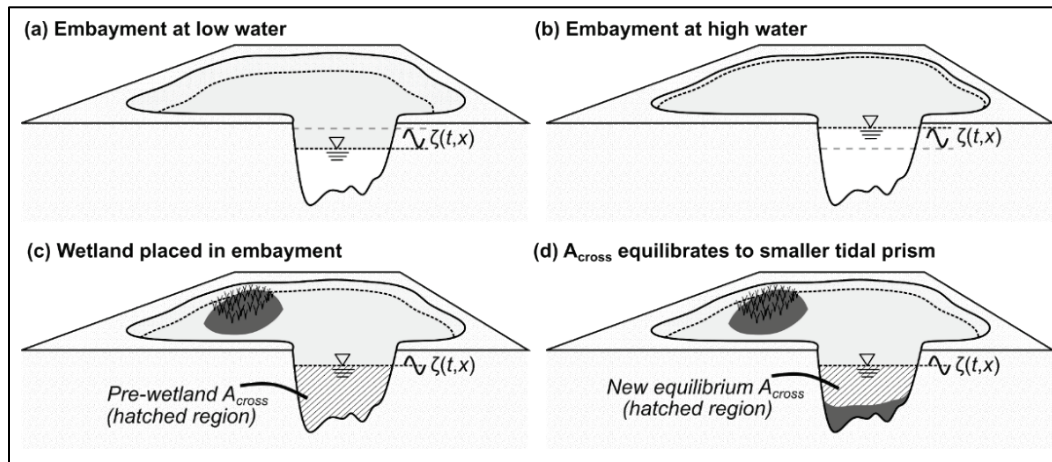
The examples presented in Sections 5.2 through 5.4 provide context for evaluating how a natural embayment may respond to wetland construction if the project will generate a change in tidal prism. Specific considerations may be summarized as follows.

First, it is necessary to consider whether the constructed wetland will increase the system's total tidal prism. If the constructed wetland increases the total tidal prism of the embayment, then (in the absence of other complicating factors) the channel is expected to scour or remain a stable depth. The magnitude of the response is dependent on the relative change in tidal prism, the littoral transport rate, the width of the channel (if fixed), frictional dissipation at the entrance, and sediment characteristics (see Equations 22 and 23). The most common scenarios in which wetland construction increases tidal prism involves marsh remediation via embankment removal, as in the San Francisco Bay (Williams et al. 2002) and Western Scheldt (Stark et al. 2017) examples.

There are other scenarios in which wetland construction may decrease the system's total tidal prism (Figure 4). If the constructed wetland decreases the total tidal prism of the embayment, then the channel is predicted to shoal in the absence of additional variables. The magnitude of the response is again dependent on the variables in Equations 22 and 23. Scenarios in which a constructed wetland would decrease the total tidal

prism include dredging sediment from the navigation channel and placing it on a shoal at any elevation exceeding lowest low water, as in the Oka Estuary example (Liria et al. 2009).

Figure 4. Illustration of inlet shoaling in response to a reduction in tidal prism. The tidal prism, Ω , is defined as the volume of water required to fill the inlet between low tide (subplot a) and high tide (subplot b). Placing a wetland at any elevation above lowest lowwater reduces Ω (subplot c). Due to the relationship between Ω and the inlet's cross-sectional area at mean water level, A_{cross} , the inlet channel shoals in response to wetland construction (subplot d).

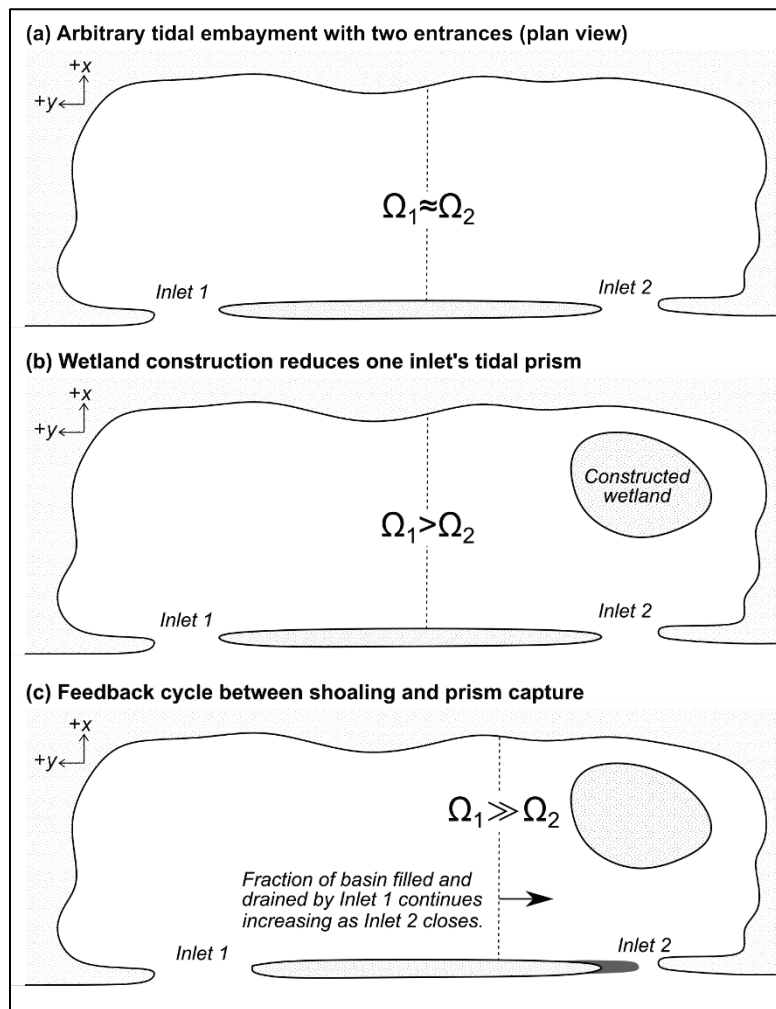


Another important consideration is the location within the system where the wetland will be constructed. An example from the Western Scheldt indicates that marsh construction via dike removal has a spatially-variable effect on tidal prism (Stark et al. 2017). No examples of spatially variable tidal prism outcomes in the context of marsh construction via dredged sediment placement were identified in the literature, but this is likely because the question has not been adequately studied. Wetland design projects should consider the possibility that a local increase or decrease in tidal prism may not extend across an entire system.

Finally, it is necessary to consider whether wetland at a given location will perturb the tidal dynamics in any nearby channels. Examples from multichannel or multi-entrance tidal environments indicate that perturbations to a system may destabilize an equilibrium configuration (e.g., Figure 5). Although no specific wetland construction examples were identified in the literature, the broad similarities between emergent wetland construction and inbay island construction (e.g., John's Pass/Blind Pass; Wang and Beck 2012) should be noted. Decreasing one channel's local tidal prism by constructing a wetland may enhance the

dominance of a nearby channel, creating a positive feedback cycle that accelerates shoaling in the first channel.

Figure 5. Hypothetical example of how wetland construction may drive shoaling and inlet closure in multi-inlet systems. In (a), an embayment is fed by two tidal inlets which each convey approximately equal tidal prisms Ω . Wetland construction then reduces the volume of water that must be conveyed by Inlet 2 (subplot b). Due to the relationship between tidal prism and inlet area, Inlet 2 begins to shoal and close in response to wetland construction (subplot c). This generates a positive feedback cycle in which Inlet 1 captures progressively more of the total basin volume.



6 Changes in tidal asymmetry

6.1 Relationship between tidal asymmetry and sediment transport

Natural or engineered changes to the landscape may also accelerate regional shoaling rates by reversing the direction of tidal current asymmetry or enhancing an existing asymmetry. As a broad generalization, flood dominant tides (i.e., peak flood velocity exceeds peak ebb velocity) tend to occur in shallow channels with negligible intertidal area while ebb-dominant tides are most common in regions where the intertidal inundation is significant (e.g., Dronkers 1986; Friedrichs and Aubrey 1988; Mazda et al. 1995; Aucan and Ridd 2000; Blanton et al. 2002; Walton 2002; Fortunato and Oliveira 2005; Brown and Davies 2010; Robins and Davies 2010; Zhou et al. 2018). Assuming that net sediment transport is in the direction of peak flow velocity, flood-dominant channels will shoal because more sediment enters the system during flood tide than is exported during ebb tide. This is particularly relevant for the coarser suspended sediment load (Dronkers 1986).

Asymmetries in the slack-water characteristics may also be relevant for the fine suspended load; for example, extending the duration of the slack water preceding ebb will give silts and clays greater opportunity to settle out of the water column and contribute to net import (Dronkers 1986).

Several authors have developed predictive tools that parameterize the relationship between tidal deformation and a system's geometrical properties. Friedrichs and Aubrey (1988) found that tidal behavior was accurately classified by the nondimensional values

$$a_0/\langle h_c \rangle \quad (26)$$

and

$$V_s/V_c$$

where $a_0 = a|_{x=0}$ is the offshore forcing amplitude, $\langle h_c \rangle$ is the channel depth at mean water level, V_s is the intertidal storage volume, and V_c is the channelized volume of water at mean water level (MWL). The $a_0/\langle h_c \rangle$ ratio quantifies the effect of time-varying frictional resistance at the waveform crest versus the waveform trough. Greater relative friction at low water

delays the inland propagation of the trough, shortening the rising limb and lengthening the falling limb of the tide (see also Parker 1984; Dronkers 1986). Greater flood dominance is therefore predicted for larger values of $a_0/\langle h_c \rangle$. The ratio V_s/V_c in Equation 26 quantifies the relative influence of channel-platform water exchange. In systems with large V_s , inefficient delivery of water from the channel to the platform may delay the propagation of the crest, lengthening the rising limb relative to the falling limb. Greater ebb dominance is therefore predicted when V_s/V_c is large. Data from 26 tidal embayments along the East Coast of the United States indicated that the vertical tide was always displayed a shorter flood duration for $a_0/\langle h_c \rangle > 0.3$, regardless of the value of V_s/V_c . A shorter ebb duration was most common for $a_0/\langle h_c \rangle \lesssim 0.3$ and $V_s/V_c \gtrsim 0.2$ (Friedrichs and Aubrey 1988). However, analogous modeling results for an idealized channel bordered by tidal flats suggest that ebb-dominant sediment transport should occur for $a_0/\langle h_c \rangle < 0.8$, and flood-dominant sediment transport should correspond to $a_0/\langle h_c \rangle > 1.2$ (Robins and Davies 2010).

Analytical results from Friedrichs and Madsen (1992) suggest that generation of the second harmonic (i.e., the M_4 overtide if the dominant forcing is the M_2 constituent) may be characterized by three parameters:

$$\gamma = \frac{5}{3} \frac{a_0}{\langle h_c \rangle^*} - \frac{\Delta b^*}{\langle b \rangle^*} \quad (27)$$

$$\|k_0\|L$$

and

$$\frac{L-x}{L}$$

Here, b is the half-width of the system (channel plus flats; see Equation 1), h_c is depth, Δb is the difference between low-water width and high-water width (note that $\Delta b = b_f$ for the vertical-banked geometry in Figure 1f), L is the length of the channel, and x is the along-channel coordinate ($x = 0$ at the mouth). Starred variables (*) indicate spatially averaged values that are treated as representative of the whole system. The variable $\|k_0\|$ was previously defined in Equation 1 and is a function of tidal frequency, Manning's n , and a set of spatial dimensions. When $\gamma > 0$, the vertical tide is predicted to have a shorter flood and a longer ebb, whereas the ebb duration is predicted to be shorter than flood when $\gamma < 0$. For a constant

value of γ , the strength of the asymmetry increases with increasing values of $||k_0||L$ or decreasing values of $(L - x)/L$. This suggests that longer embayments (and more inland positions within a given embayment) should have a higher-magnitude tidal asymmetry.

In a later study, Fortunato and Oliveira (2005) proposed predicting tidal asymmetry via the dimensionless parameters

$$\frac{a}{\langle h_c \rangle} \quad (28)$$

$$\frac{b_f}{b_c}$$

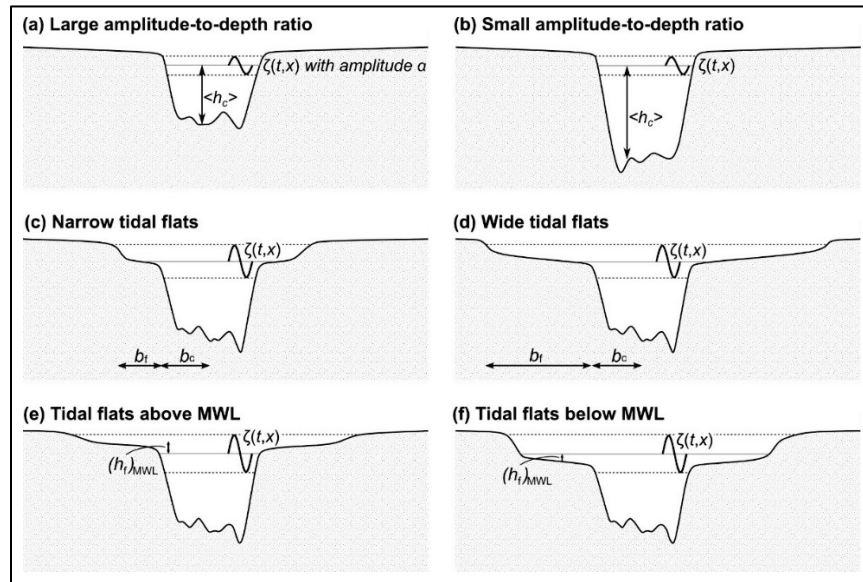
and

$$\frac{(h_f)_{MWL}}{\langle h_c \rangle}$$

where b_f is the half-width of the tidal flats, b_c is the half-width of the channel, and $(h_f)_{MWL}$ is water depth on the flats when the channel is at MWL¹ (Figure 6). The parameters in Equation 28 were considered more appropriate for systems in which the shoals convey along-channel momentum, whereas the V_s/V_c parameter in Equation 26 was derived from the assumption that the intertidal region stores water but conveys no momentum parallel to the channel. The results of a numerical model indicate that large values of b_f/b_c favor ebb dominance when the tidal flats are exposed at low tide. Maximum ebb dominance was found for $(h_f)_{MWL}/\langle h_c \rangle < 0$ (e.g., Figure 6e), which characterizes intertidal flats that are slightly above MWL.

¹ If the intertidal flat elevation is above MWL in the channel, then $(h_f)_{MWL}$ is treated as a negative number representing the increase in stage required for inundation. See Fortunato and Oliveira (2005).

Figure 6. Channel geometries with contrasting tidal asymmetry based on parameters proposed by Fortunato and Oliveira (2005). With all other parameters held constant, channels with large values of $a/\langle h_c \rangle$ (subplot a) are predicted to be more flood dominant than channels with small values of $a/\langle h_c \rangle$ (subplot b). Channels with narrow tidal flats (small b_f/b_c ; subplot c) are more likely to be flood dominant, while a reduction in flood dominance is predicted for channels with wide tidal flats (large b_f/b_c ; subplot d). The greatest ebb dominance is predicted for tidal flats slightly above mean water level (MWL), which is represented by negative values of $(hf)/MWL$ (subplot e). Lower-elevation flats (subplot f) are predicted to be less ebb dominant relative to the scenario with flats slightly above MWL.



Tidal asymmetry is also related to channel convergence, which was previously discussed in the context of tidal amplification and damping (Section 3). Lanzoni and Seminara (1998) presented analytical results for converging channels, neglecting the influence of intertidal flats. Weakly convergent systems with low friction were found to have largely symmetric tides at first order, although a weak current dominance may be necessary to conserve mass. In strongly convergent systems with low friction, ebb-dominant velocities are expected because the convergence generates a second harmonic which amplifies landward. Systems with strong friction were found to be *invariably* flood dominant, regardless of the convergence length (Lanzoni and Seminara 1998).

Vertical tidal asymmetry, horizontal current dominance, and net sediment transport are often assumed to be correlated. For example, Dronkers (1986) defined tidal asymmetry as co-existing for both the relative magnitude of the ebb and flood currents as well as the relative duration of rising and falling water level. Friedrichs and Aubrey (1988) defined *flood*

dominant systems as those with shorter-duration, higher-velocity floods and noted that measurements of the vertical tide could be used as a first approximation of net sediment transport patterns. Similar assumptions appear in the papers by Walton (2002), Fortunato and Oliveira (2005), Colby et al. (2010), and Gao et al. (2014). However, there are a variety of scenarios in which this generalization is falsified. First, in spatially extensive natural systems where large phase lags develop, the tidal current asymmetry may differ from the vertical tidal asymmetry. This was noted, for example, in the study of the Western Scheldt estuary by Bolle et al. (2010). Phase lags between the vertical tide and the currents may also result from time-varying friction. For example, Horstman et al. (2021) observed a flood asymmetric vertical tide in conjunction with ebb-dominant currents in New Zealand's Whitianga Estuary. Because maximum flood velocities occur when the Whitianga's mangrove fringe is inundated, the current is reduced by greater frictional dissipation. Maximum ebb velocities occur at a lower stage when the flow is channelized, so dissipation is minimized. Finally, a high riverine discharge may also create ebb dominant currents, even when the rising limb is of shorter duration than the falling limb. This has been observed in the Amazon (Gallo and Vinzon 2005), Loire (Winterwerp et al. 2013), Elbe (Kappenberg and Fanger 2007; Winterwerp et al. 2013), and Guadalquivir estuaries (Losada et al. 2017).

Given these deviations, it is inadvisable to draw conclusions about a given system's net sediment transport based solely on vertical tide gage data. However, if it is possible to independently confirm that the vertical tidal asymmetry, the dominant current, and the net sediment transport are aligned, evaluating a natural system's tidal asymmetry may provide information about its long-term shoaling behavior. Tidal embayments with ebb-dominant currents and ebb-dominated sediment transport will tend towards morphodynamic stability and are less susceptible to shoaling. In contrast, shoaling is more likely in flood-dominant embayments with a net import of sediment. A stable, formerly ebb-dominant system that transitions to flood dominance is therefore more likely to experience accelerated shoaling and disruption of navigation. Conversely, a transition from flood to ebb dominance may reduce local shoaling rates. The following section presents several examples of how either natural or engineered changes in a system's geometry influenced tidal asymmetry and sediment transport.

6.2 Examples of changes in tidal asymmetry

Natural reversals in tidal asymmetry are possible; for example, aggradation of the intertidal platform may sufficiently alter the basin hypsometry such that a system switches from ebb to flood dominance (Boon and Byrne 1981; Pethick 1994). In addition, changes in the offshore tidal characteristics may affect tidal asymmetry within an embayment. Numerical modeling results from several German Bight tidal inlets indicate that peak ebb velocities exceeded peak flood velocities from 1982 to the mid-1990s, after which some of the inlets reversed to flood dominant velocities (Jacob and Stanev 2021). This reversal in tidal asymmetry was attributed to naturally occurring bathymetric variations offshore, which altered the behavior of the offshore tide (Jacob et al. 2016).

In some instances, deepening a channel reduces the magnitude of flood dominance or enhances an existing ebb dominance. The Stour and Orwell estuaries (United Kingdom) were formerly flood dominant but reversed to ebb dominance when dredging rates increased in the 1960s (Roberts et al. 1998). Similarly, dredging of the Western Scheldt navigation channel between 1970 and 2002 reduced the magnitude of the flood velocity asymmetry. However, bathymetric changes alone were inadequate to explain the transition from net sediment import to net sediment export near the mouth (Bolle et al. 2010). In Australia's River Murray, dredging was found to reduce flood dominance and enhance sediment flushing (Colby et al. 2010; however, note that this paper's primary dataset was vertical tide gage records). Considering that deepening a channel may reduce flood current dominance or enhance ebb current dominance, Fortunato and Oliveira (2007) designed a unique solution to shoaling in Portugal's Óbidos Lagoon. Rather than dredging the navigation channel, the proposed solution involved dredging new channels through the tidal flats, oriented sub-perpendicular to the main navigation channel. Along with the construction of a guiding wall to promote channelization of the ebb flow, this solution was predicted to enhance ebb current dominance and promote sediment flushing from the lagoon.

Preventing intertidal inundation may likewise alter the tidal asymmetry. Li (2013) modeled tidal dynamics in Darwin Harbour for the present system configuration, which includes 238 km² of intertidal mangrove forest, and for a hypothetical scenario in which the intertidal area was converted to noninundated land. In the main arm of the estuary, net sediment transport reversed from seaward to landward when the mangroves were

removed. Interestingly, removing the mangroves reduced landward-directed transport in the smaller East Arm of the estuary, illustrating that alterations to transport dynamics may be highly localized even within a single system. In China's Pearl River Estuary, land reclamation has reduced the tidal flat area by 762 km² between the 1950s and the present. Modeling results indicated that this caused several sub-embayments to reverse from ebb dominant to flood dominant tides (Ji et al. 2019), although the model did not explicitly calculate sediment motion to verify that the direction of net transport also reversed.

The effect of land reclamation on tidal asymmetry is modulated by the position of the reclaimed land within the embayment. Gao et al. (2014) performed numerical experiments based on China's Jiaozhou Bay to evaluate these geographical effects, although the paper's emphasis was on vertical tidal asymmetry and did not explicitly consider the current asymmetry. In the first experiment, tidal flats were removed incrementally from the head of the bay towards the mouth, mimicking the actual scenario in the study area between 1935 and 1966. The initial removal of tidal flats at the head generated a large enhancement of vertical flood asymmetry magnitude. Later in the simulation, the magnitude of flood asymmetry was reduced, although the vertical tide did not become ebb asymmetric. In the second experiment, tidal flat removal was from the mouth towards the head; this led to a gradual but continuous increase in vertical flood asymmetry magnitude. Because the secondary reduction in asymmetry magnitude during the first experiment was attributed to a reduction in forcing energy, Gao et al. (2014) concluded that removing inland tidal flats would likely affect tidal hydrodynamics more strongly than removing tidal flats near the mouth.

Stark et al. (2017) also discuss the importance of intertidal location in the context of marsh remediation along the Western Scheldt estuary. Although historical embankment construction previously eliminated a large portion of the Western Scheldt's intertidal area, recent embankment removals and breaches have re-introduced intertidal inundation at certain locations within the system. Based on a numerical model of various marsh construction scenarios, Stark et al. (2017) concluded that the effect of marsh construction on tidal asymmetry was dependent on both position along the channel axis (i.e., near the mouth versus near the head) and on position within the cross-sectional profile (i.e., at the channel margin versus on a mid-channel shoal). Tidal asymmetry was most strongly

affected by wetlands constructed on bars within the main channel of the estuary because this position directly influences frictional dissipation of the flow. In this scenario, tidal flats at or above MWL tended to enhance ebb dominance while tidal flats near low water enhanced flood dominance. If the new intertidal area was instead positioned such that it would store water without conveying momentum, the vertical tide was found to become more flood asymmetric downstream of the new marsh and less flood asymmetric upstream of the new marsh. Horizontal currents were predicted to become more ebb dominant with the addition of marshland, except within a reach immediately downstream of the constructed marsh, where the current became flood dominant. The segment of the estuary with flood-dominant currents ranged in length between 4 km for marshes near the mouth to 15 km for marshes constructed farther inland.

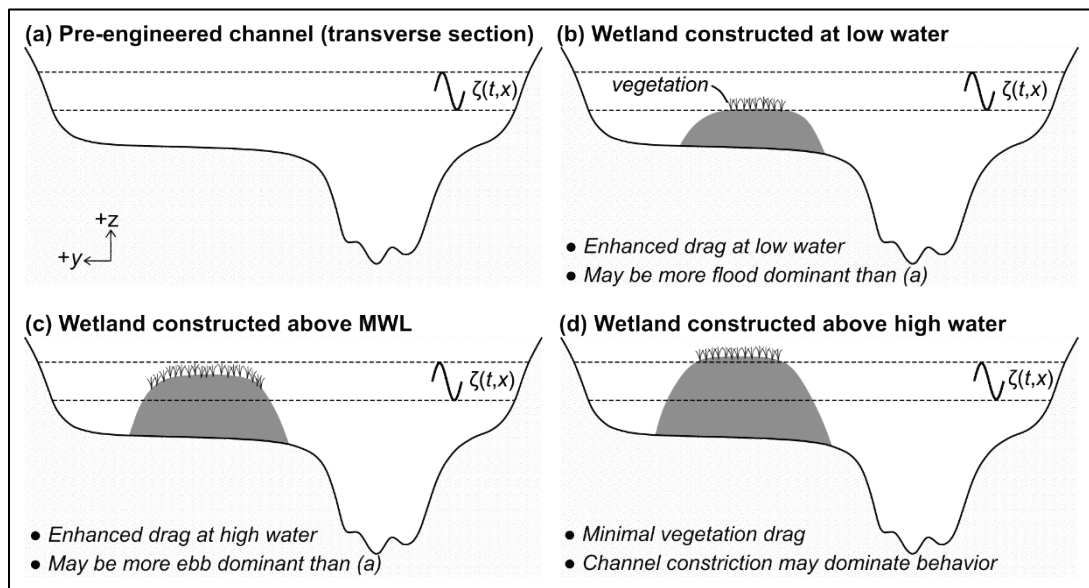
However, the elevation of the marsh was also important. In the lower and middle reaches of the estuary, maximum reduction of flood dominant currents corresponded to marshes near mean sea level. In the upper reach of the estuary, flood dominance was most effectively reduced when the marshes were constructed higher in the tidal reference frame.

For situations in which a channel is deepened (smaller a_0/h_c in Equation 26, favoring ebb dominance) but also loses intertidal area (reduction in V_s/V_c , favoring flood dominance), the overall effect on tidal asymmetry depends on the relative magnitude of both changes. As a further complication, initially reduced values of a_0/h_c may increase through time if the deepening results in tidal amplification (see Section 3). For example, the upper portion of Germany's Elbe Estuary has been dredged extensively since 1860, but the estuary simultaneously lost a large portion of its intertidal volume via dike construction and backfilling of harbor basins (Weilbeer 2014). Tidal amplification, in conjunction with the loss of intertidal volume, generated increasingly flood dominant currents over the past century. The asymmetry in current direction aligns with the asymmetry in the vertical tide, which is so extreme that the falling limb of the tide is now 3 times longer in duration than the rising limb (Winterwerp et al. 2013). Similarly, Western Scheldt (Netherlands) and upper Ems (Germany) estuaries have continued to become more flood dominant since deepening in the 1960s (Winterwerp et al. 2013).

6.3 Implications for wetland placement

The theory from Section 6.1 and the examples presented in Section 6.2 lead to several generalized questions that should be considered prior to wetland placement. First, it is necessary to evaluate the elevation at which the wetland will be constructed (Figure 7). The theoretical results of Fortunato and Oliveira (2005) suggest that if all other parameters are held constant, an intertidal wetland that is slightly above the MWL elevation will be most favorable for enhancing ebb dominant currents within the channel. This was confirmed by modeling results from Stark et al. (2017), who found that intertidal area at or slightly above MWL generated the greatest reduction in flood dominance along the Western Scheldt estuary.

Figure 7. Possible effects of wetland construction on tidal current asymmetry. Beginning from a pre-engineered system comprised of a deep channel and a shoal (subplot a), wetlands are constructed near low water (subplot b), above mean water level (MWL; subplot c), and above high water (subplot d). Based on results from Fortunato and Oliveira (2005) and Stark et al. (2017), the predicted effect on tidal asymmetry varies with elevation. Wetlands constructed near low water may delay the propagation of the waveform trough and enhance flood current dominance, whereas wetlands constructed above MWL are predicted to enhance ebb current dominance. The vegetation is predicted to have minimal influence on tidal asymmetry when the wetland is above high water. Note that these predictions do not consider the potentially competing effects of tidal prism reduction, tidal amplification, or tidal damping.



The position of the wetland relative to the momentum-conveying portion of the system should also be considered. Predictions of how intertidal area will affect tidal asymmetry are divided among those assuming that the intertidal region stores mass but does not convey momentum (e.g.,

Equation 26) and those that assume that the intertidal region is flow conveying (e.g., Equation 28). Stark et al. (2017) modeled these differences by creating simulated wetland on the edges of the channel versus on bars within the main channel of the Western Scheldt. The results indicated that although either scenario may influence tidal asymmetry, the greatest effects occurred for tidal flats within the flow-carrying cross section. Wetland designers should consider that wetlands constructed on mid-channel shoals may affect the flow differently than those constructed at the edge of the embayment.

Another consideration is the relative impact of channel deepening versus augmented intertidal area. As stated in Section 1, engineering a tidally influenced system may cause a variety of changes in tidal dynamics, possibly within a positive feedback cycle. Although initial deepening may favor ebb asymmetry due to smaller values of $a_0/\langle h_c \rangle$ (Equation 26), tidal amplification due to reduced bed friction and greater suspended particulate matter may ultimately lead to higher values of $a_0/\langle h_c \rangle$ than occurring in the pre-engineered condition. The flood asymmetry will thus be enhanced. Although the addition of intertidal area may, by itself, favor ebb asymmetry, the predicted ebb asymmetry may not manifest if other processes generate an even stronger enhancement in flood asymmetry.

Finally, it is important to evaluate whether the vertical asymmetry, the current asymmetry, and the net sediment transport are oriented in the same direction. Although this scenario is commonly assumed for small basins (e.g., Dronkers 1986; Friedrichs and Aubrey 1988; Walton 2002; Fortunato and Oliveira 2005; Colby et al. 2010), larger and more complex natural systems may have a vertical tidal asymmetry which opposes the dominant current direction or a net sediment transport which opposes the dominant current (e.g., Gallo and Vinzon 2005; Kappenberg and Fanger 2007; Bolle et al. 2010; Winterwerp et al. 2013; Losada et al. 2017). During wetland project planning, care should be taken to avoid over-interpreting vertical tidal records without independent verification (e.g., current and sediment concentration measurements) of the system's transport behavior.

7 Other Causes of Shoaling with Possible Relevance to Wetland Placement

Several earlier publications present a broad overview of shoaling causes and processes. A technical note by Pope (2000) summarized channel shoaling processes according to seven classifications:

1. Lateral channel migration
2. Natural channel abandonment in multi-channel systems
3. Preferential deposition in low-energy areas of the system
4. Loss of hydraulic gradient due to flow expansion
5. Migrating bedforms
6. Geotechnical failure of the channel sidewalls
7. Regional siltation.

The emphasis of Pope's (2000) report was on the physical mechanisms that favor sediment deposition in certain locations. Parchure and Teeter (2002a) later published a complementary report focusing on engineered solutions to shoaling issues based on case studies from around the United States. The site-specific examples provided insight into the effectiveness of jetty construction, channel realignment or diversion, sediment trap construction, channel widening, and other system modifications.

Considering the wide range of physical shoaling mechanisms, it is unsurprising that a variety of factors may simultaneously influence sediment transport in a given tidally affected bay or river. In addition, shoaling causes are site specific, and the optimal shoaling mitigation practices for one site may be of little use at a different location (Parchure and Teeter 2002a).

7.1 Deposition in sheltered areas of the basin

One of the shoaling causes highlighted by Pope (2000) is preferential deposition of sediment in low-energy environments. Pope (2000) terms the transfer of sediment from high-energy to low-energy environments as a "morphodynamic pathway" and emphasizes aeolian transport from the beach into the navigation channel. Indeed, Tate et al. (2014) note that up to 20% of sediment deposited in the Houston-Galveston navigation channel is due to aeolian winnowing of sediment from nearby beaches. The net transport of sediment from high-energy water to low-energy water

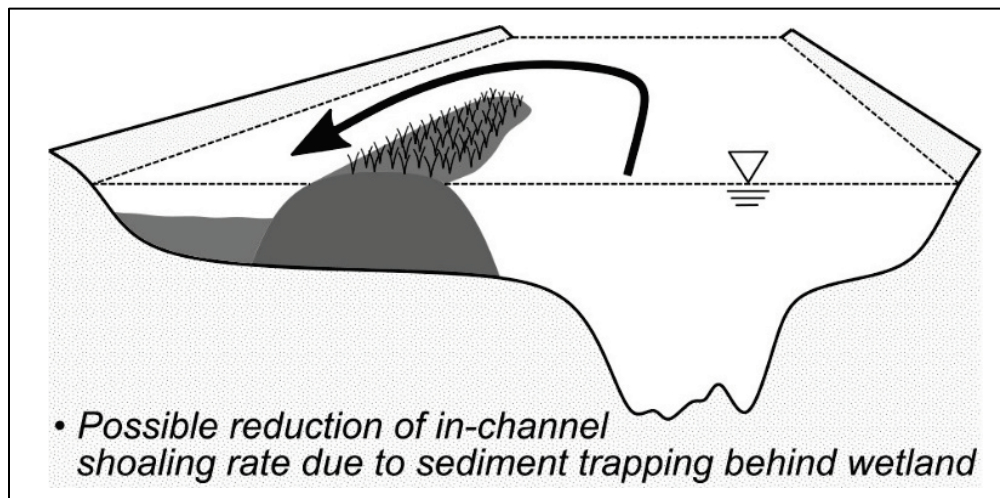
also falls within this classification. Parchure and Teeter (2002a) emphasize the necessity of strategically designing harbor geometry to prevent low-velocity areas where sediment will accumulate. For example, McCartney et al. (1991) noted that harbor width expansion led to rapid shoaling in Brunswick Harbor and the Delaware River while side channels and basins in New York Harbor and the Cape Fear River have been observed to rapidly accumulate sediment. In addition, pilings that create eddies have induced shoaling in New York Harbor and San Francisco Bay (McCartney et al. 1991).

Sediment deposition in low-energy areas may decrease the basin's tidal prism and lead to further shoaling. Flume experiments simulating a muddy tidal system indicate that the fine-grained sediment will preferentially deposit on tidal flats and on channel banks up to the high water elevation (Braat et al. 2018). The long-term reduction in tidal prism due to mudflat aggradation in low-energy regions of the system may introduce a positive feedback cycle in which flow velocities continue to decrease and additional sediment is deposited.

Although sediment deposition in low energy areas may be problematic, certain projects have taken advantage of this behavior by constructing sediment traps in which material can accumulate (e.g., Parchure 2005). These traps are most effective when they are positioned at a sufficient distance from high-current areas to prevent sediment remobilization (Jarrett and Hemsley 1988). Parchure et al. (2000) describe an example from Galveston Bay, Texas. This region experiences a net import of bedload-transported sand from the Gulf of Mexico due to a flood-dominant tidal asymmetry (see Section 6) leading to shoaling in the Gulf Intracoastal Waterway. Hydrodynamic modeling suggested that dredging a 900 m long trench parallel to the navigation channel would trap a significant proportion of the bedload and prevent deposition within the waterway itself. More recently, Saichenthur et al. (2019) concluded that a polygonal pit within the Hooghly Estuary (India) would efficiently trap silt and reduce the shoaling rate in the adjacent navigation channel. However, Tempel's analysis of the Port of Rotterdam emphasized the necessity of careful trap design (Tempel 2019). Improper sediment trap dimensions, including a trap which is too deep, may actually increase shoaling in the navigation channel.

From a wetland construction perspective, creating or enlarging a wetland within a tidal embayment may alter circulation patterns or create sheltered regions that favor accelerated local shoaling (Figure 8). For example, hydrodynamic modeling results from Tate et al. (2014) indicated that enlargement of Atkinson Island (Galveston Bay) led to reduced flow velocities and 6 cm of shoaling behind the island. However, the locally accelerated shoaling behind Atkinson Island was not correlated with a reduction in the amount of sediment entering the navigation channel on the opposite side of the island. Rather, an increase in shear stress elsewhere in the bay led to enhanced sediment transport and higher shoaling rates within the navigation channel. This example illustrates the complexities of natural tidal systems and demonstrates that the creating of a low-energy depositional area does not guarantee a reduction in shoaling elsewhere.

Figure 8. Illustration of possible sediment deposition in the low-energy area behind a constructed wetland. Although it is conceivable that enhanced deposition on the shoals could reduce the siltation rate in the navigation channel, data from Galveston Bay (Tate et al. 2014) indicate that sediment trapping effects were offset by enhanced shear and entrainment elsewhere within the system.



7.2 Hypsometric changes and effect on velocity surge

Land reclamation projects may also cause sedimentation by eliminating the instantaneous velocity surge associated with intertidal inundation. In idealized small-scale tidal marshes, a simple expression for discharge through the channel mouth is

$$Q(\zeta) = A_{plan} \frac{\partial \zeta}{\partial t} \quad (29)$$

(Boon 1975), where A_{plan} is the planform (i.e., hypsometric) area of the water surface corresponding to stage $\zeta(t)$. Equation 29 implies an abrupt increase in flow velocity through the mouth at the moment of overbanking, and this velocity surge may entrain and transport sediment, which would otherwise contribute to local shoaling. Because natural environments rarely satisfy the simplifying assumptions that underlie Equation 29, hysteresis is common between the rising and falling tidal limbs (e.g., Myrick and Leopold 1963; Bayliss-Smith et al. 1978; Pethick 1980; French and Stoddart 1992), and the direction of net sediment transport due to surge-induced entrainment depends on system-specific parameters including velocity asymmetry and marsh size (Fagherazzi et al. 2008). Nevertheless, disconnecting a channel system from its intertidal region is an important consideration for shoaling studies because these modifications reduce the likelihood that sediment deposited on the channel bed will be re-entrained. From the perspective of wetland construction, altering the basin's hypsometry through wetland construction may affect the timing of instantaneous maxima in current speed, which has the potential to alter transport dynamics.

7.3 Geotechnical failure

Geotechnical failure of channel sidewalls is another mechanism for shoaling in navigation channels (Pope 2000). McCartney et al. (1991) noted that post-dredge sloughing of channel side slopes continued for several years after deepening projects in the Matagorda Ship Channel and the Columbia River (see also Babcock 1989). Van Dijk et al. (2019) likewise concluded that channel margin oversteepening due to dredging has caused multi-annual shoal collapses in the Western Scheldt estuary, depositing several million cubic meters of sediment in the navigation channel. Geotechnical failures are more common in macrotidal embayments due to cyclical oscillations in pore-water pressure, which leads to strain-softening and elevated pore pressures that may destabilize the slope (Koopman et al. 1948; Kraft, Jr. et al. 1992; Mastbergen et al. 2016). Regardless of tidal range, excess pore pressure may also develop in the underlying sediment during periods of rapid deposition such as wetland placement (Delo and Burt 1987).

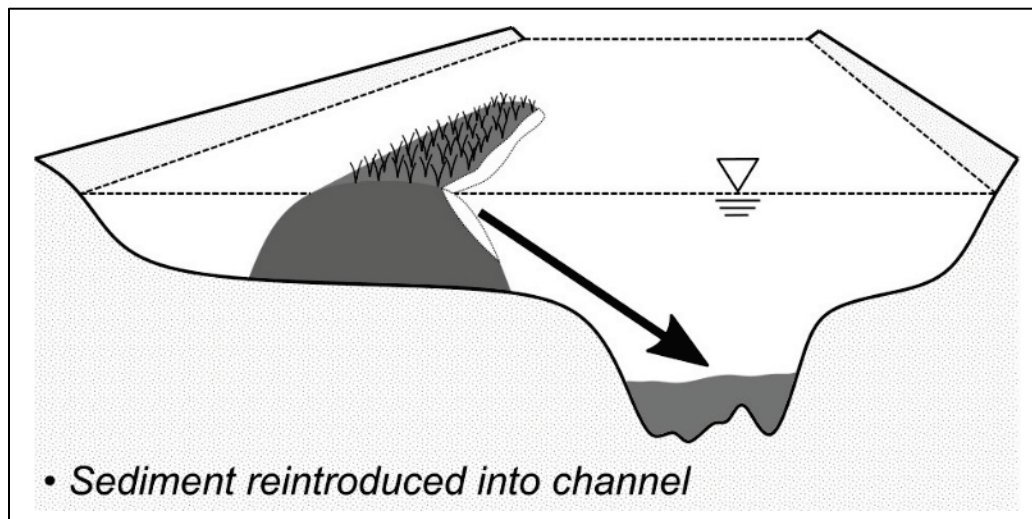
Geotechnical considerations are relevant to wetland construction for multiple reasons. If a wetland is positioned in close proximity to the channel thalweg, currents may oversteepen the wetland margin beyond the angle of repose. Salinity gradients from the shoreline towards the interior may lead to increased stress on and loss of wetland vegetation,

corresponding weakening of soils, and higher susceptibility to erosive forces (Jafari et al. 2019a,b). Vegetation establishment at wetland creation sites is directly tied to establishment of wetland shear strength and has been shown to be degraded by anthropogenic activities like construction equipment traveling over the wetland (Harris et al. 2021).

Wetland elevation is a key indicator of its health and stability, and repeated placement of sediment to create higher-elevations may increase resilience of created wetlands over time. However, freshly placed sediment is also underconsolidated and will possess lower resistance to erosion and geotechnical failures (Stagg and Mendelssohn 2011). For example, slope-stability of wetland banks at placement sites may be highly degraded by the underconsolidated nature of freshly placed sediment until the banks dewater and consolidate (Walker et al. 1987). Slope failures could then transport sediment back into the navigation channel. Kayyal and Hasen (1998) describe the example of Spilmans Island (Galveston Bay), a marsh-classified sandbar which has been used for dredged material disposal since the 1950s. The continued addition of material and the construction of containment levees atop weak sediment from previous placements led to two slope failures in the 1990s.

This example illustrates the importance of careful site design and location selection to ensure that sediment from the wetland margins does not collapse into the navigation channel (Figure 9).

Figure 9. Illustration of wetland side-slope failure reintroducing sediment to the navigation channel. Oversteepening of the bank, vegetation die-off due to salinity stress, and underconsolidation of newly placed sediment enhance the likelihood of geotechnical failure.



7.4 Channel constrictions and expansions

Shoaling may also be caused by a loss of hydraulic gradient at channel expansions or outlets. The corresponding decrease in current velocity reduces the transport capacity of the flow and permits sediment deposition. Classic examples of this behavior include the formation of ebb and flood deltas at barrier inlets and the tendency for bar formation at funnel-shaped estuary mouths. Sedimentation due to flow expansion may be prevented by the construction of parallel jetties to maintain nondepositional flow velocities within the navigation channel, although this may simply shift the shoaling area to the jetty terminus (McCartney et al. 1991; Parchure and Teeter 2002a).

With regards to wetland construction, it is theoretically conceivable that an artificial wetland could constrict the navigation channel and generate a local flow acceleration, possibly leading to scour at the thalweg position. The entrained sediment would then be deposited upstream or downstream, depending on the direction of the dominant tidal current. Higher currents in the constriction could also undercut the bank, causing the placed sediment to slump back into the channel. However, no examples of this behavior were identified in the literature, and further study is necessary to evaluate the degree to which wetland-generated basin narrowing might impact local currents and transport dynamics.

8 Other Causes of Shoaling Not Directly Relevant to Wetland Placement

8.1 Channel avulsion

Pope (2000) notes that channel abandonment is one of the primary causes of shoaling in coastal embayments. Section 5 has already described the abandonment of inlet channels due to tidal prism capture. An additional mode of channel abandonment, which is more commonly referenced in the fluviodeltaic literature, is channel avulsion to a position with a more favorable hydraulic gradient (e.g., Slingerland and Smith 1998; Kleinhans et al. 2013; Ganti et al. 2016). Since tidally influenced deltaic channels are less mobile than their purely fluvial counterparts (Rossi et al. 2016; Hoitink et al. 2017; Lentsch et al. 2018) and deviate from the avulsive behavior predicted for the purely fluvial case (e.g., tidally-driven routing of upstream discharge into a less hydraulically favorable channel [Sassi et al. 2011]; inhibiting sediment deposition in non-dominant distributaries [Kästner et al. 2017]), it is likely that avulsions are a less important shoaling process than the mechanisms discussed in previous sections of this report. Nevertheless, there are several examples of tidally driven channel avulsions, including on the Skagit River Delta (Hood 2010), Rhine-Meuse Delta (Pierik et al. 2018) and Yangtze Estuary (Wang et al. 2015), so this mechanism cannot be entirely dismissed as a possibility.

8.2 Migrating bedforms

Pope (2000) also notes that migrating bedforms may cause shoaling when they enter a navigation channel. Large-scale bed features include sand waves, which are oriented perpendicular to the channel axis, and sand banks, which are oriented quasi-parallel to the dominant flow direction near estuary mouths (Harris 1988). Sand waves are commonly associated with continental shelf environments (e.g., Katoh et al. 1998; Lobo et al. 1999; Duffy and Hughes-Clarke 2005; Dorst et al. 2011; Van Landeghem et al. 2009), but they have also been identified as major contributors to shoaling in sandy channelized settings including the Bahía Blanca Estuary of Argentina (Aliotta and Perillo 1987), the Columbia River mouth (Levin et al. 1992), St. Andrews Bay near Panama City, FL (Lillicrop et al. 1989; Levin et al. 1992), the Grådyb tidal inlet of Denmark (Bartholdy et al. 2002), the San Francisco Bay entrance channel (Barnard et al. 2006), and the Marsdiep tidal inlet in The Netherlands (Buijsman and Ridderinkhof

2008). Sand bank migration has been identified as a significant contributor to shoaling in Brazil's São Marcos Bay, leading to maintenance dredging requirements of 6 million m³/yr (Silveria 2017). Survey data from the Amazon River mouth indicates that sand banks can migrate 250 m/yr (Fernandes et al. 2007), introducing a navigation hazard if the bedform enters the navigation channel.

Despite the practical significance for navigation channel maintenance, the physical mechanisms which underlie sand wave formation and migration remain poorly understood. Modeling studies suggest that sand waves form in response to small perturbations of a flat bed, including perturbations introduced by the initiation of channel dredging (Roos et al. 2005, 2008). In addition, Borsje et al. (2014) found that sand wave formation is only possible in bedload-dominated systems (Rouse number > 1.9) because suspended-load transport generates net sediment movement towards the trough over a tidal cycle. Recent results from Campmans et al. (2021) indicate that post-dredging sand wave regrowth may be retarded if sediment from the crests is placed in the troughs to flatten the bed rather than removing the dredged sediment from the local system.

Considering these observations, it appears improbable that shoaling due to bedform migration would occur as a direct response to wetland placement. Although a newly placed wetland may be considered a *perturbation* of the bed, no studies were identified that documented a correlation between wetland placement, enhanced bedform mobility, or accelerated bedform migration rates. Dredged sediment placement has been found to inhibit natural bedform migration along exposed, ocean-facing beaches (Gijssman et al. 2019), but it is unclear whether these results may be extended to embayed coastal environments. Future wetland placements should monitor the local bathymetry for detrimental alterations to the bedform regime, but the shoaling causes described in the earlier sections of this report are likely of greater importance.

8.3 Variations in sediment availability

There are also circumstances in which regional or far-field processes generate shoaling in coastal embayments. On the meso-scale, an increased supply of sediment on the beach may accelerate shoaling in an inlet (e.g., Rosati and Kraus 1999). Beck and Kraus (2011a,b) found that the navigation channel at Shark River Inlet was formerly stable, but a large-volume beach nourishment project adjacent to the inlet allowed for the

formation of a new ebb-tidal delta due to the excess availability of sand. Rosati and Lawton (2011) likewise noted that nearshore sediment placements at Houma, LA, have historically migrated into the navigation channel. The study recommended relocating the disposal site downdrift of the inlet to prevent continued shoaling.

At larger spatial scales, changing sediment yield upstream of an embayment may affect shoaling in coastal environments. Although sediment delivery to the coast has decreased globally due to trapping in inland reservoirs (Syvitski et al. 2009), Rodriguez et al. (2020) found that coastal sedimentation more than doubled in the United States between 1950 and 2010 due to rivers' natural buffering capacity (e.g., Phillips et al. 2004; Walling 2006; Nittrouer and Viparelli 2014) and enhanced sediment yield in the catchment. Hansen et al. (2002) estimated that inland erosion was directly responsible for \$257 million of coastal dredging projects in the United States annually. The following paragraphs present several examples of non-local processes leading to shoaling in coastal channels.

Land use change associated with agriculture, mining, or logging may increase a watershed's sediment yield and enhance the coastal shoaling rate. For example, shoaling in the Gulf of Urabá, Colombia, has been attributed to the expansion of banana cultivation in the upstream catchment (Blanco-Libreros 2009). Core analysis from Tillamook Bay, Oregon, indicates a 29% increase in the shoaling rate between 1931 and 1954 due to a combination of logging and forest fires inland of the bay (Komar et al. 2004). In addition, sediment yield may increase due to changing atmospheric conditions.

Rosati and Kraus (1999) noted that the sediment entering a coastal embayment from upstream is likely to increase during an exceptionally rainy year and recommended evaluating decadal-scale to century-scale climatic cycles to anticipate shoaling trends.

The accidental or intentional removal of upstream engineered structures may likewise enhance sediment deposition in an embayment. Failure of a levee separating Lower Memorial Lake from Bear Creek Marina (near Tallahassee, FL) resulted in the immediate deposition of 0.6 m of sediment in the marina, creating a navigation hazard (Atchison et al. 2007). Foley et al. (2015) measured a > 0.5 m reduction in channel depth

in the Elwha Estuary, Washington, following removal of two dams, but a contrasting study of dam removals above the Hudson Estuary, New York, observed minimal increase in estuarine sedimentation (Ralston et al. 2021). Because only 10% of dam removals in the United States have been quantitatively monitored (Foley et al. 2017), further research is necessary to fully understand how dam removal affects coastal sediment deposition.

Because the shoaling mechanisms described in this section are generated outside the local system, it is not possible for wetland placement to cause any of these scenarios. However, project designers should recognize that wetland-generated shoaling effects may occur in conjunction with one or more of these factors. Evaluations of the influence of wetland placement on shoaling should consider that sediment may be sourced from multiple locations both inside and outside the local system and incorporate all possible sources of sediment into post-placement sediment budget analyses.

9 Conclusions and Recommendations

9.1 Conclusions

Beneficial use strategies for dredged sediment in tidally influenced bays and rivers offer a variety of sediment management, storm risk reduction, and habitat restoration and resilience benefits. The planned beneficial use goals of the future may involve extensive systems of recurring placements designed to optimize a variety of benefits. Some placement strategies may have the capacity to influence hydrodynamic and morphologic changes within the system, including navigable waterway shoaling. Altered flow behavior and sediment transport in tidal embayments has been observed following a variety of engineering modifications, but wetland creation or destruction has not been the primary influence in the majority. Generalizations have been made about hydrodynamic and sediment transport impacts in the context of some of these changes, but exceptions and site-specific deviations are numerous. Additionally, morphology can be slow to respond to system modifications, and modifications are often concurrent, so impacts can be difficult to quantify (e.g., Nestler and Long 1994; Winterwerp et al. 2013; Wang et al. 2015). However, beneficial use strategies have the capacity to alter various parameters that the literature indicates are relevant to tidal hydrodynamics and sediment transport. Many knowledge gaps remain on fundamental questions concerning possible wetland nourishment impacts to navigation.

The unknowns that this literature review indicates could be most relevant are suggested for future research in the following section on recommendations.

9.2 Recommendations

Embayment engineering efforts have been observed to alter hydrodynamics and sediment transport in many cases, and much research has investigated various causes and effects. Many knowledge gaps remain in the specific subtopic of hydrodynamic, sediment transport, and navigation impacts of different in-bay beneficial dredge sediment use strategies. This literature review has indicated that the knowledge gaps related to the following research questions may elucidate potential navigation impacts of wetland nourishments:

- What volume of in-bay wetland construction will generate comparable hydrodynamic impacts relative to other engineering modifications?

The examples presented in this report illustrate that anthropogenic modification of embayments may significantly alter the regional tidal hydrodynamics and sediment transport. The cited literature emphasizes large-magnitude engineering projects (e.g., channel deepening, sidewall hardening, land reclamation) that likely exceed the scope of individual wetland placements. It remains unclear whether relatively small-scale wetland placement projects will fundamentally alter a system's behavior, and future research should evaluate the relative magnitude of these changes in comparison to other, better studied engineering impacts.

Although individual wetland projects may be comparatively small, ongoing in-bay sediment placement could potentially accumulate into a larger-scale modification over time. Researchers have previously hypothesized that coastal systems display “morphodynamics thresholds” at which the hydrodynamic behavior enters a new regime (Wang et al. 2015), but such thresholds have not been evaluated in the context of wetland placement. A major knowledge gap is therefore to determine whether a threshold volume for wetland placement exists and how an embayment will react to exceedance of this threshold.

- How does wetland elevation within the tidal reference frame affect the system's hydrodynamic response to wetland placement?

Modeling results from Stark et al. (2017) indicate that the relative elevation of constructed intertidal wetlands will modulate the wetland's influence on both tidal asymmetry and tidal prism. However, no field studies that explicitly compared hydrodynamic impacts of varying-elevation wetlands were identified during the present literature review. Wetland construction projects often target specific vegetation populations, so it may be infeasible to vary wetland elevation within the tidal reference frame during any specific project. To circumvent this limitation, future studies may consider evaluating the relative hydrodynamic impacts of low-elevation versus high-elevation wetlands using data from separate projects with otherwise comparable parameters.

- How can newly placed sediment be strengthened through efficient retaining and buffering strategies to strategically prevent geotechnical failure when the wetland is exposed to erosional environmental processes?

Newly placed sediment requires time to consolidate and establish a soil structure capable of resisting erosive forces. Retainment structures such as containment dykes should be strategically placed to protect freshly deposited sediments against erosive forces during this process. Special care should be taken to minimize the intensity and frequency of anthropogenic modifications (Harris et al. 2021). The establishment and health of vegetation on the placed wetland is critical to increased erosion resistance, and as the vitality of wetland vegetation is largely reliant on existing in certain elevation ranges, the wetland should be maintained through repeated placements to achieve a target elevation as underlying layers consolidate or surficial sediments are eroded (Jafari et al. 2019a,b). To that end, several research questions remain unquantified: How can common geotechnical properties of sediments such as compressibility be related to the time-dependent establishment of wetland vegetation?

What is the inverse relationship between increased degree of sediment consolidation (increased shear strength) and the reduced elevation (increased stressors), and what is the best way to balance these factors in the context of wetland placement?

- To what extent are conclusions from one category of embayments applicable to other environments?

The broad classification of “tidal embayments” spans a variety of environments ranging from small-scale marsh creeks up to estuaries extending hundreds of kilometers inland. The wide range in spatial scales, along with variability in the relative proportion of intertidal versus channelized flow volume, implies that results from one system may be inapplicable to another. Future research may consider developing a framework for identifying *similar* systems that are likely to have comparable responses to wetland placement.

- If navigation channel shoaling occurs as a consequence of wetland placement, what is the sediment source?

The examples presented in this report demonstrate a variety of mechanisms by which wetland placement may lead to accelerated shoaling. Although the sediment entering the navigation channel may be sourced directly from the wetland, it is also possible that wetland-induced alterations to net transport may lead to new sediment being imported into the system from offshore. This may occur, for example, if wetland construction causes a system to reverse from ebb dominant to flood dominant sediment transport. Future research should isolate sediment sources and evaluate transport pathways to ensure that an accurate characterization of the local shoaling mechanism is obtained.

Developing a systematic understanding of in-bay sediment placement impacts which builds off of these research questions could provide a useful conceptual framework for avoiding unintended outcomes following wetland construction. The responses to other engineering modifications are frequently nuanced and sensitive to a wide array of site-specific parameters, so system responses to the beneficial use of large volumes of dredged sediment are likely to be complex as well. Future data collection, study, and similar approaches to the analysis of impacts from other engineering modifications, may help improve the understanding of the realistic range of potential responses.

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14. ABSTRACT Wetland construction in tidally influenced embayments is a strategy for beneficial use of sediment dredged from nearby navigation channels. These projects have the potential to alter basin morphology, tidal hydrodynamics, and shoaling trends. This special report provides a broad review of the literature related to engineering-induced changes in tidal range, salinity, tidal prism, tidal asymmetry, and other known causes of shoaling. Each potential shoaling mechanism is then evaluated in the context of wetland placement to provide a foundation for future beneficial use research. Based on a compilation of worldwide examples, wetland placement may reduce tidal amplitude and enhance ebb current dominance, thus reducing shoaling rates in the channels. However, constructed wetlands could also reduce the embayment's tidal prism and cause accelerated shoaling relative to the pre-engineered rate. Because constructed wetlands are often created in conjunction with navigation channel dredging, the system's morphologic response to wetland construction is likely to be superimposed upon its response to channel deepening, and the net effect may vary depending on a variety of system-specific parameters. Planning for future wetland placements should include an evaluation of local hydrodynamic behavior considering these factors to predict site-specific response.						
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