Coastal Landscape Dynamics: From the river to the coast, with a focus on the Brazos delta

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Coastal landscapes, defined:
- Low-lying, subaerial (sediment-to-air), and subaqueous (sediment-to-water) interfaces. The subaerial portion of coastlines hosts society. This land resides only a few vertical feet above the mean local sea level
- Ecologically diverse and, arguably, the most biologically productive environments on earth
- Vulnerable to climate change as well as ocean storm events (e.g., hurricanes) and river floods, which inundate the landscape with water and sediment

Coastal landscapes and societal importance:
- Host >60% of the world’s population, and are heavily developed for living, commerce, and recreation
- In the U.S.A., 1.3 million new residences in the past two decades, increasing population by 50% since 1970
- 40% increase in property value since 2004, to an estimated $10.2 trillion (Gulf and Atlantic seabords combined)

Sustainability studies:
- Necessitate multidisciplinary approach that incorporates geomorphology, engineering, and social research, to address trends of landscape dynamics, infrastructure development, and increasing population
Coastal zones and the influence of sea-level rise: Are coastal regions a lost cause? Witness: passive inundation models

Land submergence if relative SL rises 1 m: ~13,500 km²

But the most precious resource needed for sustaining coastal landscape is...
**SEDIMENT!!**

Underwhelming assumptions with passive inundation modeling:

1) Sea-level rise is linear (constant), and gently floods land over time
2) Coastlines are static and unable to evolve in time and space; e.g., no rivers
3) Ignorance of the bigger picture: large, infrequent events AND day-to-day activities are what REALLY influence landscape evolution over time

Coastal landscapes reassessed must consider:

-- Sea-level rise is **not** linear in time and space;
-- Coastal regions are **the most dynamic landscapes on Earth’s surface**
-- Major ocean storms (e.g., hurricanes) and large river floods (sediment) profoundly influence development of coasts

**Q:** Are coastlines a lost cause?

**A:** Absolutely not

**How to address?** Forward modeling of dynamic coastal landscapes...
Our geomorphology research links coastline dynamics and landscape change

- How? Combine field observations and models, to develop informed hypotheses about the future evolution of coastal systems

Our goals: a) “morphodynamic” model of modern coastal systems; b) forward model (future) predictions of landscape response to variable climate
Coastal systems, from the viewpoint of deep-time geology
County Clare, Ireland, ~310 m.a.
Physical description of sediment transport

The “morphodynamic” consideration for coastal processes

$$\frac{\partial \eta}{\partial t} = -\frac{\partial q_s}{\partial x} \left( \frac{1}{1 - \lambda_p} \right)$$

Elevation ($\eta$)

measure and model

Water Flow ($U, \tau$)

$$\tau = c \rho U^2$$

Sediment movement ($q_s$)

$$q_s = \alpha(\tau - \tau_{cr})^{>1}$$

Our approach to coastal systems: start small, and build big!
Cutting-edge field observation tools:

- Single-beam sonar (50-200 kHz)
- Multibeam sonar: high-resolution “swath mapping” bathymetry (200-400 kHz)
- Sidescan sonar imaging (400-800 kHz)
- aDcp water column velocity profiling (600-1200 kHz)
- CHIRP sub-bottom profiling (0.5-12 kHz)
- Direct sediment sampling (grab, gravity, and vibracore)
- Direct sampling of water column: suspended sediment concentration
Importance of a physical model: barrier island evolution

--Punctuated shoreline retreat

--Feedbacks between the shoreface evolution and overwash deposition: generates “stick-slip” conditions

--Internal dynamics produce complex behavior, with minimal external perturbations

Model captures a multitude of feedbacks between natural processes and sand supply using four basic equations

\[
\begin{align*}
\frac{dH}{dt} &= \frac{Q_{\text{OW},H}}{W} - \dot{z} \\
\frac{dx_S}{dt} &= \frac{2Q_{\text{OW}}}{2H + D_T} - 4Q_{\text{SF}}\frac{H + D_T}{(2H + D_T)^2} \\
\frac{dx_T}{dt} &= 2Q_{\text{SF}}\left(\frac{1}{2H + D_T} + \frac{1}{D_T}\right) + \frac{2\dot{z}}{\alpha} \\
\frac{dx_B}{dt} &= \frac{Q_{\text{OW},B}}{H + D_B}
\end{align*}
\]
A multi-disciplinary study that integrates society (Brody), engineering (Padgett and Bedient), and geomorphology (Nittouer)

**Stress nexus of coastlines:**

**Field site:** Brazos River delta and greater Freeport region

**Broad goal:** integrative research to bolster decisions about appropriate actions for Texas Gulf Coast sustainability
Why the Brazos River/Freeport region? Convergence of geomorphology, engineering, society: Extremely important economic hub for Texas, and the U.S.A.

Brazos River delta, Texas
Classic wave-dominated morphology

Freeport, TX: industry hub

Freeport, TX: 2008 Hurricane Ike

Landscape and infrastructure vulnerability
Bigger Picture: Brazos River is the second largest river in Texas

- Drainage basin: 111,000 km² extends into New Mexico
- Ephemeral river: prone to significant flood and drought events

Figure 1.1: A map of Texas showing the Brazos watershed and the study gaging stations.
20th Century history of the Brazos River delta: human perturbation

Brazos River delta, Freeport Texas:
- USACE diverts river upstream of Freeport (1929)
- Within 11 years (1940) Old Brazos Delta is destroyed
- By 1989, New Brazos Delta developed up to 15 km² of land

Old delta destroyed by energetic wave conditions of the Gulf of Mexico…“sweep” away sand

New Brazos Delta: ~50% sand and ~50% mud by volume…this despite the fact that the Brazos River sediment load is: ~90% mud ~10% sand
Development of the Brazos River delta: role of droughts and sediment supply to maintain the subaerial delta surface
**Basic motivating question:** If sediment (sand) flux is so strongly punctuated (e.g., seven years with essentially no sand input), then why is the New Brazos Delta geomorphologically stable provided consistent wave energy?

**Modeling the development of the New Brazos Delta**

**Critical balance:** $q_{in}$ vs. $q_{out}$

- $h(t)$
- $q_{in}$
- $q_{in} - q_{W}$
- $q_{W}$
- $y = 0$ (initial shoreline)

**Critical input parameters:**
- Sediment input
- Basin depth
- Wave energy
- Along-shore sediment flux

**Distance of River Mouth From Datum**

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<th>Date</th>
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Distance (m) range: 0 to 3500.

Wave energy $W$, $H$, $s$, $q$, $q_{W}$.
Critical consideration: Despite a constant wave climate and “de facto” sand cut off due to Texas-size droughts, the Brazos River delta grows and maintains a relatively consistent subaerial planform for 80+ years…HOW CAN THIS BE?

Considering the role of large woody debris (LWD) for delta morphology
LWD has been shown to play a critical role for shaping the morphology of steep-sloping, mountainous rivers across the western U.S.A.

- Critical for attenuating flow energy and generating deposition of sediment
- Many stream restoration projects implement artificial LWD blocks, so as to engineer the system and mimic nature
Crux of the role of LWD: Attenuate (dampen) wave energy, so as to leave less energy available to transport sediment during drought periods. Critical balance:

\[ \tau_b = \tau_{sf} - \tau_{fd} \]

Where:
- \( \tau_b \) is the total stress produced by the wave energy
- \( \tau_{fd} \) is the stress extracted due to form drag (i.e., LWD)
- \( \tau_{sf} \) is the stress available for sediment transport

\[ \tau_{sf} = \tau_b - \tau_{fd} \]

Our morphodynamic model must take into account the stress extracted by LWD in order to calculate the stress available to mobilize sediment

Modeling framework: Step 1—Match the location of the New Brazos Delta river mouth since the start of the diversion (1929); \( q_{in} \) as the input parameter

\( K \) represents the diffusivity of sediment along the delta shoreface (e.g., \( q_{out} \))

\( K \) values of 7000-10,000 approximate the development of the New Brazos Delta
Modeling framework: Step 2—Destroy the Old Brazos Delta over the known time duration for delta destruction (approximately 11 years); i.e., tune the model via diffusivity value to find the appropriate $K$ for the correct time scale

$K$ values of 130,000-180,000 approximate the destruction of the Old Brazos Delta over the ~11 year time scale

Therefore, we hypothesize that the Brazos River delta LWD reduces diffusivity by a factor of 10-20x, which is a value necessary to maintain the delta profile despite prolonged droughts and extremely low sediment (sand) supply to the delta
Critical next step in our analyses: relate sediment diffusivity (K) to form drag ($\tau_{fd}$) …work in progress…headed up by Rice graduate student Sarah Huff

As described previously: Old Brazos Delta destruction is considered to be related to the cut off of sediment. Here, we hypothesize that the rapid destruction was actually due to cut off of large woody debris. How could this be? Consider human activities, i.e., harvesting of wood:

Goal: assess Freeport City tax records from early 20th century to find any discussion of wood harvesting on the Brazos River delta
First-order, critical linkages through the Shell Center for Sustainability:

1) Our modeling efforts show the dynamics of the Texas barrier island and deltaic systems necessitates evaluating critical parameters, such as fluid energy (e.g. informed by storm surge inundation data via Dr. Bedient’s research)
2) Morphodynamics of coastal systems must inform infrastructure engineering, so as to produce stable and sustainable transportation networks along coast landscapes (e.g., work in conjunction with Dr. Padgett’s research)
3) Coastline evolution is critical to constrain in order to inform land development practices (e.g., information for Dr. Brody’s research)

Multi-disciplinary efforts to evaluate coastal sustainability are the wave of the future (see: NSF Coastal SEES); these studies necessitate integrating aspects of society (Brody), engineering (Padgett and Bedient), and geomorphology (Nittouer)
Final Considerations

- Coastal sustainability studies must address societal needs by advancing basic science
- Observations from modern coastal systems inform models necessary to predict trends in coastal morphology and development
- Our multidisciplinary SCS grant focuses on the upper Texas Gulf Coast, however the products from this work will contribute broadly to coastal sustainability initiatives regionally, nationally, and globally