Quantifying Delta Planform Evolution Under Sea-Level Rise: Insights from Flume Experiments and Enthalpy-Based Modeling

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Introduction

Motivation

- River deltas are shaped by the combined effects of sediment supply, water discharge, sea-level rise (SLR), and antecedent topography (Bedrock or Basement slope). These systems archive valuable information about environmental change and coastal dynamics.
- Yet, limited long-term data and the absence of satellite imagery before the 1960s constrain our ability to quantitatively assess how these drivers influence delta morphology over centennial to millennial timescales.
- To overcome this challenge, we integrate controlled **flume experiments**, **image-based geometric analysis**, and **numerical modeling** to investigate how external forcings control delta planform evolution

Goals

Quantify the influence of sediment supply, water discharge, antecedent slope, and SLR rate on the planform geometry of deltaic sedimentary prisms.

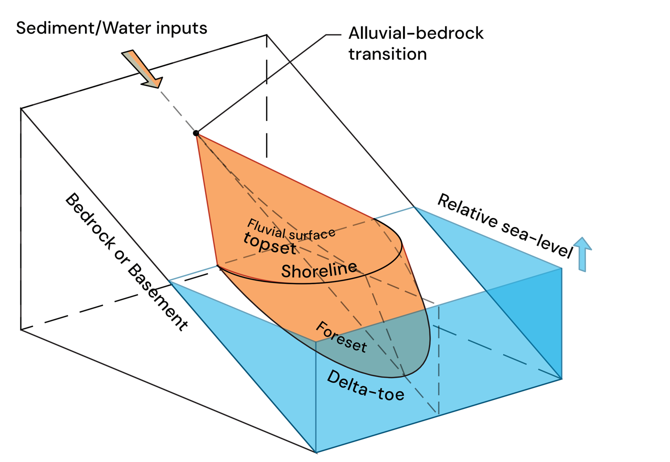


Figure 1: 3D geometry diagram representation of the Enthalpy process-based model

Approach

Combining flume experiments, computer vision techniques, and two tiers of numerical modeling:

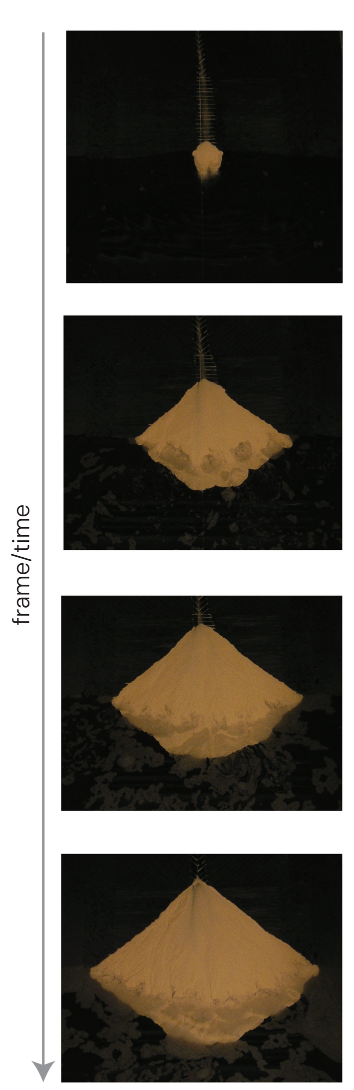


Figure 2: SI Run 4 (Kim & Muto, 2007) Fixed Sea-Level

Flume Experiments:

14 delta-building experiments by Kim & Muto (2007), with different constant sediment supply values, water discharge values, and water-level change values.

Computer Vision Analysis:

A custom open-source computer vision (OpenCV2) algorithm is applied to extract key geometric features across time

Future

Fixed Sea Level

Geometric Model

Validate & Analyze

Stable delta shape evolution

Key parameters: topset & foreset slopes calculated

Rising Sea Level

Enthalpy-Based Model

Incorporating dynamic foreset and topset transitions. more complex, time-dependent geometry

Quantify Forcing Effects on Delta's Geometry

Figure 3: Approach flowchart involve current and planned progress of this project

Computer Vision Analysis

Under fixed sea level

Sequences of flume experiment runs' image data

Computer Vision (OpenCV2) algorithm → image filters; edge detection; geometry extraction

Geometric Model

Validate CV algorithm parameters

Figure 4: Detail flowchart of the Geometric Model

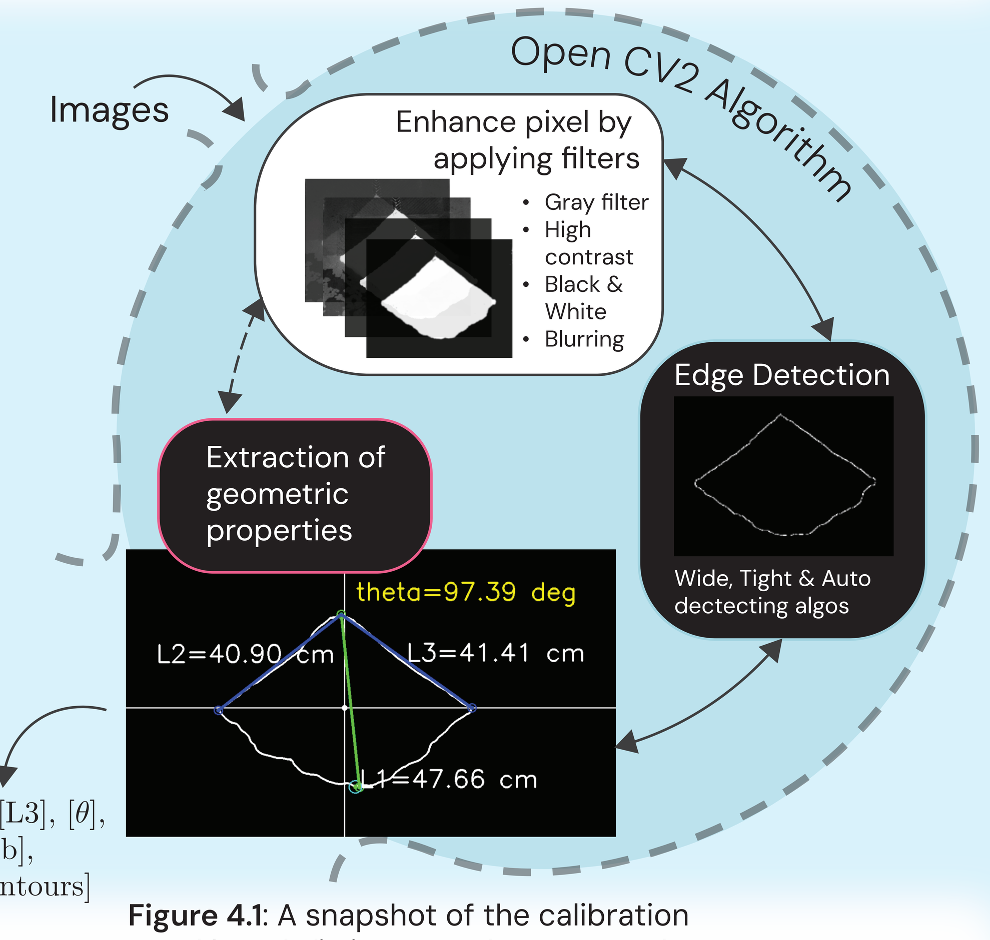


Figure 4.1: A snapshot of the calibration and length fitting onto the extracted contour of the flume delta.

Geometric Model Under fixed sea level

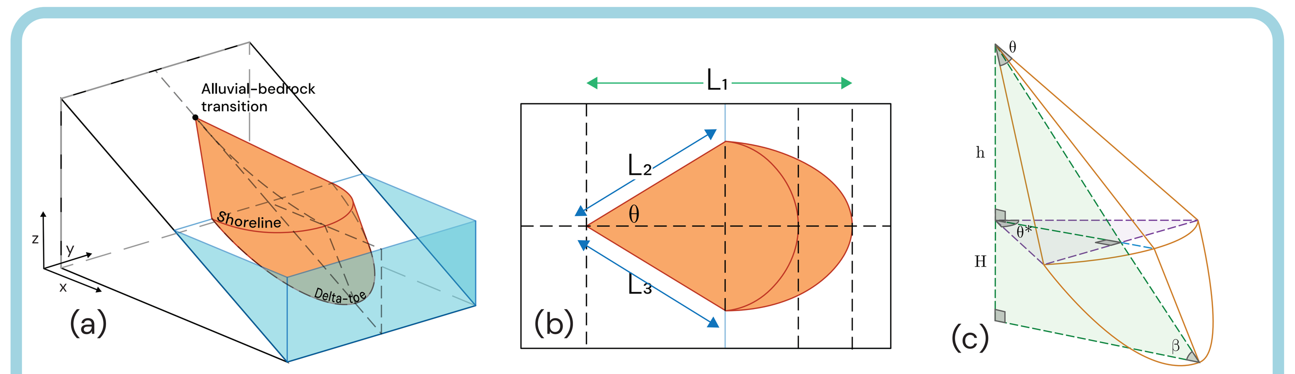


Figure 4.2: (a) 3D view, (b) plan view, (c) geometry diagram of the 3D view

$$L_{mean} = \frac{L2 + L3}{2}$$

$$h = \beta * \frac{L_{mean}\cos\left(\frac{\theta}{2}\right)}{\sqrt{\beta^2 + 1}}$$

$$r = \sqrt{(L_{mean})^2 - h^2}$$

$$\theta^* = 2 * \arcsin\left(\frac{L}{r}\sin\left(\frac{\theta}{2}\right)\right)$$

$$V = \frac{1}{3}hr^2\left(\frac{\theta^*}{2} - \cos\left(\frac{\theta^*}{2}\right)\sin\left(\frac{\theta^*}{2}\right)\right) + H\frac{R^2 - r^2}{2}\theta^*$$

Volume equation for Geometric Model

$$V_{expected} = Q_{constant\ sediment\ flux} * t_{total\ run\ time}$$

Given Q and t total run time

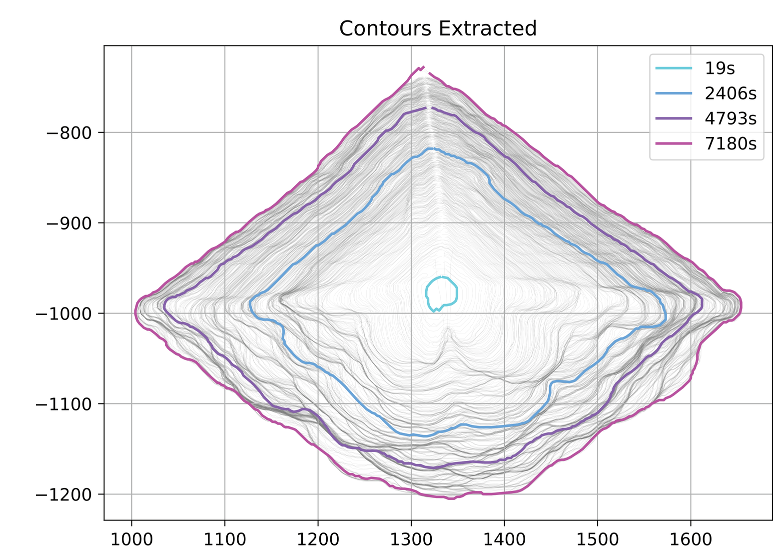


Figure 4.2. Delta shape evolution over time plot using refined contours extracted from CV algorithm

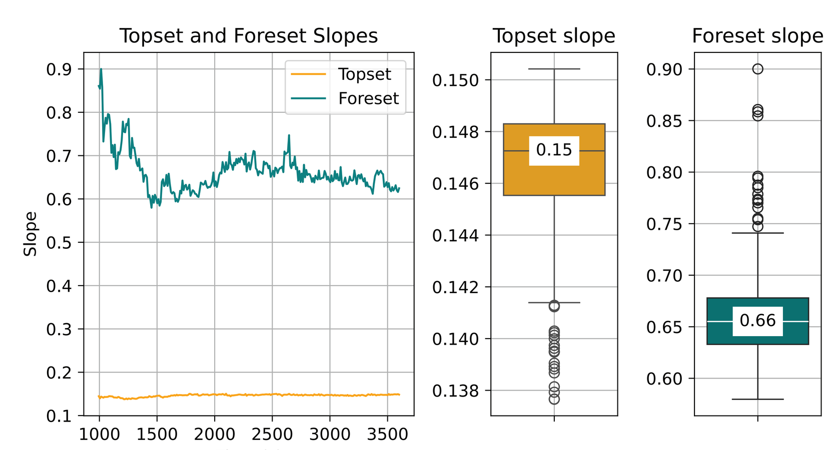


Figure 5. Topset and Foreset Slope estimate for SI Run 4

$$m_{topset} = \frac{h}{r} = \beta * \frac{L_{mean}\cos\left(\frac{\theta}{2}\right)}{\sqrt{(\beta^2 + 1)((L_{mean})^2 - h^2)}}$$

$$m_{foreset} = \frac{H}{R - r} = \beta * \frac{L_1 - h\sqrt{\beta^2 + 1}}{L_1 - \sqrt{((L_{mean})^2 - h^2)(\beta^2 + 1)}}$$

Using value calculated from the geometric model or with given initial parameters, we can find the estimated slope value for topset and foreset of the flume's delta

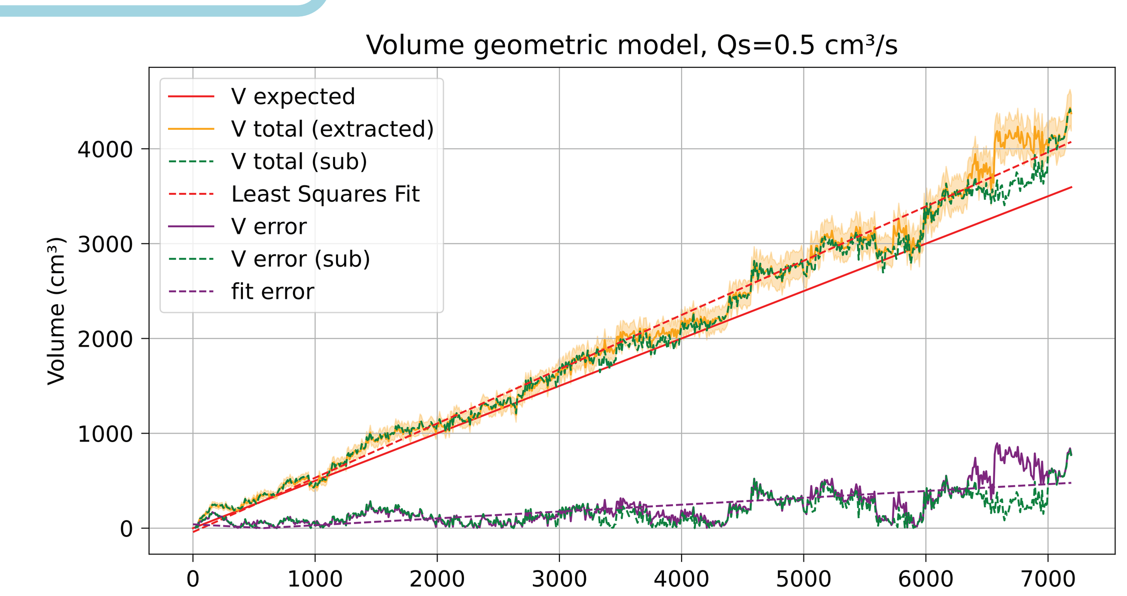


Figure 6. Comparison volumes graph

To validate CV algorithm, we compared 2 independent estimates of deltaic sediment volume over time :

1. Geometric Estimate (Volume total extracted) computed using L1, L2, L3, θ applied to a simplified geometric model of the delta.
2. Flux-based Estimate (Volume expected) calculated from the known, $Q_{constant\ sediment}$ supply for each experimental run

Agreement between 2 volumes provides confidence in the values extracted from imagery and supports its use in further modeling

Computer Vision Analysis

Under sea level rise

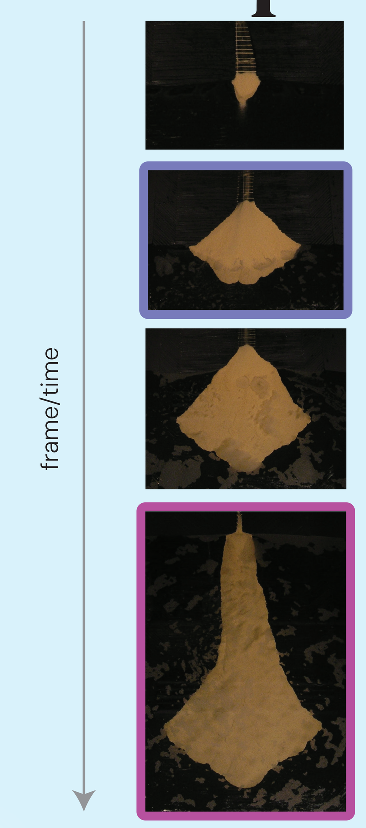
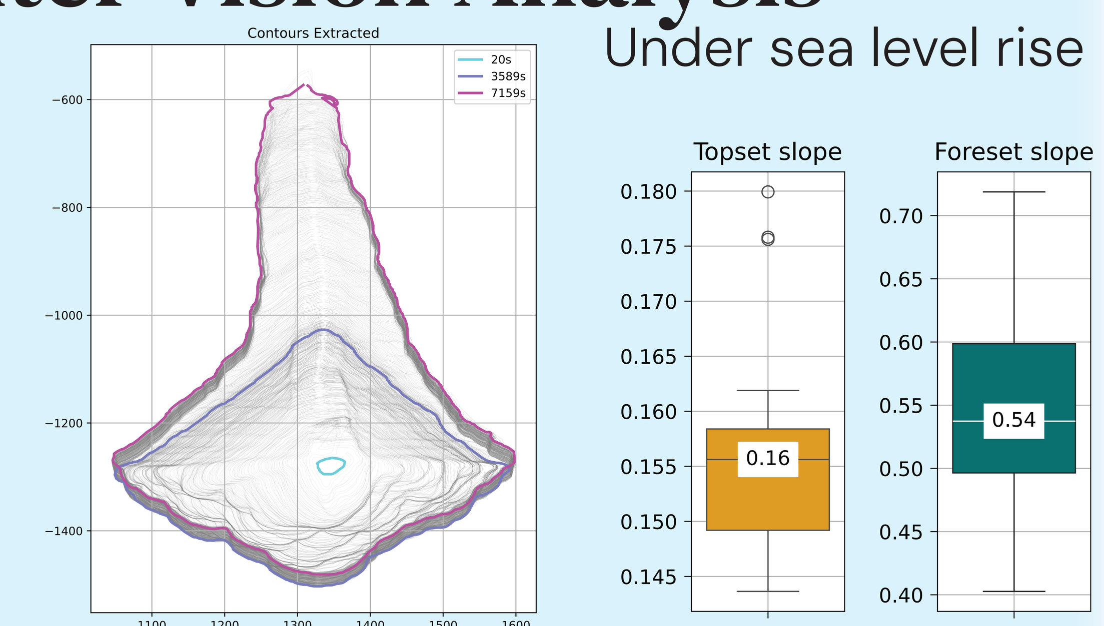


Figure 7: SI Run 5 (Kim & Muto, 2007) Rising Sea-Level

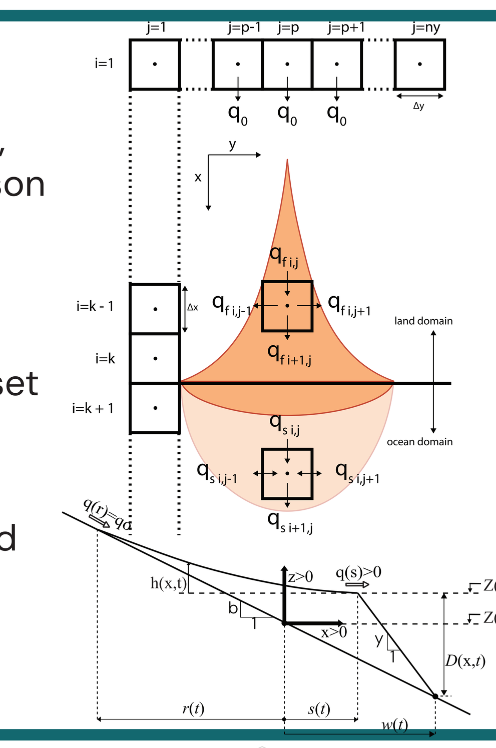


- After validating our CV algorithm for fixed sea-level runs, we apply it to extract geometric features of deltaic deposits formed under rising sea levels.
- Under SLR, delta morphology becomes more complex: the foreset becomes progressively starved of sediment, leading to the abandonment of the submarine delta front and landward retreat of the fluvial topset.
- The algorithm enables tracking of this evolving geometry over time.

Enthalpy Process-based Model

Under sea level rise

- We present initial results from a two-dimensional, moving-boundary model in development (Anderson et al., 2019; Lorenzo-Trueba et al., in prep) that simulates delta evolution under both fixed and rising sea levels.
- The model dynamically resolves foreset and topset interactions and captures key morphodynamic transitions.
- Preliminary outputs are consistent with flume and prior numerical results, reproducing foreset starvation, topset retreat, and narrowing of the delta planform under sustained sea-level rise.



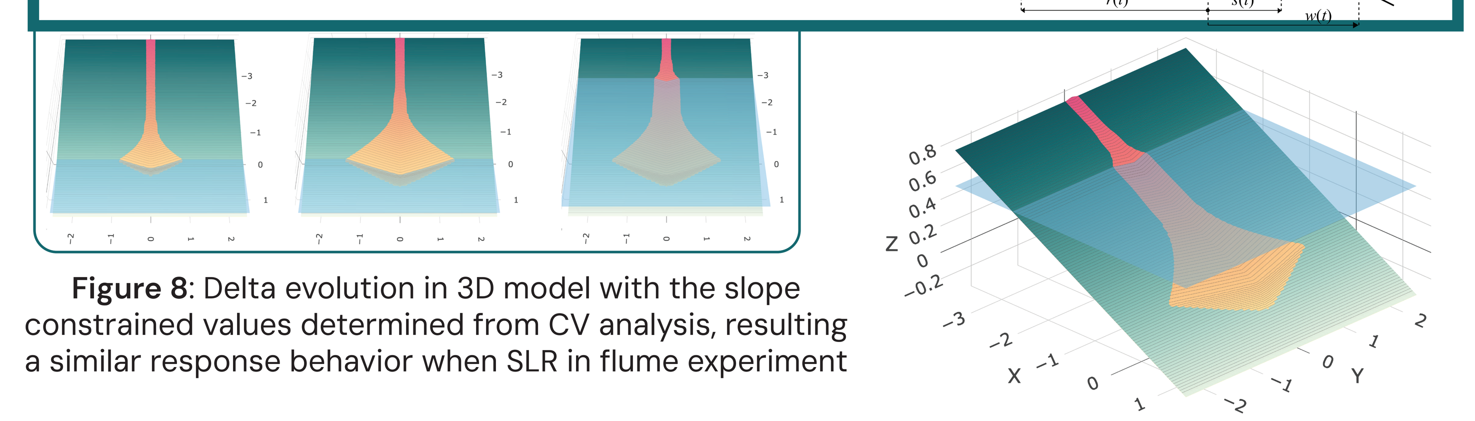


Figure 8: Delta evolution in 3D model with the slope constrained values determined from CV analysis, resulting a similar response behavior when SLR in flume experiment

Future Works

- Computer Vision: Expand validation using the geometric model on additional flume runs under fixed sea level.
- Model Integration: Continue development and calibration of the enthalpy model to explore a wide range of sediment supply, water discharge, antecedent slope, and sea-level change scenarios.
- Applications: Apply the modeling framework to Arctic deltas to infer past sea-level and sediment budget histories from preserved delta morphology, and ultimately couple with deeper crustal and isostatic processes.

References

- J. Lorenzo-Trueba (in prep.) Enhanced Geomorphic Enthalpy Framework for Modeling Coupled Subaerial and Subaqueous Evolution of Fluvial Deltas under Sea-Level Changes
- W. Anderson, J. Lorenzo-Trueba and V. Voller (2019). A geomorphic enthalpy method: Description and application to the evolution of fluvial-deltas under sea-level cycles. Computer and Geosciences.
- Kim, W. and Muto, T. (2007). Autogenic response of alluvial-bedrock transition to base-level variation: Experiment and theory.
- Voller, V.R., Swenson, J.B., Kim, W., Paola, C., 2006. An enthalpy method for moving boundary problems on the earth's surface. Int. J. Numer. Methods Heat Fluid Flow. 16, 641–654.