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The **morphology** and **scaling** of **tidal dunes** with respect to **depth**: insights into the **form roughness** associated with channels affected by **tidal forcing**

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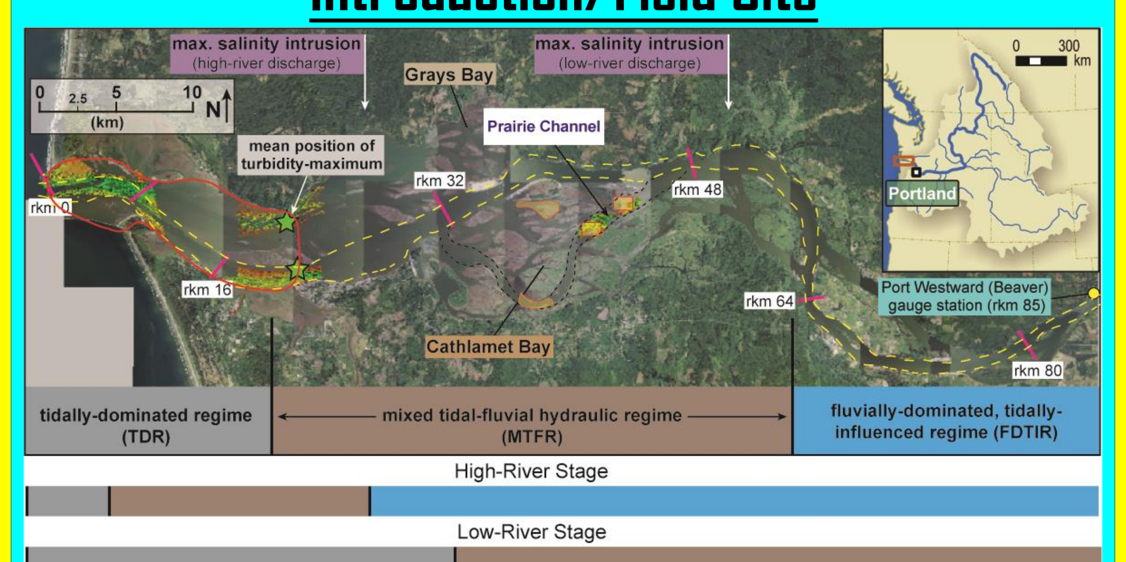
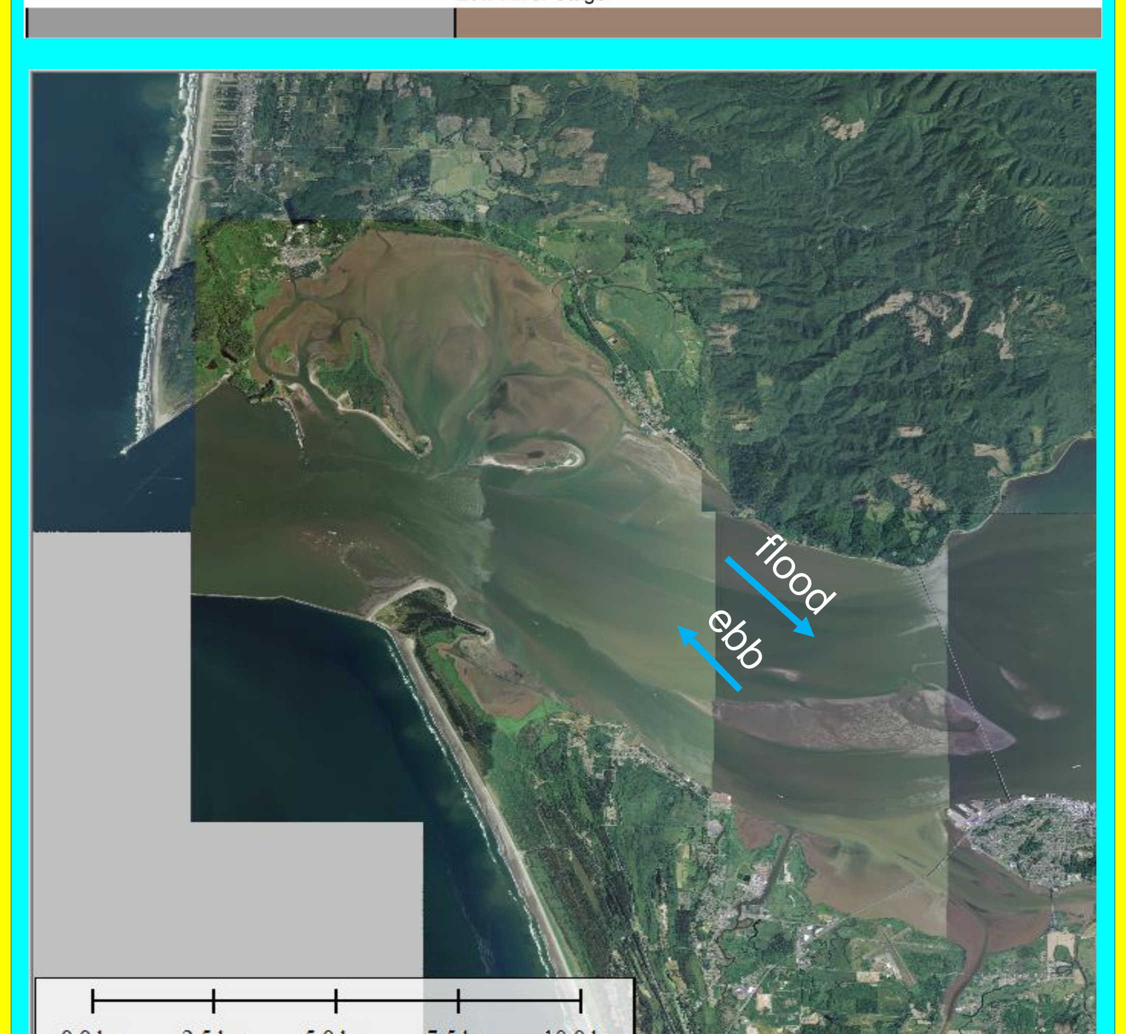
Abstract

The deposits of subaqueous dunes are a fundamental building block of vertically-stacked alluvium in river to tidal settings and are responsible for producing the largest component of frictional resistance to flow via form roughness. Thus, dunes have attracted considerable attention amongst researchers for decades since they are found in virtually all environments (headland rivers to abyssal plains) and grain sizes (coarse silts to gravels) along the source-to-sink sediment transport pathway. Of these environments, dunes produced by rivers (unidirectional flows) are the most widely studied with respect to their morphologic dynamics and their scaling of height and wavelength to flow depth, whilst our understanding of these same characteristics within bidirectional (tidal) and combined-flow (currents with a unidirectional and oscillatory component) is quite limited. This knowledge gap is addressed herein by evaluating a set of multibeam echo sounding (MBES) surveys of the main channel of the Lower Columbia River (LCR), WA/OR, USA, within its downstream most hydraulic regime, which is dominated by bidirectional tidal-flows and/or combined-flows consisting of a tidal component and a shorter period (oceanic to intrabasinally derived) wind-wave component. Specifically, variations in dune geometric parameters (e.g., height, wavelength, roundness, symmetry, dimensionality, stoss- and lee- angle, and ratio of stoss- to lee- angles) and scaling of height and wavelength to flow depth are systematically quantified within the main channel (0-32m depth) and are linked to depth transitions in formative current styles. These findings provide insight into the morphologic differences (i.e., form roughness) between dunes generated within non-uniform and unsteady flow conditions and those from more uniform and steady flows, whilst further adding to our understanding of the scaling of height and wavelength to depth within such dynamic flows. Preliminary results show that dunes remain asymmetric at all depths and possess lee-angles ≤ 15°, their roundness is maximized at both the shallowest and deepest depths, and present river-tidal scaling relations overpredict their heights and wavelengths, which suggests that new relations are needed to better understand the dunes of tidal and combined-flow settings.

Introduction/Field Site



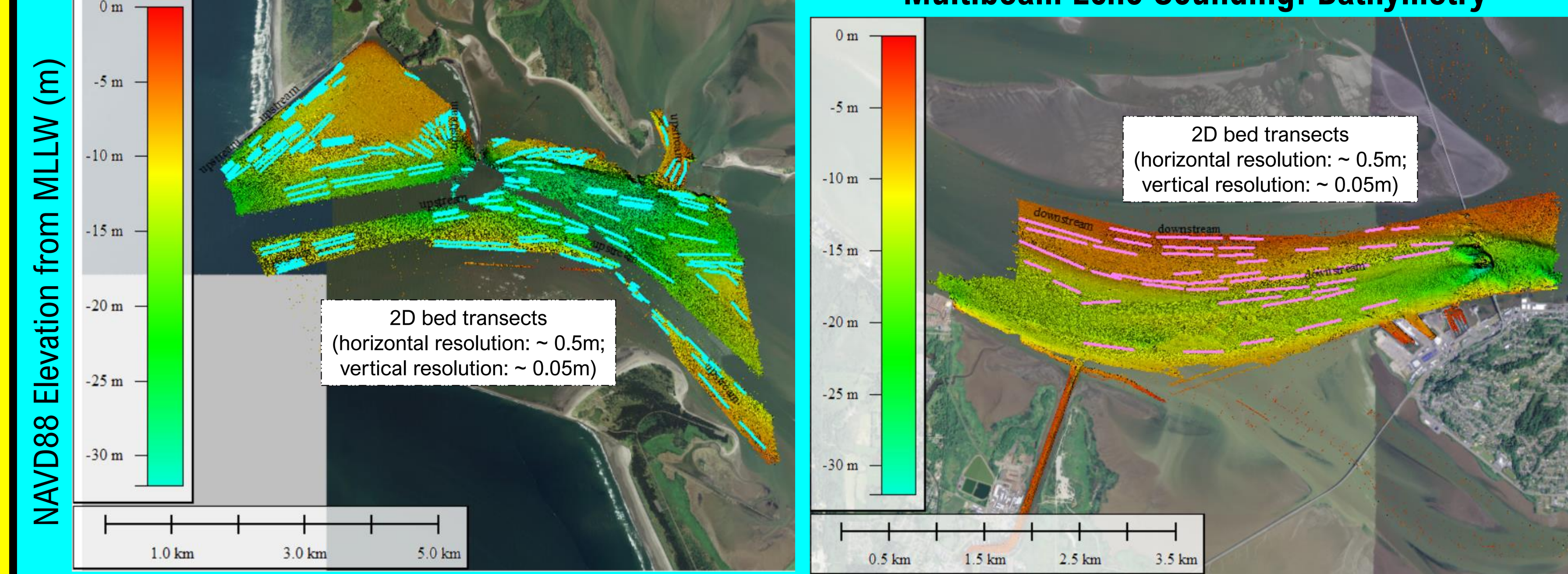


Study Area Characteristics: Lower Columbia River

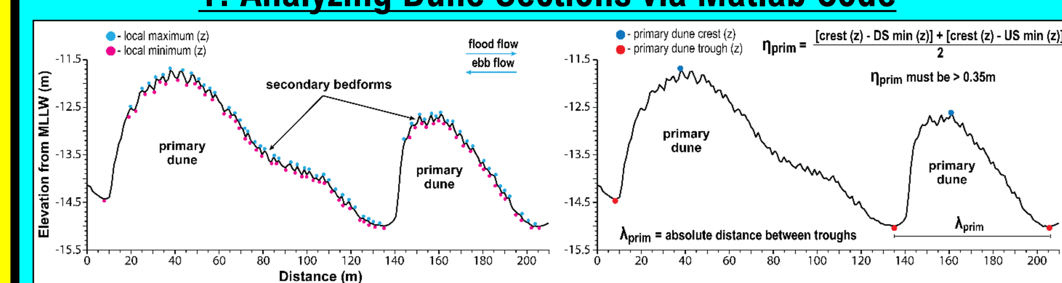
- **Tidally-dominated regime of the Lower Columbia River**
- **Average fluvial discharge is 3,600 m^3s^{-1} (low-flow)**
- **Grain size is ~ 125-250 μm (fine to medium sand)**
- **Experiences mixed semi-diurnal and diurnal tides**
- **The mean tidal range is 1.7-2.0m and the highest astronomical tide is 3.6-4.0m (mesotidal)**
- **The mean diurnal tidal prism is ~11.0 x 10^8 m^3**

Methodology

Multibeam Echo Sounding: Bathymetry



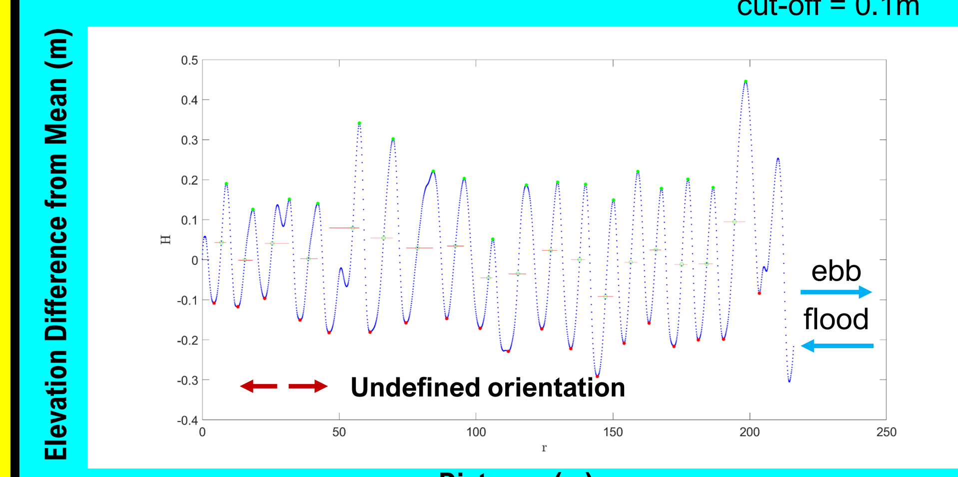
1. Analyzing Dune Sections via Matlab Code

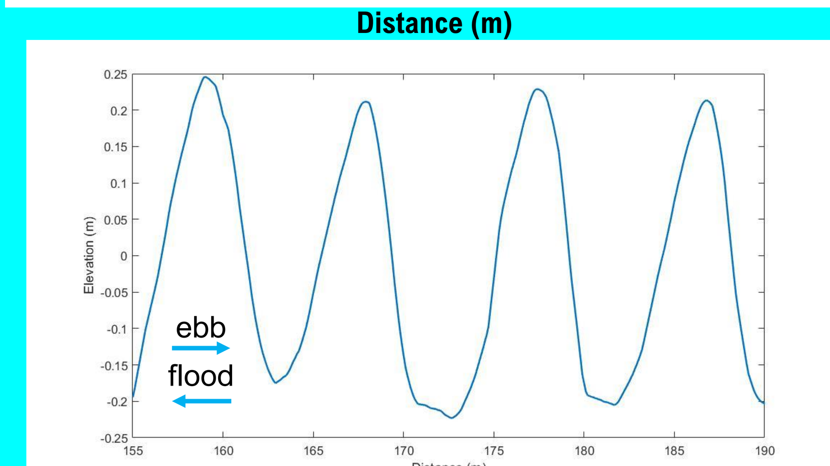


Primary Bedform Cut-Off Values

Depth Interval	Cathlamet Bay	Number of Dunes
0-5m	0.09m	137
5-10m	0.1m	1627
10-15m	0.11m	2886
15-20m	0.1m	1313
20-25m	0.1m	704
25-30m	0.08m	778

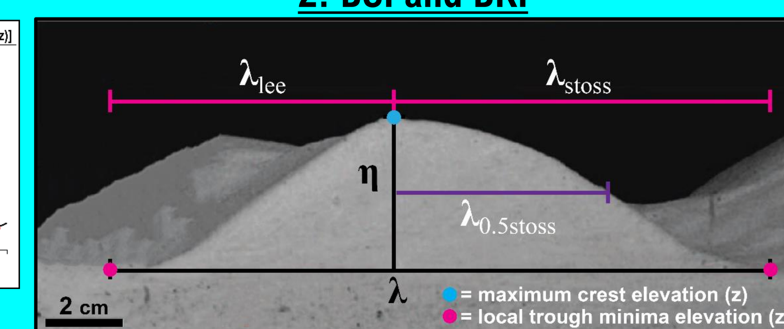
cut-off = 0.1m





LRI = 0.91, SRI = 0.91, BRI = 0.51, BSI = 1.69, BAR = 0.62, Mean lee = 8.3° mean stoss = 4.53°

2. BSI and BRI



Bedform Symmetry Index (BSI) = $\lambda_{stoss}/\lambda_{lee}$

Bedform Roundness Index (BRI) = $\lambda_{0.5stoss}/\lambda_{stoss}$

Asymmetric: BSI > 1.5 Rounded: BRI ≥ 0.6

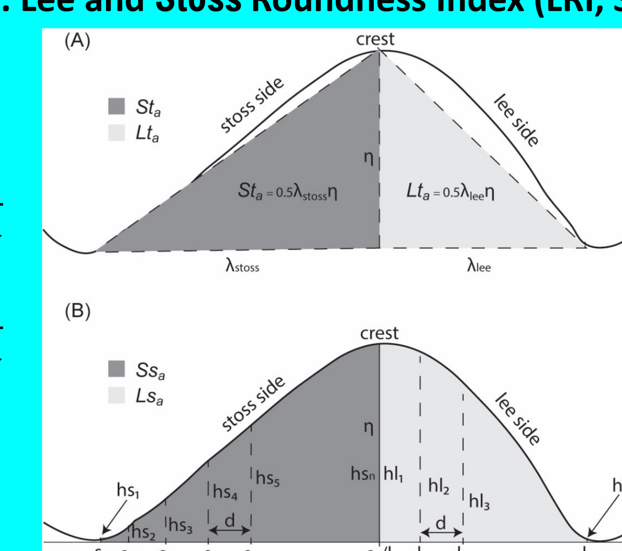
Symmetric: BSI < 1.5 Not Rounded: BRI < 0.6

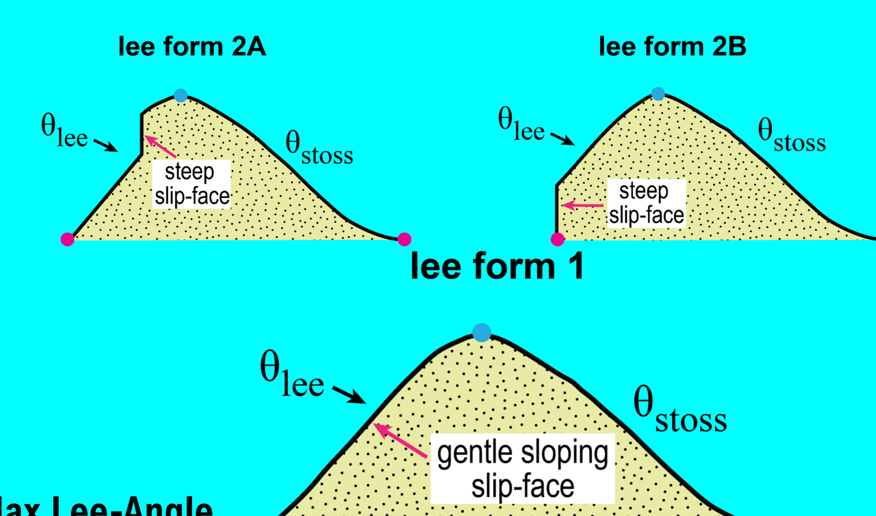
(from Perillo et al., 2014)

3. Lee and Stoss Roundness Index (LRI, SRI)

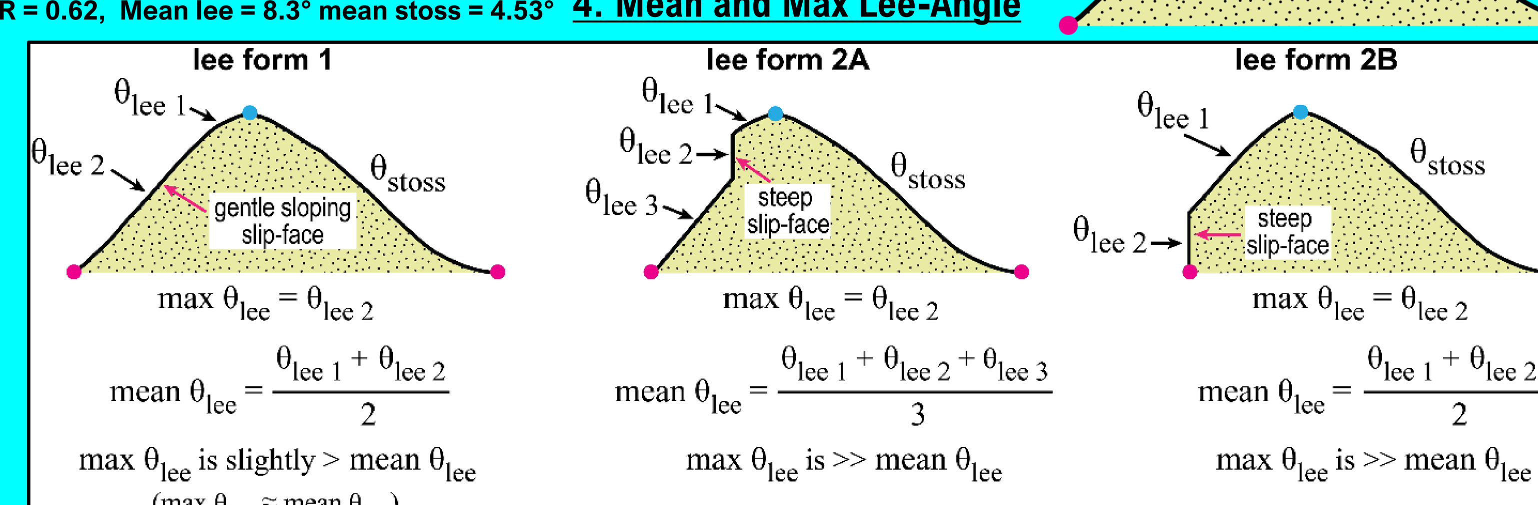
$$SRI = \frac{St_a}{Ssa}$$

$$LRI = \frac{Lt_a}{Lsa}$$





4. Mean and Max Lee-Angle



lee form 1	lee form 2A	lee form 2B
max $\theta_{lee} = \theta_{lee\,2}$	max $\theta_{lee} = \theta_{lee\,2}$	max $\theta_{lee} = \theta_{lee\,2}$
mean $\theta_{lee} = \frac{\theta_{lee\,1} + \theta_{lee\,2}}{2}$	mean $\theta_{lee} = \frac{\theta_{lee\,1} + \theta_{lee\,2} + \theta_{lee\,3}}{3}$	mean $\theta_{lee} = \frac{\theta_{lee\,1} + \theta_{lee\,2}}{2}$
max θ_{lee} is slightly > mean θ_{lee} (max θ_{lee} ≈ mean θ_{lee})	max θ_{lee} is >> mean θ_{lee}	max θ_{lee} is >> mean θ_{lee}

Hypothesis: Does environment influence the size of bedforms??

❖ Dunes in tidally-dominated environment possess smaller heights and wavelengths than those in rivers (fluvially-dominated environment) and therefore potentially exert less form drag

❖ The leesides of 'river' dunes are more rounded than their stoss-sides, and thus measuring only the roundness of stoss-sides may not be adequate to fully describe dune roundness and morphology

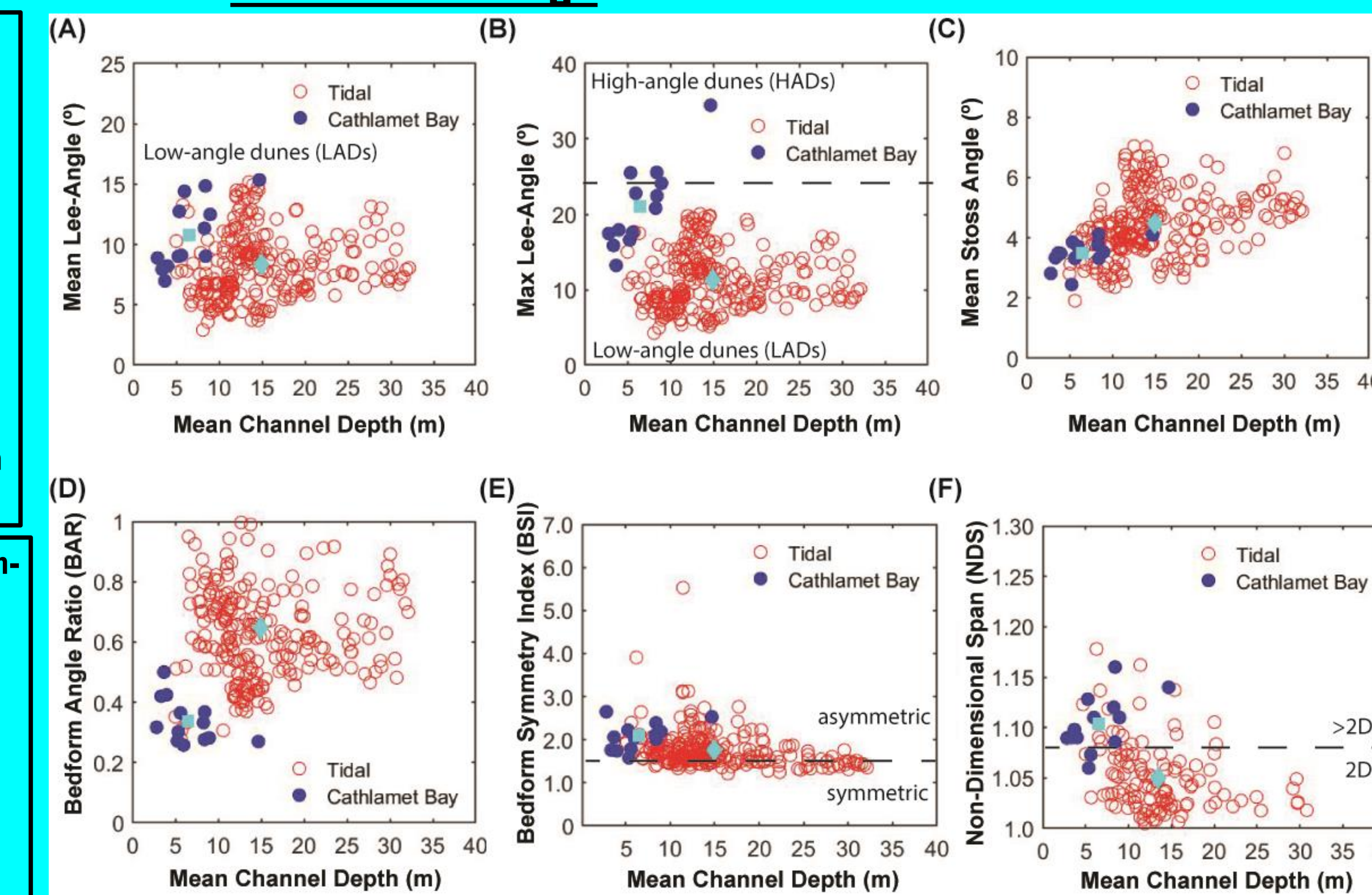
Results/Findings

(A, B, C & D) Mean, Max Lee angles, & Stoss angle

- Tidal dunes are **low-angle dunes (LADs)** and have a lower mean lee-angle than 'river' dunes of Cathlamet Bay
- Their crests and brink points are near the same elevation
- Their mean stoss-angle is higher than that of Cathlamet Bay, suggesting efficient bidirectional transport of sediment
- Therefore, they possess a higher BAR than those in Cathlamet Bay (more symmetric)

(E & F) Bedform Symmetry Index (BSI) & Non-Dimensional Span (NDS)

- Tidal dunes are more symmetric than bedforms at Cathlamet Bay
- They are generally 2D, whereas dunes become more 3D in Cathlamet Bay
- Divergence in dimensionality is potentially the product of unsteadiness in flow and thus sediment transport rates

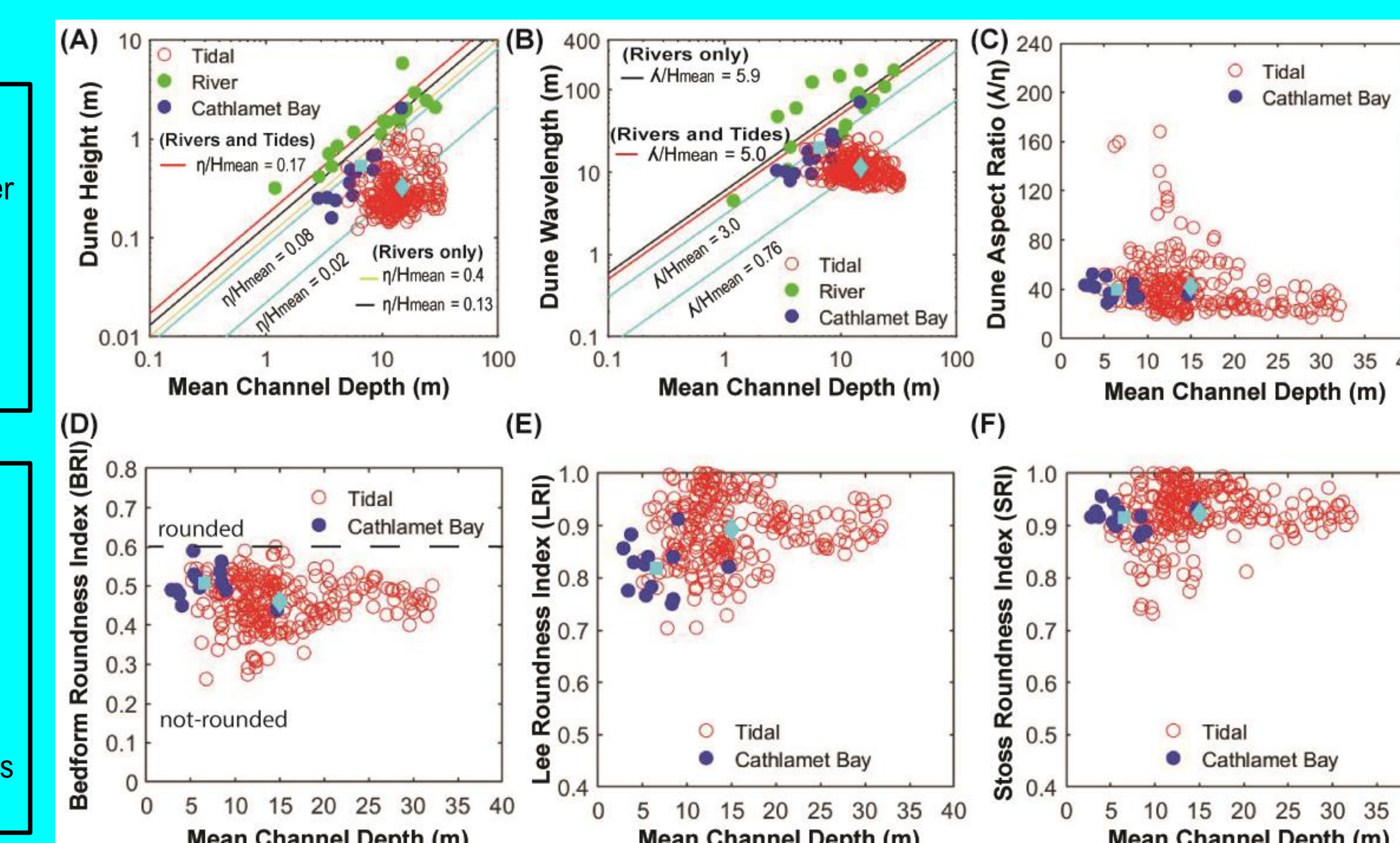


(A & B) Dune Height & Wavelength

- Dunes in tidal environment possess smaller heights and wavelengths than those in rivers
- This is due to the unsteadiness caused by bidirectional currents
- New scaling relations are introduced

(C) Dune Aspect Ratio (λ/η)

- Tidal dunes do not strongly increase their heights and wavelengths with depth
- Tidal dunes cannot reach same equilibrium heights and wavelengths as their 'river' counterparts due to enhanced unsteadiness in flow and sediment transport rates



(D) Bedform Roundness Index (BRI)

- The BRI of tidal dunes does not show significant variations with depth
- Also, they are not rounded as indicated by the classification of Perillo et al. (2014)
- This calls into question whether the BRI is an appropriate parameter to determine the difference between tidal and river bedforms

(E & F) Stoss and Lee Roundness Index (SRI, LRI)

- The new method for the estimation of bedform roundness by separating the lee- and stoss-sides displays a significant difference between 'tidal' and 'river' dunes
- The SRI and LRI for tidal dunes do not show a significant difference. Their high values (close to 1) show that both sides are not rounded and there is almost an equal distribution over the crest
- However, while the bedforms in Cathlamet Bay have a higher SRI, their LRI values are lower, which indicates that the 'roundness' of bedforms is more prominent on their leesides relative to their stoss-sides
- This indicates that there is greater separation between their brink points and their crests

Conclusions/Future Work

- Scaling relations show that tidal bedforms have **smaller heights and wavelengths** relative to river dunes with respect to depth
- They are more **symmetric** and **2D** relative to bedforms in river-dominated environments
- Their **stoss** and **lee sides** are **less rounded relative to bedforms in fluvial settings**. However, the **roundness of fluvial bedforms is taken up more so by their leesides and not their stoss-sides**
- Current 'river' scaling relations do not accurately predict the heights and wavelengths of tidal bedforms, and thus cannot be applied to tidal environments
- New scaling relations for tidal bedforms are therefore introduced ($\frac{\eta}{H_{mean}} = 0.02, \frac{\lambda}{H_{mean}} = 0.76$)

Future Work -

- Investigate bedforms under more steady conditions (fluvially-dominated)
  - ❖ How do the results of this study compare to bedforms in a fully-fluvial environment?
- Continue reassessing scaling relations
  - ❖ Deeper investigation into tidal environments through the analysis of alternate systems?

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