Bedform response to mean shear stress in the fluvial to tidal transition zone

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ABSTRACT: Bedform geometry in sand-bedded rivers is traditionally predicted with empirical equations, using reach-scale river characteristics as input parameters. Especially in the fluvial-to-tidal transition zone (FTTZ), where river discharge and tidal currents drive the flow, this is an inappropriate simplification. To understand variability in bedform geometry in the FTTZ, we assess the spatial variability of dunes in the Fraser River (Canada) and their relation to modelled flow characteristics.

Dune symmetry and aspect ratio increase in downstream direction, which is correlated with the increasing time and strength of flow reversal. However, predicting dune height in the FTTZ using tidally-averaged shear stresses resulted in an underestimation of dune height upstream (>40km from the river mouth), and an overestimation downstream. Using maximum shear stresses, only slightly overpredicted the dune height. Nevertheless, local variability could not be captured with any of these methods, which highlights the need for a new bedform predictor in tidal rivers.

1 INTRODUCTION

An estimation of bedform geometry is important for hydraulic roughness determination, navigable channel depth and sedimentary record interpretation. Bedform geometry and occurrence in sand-bedded rivers is traditionally predicted with phase diagrams and empirical equations, using reach-scale river characteristic (e.g., bed slope, water depth, grain size) as input parameters. Field observations supporting these equations are often made in regions where bedform fields are known to be present and are spatially uniform. Furthermore, in flow and sediment transport models, bedforms are often assumed to be spatially homogeneous and the resulting hydraulic roughness is therefore assumed to be quasi steady and uniform across the river, such that these empirical relations can be employed. However recent research has shown significant local spatiotemporal variation in dune height (Bradley et al., 2017) and geometry (Murphy et al., in progress), limiting the validity of this assumption. To enable the prediction of dune geometry, its spatial variability needs to be better understood.

Especially in the fluvial-to-tidal transition zone (FTTZ), variation in flow velocity occur in shorter time frames than in rivers. The FTTZ can be defined as the part of the river that is upstream fully dominated by fluvial processes, to the downstream estuary fully dominated by tidal and coastal processes (Phillips et al., 2022). Dunes in the FTTZ are often believed to decrease in size in downstream direction, which is then related to the downstream fining and shallowing of the channel. However, Lefebvre et al. (2021) and Prokocki et al. (2022) recognize various bedform geometries, shapes and 3D planforms across the FTTZ. Neither of those researchers included cross-sectional

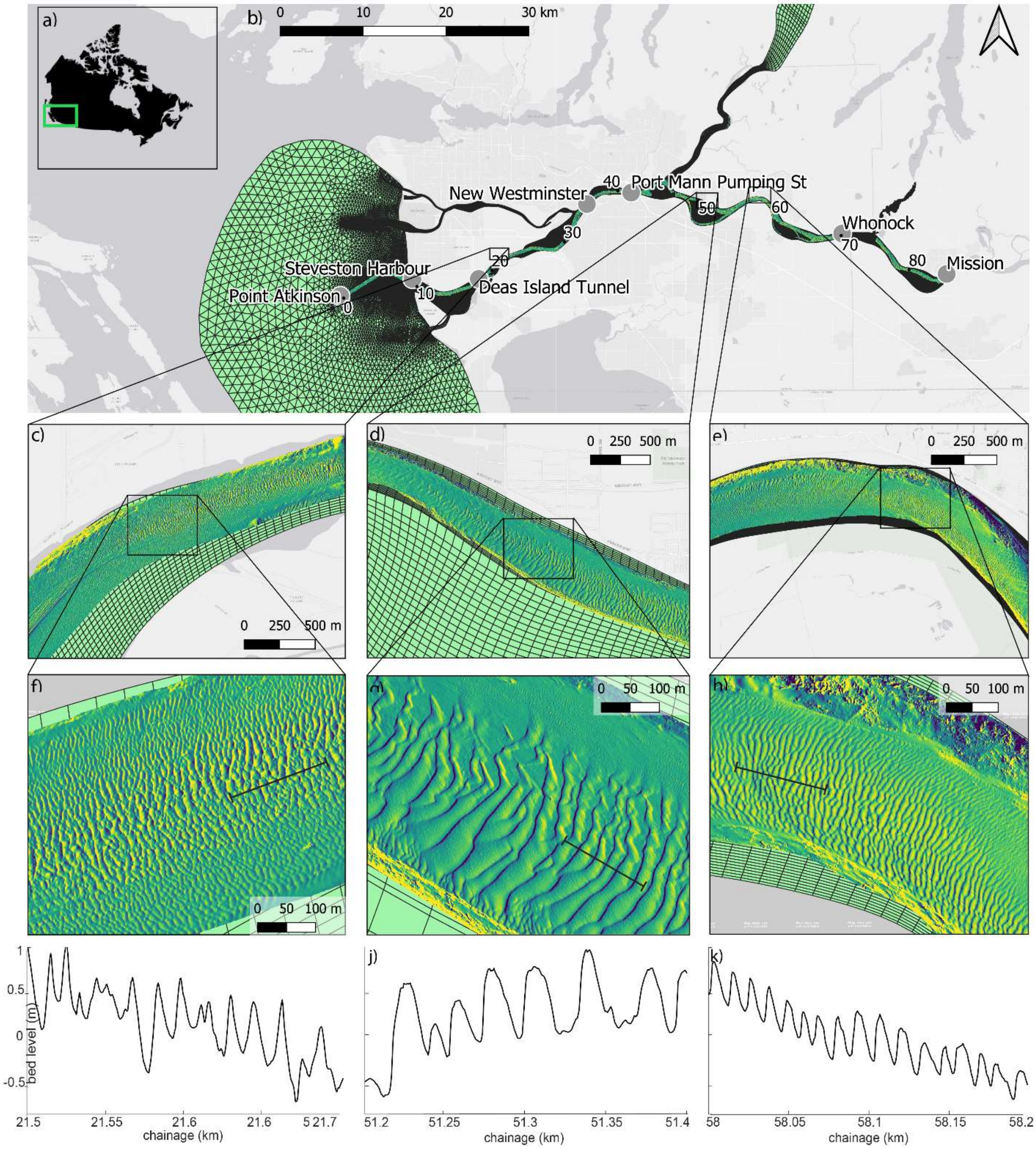

Figure 1. Study area. b) model domain. C-e) close ups of the focus areas. F-g) examples of dune fields.

variability in their work, and did not link their findings to the local hydrodynamical conditions. Therefore, to understand bedform geometry and variability in the FTTZ, we assess the spatial variability of dunes from multibeam bathymetric surveys and their relation to flow characteristics, using a 2D hydrodynamic model of a sand-bedded lowland river (Fraser River, Canada).

2 METHODS

Field data

Bathymetric field data was collected in the fluvial to tidal transition zone of the Fraser river (Figure 1) which was used to determine river and dune geometry. A Multibeam echosounder (MBES) was employed to collect riverbed data, and this data is provided by the Public Works and Government Services, Canada. The measured bathymetry comprises of data of the main channel between river kilometer -1 to 85 and covers the fairway of the river, but does not provide full bank-to-bank spatial coverage. Data were collected during base flow conditions in January, February and March 2021. MBES data is gridded onto a 1x1 m^2 grid.

Hydraulic model

A 2DH hydraulic model was set up in Delft3D Flexible Mesh (FM) model suite (Kernkamp et al., 2011). It calculates depth-averaged quantities based on the two-dimensional shallow water equation. The numerical domain covers the Fraser river from 81 km upstream, to the part where the offshore region of the strait of Georgia reaches a significant depth (>200 m). Bathymetry for the main channel is interpolated on an unstructured curvilinear grid system. The imposed upstream boundary conditions include measured discharge of 2018 at Mission (RK 81), and discharge at the confluences of Pitt River (RK 45) and Stave river (RK 74). At the downstream boundary, tidally-influenced water levels are imposed. Eight primary tidal constituents, the most important overtide (M4) and compound tides are determined via the Delft Dashboard toolbox (van Ormondt et al., 2020) using the TPXO8.0 database (Egbert & Erofeeva, 2002). The model was calibrated for low discharge by applying different Manning roughness coefficients and evaluating the resulting water levels and tidal amplitudes of the M2, M4 and K1 tide at 7 gauging stations. The best performing model had a uniform Manning's coefficient (roughness) of 0.026 m.

Data analysis

Bathymetry was analyzed to derive dune characteristics. Three longitudinal profiles were taken, along the center line and at approximately 80 m from the north and south bank. Additionally, in three focus areas (Figure 1), a longitudinal profile was taken every 10 meters. Bedform characteristics were determined by using a Bedform Tracking Tool (van der Mark et al., 2008).

River geometry was parametrized by river width, curvature (de Ruijsscher et al., 2020), transverse bed slope (de Lange et al., 2021) and excess depth (Vermeulen et al., 2014).

To get insight in the flow conditions, flow magnitude, direction, water depth and bed shear stress per grid cell was saved every ten minutes. A Godin filter (Godin, 1972) was used to calculate the tidally averaged values of flow velocity and shear stress during low discharge. The Godin filter removes the tidal and higher frequency signals to obtain a residual signal caused by the river flow.

Based on the modelled flow data, dune height was predicted using the widely accepted dune geometry predictor of van Rijn (1984):

$$\Delta = 0.11\,h\left(\frac{D_{50}}{h}\right)^{0.1}(1-e^{-0.5T})(25-T)$$

In which h = water depth (m), D_{50} = median grain size (m) and transport stage T. See van Rijn (1984) for details on calculation of T.

3 RESULTS AND DISCUSSION

Characteristics of FTTZ

The study reach is located fully in the FTTZ, where both the river discharge and the tidal current influence the water levels. In upstream direction, water levels are decreasingly influenced by tidal motion. Figure 2 indicates the decreasing amount of upstream directed shear stress when in upstream direction. This is tightly connected to decrease in the amount of time that the flow is reversed (decreasing from 40% to 10% of the time in 80 km).

Geometrically, the river does not show trends in longitudinal direction in width, curvature, transverse-bed slope or depth excess. The water depth increases in downstream direction.

The main channel of the Fraser riverbed consists of sand (D_{50} = 351 µm) and is well sorted. There is a minor trend of downstream fining in the lower 50 km of the river, (1.14 µm/km), resulting in a decrease in D_{50} approximately 100 µm over this reach. Additionally, gravel and clay patches are present in the outer banks of the river.

Dune geometry

Dune geometry along the river Fraser varies largely (Figure 3) and the dune covered part of the bed is characterized by dunes with heights up to 2.4 m (mean: 0.46, median: 0.39 m, std: 0.28 m) and lengths up to 194 m (mean: 24 m, median: 16, std: 22 m). Patterns in dune geometry can be observed, where certain areas contain relatively low and short dunes, while others show increasing or decreasing dune heights and lengths. Those patterns are not consistent over the whole river width, and where relatively large dunes prevail on one part of the river (e.g. north side), dunes can be small on the other parts (see for example around RK 68). The cross-sectional variation (expressed as the standard deviation) in dune height and length is about twice as high as the variation along the longitudinal direction.

Dune shape

The gradual decrease in tidal amplitude is not reflected in the primary geometrical components dune height and dune length, but the tidal currents do influence dune shape. We observe the dune crests become sharper,

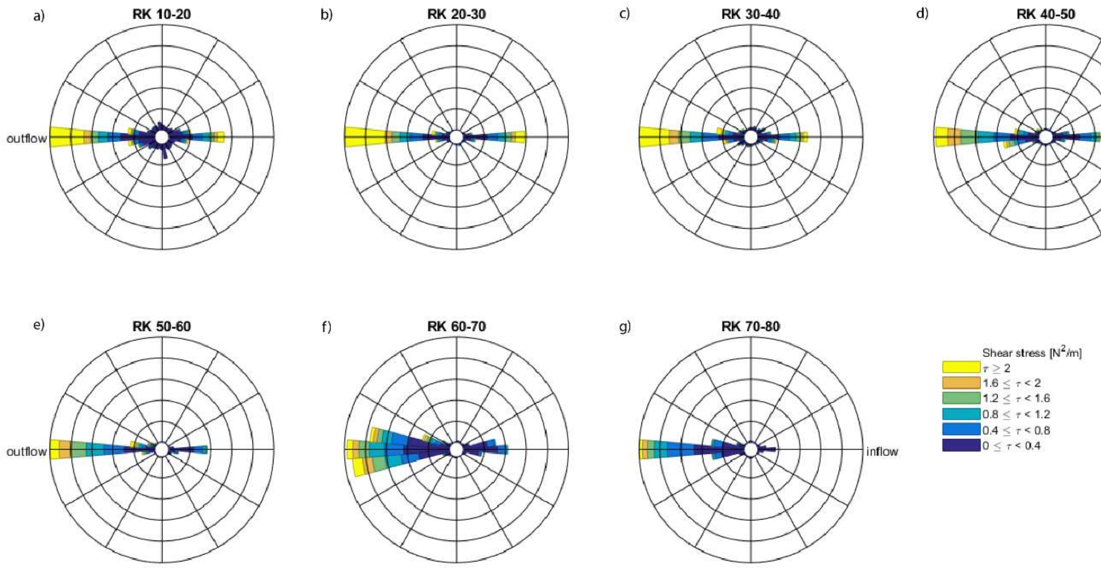

Figure 2. ‘flow’ roses, indicating the amount of shear stress that is directed either land outwards (left) or inwards (right). The amount of inward directed shear stress decreases in upstream direction. RK = river kilometer.

which is also observed in Lefebvre et al. (2021). Additionally, the aspect ratio (L/ H) of dunes increases in downstream direction, indicating dunes becoming flatter (lower and longer) (Figure 4A). Finally, dunes become more symmetrical indicated by the decrease in the ratio between leeside angle and stoss side angle (Figure 4C). Both the aspect ratio and the LSA/SSA-ratio can be linearly related to flow-reversal time (Figure 4B, D).

Dune geometry prediction

To be able to apply the predictor of van Rijn (1984) to the Fraser river, the input values need to be parameterized by either taking tidally-averaged or maximum values. Doing so, we are able to apply this predictor using more localized, modelled, values instead of reach-averaged estimations.

Using tidally-averaged shear stresses to predict dune height in the FTTZ, the predictor performs relatively well when all data is reached-averaged. However spatially, the predictor underestimates the dune height upstream (>40 km from the river mouth), and overestimates this downstream (<40 km) (Figure 5A). The underestimation of dune height upstream could be attributed to the

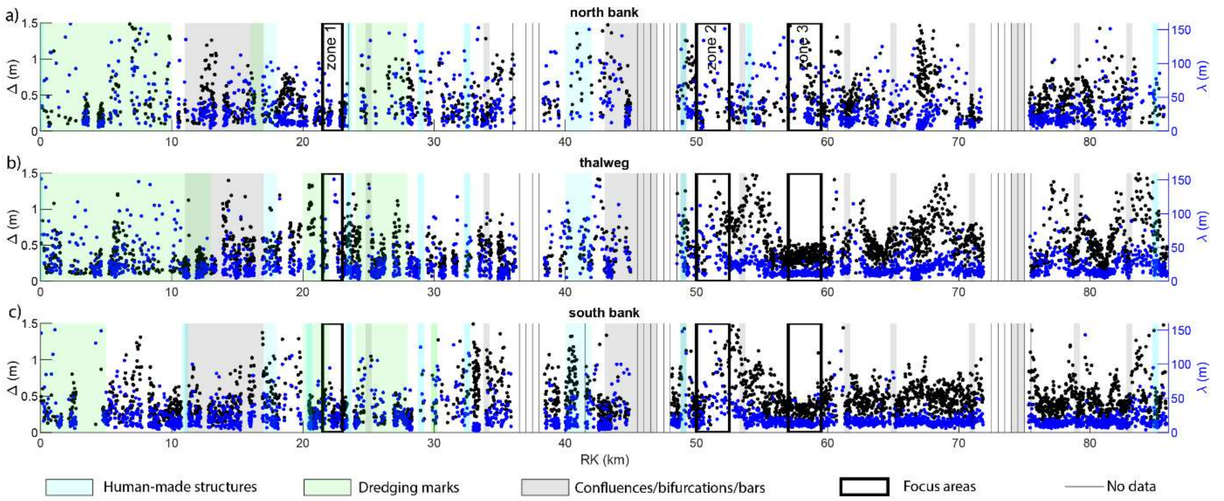

Figure 4. Dune geometry. a, b, c) Dune height Δ (black) and dune length λ (blue) through-out the research area. Human-made structures, dredging marks, confluences, bifurcations and bars, focus areas, and zones with no data are indicated (see legend).

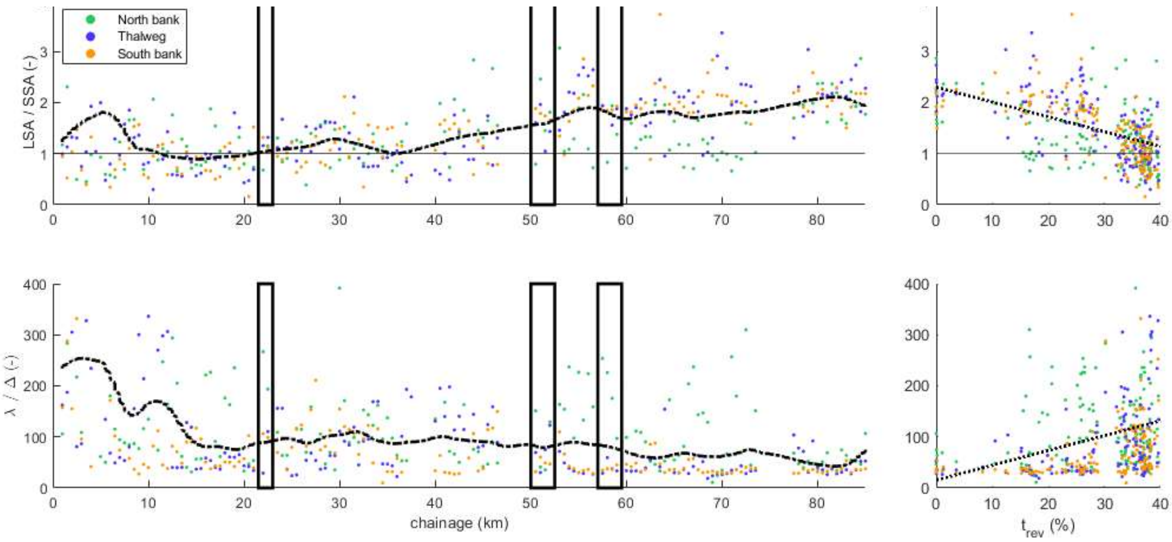

Figure 3. Dune shape. a) dune symmetry (leeside angle / stoss side angle) throughout the research area. c) aspect ratio (dune length / dune height) throughout the research area. b and d) symmetry and aspect ratio against percentage of time that the flow is reversed.

dune still adjusting to the previous high-water wave. The overestimation of dune height downstream, in the more tidally-dominated regime, is caused by the increase in water level downstream. The increase in water level is reflected by an increase in predicted dune height, but this response is not observed in our data. Most likely this can be attributed to the increase in tidal influence. T be able to apply current bedform predictors to tidal rivers, they should be adapted for tidal influence. Additionally, applying the predictor of van Rijn (1984) using the maximum values as parameterization for the shear stress, improves the spatial predictive capacity significantly, and mean dune height is slightly overpredicted with 0.16 m (~30%) along the whole reach (Figure 5B). Local variability cannot be captured in any of these methods, indicated by high RMSE values of 0.41 m for both methods. This stresses the need for more studies on localized bedform variability in the FTTZ.

4 CONCLUSIONS

Based on multibeam bathymetric data and a 2D hydrodynamic model of the FTTZ of the lowland, sand-bedded reach of the Fraser River, Canada, we can conclude that:

- Opposing the common assumption that dunes fade out towards the sea, dunes persist throughout the whole FTTZ.
- Downstream fining exists, but is irrelevant for dune height and length.
- There is a systematic change in dune shape, but not in dune height or length.
- Cross-sectional variability in dune geometry is twice as large as longitudinal variability.
- Dune geometry predictors based on tidally-averaged shear stress, overestimate dune height in the seaward part of the FTTZ.
- Intrinsic variability of dune height prevents dune predictors to function well on local scale.

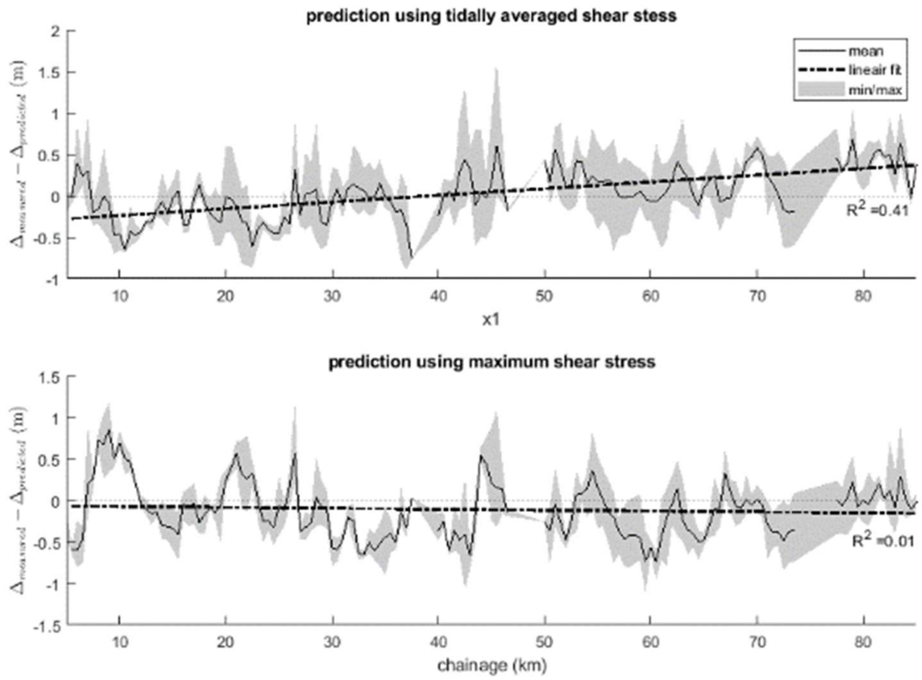

Figure 5. Measured minus predicted dune height, parametrized by a) tidally-averaged shear stress and b) maximum shear stress.

5 ACKNOWLEDGEMENT

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