Morphological response of estuarine subtidal dunes to flow over a semidiurnal tidal cycle: Fraser River, Canada

Ray Kostaschuk(1), Jason Blair(1), Paul Villard(2) and Jim Best(3)

(1) Department of Geography, University of Guelph, Guelph, Ontario, N1G 2W1, Canada. E-mail: rkostasc@uoguelph.ca, jblair@dsisp.net
(2) Parish Geomorphic Limited, 10 Mountainview Road South, Suite 207, Georgetown, Ontario, L7G 4J9, Canada. E-mail: pvillard@parishgeomorphic.com
(3) School of Earth Sciences, University of Leeds, Leeds, West Yorkshire, LS2 9JT, United Kingdom. E-mail: J.Best@earth.leeds.ac.uk

Abstract

Dune length lags behind flow velocity over a semidiurnal tidal cycle in the Fraser Estuary because time is required to transport the sediment within the dune. Changes in dune height, steepness and leeside slope precede changes in velocity, increasing early in the tidal fall because of scour in troughs caused by increased turbulence resulting from the development and expansion of the flow separation/deceleration zone. Shear stress increases at dune crests as peak velocity is approached near low tide, resulting in crestal scour and a concomitant decrease in dune height. Concentrations of sand in suspension also increase with mean velocity, leading to deposition in troughs and a further reduction in dune height and lee slope. Sand falls out of suspension and drapes the dunes as high tide approaches.

1. Introduction

Dunes are ubiquitous features in sand-bed rivers and estuaries and play an integral role in the relationships between boundary layer flow structure and sediment transport (ASCE, 2002). Many of the relationships developed between dunes and their controlling environmental variables have been established in laboratory flumes with unidirectional, steady, uniform currents (e.g., Bennett and Best, 1995; Best and Kostaschuk, 2002), which are conditions that rarely apply to dunes in natural settings. This is particularly true in estuaries where dunes are affected by temporal and spatial variability in currents resulting from changing fluvial and tidal conditions. Several studies have shown that large dunes respond to seasonal (e.g., Julien et al., 2002; Kostaschuk et al., 1989a; Wilbers and Ten Brinke, 2003) and spring-neap tidal (e.g., Kostaschuk and Ilersich, 1995) changes in flow. However, most studies of subtidal dunes in deep flows have been limited by instruments that lack the temporal and spatial resolution required to examine detailed process-response relationships over single tidal cycles. This study uses instruments that have this capability - an acoustic Doppler current profiler and digital echosounder - to study the changes in dune morphology that occur over a semidiurnal tidal cycle in the Main Channel of the Fraser River estuary, British Columbia, Canada (Fig. 1).

Discharge in the Fraser River is characteristically highest during the spring and early summer when warmer temperatures and spring rains result in the annual snowmelt freshet. Discharge during the spring freshet at Hope, 150 km upstream of the river mouth, ranges between 6000 and 12,000 m^3s^{-1}. The Main Channel flows into the Strait of Georgia, a semi enclosed, high-energy marine basin. Tides are mixed, mainly semidiurnal with a mean range of 3 m near the mouth of the Main Channel and 5 m during spring tides. Over one semidiurnal tidal cycle (approximately 13h) river discharge remains relatively constant and tidal movement controls flow variation within the estuary.

Dunes in the Main Channel have a concave-downstream planform and vary in length from 4 m to greater than 100 m and in height from 0.3 m to over 5 m (Kostaschuk and MacDonald, 1988; Kostaschuk *et al*., 1899a; Kostaschuk and Villard, 1996; Villard and Church, 2003). According to Ashley's (1990) classification, these dunes are medium to very large two-dimensional bedforms.

2. Methods

Surveys were conducted from a launch using an Ocean Data Equipment Bathy 1500 200 kHz digital survey echosounder (DES) and a SonTek 1500 kHz 3-beam acoustic Doppler current profiler (ADCP). Both instruments were tied to a Trimble AgGPS122 differential global positioning system (DGPS). Under the conditions of this study, the manufacturers estimate a precision of ±0.02 m for the DES and ±0.01 ms^{-1} for the ADCP. The DGPS uses a differentially-corrected signal from a navigation beacon located nearby, allowing for a measured spatial precision from the moving launch of around 0.1 m. Velocity and depth data were collected along a survey line in the centre of the Main Channel line during June 7-20 2000 (Fig 1). Dune transects were made over tidal cycles (tidal fall and rise) on several days, but strong winds resulted in a reliable set of transects only on June 20 - these data are presented here. River discharge was falling over June 7-20 and was moderate on June 20 at 6900 m^3/s. Tides on June 20 are shown in Figure

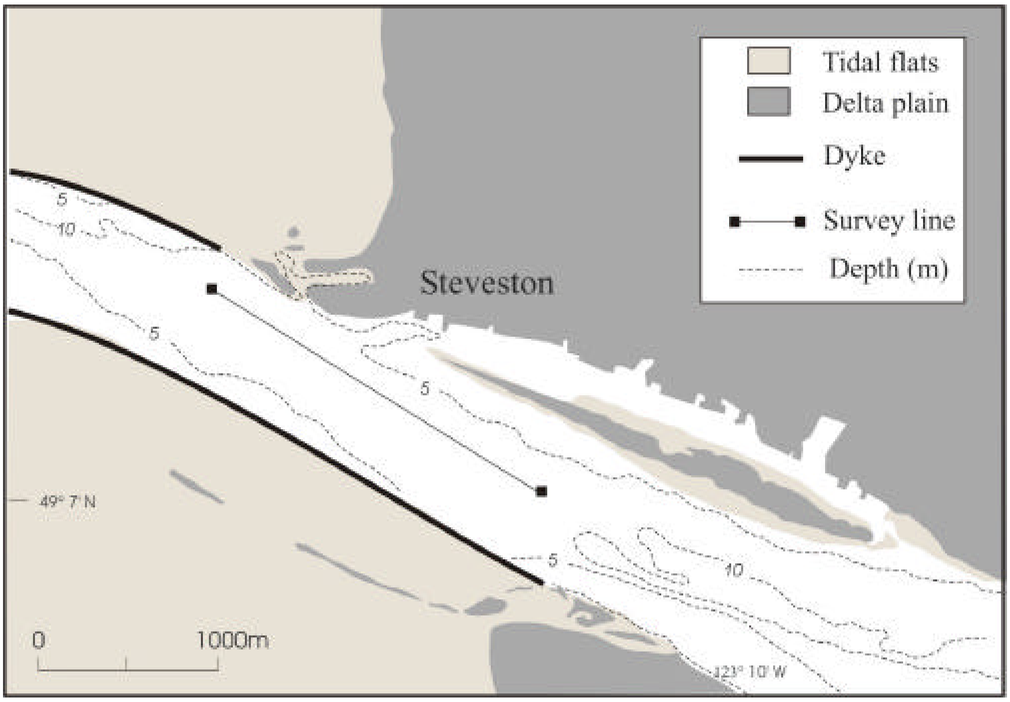

Figure 1. Study area in the lower Main Channel of the Fraser Estuary showing the location of the survey line.

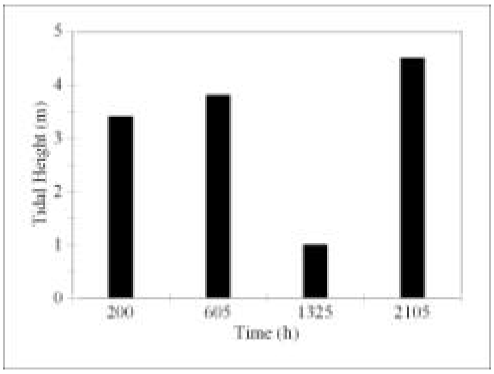

Figure 2. Tidal heights at Point Atkinson for June20. Data from Fisheries and Oceans Canada (2000).

channel and most were within 30 m.

The ADCP utilizes an internal compass to define flow direction and a tilt sensor to correct for ship pitch and roll whilst velocity measurements are corrected for ship motion using DGPS positions. The three transducers of the ADCP are Set at 25 degrees from the vertical axis and are equally spaced in the horizontal (120°), producing different orientations relative to the flow. The static diameter of the ADCP sampling area increases with depth to a maximum of 0.93 depth at the bed, which means that the velocity measurements nearest the bed in dune troughs are unreliable because the three ADCP beams will encounter the bed at different depths. Kostaschuk et al. (submitted) suggest that a mean bed position from ADCP data can be determined by a sharp increase in echo intensity, averaged over the three beams. The inflection point above the maximum echo intensity represents the transition between the bed and the water column so the ADCP bin above the inflection point can be used to define the lower limit of uncontaminated velocity measurements. These procedures were followed in this study. Kostaschuk et al. (submitted) also found that a sampling interval of 5 s and a vertical resolution of 0.25 m provides the best combination of low signal/noise ratio, stable velocity measurements, good spatial resolution over dunes and reliable positions from the DGPS. These settings were also used in this study. The DES employs a bottom-finding algorithm for flow depth that works well when suspended sediment concentrations are low but provides 'false bottoms' when concentrations are high. Contaminated DES depth measurements during high sediment concentrations were replaced by estimates based on a 'digital paper trace' record.

3. Results

Figure 3 is an example of an ADCP velocity record taken around low tide at the downstream end of the survey line (Fig. 1). Velocity is higher over dune stoss sides and crests and lower over lee sides, reflecting topographic forcing of flow by the dunes, a pattern also found by Best et al. (2001) in their field and laboratory studies. Figure 4 shows mean flow depth and mean spatially-averaged velocity over dune crests for each transect. Mean velocity on Figure 4 is depth-averaged from 5 profiles over each of the 8 dune crests in order to minimize the errors associated with ADCP measurements in dune troughs. The salinity intrusion was still present in the channel during the 0727 transect and a weak flow in the lower layer is directed upstream, while surface

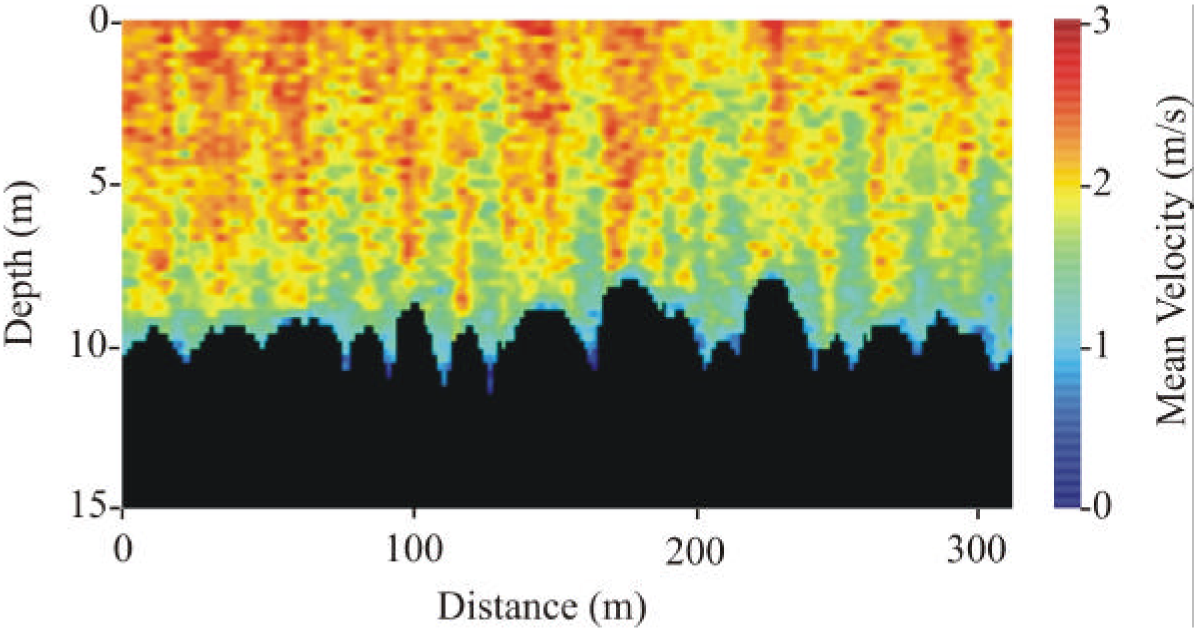

Figure 3. ADCP record along the survey line (Fig 1), taken on June 20 from 1347-1410. Flow is from right to left.

river flows in the upper layer are downstream. The salinity intrusion has been flushed seaward of the measurement reach by 0815 and all flows were downstream-directed throughout the remainder of the tidal cycle. Mean depth and velocity follow similar but inverse patterns over the tidal cycle. Mean depth and velocity change more slowly on the falling tide than on the rising tide and velocity remains relatively stable from 1200-1400, around low tide (1325). Mean velocity increases slightly on the rising tide after around 1800. Figure 5 show variations in mean dune height, wavelength, steepness (height/length) and lee side slope angle over the tidal cycle. Height and steepness generally follow the pattern of mean velocity, with length decreasing early in the tidal fall, increasing until just after low tide, and remaining relatively constant as the tide rises. Lee slope angle increases rapidly during the early part of the tidal fall, is relatively constant until after low tide and decreases as the tide rises. Mean dune height and steepness are significantly correlated with mean velocity (height: r = 0.75, p = 0.0005; steepness: r = 0.61, p = 0.009) but mean dune length and lee side slope angle are not (length: r = 0.13, p = 0.61; lee slope: r = 0.12, p = 0.64).

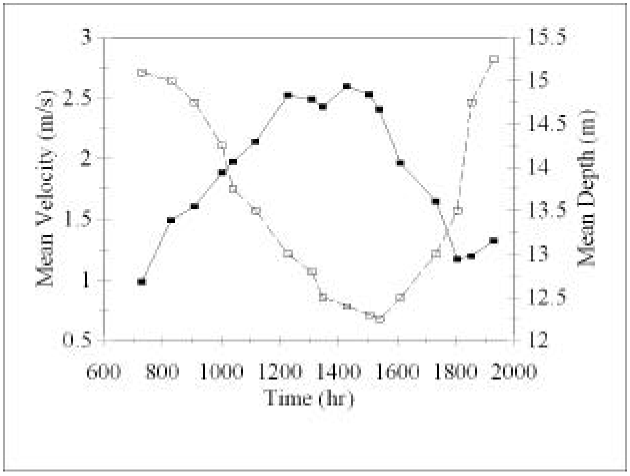

Figure 4. Mean velocity and depth over the tidal cycle on June 20.

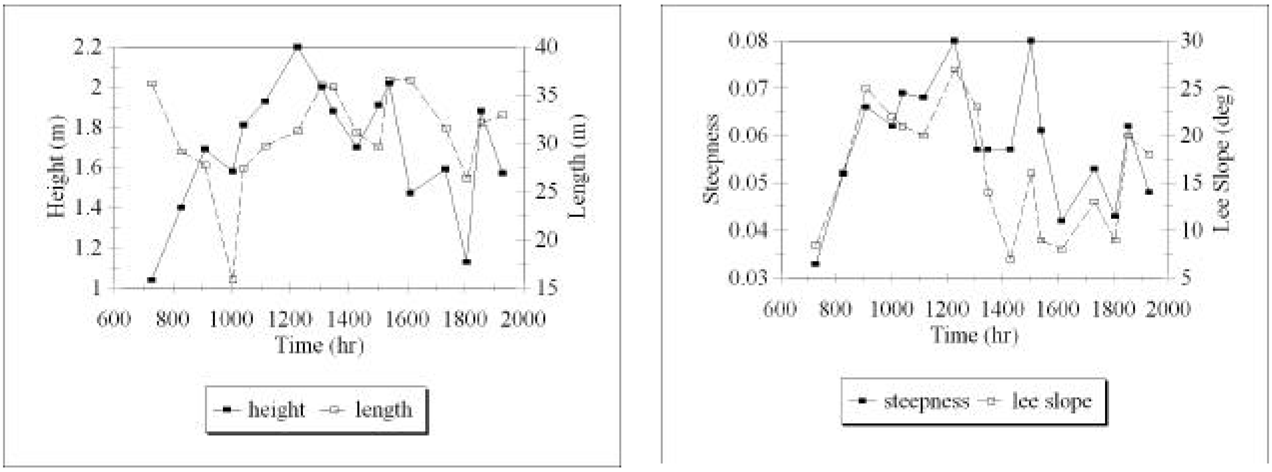

Figure 5. Mean dune height, length, steepness (height/length) and lee side slope angle over the tidal cycle on June 20.

Figure 6 shows phase diagrams for relations between dune properties and velocity. Although the relations are complex, clockwise hysteresis loops clearly predominate for dune height, steepness and lee slope angle, indicating that changes in these properties generally precede changes in mean velocity. A counterclockwise loop predominates for dune length, indicating that changes in wavelength lag behind velocity. The stronger correlations between flow velocity and both dune height and steepness reflect a more rapid adjustment of height to changes in velocity compared to length and lee slope. Similar clockwise loops and correlations for height and steepness indicate that steepness is controlled more by changes in height than by length.

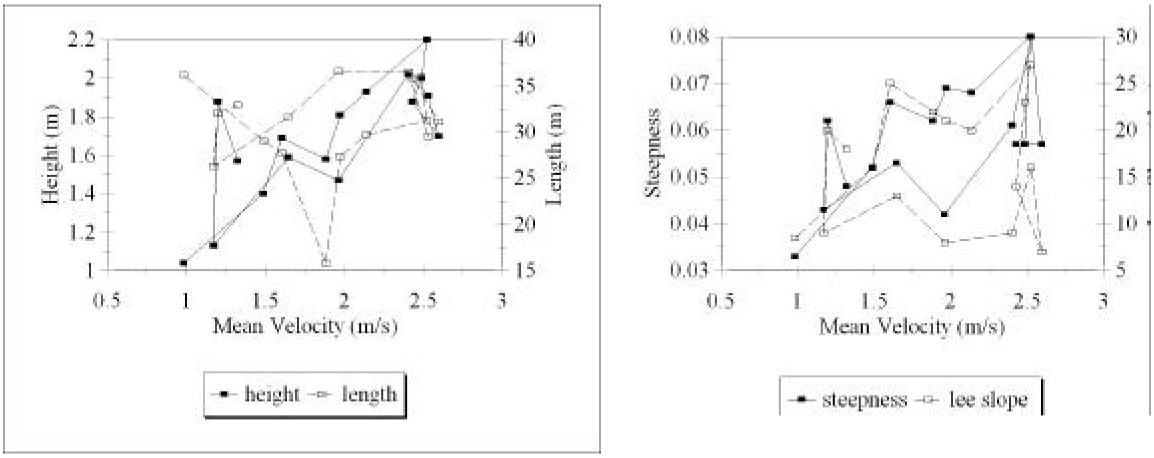

Figure 6. Phase diagrams of mean velocity versus mean dune height, length, steepness (height/length) and lee side slope angle on June 20.

4. Discussion

Dunes are constantly adjusting to changing flow conditions because time is required to move the sediment that comprises the dune (e.g., Dalrymple and Rhodes, 1995). Many studies of dunes have documented lagged responses between dune geometry and flow at a variety of time scales. Wilbers and Ten Brinke (2003), for example, found that height and length lag behind river discharge during floods in the Rhine River. Previous work in the Fraser River showed that both dune height and length lag behind seasonal variations in river discharge (Allen, 1973; Kostaschuk *et al.*, 1989a) and variations in velocity associated with bi- weekly, neap-spring tidal ranges (Kostaschuk and Ilersich, 1995). The present study has shown that hysteresis also exists at the much shorter semidiurnal time scale, with changes in height, steepness and lee slope preceding velocity and length lagging behind velocity.

The counterclockwise hysteresis loop for dune wavelength in this study is consistent with both theory (Dalrymple and Rhodes, 1995) and observations of dunes over much longer time scales than the semidiurnal cycle in this study. Dalrymple and Rhodes (1995) suggest that a ‘figure-eight’ loop can develop for dune height, with a counterclockwise loop at lower flow velocities over 2-dimensional dunes becoming a clockwise loop at higher velocities as dunes develop a 3-dimensional morphology. Although the present study has no direct data on dune planform shape, previous research in the Fraser by Kostaschuk and MacDonald (1988) suggests that, during high river discharge, dunes are primarily 2-dimensional in shape. The model of Dalrymple and Rhodes’ (1995) also refers to dune behaviour between the transition from ripples to an upper flow regime plane bed. Froude numbers calculated for the data on Figure 4 range from 0.10 at the beginning and end of the tidal cycle to a maximum of 0.25 at low tide, which are well below the requirement (around 0.85) for upper flow regime conditions. Previous work clearly does not provide an adequate explanation for the changes in dune height (steepness) and lee slope observed in this study so the following interpretation, based on dune mechanics and sediment transport processes, is proposed as a basis for further discussion.

Echosounding records show that the rapid increase in dune height early in the tidal fall (Fig. 4: 0700-1200) is due to scour in troughs, which leads to an associated increase in lee slope angle. This scour is likely due to increased turbulence in the troughs caused by the development of the flow separation/deceleration zone on the lee side, such as that measured in flume experiments (e.g., Bennett and Best, 1995; Best and Kostaschuk, 2002) and in the field (Kostaschuk, 2000). Sediment deposited during the previous tidal rise and high slack water, settling directly out of suspension during low flow velocities, would probably be relatively loose and easy to entrain. The changes in leeside angle that occur here (<10° to >20°) suggest that major flow separation would be generated that would significantly increase leeside shear layer development and the generation of large-scale turbulence (e.g., Best and Kostaschuk, 2002; Kostaschuk, 2000), which further contributes to trough scour. As peak velocity is reached late in the tidal fall and early in the tidal rise (Fig 4: 1200-1700), the velocity profile is fully developed and shear stress increases over dune crests, as suggested from field studies by Smith and McLean (1977) and Kostaschuk and Villard (1996), resulting in crestal scour and a decrease in dune height. Smith and McLean (1977) and Kostaschuk and Villard (1996) also found that sand suspension increases with mean velocity and speculated that this leads to deposition in troughs and a further reduction in dune height and lee slope. Numerical simulations by Johns et al. (1990) and flume experiments by Hand and Bartberger (1988) support this interpretation. As flows decelerate and then increase slightly late in the rising tide (Fig 4: 1700-2000), sand falls out of suspension (e.g., Kostaschuk et al., 1989b) and 'drapes' the bedforms.

5. Summary

An acoustic Doppler current profiler and digital echosounder have been used to study the changes in dune morphology that occur over a semidiurnal tidal cycle in the Main Channel of the Fraser River estuary, Canada. Changes in dune height, steepness (height/length) and lee side slope angle precede changes in flow velocity but changes in dune wavelength lag behind those of velocity. Changes in dune length lag velocity because time is required to transport the sediment within the dune. Dune height, steepness and leeside slope angle increase early in the tidal fall because of increased scour in troughs caused by greater turbulence resulting from the development and expansion of the flow separation/deceleration zone in the lee side. The increase in lee slope in turn enhances the size and turbulence of the lee side flow separation zone, which further contributes to trough scour. Shear stress increases at dune crests as peak velocity is approached near low tide, resulting in crestal scour and a decrease in dune height. Concentrations of sand in suspension also increase with mean velocity, leading to deposition in troughs and a further reduction in dune height and leeside slope angle. As flows decelerate late in the rising tide, sand falls out of suspension and drapes the bedforms.

Acknowledgements

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