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Quantitative Visualization of Flow Fields Associated with Alluvial Sand Dunes: Results from the Laboratory and Field Using Ultrasonic and Acoustic Doppler Anemometry

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***Abstract*:** This paper presents results detailing the quantitative visualization of flow fields associated with natural sand dunes, Fraser River Estuary, Canada, using the complementary approaches of laboratory modelling and field instrumentation. Ultrasonic Doppler velocity profiling is used in the laboratory to elucidate the mean flow fields of low-angle dunes (leeside slope angle ~14°) that are typical of many large natural rivers. These dunes do not possess a zone of permanent flow separation in the dune leeside and have a velocity structure that is dominated by the effects of flow acceleration and deceleration generated by topographic forcing of flow over the dune form. Turbulence associated with these dunes appears linked to both longer-period shear layer flapping and eddy generation along the shear layer. The field study uses acoustic Doppler profiling to reveal similar mean flow patterns and shows that flow is dominated by deceleration in the leeside without the presence of a region of permanent separated flow.

***Keywords*:** sand dunes, ultrasonic Doppler velocity profiling (UDVP), acoustic Doppler profiling (ADP), mean flow field, coherent flow structures.

1. Introduction

Understanding and quantifying the flow structure associated with natural sand dunes is central to better prediction of sediment transport in a wide range of natural environments (Best, 1996; Villard and Kostaschuk, 1998; Kostaschuk, 2000). The presence of large-scale form roughness considerably complicates the prediction of both bedload and suspended load sediment transport and flow resistance, and quantification of dune size and form can be of significance in planning construction, for instance of sub-fluvial tunnels (Amsler and Prendes, 2000). It has long been recognized (Matthes, 1947; Jackson, 1976; Yalin, 1992; Best, 1996) that alluvial sand dunes are responsible for the generation of large-scale turbulence that may advect through the flow depth and reach the water surface as an 'upwelling' or 'boil' (Fig. 1). Such 'macroturbulence' is responsible for appreciable suspension of sediment (Kostaschuk and Church, 1993; Babakaiff and Hickin, 1996; Venditti and Bennett, 2000) as well as being instrumental in creating instantaneous Reynolds stresses in the near-bed region that may dominate bedload sediment transport (McLean et al., 1996; Best, 1996). Although the origin of this large-scale dune-related 'macroturbulence' has been ascribed by many researchers to the presence of a zone of permanent flow separation in the dune leeside (e.g. McLean et al., 1994, 1996; Nelson et al., 1993, 1995; Bennett and Best, 1995; Roden, 1998;

Kadota and Nezu, 1999; Venditti and Bennett, 2000), it is unclear both if this process can operate over dunes with a low-angle (~10°) leeside (Kostaschuk and Villard, 1999; Best and Kostaschuk, in press) or if the flow fields of large natural alluvial dunes are similar to their scale-model laboratory counterparts. One significant problem that often faces field scientists is how to document, visualize and quantify the flow fields associated with large alluvial sand dunes, in flows which may be both deep and logistically difficult to monitor. Two linked approaches hold enormous potential. Firstly, detailed scaled laboratory modelling can help resolve questions concerning the origin of large-scale turbulence associated with sand dunes and tracing the evolution of these coherent flow structures; second, acoustic Doppler profiling (ADP) is now permitting, for the very first time, quantification of mean flow fields in natural channels that are many metres deep and in which the dune bedforms can be up to 5 m high and 200 m long. This paper describes results from an integrated laboratory and field study that sought to visualize the principal features of the mean and turbulent flow fields associated with sand dunes in the Fraser River Estuary, Canada.

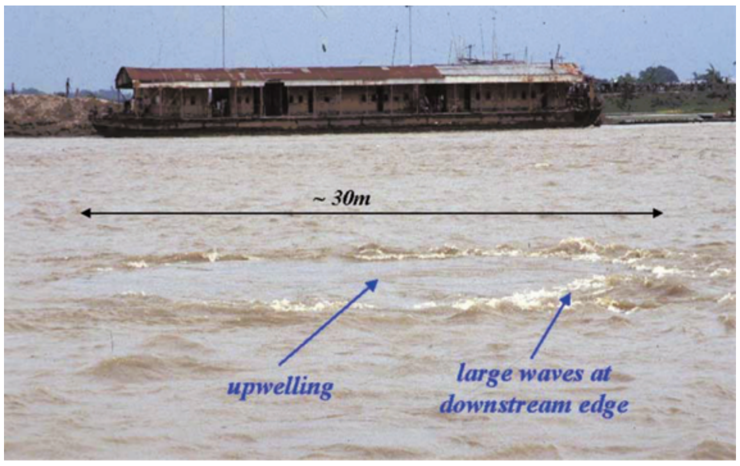
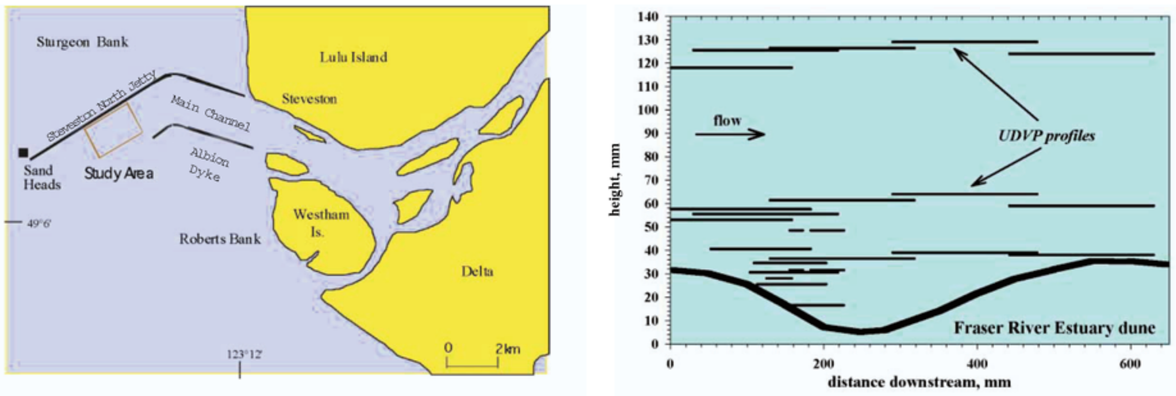


Fig. 1. The surface upwelling of large-scale macroturbulence generated over a field of sand dunes in the Jamuna River, Bangladesh. The dunes at this locality were ~4 m high and in a water depth of ~12 m. The surface 'upwellings' or 'boils' above these dunes had a regular periodicity and were associated with breaking waves at the downstream edge of the boil.

2. Methodology

2.1 Field Prototype

The field study area is the Main Channel of the Fraser River Estuary, British Columbia, Canada (Fig. 2(a)), which has a mean annual discharge of 3400 m^3 s^{-1}, maximum flows of over 11000 m^3 s^{-1}, and discharges into the Strait of Georgia, west coast of Canada. The Main Channel of the Fraser Estuary has a sand bed (median grain size = 0.25-0.32 mm; Kostaschuk et al., 1989) and dunes in the estuary range from 0.1 m to 4 m in height, 2 m to more than 100 m in length (Kostaschuk et al., 1989) and have a curved, concave-downstream planform geometry. Dunes migrate around low tide during high discharge (Kostaschuk et al., 1989; Kostaschuk and Church, 1993; Kostaschuk and Villard, 1996), although bedload accounts for < 1% of the total sand transport with the remainder travelling in suspension (Kostaschuk and Ilersich, 1995). A field programme in June 1999 used a 1500 kHz SONTEK acoustic Doppler profiler (ADP), in association with accurate positioning using a differential global positioning system, to quantify flow over sand dunes in the Main Channel (Fig. 2(a)). The field surveys were conducted during the time of peak spring runoff, during which flow velocities reached up to 4 ms^{-1}.



(a) (b)

Fig. 2. (a) Field study area, Fraser River Estuary, Canada; (b) Dune morphology used in the flume experiments, scaled at a ratio of 1:58 from the Fraser River field prototype, and position of UDVP profiles.

2.2 Laboratory Physical Modelling

Flume experiments were conducted in the Sedimentological Fluid Dynamics Laboratory, School of Earth Sciences, University of Leeds using a recirculating flume 10 m long, 0.3 m wide and 0.3 m deep. Two-dimensional model dunes were cut from high-density styrofoam, which permitted high-resolution manufacture of these low-angle and low-amplitude bedforms. The two-dimensional profile and dune height: flow depth ratio in the experiment (Fig. 2(b)) were modelled on a Fraser River dune, with the maximum lower leeside slope angle being 14°. The experiments followed the principles of Froude scale modelling and a scale ratio between flume and prototype of 1:58 was chosen in order to match the dune dimensions, flow depth and flow velocities. The entire length of the flume was covered with identical styrofoam dunes and, based on the 1:58 scale ratio, the mean flow depth in the flume was 0.20 m, the Froude number was maintained at 0.15, the flow was fully turbulent (Reynolds number = 36515) and the dune height: flow depth ratio was 0.16 (Table 1).

Quantitative flow field visualization was achieved using ultrasonic Doppler velocity profiling (UDVP) which has been successfully used in a range of studies (Takeda, 1991,1993, 1995; Takeda et al., 1994; Best et al., 2001a,b). An array of three, 4 MHz probes was used at different positions over the dune to provide 128-point profiles of downstream velocity from each probe. These probes operated at a sampling rate of 3.3 Hz and allowed both the mean flow field and large-scale flow structures to be visualized and quantified. The UDVP measurements were also allied to visualization using dye injection and neutrally buoyant 'Pliolite' particles. Detailed laser Doppler anemometer (LDA) measurements of flow over the model dune are reported in Best and Kostaschuk (in press). UDVP profiles were concentrated near to the bed of the dune (Fig. 2(b)) and were collected for 3 minutes at each profile. Further details of the laboratory modelling, including flow field quantification using laser Doppler anemometry, can be found in Best and Kostaschuk (in press).

Table 1. Characteristics of flow and dune morphology for the Fraser River Dune prototype and laboratory model (scale ratio = 1:58).

	Fraser River Dune	Model Dune
mean flow depth, *d* (m)	11.5	0.2
mean velocity, $\overline{U}$ (m s^{-1})	1.61	0.21
Froude number	0.15	0.15
Flow Reynolds number	14.2×10^6	36515
dune height, *H* (m)	1.8	0.031
dune length, *L* (m)	38	0.66
H/L	0.047	0.047
H/d	0.16	0.16
maximum lower leeside angle (°)	15	14

The scale-modelling approach has several limitations. Firstly, the smooth surface of the styrofoam dune does not capture the effect of 'skin' and 'minor-form' friction from sediment particles or smaller, superimposed bedforms (ripples/small dunes) that occur in the field (Villard and Kostaschuk, 1998). However, at the scale ratio of 1:58, the scaled grain size and ripple height are 0.004 and 0.3 mm respectively and would thus have a minimal effect on the flow. Secondly, the experimental dunes were two-dimensional and all the same shape and size, whereas the prototype field dunes are three-dimensional with considerable spatial variability in both shape and size. The possible effects of three-dimensional form were excluded in the flume model, since it was both very difficult to characterise a 'typical' three-dimensional form, and the lateral scale of this variability could not be modelled at the scale ratio dictated by the flume width. Thirdly, the fixed-dune approach does not capture the effect of sediment transport on velocity profiles. However, this effect may be expected to be relatively minor since sand concentrations in the field are not sufficiently high to have a significant impact on the shape of velocity profiles (Kostaschuk and Villard, 1996). Finally, the Froude-scale approach in this narrow flume produces a low width : depth ratio (1.5) which may be expected to generate secondary flows in the flume that are not present in the field (Nezu and Nakagawa, 1993). The influence of secondary flows is evidenced by lower velocities near the flow surface but these do not mask the significant influence of the dunes upon flow near the bed. However, despite these limitations, simplification of dune morphology to a fixed, two-dimensional profile does allow investigation of the major features of flow, as has been successfully demonstrated in previous studies of flow over two-dimensional bedforms (e.g. Raudkivi, 1966; Lyn, 1993; Nelson et al., 1993; Bennett and Best, 1995), and will provide a basis for study of the effects of dune three-dimensionality. The benefits of the experimental approach are that it permits investigation of turbulent flow over low-angle symmetric dunes to a level of detail and precision that is not possible in the field.

3. Results

3.1 Flume Modelling

The UDVP data were used to examine the mean downstream flow field and the fluctuating root-mean-square values from:

$$\overline{U} = \frac{1}{n}\sum_{i=1}^{n} u_i \tag{1}$$

$$U_{\text{rms}} = \left[\frac{1}{n}\sum_{i=1}^{n}(u_i - \overline{U})^2\right]^{0.5} \tag{2}$$

where $\overline{U}$ is the mean time averaged velocity at-a-point, n is the total number of velocity measurements and u_i is the instantaneous downstream velocity.

The mean downstream velocity field (Fig. 3) shows that flow is dominated by acceleration over the dune stoss side and crest and deceleration in the dune leeside, with the topographic forcing of flow generating this broad flow field. However, it is clear that there is no zone of permanent flow separation in the dune leeside as has been documented in studies of flow over steeper-angle dunes (Nelson et al., 1993, 1995; McLean et al., 1994; Bennett and Best, 1995). Flow in the leeside reaches a minimum mean value of 36% of the maximum velocity above the dune crest. Although the mean downstream velocity does not show the presence of any permanent flow reversal, detailed laser Doppler anemometry measurements in the immediate leeside (Best and Kostaschuk, in press) have shown periodic reversals, which may occur for only 3-4% of the time series. Peak turbulence intensities of the downstream component are also found in the region of decelerated flow (Fig. 3(b)) at the point of change in bed geometry where an intermittent shear layer is generated: this again suggests the presence of a periodic layer of shear generated in the leeside of these dunes. The immediate leeside is the region of highest turbulence intensity, with the presence of a region of increased u rms values higher in the flow (Fig. 3(b)) demonstrating the possible advection of turbulence into the upper flow from shear layers generated on upstream dunes (a wake region from upstream dunes).

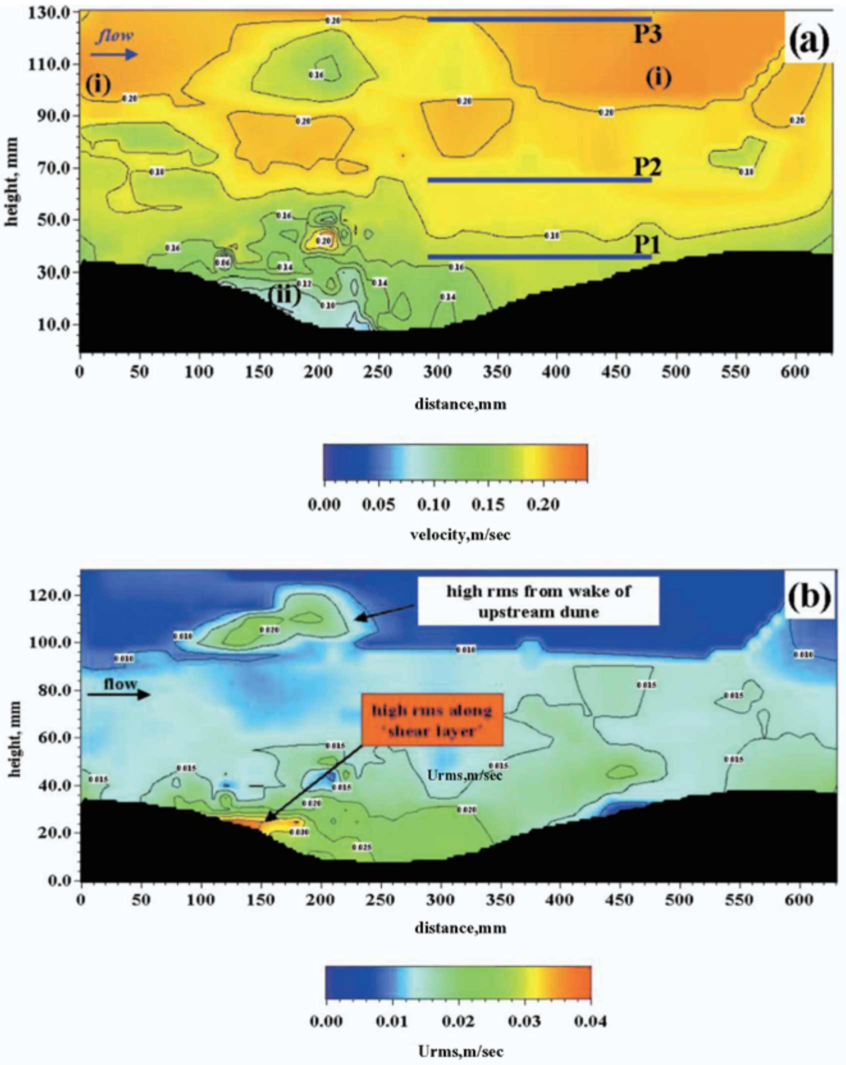


Fig. 3. (a) Flow field of downstream velocity over the model dune. Flow acceleration is present over the dune crest and stoss side (i) and a zone of reduced flow velocity, without permanent flow separation, is formed in the dune lee (ii); (b) Distribution of root-mean-square values of downstream velocity over the low-angle dune. Note the zone of high U_{rms} in the dune lee and also a region of elevated U_{rms} higher in the flow, possibly arising from the wake of an upstream dune. Profiles P1-P3 in Fig. 3 (a) denote positions of UDVP profiles shown in Fig. 4.

Besides documenting the mean flow field associated with these sand dunes, ultrasonic Doppler velocity profiling also allows quantification of the evolution of the flow field in a downstream profile for 128 points for each probe. Plots of the spatio-temporal series of downstream velocity for probes P1-P3 (Fig. 4; see Fig. 3(a) for location of profiles) show the potential of UDVP to yield quantitative information concerning the evolving flow field. Figure 4 plots the deviation from the mean of the downstream velocity component at each of three probes for a measurement distance of 190 mm upstream from each UDVP transducer. Two principal features are evident from Fig. 4:

i) The gradient of the colour bands on Fig. 4 depicts the celerity of coherent flow structures as they advect downstream. It is readily apparent that the velocities of structures detected in probe P3 are greater than those in probes P1 and P2, which are lower in the flow.

ii) Spectral analysis indicates that the signals are dominated by two periodicities: a) a longer period (~0.03-0.07 Hz) frequency that is most likely generated by 'flapping' of the entire shear layer, and b) a shorter frequency (~0.25 Hz) signal that can be ascribed to the advection of individual Kelvin-Helmholtz instabilities along the shear layer (Best and Kostaschuk, in press).

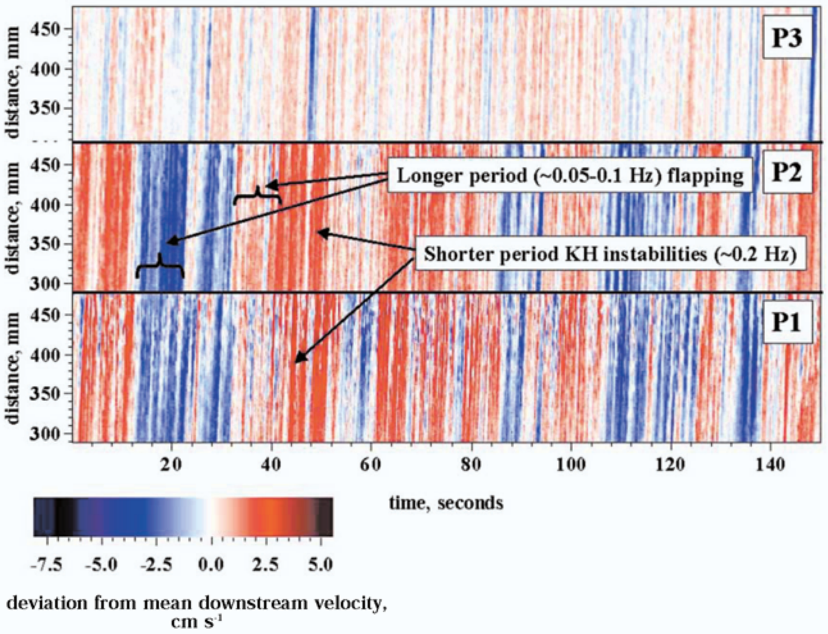


Fig. 4. Spatio-temporal UDVP series of downstream velocity for Probes P1-P3 (distance is given as millimetres, see Figs. 2(b) and 3(a) for location). This plot shows the deviation from the mean velocity for each probe along a profile 190 mm long. The gradient of the colour bands depicts the advection velocity of the coherent flow structures.

Most of the coherent flow structures shown on Fig. 4 advect along the entire profile (190 mm), although there are some changes in the velocity of these structures as they advect downstream, this representing either the mixing/dissipation of these structures or their advection out of the measurement profile of that probe. It is noticeable that the structures detected by probes P1 and P2 are similar whereas those detected by probe P3 do not appear to be correlated with the lower profiles. This demonstrates the angle of advection of these structures, with the coherent structures detected in P3 most likely being the result of eddy generation from upstream dunes. The spatio-temporal series of P3 is thus uncorrelated with the coherent flow structures detected by probes P1 and P2.

3.2 Field Quantitative Flow Visualization

An ADP transect was run along a dune field in the Fraser River estuary (Fig. 2(a)) over a series of large sand dunes, whose longitudinal profile is shown in Fig. 5. The dunes are between 2 and 3 metres high and are generated during the river-dominated ebb tide during the period of high flood discharge (in this case on June 15th, 1999). The dunes are asymmetrical in longitudinal profile, but their lee slopes are low-angle (~10°) with some dunes showing a compound form indicative of dune amalgamation (Fig. 5).

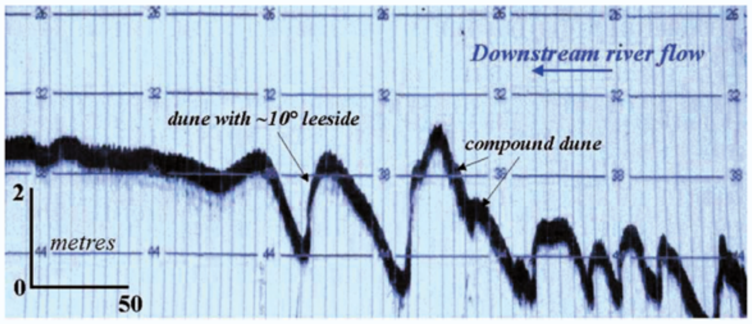


Fig. 5. Longitudinal profile of dune morphology at the study site in the Fraser River estuary obtained from echo sounder survey parallel to flow. Flow is from right to left and chart depths are in feet.

Acoustic Doppler profiler records obtained during this survey permit quantitative flow visualization of both the downstream and vertical flow velocities over these large, natural sand dunes (Fig. 6). These plots show a very similar mean flow field to that documented in the flume model: the downstream velocity (Fig. 6(a)) is dominated by flow acceleration over the dune crest and stoss and a distinct region of flow retardation in the dune leeside, although it should be noted that no reliable measurements were possible within 0.25 m of the bed, as indicated by the white band near the bed in Fig. 6. The vertical velocities (Fig. 6(b)) show downward flow towards the bed in the dune leeside and flow upwards towards the surface over the stoss side of the dunes, a common feature of flow over bedforms, and generated by topographic forcing of the flow (Nelson et al., 1993; Bennett and Best, 1995). Although these dunes have a low-angle leeside, the high-magnitude of turbulence generation in the leeside was evidenced by upwellings of fluid at the water surface during the survey. Although the gross flow patterns and whole flow field visualizations shown in Figs. 3 and 6 reveal the similarity in flow between flume and field, detailed at-a-point time series were not possible over dunes in the field due to the difficulty in mooring a boat at a fixed location in these deep, high-velocity flows.

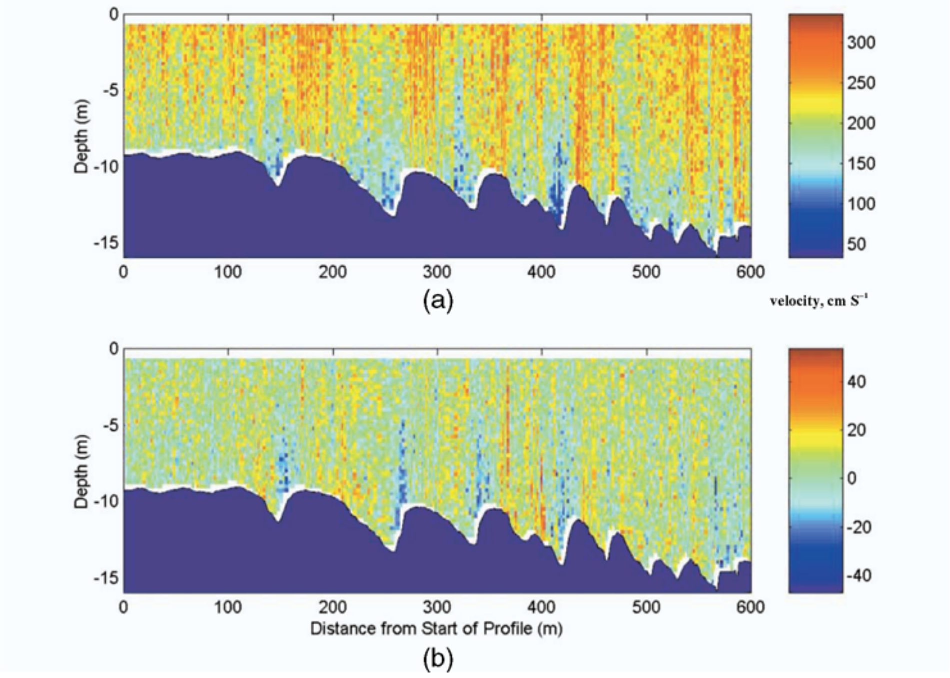


Fig. 6. Quantitative visualization of flow over dunes in the Fraser River estuary obtained using acoustic Doppler profiling (see Fig. 2(a) for location of study site). (a) Downstream velocity and (b) Vertical velocity. Flow is from right to left and a region of decelerated flow with a negative vertical velocity (towards the bed) can clearly be seen in the leeside of each sand dune.

4. Conclusion

Combined laboratory scale modelling using ultrasonic Doppler velocity profiling and field measurements using acoustic Doppler profiling, have enabled quantitative visualization of the mean flow fields associated with alluvial sand dunes that possess low angle leesides. This work, together with detailed LDA quantification detailed elsewhere (Best and Kostaschuk, in press), enables proposition of a model for flow associated with these common dune types (Fig. 7).

Flow is dominated by a simple pattern of acceleration over the stoss side and crest and deceleration in the leeside, with topographic forcing of flow. However, although a permanent region of flow reversal is not present in the dune leeside, intermittent separation and generation of temporally-variable shear gradients in the dune leeside lead to the intermittent generation of large-scale, shear-layer related turbulence. This phenomenon is identical to that of 'transitory stall' described in past literature on flow in low-angle diffusers (Azad, 1996; Azad and Kassab, 1989; Singh and Azad, 1995; Best and Kostaschuk, in press) and leads to formation of a shear layer rising from the

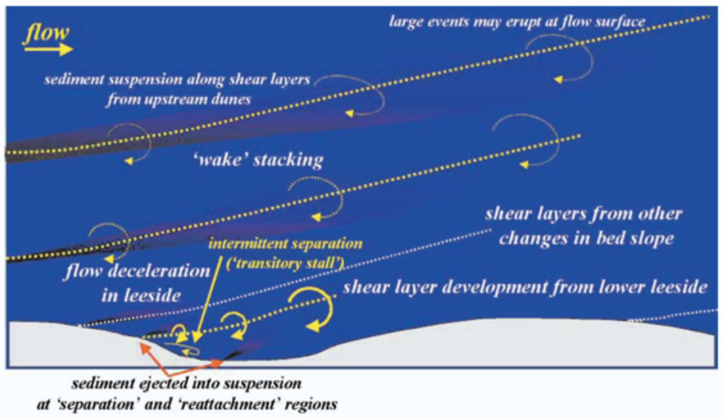


Fig. 7. A schematic model of flow over alluvial sand dunes with low leeside angles (~5-15°).

dune leeside. These shear layers, generated from both the change in angle at the leeside and also other more subtle changes in bed geometry (Fig. 7), may be expected to lead to a complex series of stacked wakes over a series of these dune forms, this being similar to that envisaged in past work on steeper angle leeside dunes. However, the nature of the stacked wakes over these low-angle dunes will be more intermittent than where permanent flow separation is present, and may lead to considerable complexity in the resultant velocity time series. Ongoing work, using PIV, is seeking to better establish the nature and magnitude of this periodic flow.

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