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Suspended sediment transport and deposition over a dune: Río Paraná, Argentina

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ABSTRACT: Field data from the Rio Paraná, Argentina, are used to examine patterns of suspended sediment transport over a sand dune. Measurements of three-dimensional velocity are made with an acoustic Doppler current profiler whilst suspended sediment concentration and particle size have been quantified using a laser *in situ* sediment scattering transmissometer. Suspended sediment concentration and streamwise and vertical sediment flux are highest close to the bed, with an upward vertical flux over the stoss side of the dune and downward flux over the lee side. Suspended sediment concentrations are higher over the crest compared with the trough and suspended sediment is coarsest near the bed. About 17% of the suspended-load transported over the crest is deposited in the lee side before it reaches the trough. Most of this deposited sand is coarser sediment that originates close to the bed over the crest, a result consistent with simulations based on the model of Mohrig and Smith (*Water Resources Research* 1996; 32: 3207–3217) for the excursion lengths of sediment dispersed in the lee side of a dune. Copyright © 2009 John Wiley & Sons, Ltd.

KEYWORDS: dune; sand transport; deposition; Rio Parana

Introduction

Dunes are ubiquitous features in sand-bed rivers and estuaries and play an important role in the relationships between boundary layer flow structure and sediment transport (ASCE, 2002; Best, 2005). The bed-material load in sand-bed rivers is frequently composed of coarser bed sediment that is transported by traction and saltation as bedload, and also in intermittent suspension as suspended bed-material load, herein termed 'suspended-load'. Sediment transported within migrating bedforms is usually assumed to be bedload, although several studies have shown that suspended load comprises a significant fraction of the total bed-material load in many sand-bed rivers (e.g. Kostaschuk and Villard, 1996; Nittrouer *et al.*, 2008; Smith and McLean, 1977) and likely contributes to bedform migration (Kostaschuk, 2005).

Several numerical, laboratory and field studies have demonstrated the importance of suspended-load in dune dynamics and morphology. Numerical simulations and field measurements over estuarine dunes conducted by Johns *et al.* (1990) showed that sand transport in suspension was more important than bedload in causing changes to the bedform structure. Johns *et al.* (1990) found that a combination of high flow velocity and fine sand bed-material resulted in a lowering of the dune crest and filling of the trough by deposition from suspension. Flume experiments by Hand and Bartberger (1988) demonstrated that high flow velocities result in a relatively uniform sediment concentration profile with height above the bed. This causes the position of maximum sediment deposition on the lee to shift downstream, resulting in a rounded dune crest and a more symmetrical dune long profile. Such changes in dune morphology and sediment concentration profiles were also found in experiments concerning the dune-upper-stage plane bed transition by Saunderson and Lockett (1983) and Bridge and Best (1988). McLean *et al.* (2007) used an acoustic Doppler profiling system in the laboratory to examine spatially-averaged velocity and suspended sediment concentration over bedforms.

Field measurements performed by Smith and McLean (1977), Kostaschuk and Villard (1996) and Kostaschuk (2000) suggest that increased sand transport in suspension, relative to bedload, was associated with flatter dunes and lower lee slope angles. Amsler and Schreider (1999) used simulated values of the ratio of suspended-load: bedload and found that higher ratios were associated with a diminishment of dune height during floods in the Rio Paraná, Argentina. Kostaschuk (2005) extended this approach to several rivers and concluded that deposition of suspended sediment in the trough and on the dune lee side acts to reduce dune height and lower the lee slope angle. Building on this work, Kostaschuk and Best (2005) estimated sediment transport using an acoustic Doppler profiler and applied a sediment transport model to identify that deposition from suspension in the dune trough lowered dune height and made the dune profile more symmetrical in shape.

Mohrig and Smith (1996) developed a model designed to determine the fraction of bed load and suspended load likely to be incorporated into dune migration and tested it with field and flume data. Mohrig and Smith (1996) found that their model successfully estimated the measured values for the bypass fraction and they concluded that the division between grains that are deposited versus those that are bypassing falls within the range of sand sizes making up the suspended load at dune crests.

Although the studies summarized earlier provide considerable evidence for the potential role of deposition of suspended sand on dune morphology, there has not been any field research that directly examines the detailed patterns of both velocity and suspended sediment transport and deposition over an individual dune. The purpose of this study is to provide such data from the Río Paraná Argentina, in order to isolate and fully quantify these complex flow-sediment transport interactions over both the crest and lee side of a natural sand dune. Such a study is significant for improving our predictive capabilities regarding capacity of sediment transport over bedforms.

Field Site

The watershed of the Río Paraná is over $2{\cdot}6 \times 10^6$ km^2, making it one of the world's largest fluvial systems and the second largest in South America (Orfeo and Stevaux, 2002). The Río Paraná is ~3965 km in length from its source in the Brazilian highlands to its mouth in the Rio de la Plata estuary, Argentina. The Río Paraguay, its main tributary, joins the Río Paraná close to Paso de la Patria (Figure 1), 1244 km upstream of its mouth near Buenos Aires. The river has a braided planform pattern in the study reach, with a wandering thalweg that holds up to 60% of the total discharge flowing through a given cross-section (Orfeo and Stevaux, 2002).

The present study was conducted on a reach of the Río Paraná just upstream of the confluence with the Río Paraguay (Figure 1), where the mean annual discharge is ~12 000 m^3/s

Figure 1. Satellite image of the Rio Paraná study reach. The rectangle shows the location of the dune field. Flow in the river is from top right (northwest) to bottom left (south east). This figure is available in colour online at www.interscience.wiley.com/journal/espl

(Orfeo and Stevaux, 2002). Summer floods and low spring water levels are common, although during the field season, in the austral summer of 2004, the river experienced slightly lower flows than usual of ~11 000 m^3/s. At the study site, the Río Paraná is approximately 2·5 km wide and has mean depths from 5 to 12 m in the area.

Multibeam echosounding (MBES) and acoustic Doppler current profiling (aDcp) of the study reach (Figure 1), presented in detail by Parsons *et al.* (2005), were obtained at the same time as the research reported herein. Parsons *et al.* (2005) show that the dunes have a relatively complex three-dimensional (3D) planform throughout the surveyed area. The dunes within the study reach were ~1·2 to ~2·5 m high with wavelengths from 45 to 85 m. Most dunes were highly asymmetric in longitudinal profile, with lee side slope angles typically around 8.5° to 18° but up to 22° on individual dunes. Dune stoss slope angles were much shallower, typically around 1·5° to 2·5°. The stoss sides of the dunes were covered with secondary, superimposed, bedforms that tended to increase in both amplitude and length toward the dune crest, reaching a maximum of 0·3 in height and 10 m in length. A 'humpback' shape characterized most of the primary dunes, with rounded crests followed by a sharper break of slope at the 'brinkpoint' before the steeper angle lee side. In planform, the dunes have clearly identifiable crestlines, many of which are laterally continuous throughout the 200 m width of the survey area. Most crestline planform profiles also have zones of pronounced curvature (Parsons *et al.*, 2005), which produces saddles (where the planform crestline is concave downstream) and lobes (where the planform crestline is convex downstream) along individual crest lines, similar to the 3D shapes of dunes investigated by Venditti (2007). Parsons *et al.* (2005) postulated that the dune three-dimensionality is related to the morphology of the upstream dune, with changes in crestline curvature and crestline bifurcations significantly influencing the downstream crestline patterns. Parsons *et al.* (2005) also identified that dunes with lobe or saddle-shaped crestlines had larger, more structured regions of vertical velocity with smaller separation zones than straighter-crested dunes within the reach.

Shugar *et al.* (in press) examined the links between large-scale turbulence and the suspension of sediment over the dune using wavelet analysis of aDcp-derived time series of velocity and suspended sediment concentration. They found an inverse relationship between streamwise and vertical velocities over both the dune crest and trough, where streamwise flow deceleration is linked to the vertical flux of fluid towards the water surface in the form of large turbulent fluid ejections. Regions of high suspended sediment concentration were strongly correlated with such events, this supporting the earlier field observations of Lapointe (1992, 1996). The frequencies of these turbulent events were found to be concentrated in two ranges that matched predictions from empirical equations (Shugar *et al.*, in press). These results suggest that the combination and interaction of, vortex shedding and wake flapping/changing length of the lee side separation zone are the principal contributors to the turbulent flow field associated with large alluvial sand dunes, which act to suspend sediment as they are advected downstream.

Methods

Three-dimensional flow velocity was measured with a Teledyne RDInstruments® RíoGrande 600 kHz acoustic Doppler current profiler, whilst suspended sediment concentration and particle size distributions were measured with a Sequoia® Scientific laser *in situ* scattering transmissometer (LISST-100C). Both of these instruments were deployed from a small survey launch on March 9, 2004. The position of the launch during the surveys was determined using a Leica Differential Global Positioning System (dGPS) in Real Time Kinematic mode, which resulted in a differential relative accuracy of ±0·02 m and ±0·03 m in the horizontal and vertical positions respectively.

The MBES-derived map (Parsons *et al*., 2005) was used to navigate the launch precisely to positions at two anchored locations over the study dune, one over the dune crest and the other over the dune trough. At each location, the LISST was lowered to the bed, which resulted in a measurement height of approximately 0·1 m above the bed. LISST measurements were also made at 2, 3, 4 and 7 m above the crest and 2·5, 4·5, 6 and 8·5 m above the trough. Once in position at each of the heights, LISST data collection was started simultaneously with the aDcp and was sampled for 10 minutes at each point. Additionally, at each location, bed sediment was collected with a pipe sampler and its particle size distribution later determined using standard sieving techniques in the laboratory. In addition to these at-a-point surveys, several aDcp transect surveys were conducted with the launch travelling in an upstream direction over the dune field to assist in placing the at-a-point results in context.

Results and Discussion

Dune surveys

The study dune (Figure 2) was ~55 m long and had a height of ~2·05 m, with superimposed bedforms on the upper stoss slope. The dune possessed a lee side angle of 22° on the steepest part of the lee slope, which was one of the steepest lee slopes in this dune field (Parsons *et al*., 2005). The multibeam surveys reported by Parsons *et al*. (2005) show that the study dune had a slightly lobate, convex-downstream planform.

Figure 2 shows contour maps of streamwise velocity, vertical velocity and suspended sediment concentration measured at 1 Hz intervals over the dune. Concentration values on the contour map are based on a linear regression of beam-averaged aDcp acoustic backscatter with LISST measurements for the study dune (Shugar *et al*., in press: $y = 10{\cdot}834x + 895{\cdot}85$, $R^2 = 0{\cdot}83$). Spatial patterns of streamwise and vertical velocity reflect the impact of topographic forcing (e.g. Kostaschuk *et al*., 2004), with higher streamwise and positive vertical velocities over the upper stoss and crestal area, and lower streamwise and negative vertical velocities over the lee side trough. Suspended sediment concentration over the dune is highest close to the bed, particularly near the brinkpoint separating the stoss and lee sides of the dune. There is also a zone of slightly higher sediment concentration extending above the crest to the flow surface, reflecting turbulent sand suspension events such as those described by Shugar *et al*. (in press) over this dune. Streamwise suspended sediment flux (Figure 3), the product of streamwise velocity and suspended sediment concentration (Figure 2), is highest near the bed and at the brinkpoint. The vertical suspended sediment flux (Figure 3), the product of vertical velocity and suspended sediment concentration (Figure 2), is also higher close to the bed, and is upward over the stoss side of the dune and downward over the lee side. These patterns of flow and sediment transport match well with previous studies of flow and sediment movement over dunes (e.g. Lapointe, 1992, 1996; Kostaschuk, 2000; Kostaschuk and Villard, 1996; Kostaschuk *et al*., 2004; Best, 2005; Shugar *et al*., in press; McLean *et al*., 2008).

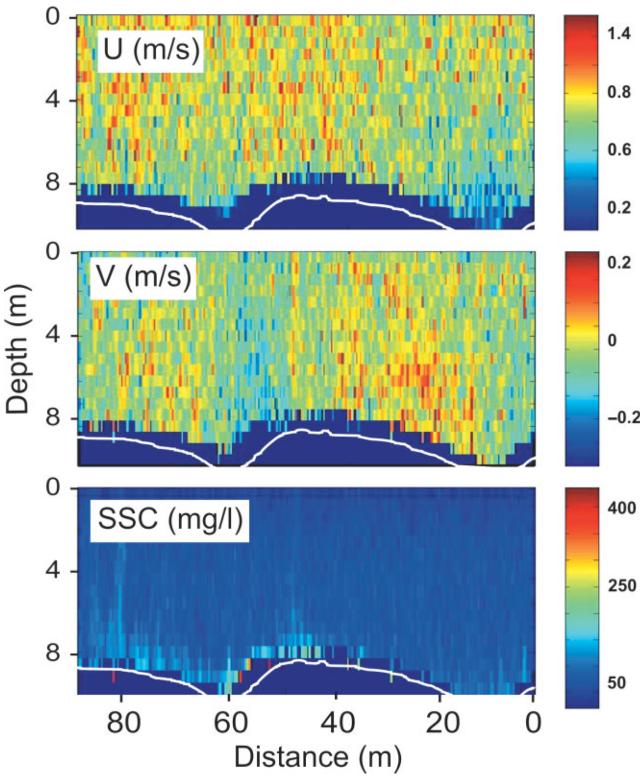

Figure 2. Acoustic Doppler current profiling (aDcp) measurements over the study dune: *U* is streamwise velocity, *V* is vertical velocity, SSC is suspended sediment concentration. Data were collected at 1 Hz intervals. This figure is available in colour online at www.interscience.wiley.com/journal/espl

Velocity and sediment transport profiles

The time-averaged streamwise velocity profile obtained when the launch was anchored at-a-point over the crest shows the 'kinked' log-linear profile typical of flow over dunes (e.g. McLean *et al*., 1999; McLean *et al*., 2008; Kostaschuk *et al*., 2004) while the profile over the trough shows a logarithmic

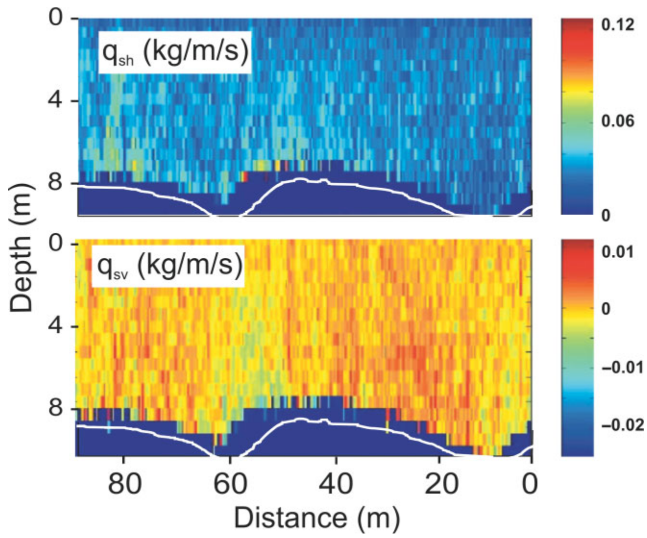

Figure 3. Acoustic Doppler current profiling (aDcp) measurements over the study dune: q_{sh} is streamwise suspended sediment flux per unit channel width, q_{sv} is vertical suspended sediment flux per unit channel width. This figure is available in colour online at www.interscience.wiley.com/journal/espl

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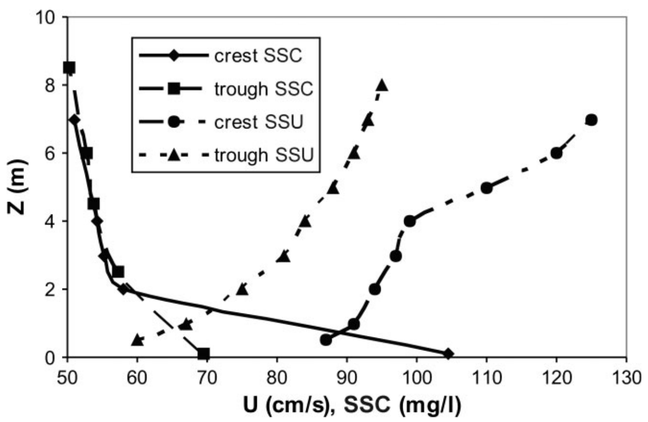

Figure 4. Steamwise velocity (U) and suspended sediment concentration (SSC) profiles over the study dune crest and trough. Suspended sediment was measured with the LISST deployed from an anchored launch. The value of Z is height above the bed.

trend with height above the bed (Figure 4). Moreover, suspended sediment concentrations measured with the LISST over both the crest and trough are highest near the bed and decrease toward the surface (Figure 4). However, Figure 4 also shows that sediment concentrations are considerably higher near the bed over the crest as compared with the same height above the bed in the trough region.

Figure 5 compares particle size distributions from the bed surface, measured by sieving the bed samples, with those measured in suspension with the LISST at 0·1 and 2 m above the bed over the crest. The median grain size is similar for the bed material and the sample 0·1 m above the bed, but is considerably smaller at 2 m above the bed. The LISST samples indicate that sand up to 0·5 mm in diameter (the upper limit of grain detection for the LISST) is suspended in the lower portion of the flow, although the coarser fraction comprises a much smaller contribution at 2 m above the bed. Moreover, the sample from the bed has a coarser tail than the suspended sand. A comparison of median particle sizes over the crest with those over the trough shows that suspended sand is coarsest near the bed in both cases and coarser near the bed over the crest. Median size decreases rapidly to 2 m above the bed over the crest and then remains relatively constant toward the surface. Over the trough, median particle size decreases linearly from the bed to 6 m but is the same size as that over the crest near the flow surface.

Profiles of suspended sediment transport rates per unit width (Figure 6) were calculated from the profiles of streamwise velocity and sediment concentration obtained from the anchored launch (Figure 3). Sediment transport is higher over the dune crest as compared to the trough at every height above the bed. Over the crest, sediment transport is at a maximum near the bed, decreases to 3 m above the bed, remains constant to around 5 m and then increases slightly toward the surface (Figure 6). This pattern reflects the rapid decrease in sediment concentration with height above the bed and the increase in velocity near the flow surface. In contrast, sediment transport is lowest near the bed over the trough and gradually increases toward the surface (Figure 6). The sand transport profile in the trough results from a slower decline in sediment concentration with height above the bed than the comparable increase in velocity within this profile. If these sediment transport rates are integrated over the full flow depth, this yields a transport rate of 0·42 kg/s/m over the crest compared to 0·35 kg/s/m over the trough. This thus indicates that about 17% of the suspended-load transported over the crest is deposited on the lee side before it reaches the trough. The differences in these transport profiles thus suggest that most of this deposited sand originates close to the bed over the crest.

Kostaschuk and Villard (1996) conducted velocity and sediment transport profiles, using an electromagnetic current meter and pump sampler respectively, over dunes in the Fraser River, Canada. Bed-material size in the Fraser River is similar to the Río Paraná but the velocities and suspended sand concentrations in the Fraser River were both higher (Kostaschuk and Villard, 1996). During high river discharges, the Fraser River dunes were more symmetrical in shape than those in the Río Paraná but during lower discharges they had a similar asymmetrical shape. The percentages of sand deposited between the crest and lee side over the Fraser River dunes ranged from 25% to 56% and the corresponding lee side slopes ranged from 8° to 19°, with the higher deposition rates being associated with lower lee slope angles. When combined with these observations

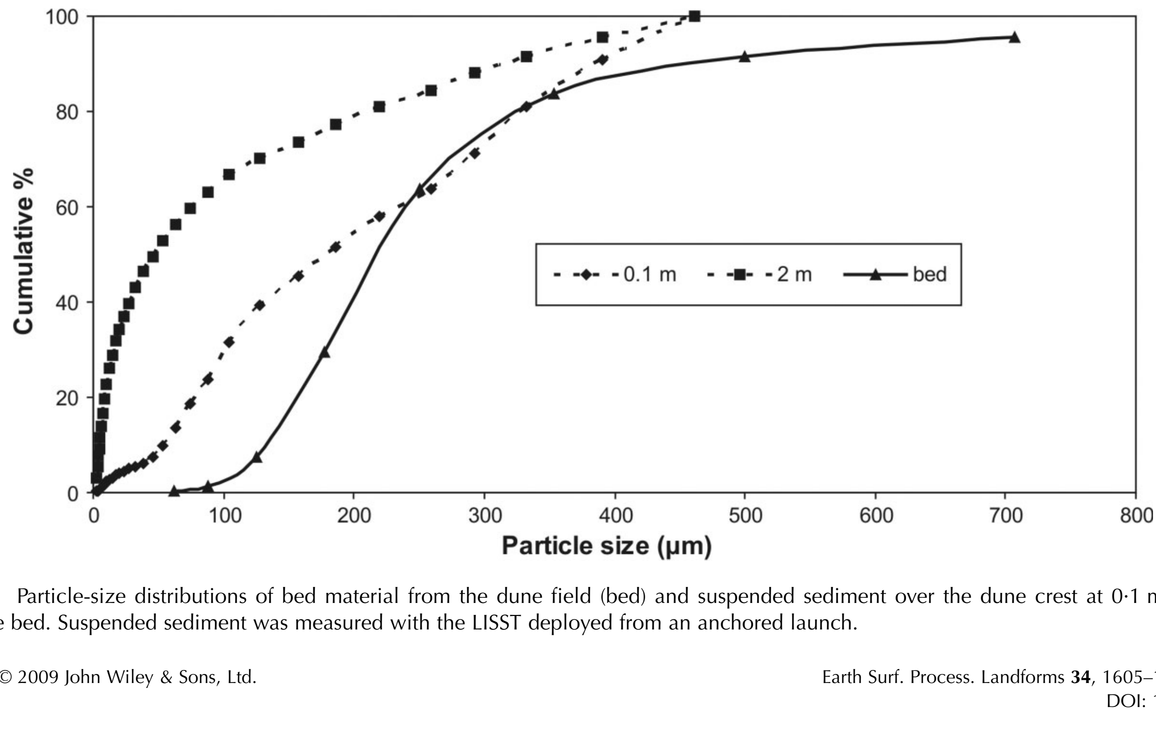

Figure 5. Particle-size distributions of bed material from the dune field (bed) and suspended sediment over the dune crest at 0·1 m and 2 m above the bed. Suspended sediment was measured with the LISST deployed from an anchored launch.

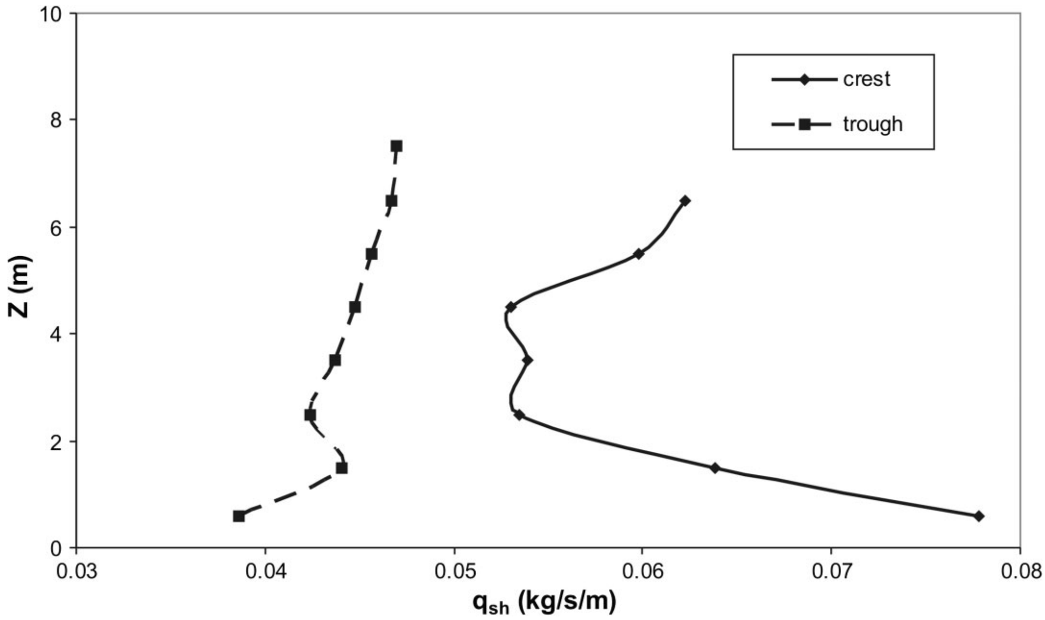

Figure 6. Streamwise suspended sediment transport over the crest and trough measured from the anchored launch. The value *Z* is local height above the bed.

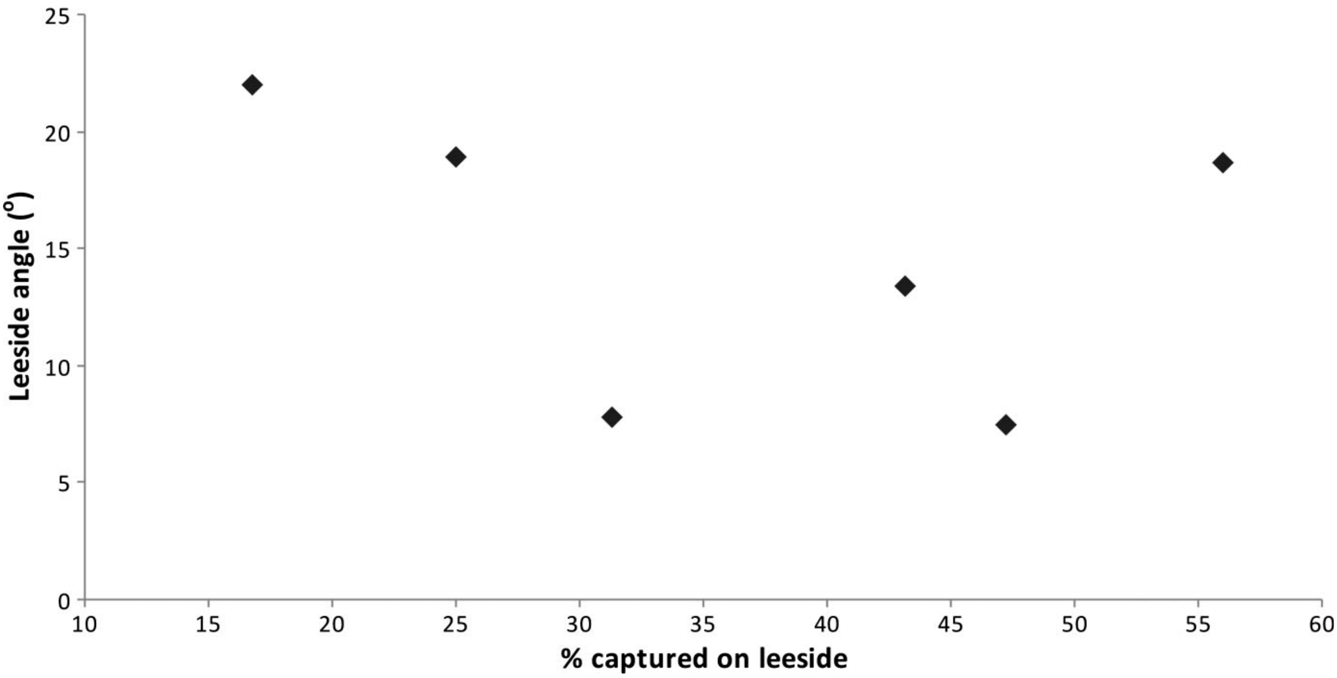

Figure 7. Lee side slope angle versus the percentage of bed-material captured between the crest and trough of the study dune and five dunes measured by Kostaschuk and Villard (1996). The study dune is on the left side of the plot and has a lee side angle of 22° and a percentage captured at 17%.

from the Fraser River, the results from the present study indicate that higher suspended sediment transport rates may produce lower lee slopes (Figure 7), as suggested by the modeling results of Kostaschuk (2005).

Transport modeling

Mohrig and Smith (1996) developed a model to predict the distance that saltating and suspended particles will travel beyond a dune brinkpoint over the lee side of a dune. They assumed that if particle density, shape and sphericity are consistent for a given particle size class, then each size class will have a characteristic trajectory length. For particles travelling in suspension, this 'excursion length' is the distance a particle is advected downstream before settling to the bed and is given by:

$$e_n = \frac{Z_n}{w_n} U \qquad (1)$$

where e_n is the excursion length, Z_n is the elevation above the bed of the center of the suspended sediment mass for that grain class, w_n is the settling velocity for that grain size class, and U is the average streamwise fluid velocity between Z_n and the channel bed. If e_n is less than the horizontal extent

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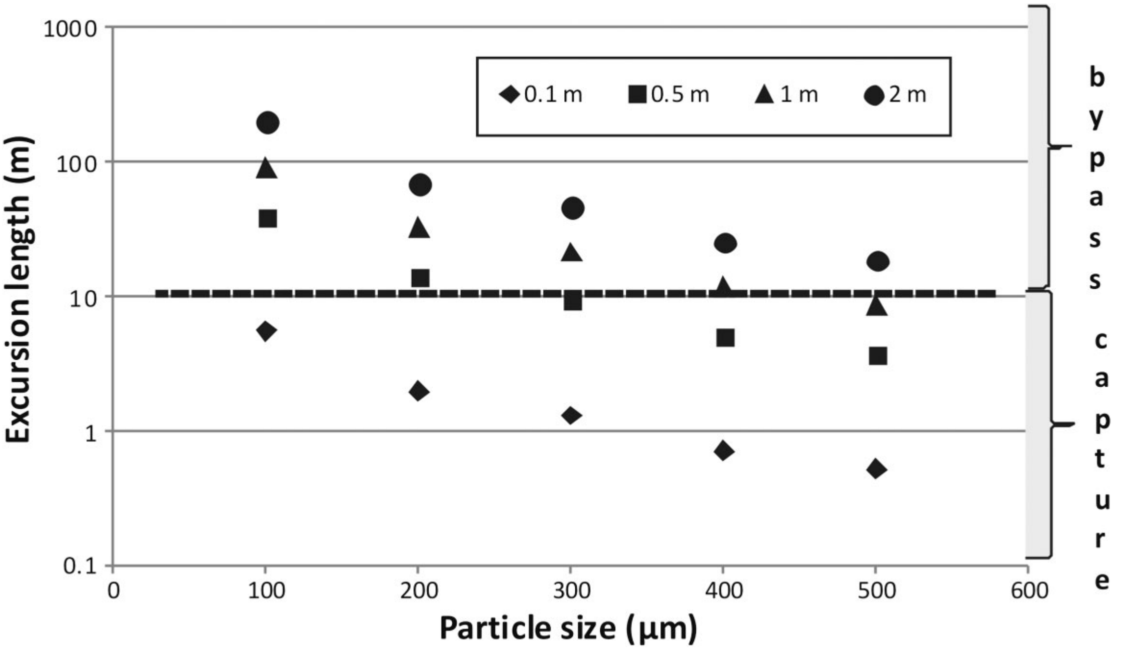

Figure 8. Excursion lengths (from brinkpoint) of suspended bed-material at four heights above the bed (0·1–2 m) for sand particle sizes on the study dune. The dashed horizontal line is the length of the lee side slip face (9 m) that separates capture and bypass of sand in suspension.

of the lee slip face, then all sediment in that class is assumed to be captured by the dune. If e_n is greater than the extent of the lee face, then the sediment bypasses the dune.

Figure 8 shows excursion lengths (from the brinkpoint) of suspended sediment at four heights above the bed (0·1–2 m) for sand particle sizes from 100 to 500 μm in diameter, these being sizes consistent with those measured by the LISST at the crest and with those present on the bed (Figure 5). Height above the bed is assumed to represent Z_n in this case, since we are only interested in the possible capture of particles of various sizes. Settling velocities were determined from the empirical model of Soulsby (1997), which is based on quartz grains settling in fresh water at 20 °C. Velocity cannot be measured directly with certainty with the aDcp closer than ~0·3 m from the bed from the anchored launch (Figure 4), and thus velocities closer to the bed were extrapolated from a logarithmic curve fitted to the velocity profile data 0·5–4 m above the bed at the crest (R^2 = 0·992) (Figure 4). Values of the horizontal length of the lee slipface of the study dune is about 9 m (Figure 2). The model results show that all of the sand in suspension at a height 0·1 m above the bed will be deposited on the lee slope. However, at 0·5 m above the bed, only sediment greater than 300 μm will be deposited whilst at 1 m height only sand greater than 500 μm is captured. These results also indicate that all sand in suspension 2 m above the bed will bypass the lee slope. The LISST measurements presented in Figure 4 support these predictions from the model of Mohrig and Smith (1996), since the concentrations 0·1 m above the bed are higher over the crest compared to the trough, but concentrations at 2 m and higher are virtually identical.

Conclusions

This study has examined patterns of suspended sediment transport over a dune from the Rio Paraná, Argentina, based on integrated measurements of 3D velocity made with an acoustic Doppler profiler and suspended sediment concentration and particle size made with a LISST. Results based on aDcp transect data show that the dune topographically forces the flow, producing higher streamwise and positive vertical velocities over the stoss and crest, and lower streamwise and negative vertical velocities over the trough. Suspended sediment concentration and streamwise sediment flux are highest close to the bed, particularly near the brinkpoint. Vertical suspended sediment flux is also higher close to the bed, but is upward over the stoss side of the dune and downward over the lee side.

At-a-point aDcp measurements from a launch anchored over both the dune crest and trough show that streamwise velocity increases with height above the bed and is higher over the crest than the trough. LISST profiles show that suspended sediment concentrations are highest near the bed over both the crest and trough, but are similar at equal heights above the bed at both locations. However, suspended sediment concentration near the bed is much higher over the crest compared to the trough, and particle size is coarsest near the bed and decreases in size toward the surface. Measurements of the streamwise suspended sediment flux indicate that about 17% of the suspended load transported over the crest is deposited on the lee side before it reaches the trough.

Estimates based on the excursion length model of Mohrig and Smith (1996) indicate that all of the sand passing the brinkpoint 0·1 m above the bed will be deposited on the lee slipface, but this decreases to about 50% at 0·5 m above the bed. Sand travelling more than 1 m above the brinkpoint will bypass the slipface entirely. These results are consistent with the at-a-point field measurements of concentration and suspended sediment flux.

The field measurements and model predictions both indicate that deposition of sand travelling in suspension close to the bed contributes to dune migration and may impart considerable control on the lee side slope angle. Additional field data from a larger range of dunes, ideally with a higher measurement resolution near the bed, are required to more fully detail the processes and rates of lee side deposition and serve as a basis for validating numerical models of dune morphology and process.

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