# Sediment transport distribution along equilibrium sand dunes

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## Abstract

The present study focuses on distribution of sediment transport along mobile dunes in equilibrium. To this end, using ACVP (Acoustic Concentration and Velocity Profiler), we have obtained simultaneous, co-located, high temporal-spatial resolution measurements of the multi-component flow velocity and suspended sediment concentration above dunes. In contrast to previous measurements of flow and sediment dynamics above dunes which are mostly carried out with more than one instrument, we are now able to address sediment fluxes directly for flow scales smaller than the separation distance between different instruments. In this paper, preliminary ACVP results are shown in terms of flow velocities, suspended sediment concentrations and suspended sediment fluxes along dune profiles
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## 1. INTRODUCTION

Dunes are the most common bed forms in lowland river channels consisting of sand and gravel, generated by divergences and convergences of sediment over the bed. They act as roughness to the flow leading to increasing water levels. To be able to model dune evolution and dune dimensions adequately, knowledge on flow and sediment transport processes are crucial.

Sediment is transported as bed load and suspended load, of which a part can be wash load. Wash load is fine sediment that is transported in permanent suspension and therefore less important for morphological development of bed forms. Despite the dominance of suspended load in sand bed rivers (Kostaschuk, 2006), it is often assumed that bed load is the dominant transport mechanism in generating and migrating dunes. Suspended load is then neglected in modelling dune morphology and evolution for flood management purposes (Jerolmack et al. 2005; Paarlberg et al. 2009). However, several theoretical as well as field studies have shown significant difference in dune mechanisms under bed load and suspended load dominant transport regimes. Generally, researchers have found that asymmetric dunes with flow separation zones (high-angle dunes) occur when bed load is the dominant transport mechanism while symmetric dunes without flow separation zones (low-angle dunes) develop when most sand is transported in suspension (Smith and McLean, 1977a; Kostaschuk and Villard, 1996; Kostaschuk, 2000; Kostaschuk and Best, 2005). However, it is not yet clear which processes are responsible for this difference between dunes under bed load and suspended load dominant transport regimes.

For a better understanding of flow and sediment dynamics above dunes, to-date velocity and concentration measurements above mobile and immobile dune beds were collected using separate acoustic and or optical measuring systems (Nelson et al. 1993; Venditti and Bennett, 2000; Kostaschuk et al. 2004; McLean et al. 2008; Wren and Kuhnle, 2008), resulting in a limited investigation of sediment fluxes to large scale processes. In particular, turbulence processes e.g. turbulent bursts and turbulence generation in the dune flow separation zones, which are the most important mechanisms of sediment entrainment, could not be directly addressed for flow scales

smaller than the separation distance between the different instruments.

Our aim in this study is to understand and quantify the sediment transport distribution along equilibrium dunes. In particular, we are interested in the contribution of suspended sediment transport to dune migration. To this end, detailed measurements of flow velocity and sediment concentrations have been obtained using the Acoustic Concentration and Velocity Profiler (ACVP), developed by Hurther et al. 2011. ACVP is capable of measuring vertical profiles of the multi-component flow velocity and sediment concentration simultaneously and co-located with high temporal-spatial resolution. In addition, corresponding bed interface position is measured thus providing direct sediment flux measurements along the bed profiles (Hurther and Thorne, 2011). In this paper, preliminary results are shown of the flow velocity, suspended sediment concentration and sediment flux measurements along mobile dunes.

## 2. LABORATORY EXPERIMENT

### 2.1. Set up and instrumentation

We have conducted experiments in the Hydraulics Laboratory of the Leichtweiss institute of the Technical University of Braunschweig, Germany. The flume used has a width of 2 m and length of 30 m, where the effective measuring length was approximately 10 m. As we are interested in flow and sediment transport over quasi 2D dunes, the width of the flume was reduced to 0.5 m. This, in addition, reduces the measuring complications that are related to the occurrence of 3D dunes.

The experiments were conducted with uniform, fine sand (see Table 1 for sand properties). Flow discharge to the flume is delivered from a constant head-tank approximately 5 m above the flume level. Using an Inductive Discharge Measurement device (IDM), the desired discharge was set with an accuracy of 1%. The flume slope and the weir at the end of the flume are adjustable, which made it possible to realize equilibrium flow conditions at a predefined discharge and water depth. The sediment at the end of the flume was caught by a funnel and transported back to the upstream end of the flume after the completion of each experiment. At the effective measurement section of the flume (over a length of 10 m), the bed and water levels

were measured continuously using echo sensors that were mounted on a semi-automatic measurement carriage. The water level was measured at the centre of the flow, where the bed level measurements were taken at three parallel transects across the flume width. The accuracy of the bed level measurements were determined by repeatedly measuring a fixed bed profile (see Tuijnder et al. 2009). The vertical standard deviation was less than 1 mm, where the horizontal standard deviation was approximately 3 mm. In the horizontal direction the accuracy was limited by the area of the measurement surface of the echo sounders, which was a few centimetres. This makes the echo sounders suitable for studying large-scale features of the dunes, but the grain scale processes cannot be resolved.

In order to determine the sediment fluxes along the dune profiles, flow velocities and sediment concentrations are measured using the ACVP (see also Naqshband et al. 2012). The major advantage of this single system, compared to separate instruments for measuring flow velocity and sediment concentration, is the ability of addressing sediment fluxes to small scale processes. In particular, turbulence processes e.g. turbulent bursts and turbulence generation in the dune flow separation zones, which are the most important mechanisms of sediment entrainment, could not be directly addressed for flow scales smaller than the separation distance between the instruments.

The ACVP was submerged and deployed at approximately 20 cm above the mean bed level. The transmission rate of the ACVP was 1 MHz and the collected data were processed to give horizontal velocity u along the flume, vertical velocity w and sediment concentration profiles at a vertical spatial resolution of 2.5 mm. Furthermore, an Acoustic Doppler Velocimeter and transverse suction sampler (Bosman et al. 1987) were used to measure the flow velocity and sediment concentration at several locations along the dune profile. The data collected with these instruments will be used for the validation of the ACVP.

### 2.2. Experimental procedure

A sand layer of approximately 25 cm thick was installed over the entire length of the flume and the sand bed was flattened at the beginning of each experiment. For each experiment the water discharge, flume slope and water depth were

predefined (see table 1). The flume was slowly filled with water from both the downstream and upstream end of the flume to make sure the bed was not disturbed. Subsequently, the predefined discharge and weir level were set at the required level and the measurement program was started. Every 2 to 3 minutes, water levels and bed profiles were measured with echo sensors on the carriage, over the entire effective measurement section of the flume. The data were stored and processed after each measurement to monitor the water and bed level development in the flume. The weir level was adjusted if the water levels in the flume significantly differed from the predefined water depth.
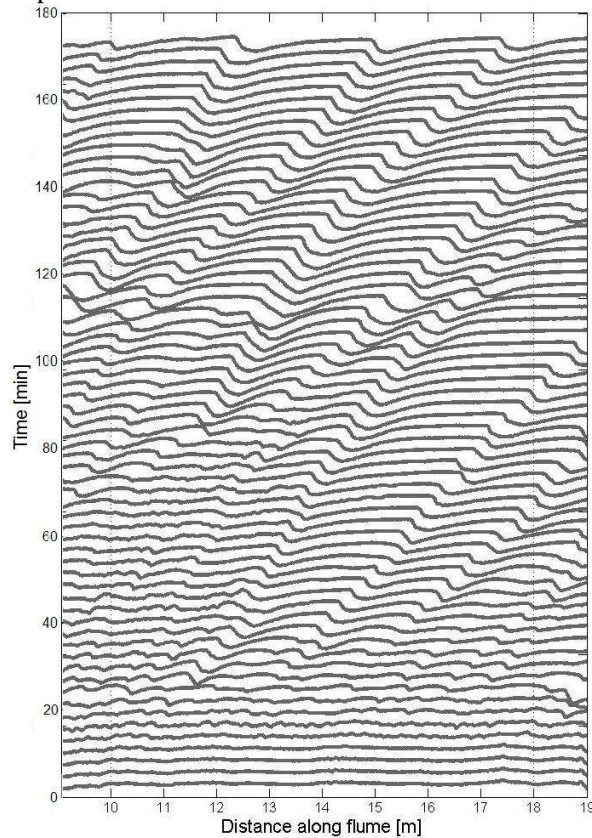


Figure 1. Bed development in time for EXP1 at the effective measurement section of the flume (10-18 m); starting from plane bed towards dunes in equilibrium.

The ACVP measurements were started as soon as equilibrium flow conditions were obtained and the dunes were found to be in a dynamic equilibrium at the effective measurement section of the flume. This dynamic equilibrium is reached when dunes migrate without changing shape as illustrated in Figure 1. Starting from plane bed, ripples develop

into dunes and after approximately 150 minutes dunes are migrating with a constant velocity maintaining their shapes.

In addition, average dune heights (Figure 2a) and dune lengths (Figure 2b) together with standard deviations were calculated over the effective measurement section of the flume showing that a dynamic equilibrium is reached after approximately 150 minutes.

During this equilibrium, the carriage with the ACVP was placed at a fixed position along the flume and the dunes migrated underneath the ACVP. After the completion of the measurement program, the discharge through the flume was stopped and the sediment accumulated at the end of the flume was put back to the upstream end of the flume.
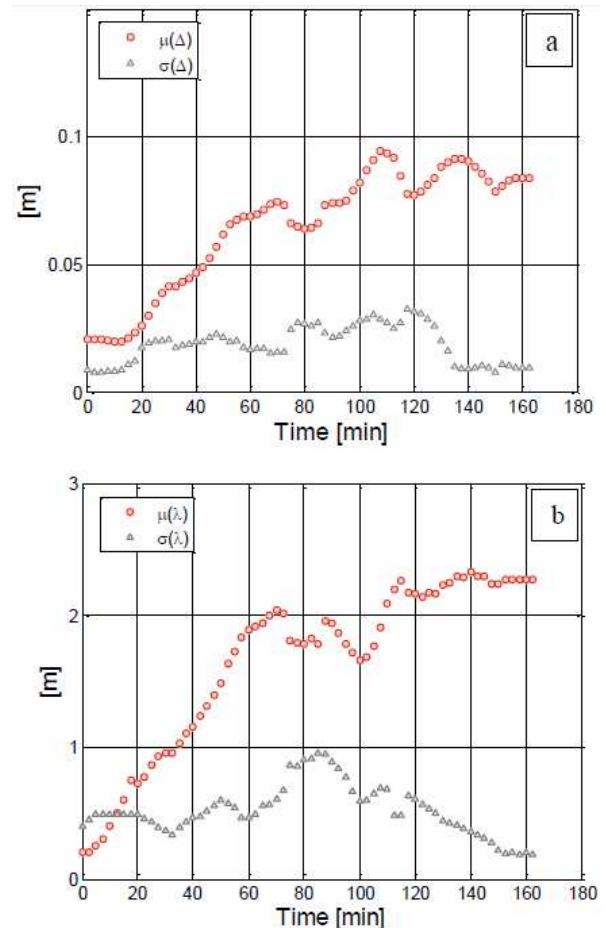


Figure 2. Average bedform heights (a) and lengths (b) in time for EXP1 together with the standard deviations.

## 2.3. Experimental conditions

Two detailed experiments were carried out, each with a different discharge and flume slope but constant water depth. The results discussed in this paper correspond to experiment 1 (EXP1, Table 1). For this experiment, the equilibrium dune height Δe, dune length Λe and time to equilibrium Te are also shown in the table below.

| Parameter | Value |
|---|---|
| Discharge range [L s$^{-1}$ ] | 80-100 |
| Discharge EXP1 [m3 s$^{-1}$ ] | 0.08 |
| Flume slope [-]*10-3 | 1.0 |
| Water depth [m] | 0.25 |
| D10 [mm] | 0.21 |
| D50 [mm] | 0.29 |
| D90 [mm] | 0.40 |
| Λe [m] | 2.27 |
| Δe [m] | 0.084 |
| Te [min] | 150 |

Table 1. Experimental conditions and average equilibrium dune dimensions for EXP1.

## 3. RESULTS AND DISCUSSION

In this section, preliminary time-averaged ACVP results are shown of the measurements of flow velocity, sediment concentration and corresponding bed interface positions along the dunes. The averaging time for now is chosen to be 60 seconds and needs more attention as the data is sensitive to this averaging time. The sediment flux is calculated directly from the product of flow velocities and sediment concentrations, which is also shown here.

Figure 4 shows the time-averaged horizontal flow velocity corresponding to EXP1. The Flow direction is from right to left and the solid line represents the dune profile as measured by the ACVP. Several characteristics of fluid flow over dunes can be observed in this figure as expected from theory and experimental studies in literature (Raudkivi, 1966; Engelund & Fredsse, 1982; Bennet & Best, 1995; Holmes & Garcia, 2008): (1) a zone of flow separation on the dune crest lee-side with reversing flow velocities; (2) flow acceleration at the dune crest; (3) flow deceleration in the wake region overlying the separation zone and extending downstream; (4) an outer, near-surface region with higher velocities overlying the

wake region; and (5) developing of a near-bed boundary layer starting on the stoss-side of the dune towards the dune crest. In addition, good agreement is obtained for the comparison of the time-averaged horizontal flow velocity with data from the ADV as shown in Figure 3.
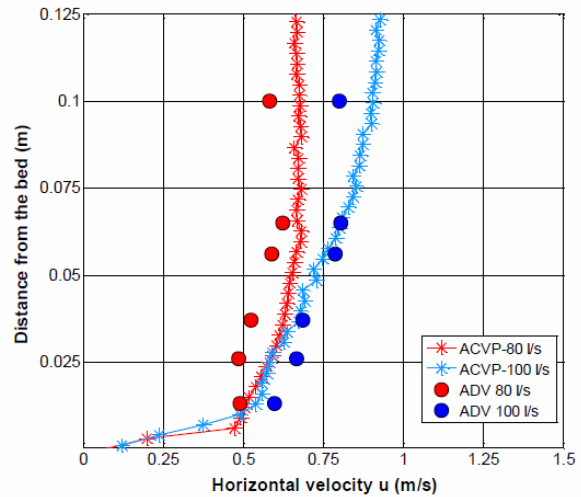


Figure 3. Comparison of time-averaged horizontal velocities between ADV and ACVP for EXP1 (80 L/s) and EXP2 (100 L/s)

The time-averaged sediment concentration corresponding to EXP1 is shown in Figure 5. It can be seen that most of the sediment is concentrated in the lowest 1 to 2 cm from the dune bed. From the dune crest towards the dune trough, the thickness of this high concentrated sediment layer increases. This is due to the flow acceleration at the crest and flow deceleration at the trough, and the corresponding turbulent intensity which is important for sediment entrainment. The turbulent intensity (not shown here) is much higher at the dune trough region due to flow separation.

The product of horizontal velocity and sediment concentration, averaged in time, is shown in Figure 6. It can be seen that most of the sediment is transported near the bed and that sediment flux increases towards the dune crest. A region of relatively small negative flux is observed in the flow separation region which is due to flow reversal. Furthermore, the avalanching of sediment on the lee-side is made visible. These patterns show a good match with previous studies of flow and sediment transport over dunes (e.g. Lapointe, 1992; Kostaschuk et al. 2004; Best, 2005; McLean et al. 2008; Kostaschuk et al. 2009).

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## 4. CONCLUSIONS

The present study discusses preliminary results of mobile dune experiments conducted in the hydraulics laboratory of the Leichtweiss institute (LWI) of the technical University of Braunschweig, Germany. Using the ACVP, simultaneous, co-located, high resolution data was collected of the multi-component flow velocity and suspended sediment concentration over mobile sand dunes. The patterns found in the flow velocity, sediment concentration and sediment transport over dunes show good agreement with previous studies of dune dynamics.

## 5. FUTURE WORK

In order to quantify the contribution of suspended sediment to dune migration, net suspended sediment fluxes will be derived next. In addition, total sediment transport rates (bed and suspended load) will be calculated from dune migration profiles. Furthermore, the velocity data will be used to derive turbulent bed shear stress formulations.

## 6. ACKNOWLEDGMENT

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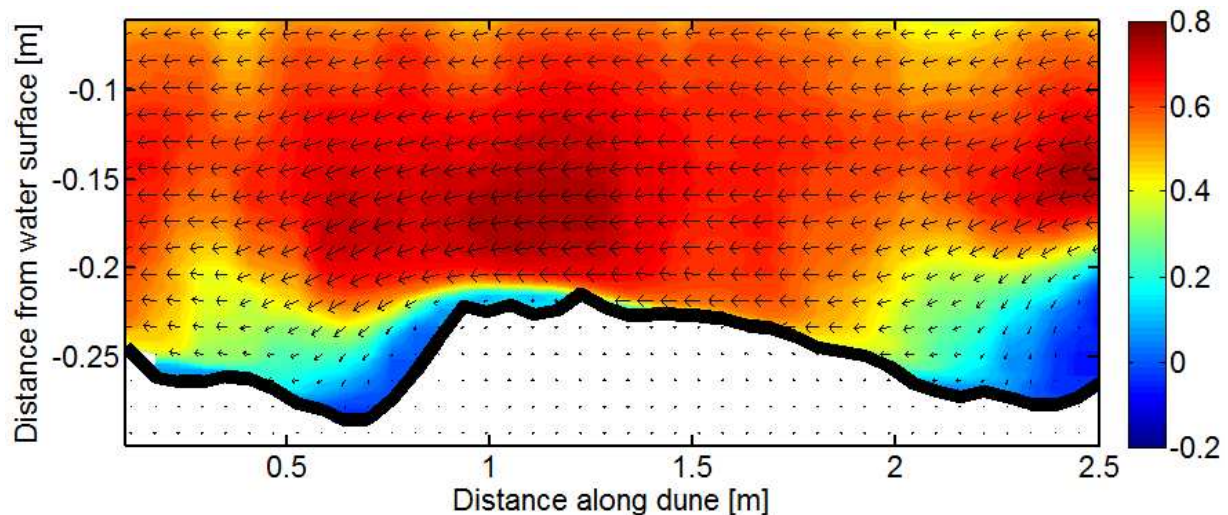
Figure 4. Time-averaged horizontal flow velocity u [m.s-1] over the dune profile, from ACVP measurements of EXP1. The arrows represent the 2D, time-averaged flow direction. Flow is from right to left.
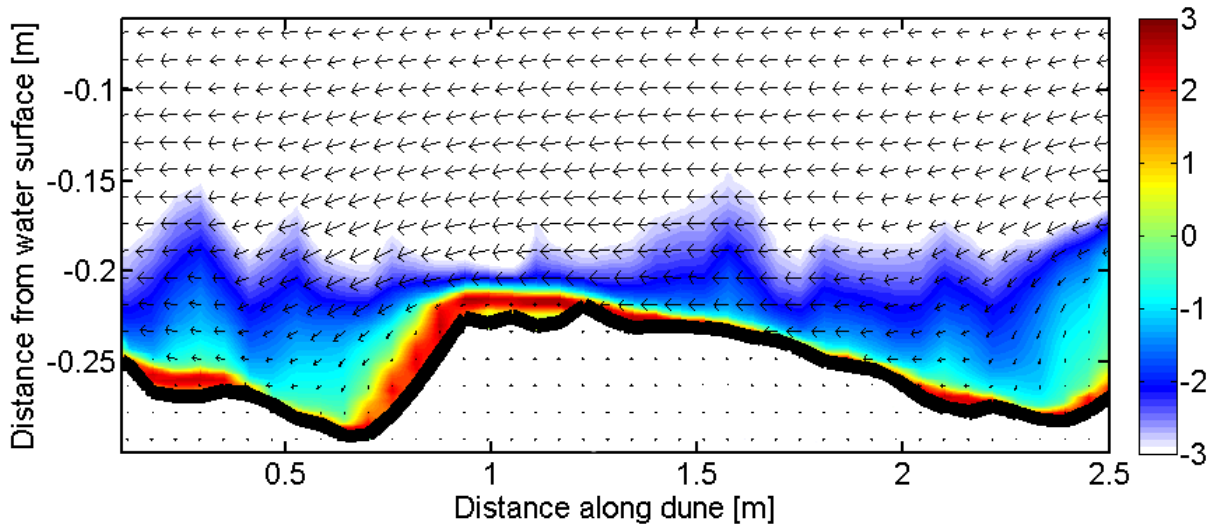
Figure 5. Time-averaged sediment concentration $\log_{10}(c)$ [kg.m-3] over the dune profile, from ACVP measurements of EXP1. The arrows represent the 2D, time-averaged flow direction. Flow is from right to left.



Figure 6. Time-averaged sediment flux uc [kg.m-2.s-1] over the dune profile, from ACVP measurements of EXP1. The arrows represent the 2D, time-averaged flow directi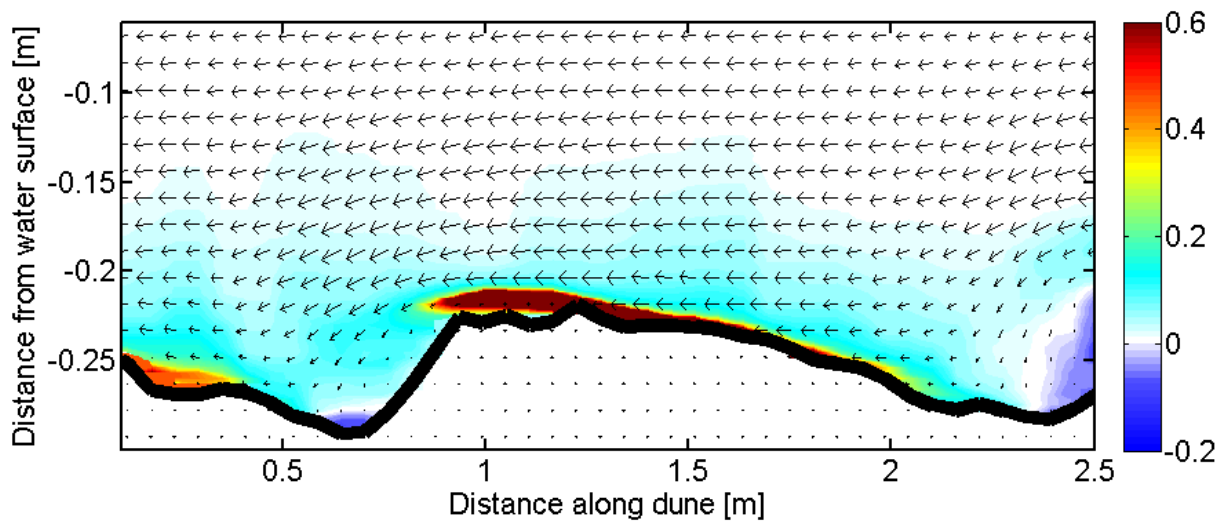on. Flow is from right to left.