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Key Points:

- Flow separation zone behind dunes differs between equilibrium and nonequilibrium flow conditions
- Sediment transport reveals positive lag between dune crest and maximum sediment transport during dune transition to upper stage plane bed
- An extremely high bypass fraction causes a sediment deficit in dunes that eventually leads to washing out of dunes

Supporting Information:

- Supporting Information S1
- Data Set S1
- Movie S1
- Table S1

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A Sharp View on River Dune Transition to Upper Stage Plane Bed

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Abstract Sandy river beds are dominated by rhythmic features known as dunes. Experimental investigations of turbulent flow and sediment transport over dunes have predominantly focused on equilibrium flows that are rare in natural rivers. Using a novel acoustic instrument over migrating dunes in a laboratory setting, we quantify a number of dynamical properties that are crucial in our understanding and modeling of dune morphology and kinematics, particularly under nonequilibrium flows during dune transition to upper stage plane bed. Measured sediment transport distributions reveal a positive spatial lag between dune crest and maximum sediment transport rate that eventually caused washing out of dunes. Bed load was entirely captured in dune troughs, contributing to dune translation where most of suspended load was advected further downstream contributing to dune deformation. Measured bypass fraction was about 76%, which means that only 24% of the total sediment load at the dune crest contributed to dune migration.

1. Introduction

Dunes are periodic sediment structures that arise from the interaction between a flow field and the underlying mobile sand bed. Dunes have been extensively studied under laboratory settings due to their importance in determining flow resistance and sediment transport (see reviews in Best, 2005; Coleman & Nikora, 2011; Venditti, 2013). In addition, their preserved deposits contain essential information on formative environmental conditions providing constraints on current and past climate and landscape evolution, which is needed to interpret stratigraphy and reconstruct paleoclimates on Earth as well as on other planets (e.g., Bridges et al., 2012; Brothers et al., 2017; Milliken et al., 2014; Runyon et al., 2017).

Dune-related experimental investigations of turbulent flow and sediment transport have mainly focused on dune morphology and dune kinematics under equilibrium conditions that are quite rare in natural rivers. Detailed experimental investigations of turbulent flow fields and analogies for sediment transport rates are often limited to measurements over fixed laboratory dunes (e.g., Best, 2005; Venditti, 2007; Lefebvre et al., 2014; Kwoll et al., 2016). As a result, most of our understanding of dune dynamics, kinematics, flow resistance, and sediment transport originates from steady flows, whereas a fundamental property of rivers is that flow fluctuates on different time scales due to backwater effects, anthropogenic effects, and meteorological and astronomical forcings. Consequently, we do not yet have a proper understanding of how dunes respond to nonequilibrium flows. In particular, there is no mechanistic explanation of how changes in a turbulent flow field and the corresponding changes in sediment transport gradients along the dune bed result in the transition of dunes to upper stage plane bed.

It is widely recognized that the location of the maximum sediment transport rate relative to the dune crest determines bed form growth and diminution (e.g., Allen, 1982; Bennett et al., 1998; Fredsøe, 1981; Smith, 1970; Venditti, 2013). The theory of linear stability analysis that has extensively been applied to gain understanding in bed form initiation and development necessitates imposing a spatial lag φ between sediment transport rate and bed topography allowing amplification or damping of initial bed perturbations (e.g., Kennedy, 1963; Engelund, 1970; McLean, 1990; Colombini & Stocchino, 2008; Shimizu et al., 2009; Naqshband et al., 2016; Van Duin et al., 2017). Without introducing this spatial lag between sediment transport maximum and dune crest, the initial bed perturbation of any wavelength will be stable, which means that bed forms will migrate in the direction of mean flow without growth or diminution (Figure 1a). When

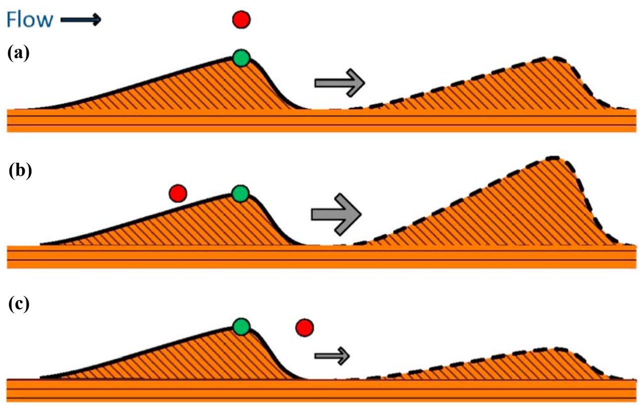

Figure 1. Schematic of dune response to a sediment transport field with the sediment transport peak indicated by red circles. The green circles represent the dune crest. Dune transition is crucially governed by the position of the transport peak relative to the dune crest, leading to (a) dune maintenance, (b) dune growth, or (c) dune decay.

the sediment transport maximum is imposed upstream of the dune crest (Figure 1b), sediment will be deposited on dune stoss side and the dune crest, leading to dune growth. On the other hand, if sediment transport maximum is set downstream of the dune crest, sediment will be eroded from the dune stoss and dune crest faster than it is deposited in the dune lee and dune trough, diminishing the dune height (Figure 1c; see also Venditti, 2013). The fraction of the total sediment transport that is eroded from the dune stoss and dune crest, and that is subsequently deposited in the dune lee and dune trough, contributes to dune translation (downstream migration of the dune), whereas the other fraction that is not captured in the dune lee and dune trough (referred to as the bypass fraction) contributes to dune deformation (topographic changes of the dune bed that are not associated with downstream migration of dunes and may include changes in bed form shape, size, and spacing; Venditti et al., 2016). Previous research under equilibrium conditions of low to moderate flow showed that the bypass fraction increased with increasing depth-averaged mean streamwise flow velocity. Based on this, it was suggested that the increasing bypass fraction might play an important role in eroding dune crests and, eventually, washing out of dunes into upper stage plane bed under high, nonequilibrium flows (Naqshband, Ribberink, & Hulscher, 2014).

Although the discussed spatial lag between sediment transport rate and dune crest and the bypass fraction are crucial in our understanding and modeling of dune morphology (dune shape and dimensions) and dune kinematics (translation and deformation), quantitative observations are virtually absent. In particular, we have no insight into the relative contribution of bed and suspended load to sediment erosion at the dune crest and deposition at the dune trough under nonequilibrium flows and how this erosion and deposition result into the transition of dunes to upper stage plane bed. The most important reason for this knowledge gap is the inherent limitation of instruments available for the simultaneous, co-located, and bed-referenced measurement of flow velocity and sediment concentration over migrating dune bed, especially in the near-bed region (see Naqshband, Ribberink, & Hulscher, 2014 for an overview of available instruments and associated experimental investigations of sediment fluxes over mobile dunes).

A novel acoustic instrument, the Acoustic Concentration and Velocity Profiler (ACVP), enables the measurement of simultaneous, co-located, high-resolution profiles of flow velocity and sediment concentration referenced to the exact measured position of the sand bed (for details on the ACVP see Hurther et al., 2011; Naqshband, Ribberink, & Hulscher, 2014; Naqshband, Ribberink, Hurther, Barraud, et al., 2014). By deploying the ACVP in the present study, we are able to quantify—for the first time—the exact sediment transport distribution (both bed and suspended load) over changing dune morphology under nonequilibrium flow. This enables us to obtain quantitative knowledge of the mechanisms governing the transition of dunes to upper stage plane.

2. Flume Experiments

Large-scale experiments were carried out at the Technical University of Braunschweig (Germany) in a 0.5 m wide and 30 m long flume. The experimental conditions, setup, and procedure are briefly outlined below. For a more complete description of experimental techniques, methods and instrumentation references are made to recent published works (Naqshband, Ribberink, & Hulscher, 2014; Naqshband, Ribberink, Hurther, Barraud, et al., 2014; Naqshband et al., 2016).

To investigate dune transition to upper stage plane bed under nonequilibrium flow, first, a dynamic dune equilibrium was achieved at a predefined flow discharge Q_0 and water depth H by continuously monitoring the effective measurement section of the flume (x = 10 m to 18 m) with three echo sounders mounted on a semiautomatic measurement carriage (see Table S1 in the supporting information). Two echo sounders were positioned each 10 cm away from the flume sidewalls with one echo sounder positioned at the flume

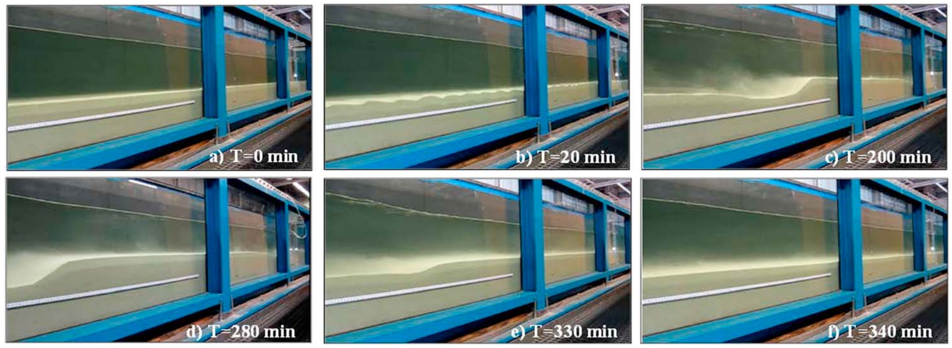

Figure 2. Snapshots of dune evolution from initial (lower) plane bed to dynamic dune equilibrium and upper stage plane bed (adopted from Naqshband et al., 2016). A dynamic video is associated with this figure.

centerline. Starting from plane bed, after approximately 150 min, the dynamic dune equilibrium was obtained. This dynamic equilibrium was found by analyzing dune height and length statistics from the measured echo sounder bed profiles using the bed form tracking tool of Van der Mark et al. (2008). Equilibrium dune dimensions (height, length, and migration velocity) were calculated by monitoring the effective measurement section of the flume over a period of 100 min (see Table S1). Next, flow discharge was increased instantaneously to Q_1 (T = 250 min), and morphological response of dunes to nonequilibrium flow was measured. During the initial transitional stage (250–300 min), dune heights decreased gradually whereas dune lengths rapidly increased up to 2 times the equilibrium dune length. During the second transitional stage (300–340 min), dune heights entirely diminished and dune lengths increased up to 4 times the equilibrium dune length after which dunes were totally washed out and upper stage plane bed was reached. Snapshots of the discussed morphological dune evolution from initial (lower) plane bed to upper stage plane bed are shown in Figure 2 (adopted from Naqshband et al., 2016).

Instantaneous and collocated profiles of flow velocity and sediment concentration were measured during the initial dune transitional stage along an entire dune profile using the ACVP for a better understanding of the mechanisms governing the washing out of dunes toward upper stage plane bed, and in particular the contribution of both bed load and suspended load to dune translation and deformation. Measurements with the ACVP started at the same time as the discharge was increased after reaching the dune dynamic equilibrium (T = 250 min). ACVP data illustrated in the following sections (Figures 3 and 4) are obtained by transforming the measured time series into horizontal distance x along the flume using mean dune migration velocity determined from the initial stage of dune—upper stage plane bed transition. Both vertical and horizontal axes are nondimensionalized through mean dune height (Δ) and dune length (λ), respectively. An averaging period of 10 s was chosen for the ACVP measurements so that bed displacement within this period was very small compared to the dune length (see Naqshband, Ribberink, & Hulscher, 2014 for additional details).

3. Results and Discussion

3.1. Mean Flow Field, Sediment Concentration, and Sediment Flux

A measured dune profile during the initial stage of dune transition to upper stage plane bed together with mean flow field, sediment concentration, and sediment fluxes is shown in Figure 3. The results of a single dune profile are presented as the measured quantities do not significantly differ from dune to dune across the effective measurement section of the flume. Irregularities in the dune topography indicate the presence of small, secondary bed forms (also referred to as low-relief bed waves or bed load sheets) that migrated on the stoss side of the main dune toward its crest. During the initial stage of dune transition, a decreased number of migrating secondary bed forms over a dune's stoss was visually observed. Secondary bed forms vanished throughout the second stage of dune transition, when dune height totally diminished and upper

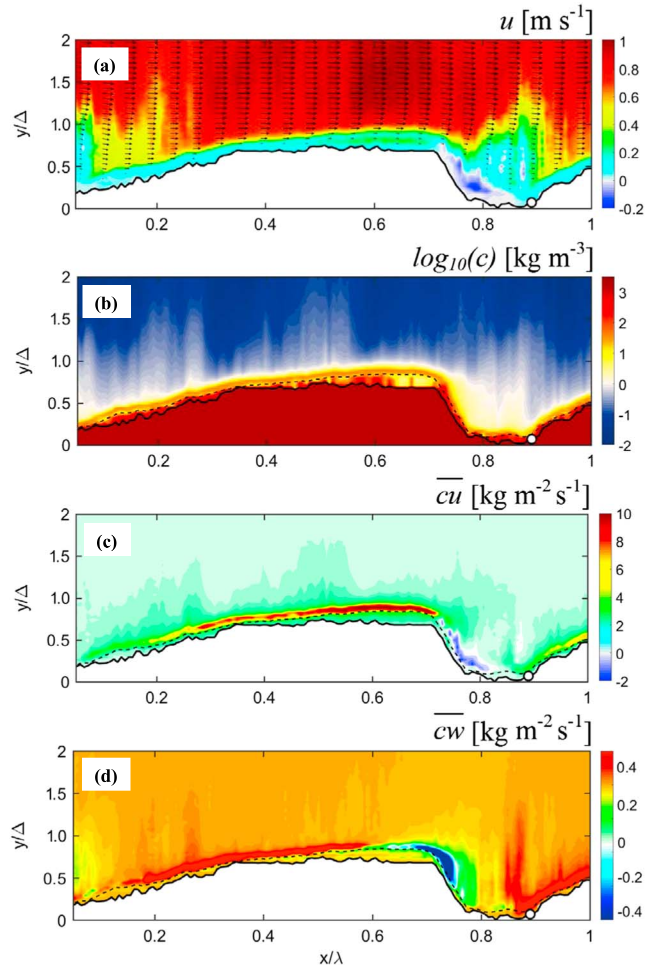

Figure 3. Contour maps of (a) mean streamwise flow velocity, (b) mean sediment concentration, (c) mean streamwise sediment flux, and (d) mean vertical sediment flux. The solid black line is the measured dune profile, with the open circle indicating the location of flow reattachment point with flow direction from left to right. The dotted black line is the acoustically determined interface between the suspended load and the near-bed load layer (see Naqshband, Ribberink, & Hulscher, 2014).

stage plane bed was eventually reached. This implies that secondary bed forms might not play an important role in the washing out of primary dunes through bed form amalgamation and corresponding flow field interactions, contrary to what was suggested earlier (e.g., Best, 2005).

A contour map of the mean streamwise flow velocity ($\overline{u}$) during the initial stage of dune transition is shown in Figure 3a overlaid with arrows that represent time-averaged velocity vector field $\boldsymbol{V}(\overline{u}, \overline{w})$. Dune characteristic flow features are observed that are caused by topographic forcing and flow interaction with the free water surface (high Froude number, see Table S1), which includes a zone of flow separation, a region of flow acceleration on the dune stoss side followed by a zone of flow deceleration in the dune trough, and an outer near-surface region overlying the zone of flow reversal that is associated with high velocities and low pressure. Compared to equilibrium migrating dunes under steady flow with similar shape and dimensions (see Naqshband, Ribberink, & Hulscher, 2014, Figure 7a), the flow separation zone during dune transition is significantly smaller and weaker, with relatively less pronounced near-bed negative flow velocities. The mean distance from the flow separation point to the flow reattachment point (indicated with open circle in Figure 3a and referred to as the flow separation length) is about 4 times the measured dune height, whereas under equilibrium flow conditions, the flow separation length was close to 6 times the measured dune height. Accordingly, large-scale streamwise and vertical turbulent motions in dune troughs (eddies and vortices) are significantly smaller during dune transition. This so-called suppression of turbulence in dune troughs is caused by high near-bed sediment concentrations, especially in the flow separation zone as is observed in Figure 3b (see also Bridge & Best, 1988). The flow separation is further weakened when the suspended load starts to dominate the flow and suppresses turbulence to a point that flow separation cannot occur at all in the upper stage plane bed regime (e.g., Leeder, 1999). A contour map of the mean sediment concentration $\log_{10}(c)$ [kg m^{-3}] is presented in Figure 3b. The black, dotted line indicates the interface between the suspended load and the bed load layer determined by the acoustic interface detection method (Naqshband, Ribberink, & Hulscher, 2014). Sediment concentration at the bed is set equal to the bulk density $\rho_s(1 - \varepsilon)$ = 1,590 [kg m^{-3}], where ρ_s = 2,650 [kg m^{-3}] is the sand density and ε = 0.4 [−] is the sand porosity. During the dune transition, large clouds of suspended sediment reaching the water surface are observed that originate from the dune trough area, caused by flow deceleration and the associated turbulence generation. These suspension peaks persist over the entire dune stoss side and hardly weaken, while approaching the dune crest. Under equilibrium low to moderate flow conditions with significantly lower Froude numbers, however, these suspension peaks were found to be largest in the dune trough area and they progressively decayed over the dune stoss side toward the dune crest (see Naqshband, Ribberink, & Hulscher, 2014, Figures 12a and 12c). The existence of suspension peaks over the entire dune stoss during dune transition is probably due to an additional flow acceleration and associated increased shear stress from the interaction of free surface at relatively high Froude numbers (Naqshband, Ribberink, Hurther, & Hulscher, 2014).

Contour maps of mean streamwise sediment flux $\overline{cu}$ and mean vertical sediment flux $\overline{cw}$ are shown in Figures 3c and 3d, respectively. On the dune stoss side, $\overline{cu}$ increases toward the dune crest as a result of topographic forcing and free surface effects. The largest sediment fluxes are encountered in the suspended load layer. On the dune lee side, near-bed sediment transport is negative (upstream) and against the dune crest where a positive streamwise flux is observed at higher flow depths. Compared to equilibrium migrating dunes under steady flow conditions, where most of the sediment that is transported over the stoss side of the dune remains in the same dune by deposition on the lee side and in the dune trough thus contributing to dune translation (see Naqshband, Ribberink, & Hulscher, 2014, Figures 13a and 13c), a significantly larger amount of sediment is advected downstream during dune transition, toward the following dune. Therefore, it contributes to dune deformation. This is represented by the positive $\overline{cu}$ flux just downstream of the flow reattachment point (see bypass fraction in section 3.2). In addition, during dune transition, the area of negative sediment flux is significantly smaller due to turbulence suppression in the flow separation zone. A contour map of $\overline{cw}$ in Figure 3d further illustrates that during dune transition, sediment is picked up over the entire dune stoss side including dune crest with large peaks around the flow reattachment point (positive, upward fluxes).

3.2. Sediment Transport Distribution and Spatial Lag

The total sediment load (bed load + suspended load), suspended load, and bed load transport distributions along the initial stage of the dune to upper stage plane bed transition are illustrated in Figure 4 (for sediment transport calculation details see Naqshband, Ribberink, & Hulscher, 2014). In contrast to what was the case for equilibrium migrating dunes under steady low to moderate flow conditions (bed load dominated), the distribution of the total sediment transport under nonequilibrium high flow conditions (suspended load dominated) during dune transition deviates from the measured dune shape (Figure 4a). The shape and the magnitude of the total sediment transport are dominated by the distribution of suspended sediment transport (Figure 4c) with two distinct positive gradients on the stoss side of the dune that continues beyond the dune crest. From this it can be concluded that the suspended sediment transport is more determinative in dune deformation during the transition regime from dunes to upper stage plane bed, compared to bed load transport. The first gradient in the total sediment transport distribution originates from the flow reattachment point due to turbulent bursts and flow convergence, whereas the second gradient that continues beyond the dune crest toward the dune trough is due to free surface effects, acting as an additional shear stress on the dune bed and causing erosion on the dune stoss and dune crest. A positive spatial lag φ between the dune crest and maximum sediment transport rate is clearly observed. Although this spatial lag is widely discussed and modeled in literature, the experimental results presented here are the first to offer direct observation. From linear stability analysis, this lag is found to be on the order of the flow depth (e.g., Fredsøe, 1981). For the flow conditions measured here, the spatial lag is about three-fourth of the water depth (0.188 m), which is close to what is theoretically expected.

Although experimental conditions were chosen such to obtain straight-crested 2-D dunes, during dynamic dune equilibrium under steady flow (Q_0), sinuously crested 3-D dune segments were repeatedly observed over the entire length of the flume that are associated with dune spurs (ridges of sediment that extend downstream from the lee surface of dunes). Dune spurs are formed by flow-parallel helical vortices that trail from the lee surface of the oblique segments of dune crest lines, and they are shown to play a crucial role in bed form deformation, interactions, and transition between 2-D and 3-D dunes (e.g., Swanson et al., 2017). In the lee surface of these 3-D dune crest segments, sediment was quickly routed away causing local scours. During dune transition to upper stage plane bed under nonequilibrium flow, the number of sinuously crested 3-D dune segments was reduced (probably due to the suppression of turbulence in dune flow separation zone as discussed earlier) and dune crest orientation became more orthogonal to the mean flow direction, suggesting that dune spurs may not dominate the washing out of dunes to upper stage plane bed for the measured flow and sediment conditions.

Sediment transport distribution in the dune trough illustrates the sediment avalanching process of bed load with a gradual decay of bed load transport in the flow separation zone, reaching zero transport just before the flow reattachment point. This means that bed load is entirely captured in the dune and therefore contributes to dune translation, as was the case for equilibrium dunes. Suspended load, however, is hardly deposited in the dune trough, and it is advected further downstream contributing to dune decay. At the flow reattachment point, the total sediment transport is positive and equal suspended sediment transport, as bed load transport is virtually zero at this location. The bypass fraction—which is defined as the suspended load transport at the flow reattachment point relative to the total sediment transport arriving at the dune crest—is equal to 76% during the initial stage of dune transition. This means that only 24% of the total sediment load that arrived at the dune crest contributed to dune migration and 76% obviously contributed to washing out of dunes (dune decay). The bypass fraction during the dune to

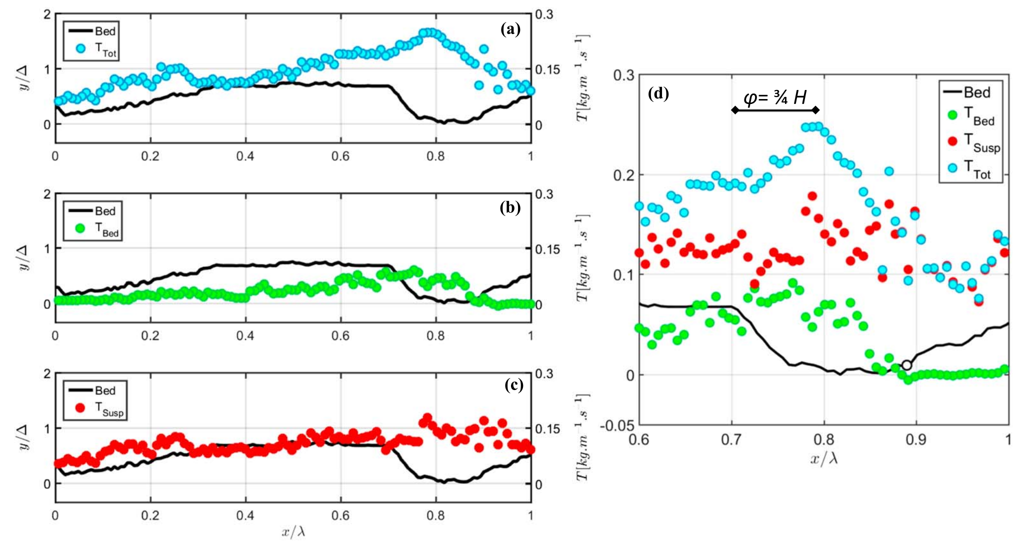

Figure 4. (a) Total load (T_{tot}), (b) bed load (T_{bed}), and (c) suspended load (T_{susp}) transport distribution during the initial stage of dune transition. (d) The enlarged lee side of the dune is shown with the open circle indicating flow reattachment point. The spatial lag between the dune crest and the maximum sediment transport φ is equal to three-fourth of the water depth (H).

upper stage plane bed transition is significantly greater than bypass fractions determined earlier for equilibrium migrating dunes under steady low to moderate flow conditions, viz., 10% for low flow and 27% for moderate flow.

3.3. Implications for Future Bed Form Research

This study has highlighted details of turbulent flow field and sediment transport over migrating sand dunes under nonequilibrium flow conditions. In particular, we have quantified the theoretically expected spatial lag between dune crest and maximum sediment transport rate, the contribution of both bed load and suspended load to dune translation under nonequilibrium flow, and the bypass fraction that results into dune deformation during the initial stage of the transition from a dune field to upper stage plane bed. Although quantifying the exact contribution of these mechanisms to our understanding of dune morphology and dune kinematics is crucial, it is worthy of note that implications of the present study may be limited due to the two-dimensional character of the investigated dune field in a laboratory setting with a uniform grain size distribution (see Table S1). Future research should focus on typical 3-D, low-angle field dunes under a wider variety of flow and sediment characteristics.

Another challenge for upcoming research on bed forms is developing of (semi-)empirical sediment transport models that are likely to be valid across a wide range of conditions, including bed forms. We have shown a nonuniform sediment transport distribution over dune beds that follows the dune shape with a spatial lag between the position of dune crest and maximum sediment transport rate. Applying traditional flume-based sediment transport formulations in natural streams and rivers that are commonly dominated by bed forms will therefore result in inaccurate predictions of sediment discharges, as previously illustrated in a number of studies (e.g., Seminara et al., 2002). Sediment transport has recently been recognized as the superimposition of the motion of individual grains along a continuum of particle travel distances rather than the traditional concept of bed and suspended load, based on somewhat arbitrary thresholds. Parsons et al. (2015) argue that suspended sediment, like bed load, travels in series of hops (saltations) that is repeatedly deposited on the bed where it remains until it is reentrained. The difference with saltating bed load particles is the size of jump lengths and the frequency of reentrainment. More recently, by tracking individual motion of grains over relatively large distances using a series of 8 video cameras, Naqshband et al. (2017) showed that the distribution of particle travel distances over plane bed lies along a continuum moving from bed load to suspended load dominant flow conditions. To better understand the mechanics of sediment transport over bed forms and to develop a widely applicable sediment transport model, future research may consider the nonuniform structure of dune wakes to better address the distribution of particle travel lengths over bed forms.

4. Conclusions

Using a novel acoustic instrument for measuring simultaneous, co-located flow velocity, and sediment concentration (ACVP) in a laboratory setting over migrating dunes, we quantified a number of dynamical properties that are crucial in our understanding and modeling of dune morphology and dune kinematics particularly under nonequilibrium flows during the transition of dunes to upper stage plane bed. The unique high-resolution data presented in this paper may support and test full-complexity numerical models that intend to simulate bed form growth and diminution under variable flows (e.g., Nabi et al., 2015; Van Duin et al., 2017). By incorporating the obtained new insights in empirical formulations of flow resistance and sediment transport, our ability to predict water levels during floods may improve. The main findings of our study are summarized as follows:

1. Flow separation length and flow separation zone during dune transition are significantly smaller and weaker, relatively, with less pronounced near-bed negative flow velocities, compared to equilibrium migrating dunes under steady flow with similar shape and dimensions.
2. The sediment transport distribution reveals a positive spatial lag between the dune crest and maximum sediment transport rate during dune transition. For the measured flow conditions, the spatial lag is about three-fourth of the water depth, which is close to what is theoretically expected.
3. During dune transition, bed load is entirely captured in the dune and therefore contributes to dune translation as was the case for equilibrium migrating dunes. Suspended load, however, is hardly deposited in the dune trough and is advected further downstream, contributing to dune deformation. The bypass fraction is about 76% during the initial stage of dune transition, which means that only 24% of the total sediment load that arrived at the dune crest contributed to dune migration and 76% contributed to washing out of dunes.

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