Sediment Transport on a Sand Bed With Dunes: Deformation and Translation Fluxes

R. C. Terwisscha van Scheltinga, G. Coco, M. G. Kleinhans, and H. Friedrich

Abstract As dunes move along the riverbed, they change in size, shape, and arrangement. This involves sediment fluxes on top of the net downstream motion of the dune field, but how much dune dynamics affect total sediment flux remains unclear. In this study, we obtain high-resolution and high-frequency digital elevation models of migrating submerged dunes in the laboratory. We use the measurements to identify three-dimensional dune sediment fluxes and characterize dune interaction processes. We show how variations in dune migration lead to flux variations. Varying bed and water surface slopes and time-varying sizes and shapes of dunes are imprinted in the observed flux variations, with a corresponding time lag. Feedback between bed morphology and water surface slope causes (some) dunes with high crests to lengthen into long dunes (of about twice the mean dune length), until a breakup of this dune into shorter dunes occurs, typically facilitated by merging of superposed bedforms until the primary dune splits. A large number of short dunes have high overall transport rates. Dune interaction causes patterns in the dune deformation flux. Dune splitting, defect creation and defect repulsion cause a peak in the deformation flux, whilst merging triggers a temporal increase of the total flux. Estimating the fluxes with spatially varying dune migration, and contributing fluxes to either deformation or translation processes continues to be a challenge, even for the detailed data set we have presented. Our analysis suggests that sediment transport variability over dune-covered riverbeds is best described by considering the topography of multiple dunes.

Plain Language Summary Riverbeds are often covered by dunes, which move downstream as sediment is transported by the river flow. During the downstream movement, dune shape changes, even under constant flow. Sediment fluxes that describe the change are typically calculated using average dune movement, neglecting the effect of changing dune shapes. How much changing dunes affect the sediment flux remains unclear. Here we present a new data set of moving dunes in a laboratory flume. We used advanced image analysis to obtain three-dimensional high-resolution bathymetric maps of moving dunes. Erosion and deposition patterns were identified and were linked to the observed dune changes. The results show that dune deformation, one of the studied dune change processes, causes variations in total sediment flux of 15%, which is less than previously found. However, deformation also affects the dynamics of neighboring dunes, which causes long-term average flux variations not captured by using average dune movement. We recommend that moving dunes in the field should be studied taking this new insight based on a laboratory study into account.

1. Introduction

A planar riverbed composed of sand will generate bedforms when water worked (Vanoni & Brooks, 1957; Yalin & Karahan, 1979). Dune heights and lengths of submerged dunes scale with the transport stage, which is defined as a function of slope, grain size and water depth (Bradley & Venditti, 2019; van Rijn, 1984). A dune bed can undergo significant change in time, whilst the statistical characterizations of the dune field (dune height, dune length, steepness, and migration rate) can remain the same (Kocurek et al., 2010; McElroy & Mohrig, 2009).

Dune sediment transport rates are typically quantified with repeated bathymetric field surveys, using dune tracking techniques and measuring dune migration (translation) (Abraham et al., 2011; Frings & Kleinhans, 2008; Leary & Buscombe, 2019; van Rijn, 1984; Wilbers & Ten Brinke, 2003). This method is valid assuming migration is the major component of the dune sediment transport rate, and shows that migration rates increase with transport stage (Lin & Venditti, 2013; Yalin & Karahan, 1979). To maintain constant sediment transport rates, the migration rate of an individual dune would be inversely related to its height, and the migration rate decreases as dune
height increases (Allen, 1973a; Coleman & Melville, 1994; Lin & Venditti, 2013; Venditti et al., 2005). However, migration rates of individual dunes in a dune field vary more than can be expected from differences in height only (Jerolmack & Mohrig, 2005a, 2005b; Lin & Venditti, 2013; Terwisscha van Scheltinga et al., 2020). This greater variation indicates non-linearity in the feedbacks between flow, sediment transport and bed morphology. The shape of the dune induces flow acceleration and for steep dunes, flow separation zones form downstream of the dune, which significantly influences hydraulic roughness and thus water levels (Bennett & Best, 1995; Kwoll et al., 2017; Lefebvre et al., 2014; Nelson et al., 1995; Van der Mark, 2009). A fundamental difference exists between friction due to dune geometry and that due to dune height variability, suggesting dynamically unstable conditions at the scale of multiple dunes, with the relation between the spatiotemporal bedform variability and the sediment transport rate not having been extensively studied.

Despite the differences in dune shape, typical responses are recognized when dunes and defects, that is, crest terminations or imperfections in the bedform field-scale pattern (Ewing & Kocurek, 2010; Werner & Kocurek, 1997), approach each other: splitting increases the number of dunes, and merging causes a decrease in the number of dunes (Kocurek et al., 2010). Superposed bedforms travel faster than dune crests, leading to defect-crest interactions and crest deformation (Terwisscha van Scheltinga et al., 2020). Dune interaction processes, such as differential migration and dune merging, are ubiquitous during all flow conditions, with dunes competing for space (Kocurek et al., 2010; Reesink et al., 2018). Dune interaction processes are also important contributors for dunes to adapt to changes in flow (Reesink et al., 2018).

1.1. Dune Deformation and Translation Fluxes

The sum of all topographic bed field changes, not associated with the downstream translation, is called deformation (Venditti et al., 2016). The flux related to the mean migration of the bed is the translation flux. In the presence of dune interactions, deformation causes differences between the translation flux and the total flux (here total flux is the bedform-related sediment flux not accounting for over-passing and suspension load). As it is difficult to calculate the flux associated with deformation directly from dune transects, an alternative is to calculate the deformation flux as the difference between the total flux and the translation flux (Venditti et al., 2016). The deformation flux as a fraction of the total flux is equivalent to the translation flux at the bedload dominated stage (McElroy & Mohrig, 2009; Venditti et al., 2016). As the transport stage increases, larger and faster moving bedforms are observed, resulting in the contribution of the translation flux to the total flux to increase, whilst the contribution of the deformation flux decreases (Venditti et al., 2016). Bedload observations in shallow water have shown that with increasing transport stage, short steep dunes transform into high-amplitude dunes and eventually into washed-out bedforms (Bradley & Venditti, 2019; Unsworth et al., 2018).

Any adjustments of dune morphology and spacing from dune interactions directly affect dune shape parameters, and in turn calculated friction parameters. Friction coefficients of three-dimensional dunes are on average higher than friction coefficients of their two-dimensional counterparts (when subjected to flows of similar depths and discharges), but notably, the turbulence generated by three-dimensional dunes is weaker than the turbulence generated by their two-dimensional counterparts (Maddux et al., 2003). The presence of secondary currents is attributed to causing this difference, with flow over three-dimensional dunes diverting around the maxima of the dune crest line (Maddux et al., 2003). However, the relationship between three-dimensional sediment flux and the variability caused by dune deformation is largely unexplored.

1.2. Quantifying Bedload Transport Rates in the Presence of Dunes

Dune fluxes are commonly determined from measuring erosion and deposition of a longitudinal transect of multiple dunes in a survey, thus neglecting cross-stream transport and effects of dune three-dimensionality. The fluxes are generally obtained as a function of time interval between surveys, making it difficult to compare results from different surveys (Aberle et al., 2012; McElroy & Mohrig, 2009; Venditti et al., 2016). The deformation flux is determined over the same time interval as the translation flux, and the translation distance (and mean migration rate) of the dune field is mathematically obtained as the lag distance of the cross-correlation maxima for respective longitudinal transects (Ganti et al., 2013; McElroy & Mohrig, 2009; Venditti et al., 2016).

The availability of digital elevation models (DEMs) of dune topographies allows using the continuity equation for sediment transport (Lane et al., 1995) obtaining a total flux including cross-stream transport:
\[
\frac{\Delta q_y}{\Delta y} - \frac{\Delta q_x}{\Delta x} = \frac{(1-p)\Delta z}{\Delta t},
\]

where \(\Delta q_x\) and \(\Delta q_y\) are the change in sediment flux (volumetric rate, m\(^3\)/s) in the \(x\)- and \(y\)-direction, \(\Delta z\) is the change in bed elevation at each grid cell for discrete timesteps:

\[
\Delta z_{x,y} = z_{x,y}(t_2) - z_{x,y}(t_1),
\]

where \(z(t_2)\) is bed elevation at time 2, \(z(t_1)\) is bed elevation at time 1, and \(\Delta t\) is change in time between repeat intervals (here time 1 and 2), \(p\) is the porosity (\(-\)), \(x\) the longitudinal direction and \(y\) the cross-stream direction.

Differencing of dune field DEMs (commonly referred to as DEMs of Difference (DoD)) with dune crest migration between repeat intervals produces a spatial distribution of positive elevation change, showing most sediment deposition on the lee face (Nittrouer et al., 2008). In case a flux was equal everywhere over a dune stoss, using DoDs neither deposition nor erosion would be quantified over the stoss. When sediment is conveyed toward the dune lee side, deposition occurs. The latter is captured by the DoDs and provides the temporally and spatially averaged flux over the stoss side. An important consideration is the sampling density and distance for DEMs, as a larger grid size leads to loss of information, depending on the complexity of the surface (Lane et al., 2003). By increasing the spatial resolution of the DEMs, the loss of information could be reduced significantly.

Bedload transport rates depend on many processes that vary nonlinearly, involving various time and space scales, and are interrelated to each other (Ancey, 2020a). Diffusion-like behavior is observed at small time intervals, as particles move with varying velocity and velocity fluctuations add further diffusion (Ancey, 2020a). Noise (e.g., bedload transport rate fluctuations) should be recognized as an intrinsic feature of bedload transport (Ancey, 2020b). Here bedload transport rates at much larger time intervals and at the scale of dunes are considered, at these large temporal and spatial intervals, diffusion-like behavior of particles can be averaged out over time and space (Terwisscha van Scheltinga et al., 2021).

1.3. Objectives

Based on the identified knowledge gaps, bedload transport experiments were designed to examine the extent to which individual dune geometries and geometries of multiple dunes scale with sediment flux (variability). We examine how dune topographies influence local water surface slopes (due to flow expansion), and to which extent dune interaction processes drive differential motion of the adjacent dunes. We obtain high-resolution (0.003 \(\times\) 0.003 m) and high-frequency (every 5–6 min) DEMs of laboratory dune fields using Structure from Motion (SfM) in a unidirectional current. We use our new data set of migrating laboratory dunes, obtained without draining the flume, to quantify the contribution of dune interaction processes to the deformation flux for conditions without a change in flow forcing, under bedload transport conditions.

2. Experimental Setup and Methods

Experiments were performed in a 0.44 m wide, 11.9 m long and 0.38 m deep artificial channel that recirculates water and sediment (Figure 1a). An initial sediment layer of 0.1 m covered the bed, with an initial water depth of 0.18 m. The used unimodal natural sand has a median diameter of 0.6 mm (see Figure S1 in Supporting Information S1), thus not generating ripples (Kleinhans et al., 2017). To generate migrating dunes of similar dimension with an order of magnitude difference in sediment flux, we used two different flow velocities (0.003 \(\times\) 0.003 m) and high-frequency (every 5–6 min) DEMs of laboratory dune fields using Structure from Motion (SfM) in a unidirectional current. We use our new data set of migrating laboratory dunes, obtained without draining the flume, to quantify the contribution of dune interaction processes to the deformation flux for conditions without a change in flow forcing, under bedload transport conditions.
Figure 1. (a) Sketch of the used 11.9 m long flume. Dunes are not to scale. (b) Flow diagram describing the visual identification procedure used to classify between merging-cannibalization, merging-coalescence, defect repulsion and defect creation.

Table 1
Experimental Settings and Approximation of Shields Number, Suspension Number, and Sediment Transport Predictions (Kleinhans, 2005; van Rijn, 1984; Wong & Parker, 2006), Which Are Based on the Average of Shear Stress Derivation of Three Methods

| Exp. | Flow velocity (m/s) | Water depth (m) | Froude number (–) | Discharge (m³/s) | Bed slope from DEMs (x10⁻³ [-]) | Water surface slope (x10⁻³ [-]) | Shear stress τ = ρwghRwR (N/m²) | Shear stress τₚₚ (N/m²) | Shear stress (τₚₚ in van Rijn [1984]) (N/m²) | Shields number θ (average) (–) | Shields number θ (average of methods) (N/m²) | Shields number θ (average of methods) (N/m²) | Sediment flux qₚₚ (MPM of Wong and Parker [2006]) (x10⁻⁵ m²/s) | Sediment flux qₚₚ (Ribberink predictor) (x10⁻⁵ m²/s) | DEM of difference flux qₚₚ,DoDc (x10⁻⁵ m²/s) | Translation flux qₚₚ,TF (x10⁻⁵ m²/s) | Dune flux from bedform tracking (Equation S2.1 in Supporting Information S1) (x10⁻⁵ m²/s) |
|------|----------------------|-----------------|-------------------|-----------------|---------------------------------|---------------------------------|-------------------------------|-----------------|---------------------------------|-------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| FR05 | 0.49 | 0.185 | 0.36 | 0.041 | 1.57 | 1.03 | 0.92 | 1.04 | 1.07 | 0.91 | 0.11 | 0.38 | | | | | |
| FR06 | 0.60 | 0.180 | 0.45 | 0.050 | −8.41 | 3.18 | 2.83 | 1.50 | 1.62 | 1.98 | 0.21 | 0.54 | | | | | |

Note. Mean dune field characteristics (for dunes with dune height >0.02 m), the various sediment fluxes (see Section 2.4) and the dune flux from bedform tracking based on the mean dune field characteristics (Equation S2.1 in Supporting Information S1) are listed.
2.1. Data Collection, Processing, and Validation

To ensure high-resolution topographic data, images of the submerged bed are collected every 0.05 m with a moving carriage, covering the 8.5 m long measurement section. The flume was not drained for the measurements, yet the flow was paused. To ensure high-frequency data of dune migration, a set of images was taken every 6 and 5 min for FR05 and FR06, respectively. For FR05, 46 DEMs of the submerged bed were obtained, for FR06 24 DEMs. DEM processing using SfM has been validated previously (Terwisscha van Scheltinga et al., 2020).

The flume was drained after obtaining six or 12 DEMs to perform subaerial data collection for validation of the submerged DEMs. Point cloud data quality is presented in Table S1 of Supporting Information S1. Validation shows that the data set has an accuracy of $5.14 \times 10^{-5}$ m (mean error) and $1.45 \times 10^{-3}$ m (mean absolute error) and a precision of $1.86 \times 10^{-3}$ m (standard deviation error) at the DEM grid-resolution of 0.003 × 0.003 m for 10 validation sets (Table S1 in Supporting Information S1). Georeferencing errors of the raw point clouds and DEMs are also reported in the supplemental material (Figure S2 and Table S2 in Supporting Information S1), with a description of the optimization steps used to reduce systematic errors (Text S1 and Figure S3 in Supporting Information S1). A threshold is applied to the point cloud values and gridded with a nearest neighbor procedure. Errors occurred mainly near the glass-wall, and data within 0.02 m of the flume wall were eliminated. Thereafter, the surface is smoothed in the x-direction with a moving average filter to eliminate grain-scale differences. Data processing and validation thus ensured minimal susceptibility to known error propagation (Lane et al., 2003), suited for the calculation of erosion and deposition.

2.2. Classification of Dune Interaction Processes

The dune interaction classification and process description is described in Table 2 and is based on Kocurek et al. (2010). In general, merging-coalescence and merging-cannibalization decrease the number of dunes, whilst splitting increases the number of dunes. When two dune crests merge and the merged crest is located downstream of both crests, coalescence occurred, whilst when the merged crest is located upstream of the most downstream crest, merging-cannibalization occurred (Figure 1b). The processes of defect creation, defect repulsion and calving affect the local topography, but not necessarily lead to a change in the number of dunes, unless they are followed by merging or splitting. Splitting is observed when a process leads to a new crestline and an increase in the number of dunes. Defect repulsion is observed when the approaching crestline merges before breaking up (Figure 1b). Defect creation and defect repulsion are considered only for labeled dune crests, not for superposed bedforms. Our analysis also observed splitting when the highest crestline of the bedform changes to another crestline (according to bedform tracking of crests and tops), leading to a significant change in the bedform characteristics of dune length and bedform height. Calving is observed when there is a significant effect on the dune shapes.
2.3. Bed Slope, Water Surface Slope, and Dune Morphology

The bed slope is calculated as a linear fit through the width-averaged cross-section. The difference between the bed slope ($S_{bR}$) and the water surface slope ($S_{wR}$) is part of the convective acceleration term of the one-dimensional shallow water equation that determines the shear stress (Bradley & Venditti, 2019; Le Bouteiller & Venditti, 2014):

$$
\tau_R = \frac{\rho_w g h_R S_{wR} + \rho_w U_{2R}^2 (S_{bR} - S_{wR})}{1 + 0.18 h_R/w^2},
$$

with $\rho_w$ the water density, $g$ the gravitational acceleration, $h_R$ the hydraulic radius (m), $U_{2R}$ the reach-averaged mean velocity of the flow (m/s), and $w$ the flume width (m). The sidewall correction based on Williams (1970) is incorporated in this equation.

Bedform height, length and steepness of the primary dunes were determined using the bedform tracking tool (BTT), which classifies bedforms based on positive up crossings of the mean bed level (Van der Mark et al., 2008). The highest point between an upcrossing and a down crossing is defined as the top (crest) and the lowest point between a down crossing and an upcrossing as the trough (Figure 2b). The BTT method is providing an objective analysis, including the identification of superposed bedforms (Figure 2a). Here, any identified superposed bedforms were removed by adding a minimum dune height and length as a criteria (Reesink et al., 2018). Additionally, the coordinates ($x, y, z$) of the tops and troughs at each time step for each dune were determined. With this information, the temporal dune migration (rate) of each dune was determined. Troughs and crests tracking, and their temporal change, depend on the location of the longitudinal transect. Rather than analyzing each longitudinal transect and averaging bedform height, length, steepness and migration rates, we used the width-averaged longitudinal cross-section to define these values. To identify the appearance and disappearance of bedforms, the non-primary bedforms were tracked by manually adding their coordinates (tops and crests), if over time they merged with one of the dunes crests or grew into a primary dune. We stopped tracking non-primary bedforms when the crest deforms and no longer covers the flume width, or two crests merge. Table 1 shows the obtained averaged dune shape characteristics for both experiments.

2.4. Sediment Flux From DEM of Difference (DoD)

Using DoDs, we resolve the complex sediment redistribution of deforming dunes to derive the sediment flux in an automated way (Lane et al., 2003; Nittrouer et al., 2008). The total flux is obtained by converting the volume of sediment redistribution from DoDs in the measurement section to a flux per unit length and width ($q_b$, in m$^2$/s), whilst excluding the porosity of 0.4 (−). It is known that chosen time intervals affect the flux for migrating dunes (Nittrouer et al., 2008), due to dune shape changes during migration. Sediment flux in general is underestimated. This observation is stronger for smaller dunes and superposed bedforms, as they typically migrate faster, whereas for larger dunes, the flux derivation performs well.

To determine the translation flux, every DEM is shifted with its mean migration and the shifted DEM is subtracted from the original DEM (Figure 3a), whereafter Equations 1 and 2 are applied. The mean translation of the dune bed was determined for each DEM from the lag distance of the maximum in the cross-correlation of the longitudinal transects. To quantify the effect of the time interval on the flux, the translation flux is being quantified through small shifts, covering equal fractions of the migration. The quantity of the (small) shift that we used was found by decreasing the shift until a further decrease did not affect the volume of sediment redistribution. Comparison showed that the flux differs 8% for FR05 and 25% for FR06 due to the used time interval. The net effect is converted into calibration factors of 1.08 and 1.39, respectively, which is an estimate of the missed fluxes, by selecting the topographic repeat interval. The calibration factor ($f$) is then multiplied with the sediment flux derived from the DEM of difference of two subsequent maps ($q_{b,DoD}$; Figure 3b) to obtain a corrected total
The corrected total flux and the translation flux ($q_{b,TF}$) are then used to derive the deformation flux ($q_{b,DF}$) as followed:

$$q_{b,DF} = q_{b,DoD} \ast f - q_{b,TF}.$$  (4)

Deformation is either a positive or a negative bed change (Figure 3c). When deformation is positive, the bed changed more than what would have been expected from translation only. When the deformation is negative, the bed change is less than what would have been expected from translation only. In the latter case, deformation is observed, yet not causing an actual flux as no sediment was transported. Merely, the deformation flux and translation flux in Equation 4 are conceptual fluxes. Occasionally we observed a complex sediment redistribution, involving the interplay between scouring and deposition processes, that cannot be calculated with DoDc-flux.

### 3. Results

#### 3.1. Dune Evolution and Interaction Processes

The 46 and 24 DEMs of migrating dunes obtained from experiments FR05 and FR06, respectively, are presented in Figures 4 and 5. All identified dunes are labeled with a number, and a subsequent letter is assigned for newly emerged dunes. The three-dimensional migrating dune topographies show the exceptional level of detail that is captured in submerged conditions without draining the flume. The dunes in FR06 migrate faster compared with FR05. The mean dune heights are 0.040 and 0.047 m for FR05 and FR06, respectively and the mean dune lengths are 1.02 and 1.06 m, respectively (Table 1). New dunes formed over dune stoss slopes and from crest-defect interactions (e.g., splitting, repulsion). For example, a superposed bedform emerges on the stoss slope of dune 2, with dune 2b forming, as dune crest 2 is destructed. Subsequently, dunes 2c and 2d form. In total, 13 dune crests were tracked, and 13 additional dunes emerged from the primary dunes in FR05.

The second experiment at higher flow velocity, FR06, tracks 14 dune crests and 11 emerging dunes from the primary dunes during the duration of the 24 DEM-captured migration. Tracking the highest point of each dune in subsequent DEMs shows that migration rates of individual dunes vary (Figure S6 in Supporting Information S1) and fluctuate around the mean migration rate for the recorded dune field (Table 1). FR05 shows for example, that dune 10 decelerates and dune 3 accelerates, and dunes 4–4b and 12 have periods of acceleration and of deceleration (Figure 4 and Figure S6 in Supporting Information S1). On the other hand, FR06 (Figure 5) shows less pronounced deceleration and acceleration when considering dunes 3 and 11–12, whilst dunes 10 and 7–7b are accelerating. Deceleration and acceleration of dune crest migration causes dune length variability, for example, deceleration of dune 10 in FR05 leads to dune shortening. The high-resolution and high-frequency DEMs are particularly suited for three-dimensional sediment flux derivation and classifying dune interaction processes, which would be otherwise difficult to classify.
3.2. Bed Slope, Water Surface Slope, and Dune Morphology

Dunes have complex shapes due to the presence of superposed bedforms (Best, 2005), variations in the profile of stoss and lee slopes (Lefebvre et al., 2016), and variations of crestline shapes (Terwisscha van Scheltinga et al., 2020). Temporal stacking of bed-elevation distributions shows that varying dune shapes have little effect on the bed height distribution of multiple dunes in non-varying flow (Figure 6a). The bed slope varies gradually for both experiments, whilst the water surface slope follows an opposing trend to the bed slopes (Figure 6b). The bed slope variation is relatively large, which is caused by the formation of long dunes or high crests, as well as by deep troughs and observed flow expansion.

The variation of dune shapes is presented in the supplemental material (see Figure S4 in Supporting Information S1) and shows that dune lee angles vary and increase with dune steepness. The lee faces are often steep (see DEMs). Avalanching of sediment along the lee face was commonly observed. This observation suggests that the majority of the dunes have leesides close to the angle-of-repose (high-angle dunes), and flow separation occurs (Best, 2005; Kwoll et al., 2017; Lefebvre, 2019). Long dunes typically have a shape parameter ($\beta$, see Equation S2.1 in Supporting Information S1) larger than 0.55.

3.3. Translation Flux and Total Flux

The mean migration for each pair of DEMs is presented in Figure 7a, comparing a width-averaged longitudinal profile and a profile at the center-line. Observed differences are small. The latter is based on three-dimensional information and is therefore used as the mean migration, similar to Venditti et al. (2016). Mean migration of the dunes is $2.89 \times 10^{-4}$ m/s for FR05 and $9.75 \times 10^{-4}$ m/s for FR06 and is the mean migration rate of all the dunes between subsequent DEMs and not the migration of each single dune. The temporal trend in the translation flux (Figure 7b) partly mimics the temporal variation in mean migration rate (Figure 7a), and is also caused by small differences in shape, spacing and size of the dunes between time steps. The mean translation fluxes are $8.9 \times 10^{-6}$ and $3.2 \times 10^{-5}$ m$^2$/s and the translation fluxes gradually vary through time for both experiments between $5.6 \times 10^{-6}$ – $1.4 \times 10^{-5}$ m$^2$/s and $2.6 \times 10^{-5}$ – $4.9 \times 10^{-5}$ m$^2$/s.

The total sediment flux is shown in Figure 7b. For each time step, the net deposition is obtained (also see Figure 3b). The total flux is 13% higher than the translation flux for FR05, whilst the fluxes are similar on average for FR06. The total flux of the two experiments shows temporal pulsing around the mean flux, as well as prolonged periods (>60 min) in which the flux is higher than the mean or lower than the mean. For FR06, the prolonged period appears shorter, notwithstanding the shorter period of measurements. Fluctuations are in the order of −40 to +50% from the mean for FR05, and −20 to +35% for FR06. The total flux decreases significantly during the existence of long and high dunes 9b–9f (FR05) and dunes 7b–7f (FR06) in the measurement section, at the same time relatively few dunes are present. The flux is highest when the dunes are more regularly spaced and a maximum number of eight (FR05) and ten (FR06) dunes exists in the flux measurement section (Figure 8b). The fluctuations in the flux are mimicked in the sum of dune heights, which in general tends to increase when there are more dunes, although there are exceptions (Figure 8b).
3.4. Shear Stress of Multiple Dunes

Sediment flux non-linearly depends on shear stress. If bed shear stress is obtained from the water surface slope, uniform flow is assumed, whereas in the presence of dunes, rapidly varying bathymetrically driven stress fields occur. In Figure 8, the total sediment flux of both experiments is compared with shear stress obtained from the water surface slope, as well as with total shear stress according to Equation 3. The fluxes have a stronger correlation with the shear stress when an advective acceleration term is included (Equation 3; Figure 8c). The positive cross-correlation between shear stress and the sediment flux indicates that a time lag exists (FR05, 30 min; FR06, 20 min). A lag between bed configuration and flow conditions has already been shown to exist for time varying flows (Allen, 1973b), and we now show that it exists for constant discharge as well. The difference in lag between
the experiments is consistent with the difference in dune migration rate: for a certain deformation to happen, dunes need time to adjust. The results do not allow analytical identification of the relationships between local flow and morphological adjustments, yet they allow hypothesizing that the lag could be linked to the dunes as following: (a) dunes self-organize, triggered by a change in the stress; (b) morphological adjustment is slower than the timescale needed to transport a sand grain; and (c) sediment flux depends on both, drag and stress, with the drag being directly related to the morphology, thus the drag being responsible for the observed lag. To note, the used flume is several meters longer than the measurement sections of the bed slope (8 m) and the water slope (7.5 m). This results in discrepancies between the actual slopes along the whole length of the flume and the measured slopes, affecting the time lag in Figure 8c.

An extreme in the bed slope emerges when a deep trough forms in front of a long dune, which occurs for dunes 9c–9f from 130 to 270 min in FR05 and dunes 7b, 7d, and 7f from 0 to 80 min in FR06. The coinciding mean bed slope is negative, and as flow expands over the deep trough, a steep water surface slope develops. This effect is strongest when the long dunes are present in the middle of the longitudinal section at 50 min (FR06) and 205 min (FR05). It is thus shown that sediment transport by dunes does not present a steady flux. A large part of the long-term flux variations can be explained by the variations in bed and water surface slopes, as well as the time-varying sizes and shapes of dunes, when accounting for time lag. It is thus possible, assuming the form roughness depends on the flow separation zone and turbulence dissipation in the wake (Figure 2b), that larger dunes disrupt the flow separation cells for simple dune shapes (with steep lees), and possibly even reduce overall transport. The total flux from DoDc underestimates the transport from defect migration that is typically observed over long dunes, and the presented data are thus not conclusive on whether to expect higher form roughness for more, smaller dunes, in contrast to fewer higher dunes.

3.5. Sediment Flux and Dune Morphology

In Figures 9 and 10 dune morphology (height, length, steepness, crest level, and trough level) and dune fluxes are related. Higher dunes are typically associated with higher fluxes, and for longer dunes the dune flux decreases. Therefore, the steeper the dune, the larger the flux. The degree of fit of the linear regression is poor as significant scatter is observed, that can be related to variable dune morphologies, such as high crest levels, deep troughs, and morphology of the upstream dune (presented with symbols). For FR05, upstream deep troughs decrease the flux, whereas upstream high crests increase the flux. For FR06, the influence of variable dune morphology is not pronounced, whilst there is significant scatter. The strongest deviation in dune fluxes coincide with occurrence
of interaction processes (see Figures S7 and S9 in Supporting Information S1) and we can generally observe that the temporal variation in the total flux of the individual dunes is higher compared with the total flux variation averaged over multiple dunes.

The degree of fit between dune flux and dune water surface slope is weak, with clustering of various morphologies. Flow expansion (low and negative slope) and acceleration (positive slope) are related to dune morphology, and high crests typically have steep local water slopes, suggesting flow acceleration over the dune stoss slope. Low crests show lower, negative water slopes, suggesting flow expansion, not acceleration. The spread is relatively high, as the water surface slope over a dune can be affected by the upstream crest or downstream trough. The water surface slope increases with an increase in dune length (for our conditions, increased flow acceleration is observed for dunes whose length increases up to 2 m). As the dunes lengthen further, the flow acceleration decreases, and steepness reduces.

3.6. Deformation Flux and Interaction Processes

The DF of FR06, when positive, is larger than the DF of FR05, as a higher total flux is observed in FR06 (Figure 11, Equation 4). Though, on average, the DF of FR06 is negligible causing fluctuations of approximately −15% to 15% on the total flux. For experiment FR05, deformation causes fluctuations of −15% to 50% on the total flux. Thus, dune deformation is more important for FR05 than for FR06 as a relative flux, but the absolute values have similar ranges. The standard deviation of the total flux of FR06 is smaller than the standard deviation
of the TF, whilst the opposite is the case for FR05. It indicates that deformation in FR06 mitigates some of the translation fluctuations, whilst deformation causes a stronger varying flux in FR05.

The DF is compared with the occurrence of interaction processes in FR05 and FR06 for example, merging (open circle) and splitting (star) in Figures 11b and 11d.

1. Splitting and defect creation cause the strongest peaks, and a combination of different interactions processes increases the DF further. For FR06, a peak in DF only occurs when multiple interaction processes co-occur (Figure 11d).
2. It is shown that merging precedes an increase in the sediment flux, but not necessarily coincides with a large DF, for both FR05 and FR06.
3. Calving occurred often during periods of low deformation, which suggests that calving does not have a substantial effect on the overall shape of the dunes.
4. One can summarize that the interaction processes correlate with trends in the DF. A difference between the effect of merging and that of splitting, defect creation, defect repulsion and calving is observed in the DF.
5. Interaction processes often coincide with other interaction processes, which increased the DF, but trends are not uniform.
6. By averaging over several dunes, a lower net effect is observed, with DF likely being higher.
4. Discussion

4.1. Dune Geometry in Relation to Sediment Flux

We compared the mean flux from DoDc of each dune with the dune migration flux obtained with dune tracking techniques. At low transport rates (FR05), the dune tracking flux is less than half of the total flux from DoDc (Figure S5 and Text S2 in Supporting Information S1). Correspondence improves when fluxes are higher (FR06), but considerable scatter remains. An estimation of transport based on dune migration is dependent on assumptions of the shape of the dunes, and better avoided in order to increase accuracy of transport rate estimates, in line with Aberle et al. (2012).

The number of dunes changed throughout both experiments (Figure 8), with dune interaction processes facilitating the change in dune numbers. In general, a large number of dunes were observed when regular dunes were present. For both experiments, we showed that high dunes have high transport rates, in line with general observations (Lin & Venditti, 2013; Yalin & Karahan, 1979). Strong flow acceleration is observed for high crests and over long dunes, but Figures 9 and 10 show that long dunes have lower transport rates in comparison with...
short steep dunes. The latter observation is counterintuitive in terms of form drag, as short dunes cause stronger form drag compared to long dunes (see Equation 3.38 in Van der Mark [2009]). Several brink points can be observed on top of primary dunes, caused by superposed bedforms (Lefebvre et al., 2016). The likeliness of brink points forming over the dune stoss increases when dunes lengthen, due to the increased presence of superposed bedforms. If the flow separates at a brink point upstream of the dune crest, the flow separation zone may be small, due to a relatively low height, but the energy loss and separation zone occur over the dune itself, reducing the dune sediment transport.

To describe the changing patterns in the individual dune fluxes, we found the behavior of the upstream primary dune(s) to be important. For our data, the downstream influence is most pronounced when a high crest level is present upstream of a dune, causing flow expansion downstream of the high crest, or in the presence of a deep trough. This observation aligns well with numerical simulations, which showed that the effect an upstream dune has on form drag depends on the ratio of bedform length to bedform height (Van der Mark, 2009). For increasing values of this ratio, the flow pattern over a bedform is less influenced by the flow pattern over the upstream bedform (Van der Mark, 2009). We recommend further research into the relation between a field of multiple dune
morphologies and sediment transport efficiency, and how superposed bedforms (that typically form over the long dunes) affect brink points, and whether these cause a low dune flux. The influence of three-dimensional dune shapes on transport rates is of further interest, especially considering that the flow eludes the highest part of the dune (Maddux et al., 2003), which potentially could lead to lower transport rates.

4.2. Feedbacks Between Dune Topography and Water Surface Slope

In the DEMs, the superposed bedforms are most prominent over dune 7 and dune 9 of FR05 and dune 4 and 6 of FR06 (Figures 4 and 5). Superposed bedforms on dunes with an extra-long crest-to-crest distance were also observed by Reesink et al. (2018), with the superposed bedforms migrating relatively fast. A high bed (see 1 in Figure 12a) suggests that more sediment is available for redistribution, whilst steep local water surface slopes (see 2) in Figure 12a) increase the potential energy available for sediment redistribution. The strong flow causes
faster migration of the dune relative to the downstream dune, and thus the dune lengthens further (3). If the primary upstream dune cannot provide enough sediment to “feed” the dune (4), nor keep up with the dune migration, the trough deepens (5) and local flow expansion over the deepening trough gradually increases (6). This process in turn decreases the water surface slope over the lower part of the long and high dune, whilst the latter further lengthens downstream (7). After some time, this typical triangular dune shape is no longer visible (8; quantified with high β in Figure S4 of Supporting Information S1) and the flow over the long stoss slope becomes similar to flow over a flat bed, over which superposed bedforms form.

As the interaction processes are of higher frequency than the measurement frequency, some process identifications such as the emergence of superposed bedforms on the stoss side of primary dunes (splitting), defect repulsion, merging, defect creation and calving are only of observational nature. We can see that newly formed superposed bedforms are initially small, with fast migration rates. In a timeframe of several DEMs, the superposed bedforms merged into larger and lesser superposed bedforms and thus created several small dunes (see 9) in Figure 12c). In FR05, dune 9 undergoes these changes for 2.5 hr, whilst in FR06 dune 7 undergoes these changes for 1.5 hr and eventually “stabilizes” into dunes 7d and 7g. This deformation also is observed at the end of experiment FR05. According to the feedbacks described, dunes with a high crest level are most likely to evolve into a long dune, with those dunes often having a strong local water surface slope over their leeside (Figures 10 and 11).

4.3. Interactions Driving Changes in Dune Deformation

Dunes that developed under both discharges show numerous interaction processes, with overall DF patterns being similar for both FR05 and FR06 (Figure 11), such as co-occurring dune interaction processes. Dunes that developed under high discharge (FR06), experienced increased DF in agreement with Venditti et al. (2016), and we find that net time-averaged transport from deformation is non-existent, as occasionally TF > total flux (and DF can be negative). Total flux is less than would be expected from the translation of the profiles over the time interval. With TF and DF both being dependent on the time interval (and thus the ratio DF/total flux and TF/total flux), the interpretation becomes more difficult. At the time interval of our measurements, using our methodology, we can accurately determine TF and a total flux, with TF and total flux varying significantly, more than the temporal variability of DF. Our results suggest lower ratios of DF/total flux (~15%) for both experiments, than found by Venditti et al. (2016) (~50%). The differences in the applied methods are as following: Venditti et al. (2016) calculate DF and TF for the centerline transects only, while in this work we calculate the fluxes for the entire dune field. We use a calibration factor to account for the “loss of information” from the time interval, whilst our time step is shorter. With varying dune migration, contributing fractions of total flux to either DF or TF continues to be challenging, even for the detailed data set we have presented.

5. Conclusions

We have mapped dune migration, dune deformation and dune interaction processes for two shallow water experiments. A new data set of high spatial and temporal resolution DEMs is presented, and dune bedload transport rates are calculated. We show how dune mapping benefits from going beyond conventional dune tracking of longitudinal transects. We found that sediment flux should be considered over multiple dunes, as compared with assessing changes in individual dunes, with superposed bedforms having a non-negligible effect. The existence of short dunes without excessive crest levels coincides with higher overall sediment transport. Steep dunes have high transport rates, yet sufficient scatter is observed that can be related to the morphology of the upstream troughs and crests, influencing flow acceleration and expansion over dunes. Flow acceleration is strongest over dunes with high crests and long dunes, yet long dunes have low transport rates when compared with short dunes.
Feedback between the bed morphology and local water surface slope causes (some) dunes with high crests to lengthen into long dunes (of about twice the mean dune length), until a breakup of this dune into short dunes occurs, typically facilitated by merging of superposed bedforms until the primary dune splits. Dunes with a high crest level are most prone to the described feedback, due to the increased water surface slope when compared with their neighboring dunes.

We show that limited performance of traditionally used bedform-bedload tracking techniques and differences in the applied methodology likely contribute to how dune sediment flux in a unidirectional current is observed to vary in relation to identified dune deformations and interactions. Our results suggest lower ratios of the deformation flux to the total flux than previously found and that interaction processes coincide with peaks in the deformation flux. Splitting, defect creation and defect repulsion increase the deformation flux, whilst merging is followed by a positive gradient in the total flux. Therefore, we have shown how dune interaction drives variations in the deformation flux. For dunes exposed to a fast flow, deformation mitigates some of the translation fluctuations, whilst at a low transport stage deformation causes a stronger varying flux.

Our analysis can be performed in field applications and requires frequent high-resolution bathymetric data. As we continue to unravel variability in dune morphodynamics, future work is required to translate experimental-scale findings into robust regional sediment flux estimates and thus into better estimation of morphological change at the scale of the natural environment.

Data Availability Statement

Data from the experiments are permanently archived at the University of Auckland figshare repository https://doi.org/10.17608/k6.auckland.13089794. The repository contains each DEM and the water surface elevation along the middle transect for each DEM.

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