

Interaction between lateral sorting in river bends and vertical sorting in dunes

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ABSTRACT

Sediment is sorted in river bends under the influence of gravity that pulls the heavier grains downslope and secondary flow that drags the finer grains upslope. Furthermore, when dunes are present, sediment is also sorted vertically at the dune lee side. However, sorting functions are poorly defined, since the relation to transverse bed slope and the interaction between lateral and vertical sorting is not yet understood for lack of data under controlled conditions. The objective of this study is to describe lateral sorting as a function of transverse bed slope and to gain an understanding of the interaction between lateral and vertical sorting in river bends. To this end, experiments were conducted with a poorly sorted sediment mixture in a rotating annular flume in which secondary flow intensity can be controlled separately from the main flow velocity, and therefore transverse bed slope towards the inner bend and dune dimensions can be systematically varied. Sediment samples were taken along cross-sections at the surface of dune troughs and dune crests, and over the entire depth at the location of dune crests (bulk samples), which enabled comparison of the relative contribution of vertical sorting by dunes to lateral sorting by the transverse bed slope. The data show that lateral sorting is always the dominant sorting mechanism in bends, and bulk samples showed minor effects of vertical sorting by dunes as long as all grain-size fractions are mobile. An empirical bend sorting model was fitted that redistributes the available sediment fractions over the cross-section as a function of transverse bed slope. Comparison with field data showed that the model accurately reproduces spatially-averaged trends in sorting at the bend apex in single-thread channels. The bend sorting model therefore provides a better definition of bend sorting with conservation of mass by size fraction and adds to current understanding of bend sorting. The implication for numerical modelling is that bend sorting mechanisms can be modelled independently of dunes, allowing the application of the active layer concept.

Keywords Bend sorting, dunes, experiments, modelling, transverse slope.

INTRODUCTION

Sediment sorting patterns in curved river channels arise from grain-size dependent interactions between sediment transport processes and local secondary flow patterns. The cross-sectional

morphology of river bends near the bend apex results from the interaction between helical flow that is directed inward near the bed and drags sediment upslope on the point bar, which is balanced by the transverse bed slope effect deflecting grains downslope towards the outer bend

under the influence of gravity (e.g. Engelund, 1974; Struiksma *et al.*, 1985). Here, the imbalance between flow drag, depending on particle surface area, and gravity, depending on particle volume and density, leads to size-sorting. These sorting patterns are important for a range of processes. For example, grain-size differences influence the flow by determining the distribution of friction, the sediment transport rate and maximum scour depth through mobility, and the morphology by determining the distribution of sediment over bifurcations when lateral slopes are present upstream of a bifurcation (Mosselman *et al.*, 1999; Kleinhans, 2001; Frings, 2008). While quite relevant for river bends with shipping fairways and in river bifurcations with a bend just upstream (Frings, 2008), most current morphodynamic models do not include physics-based relations for sediment sorting.

Sediment is actively sorted during transport, both laterally and vertically. Lateral sorting results from differences in interaction between gravity and shear stress exerted by the bend flow on different grain sizes. During transport, shear stress exerts drag as a function of the exposed surface area of particles, while gravity acts on particle weight as a function of volume and density. Therefore, larger grain sizes are subject to a relatively larger pull of gravity than of flow shear, while finer particles are more easily dragged along by the flow (Ikeda, 1989). Finer particles are gradually dragged higher up the point bar, given an upslope-directed flow component forced by channel curvature, while coarser grains are pulled further down by gravity and are deposited near the outer bend (e.g. Parker & Andrews, 1985; Bridge, 2003). This is the same sorting pattern as observed in inclined heterolithic strata (IHS) in meander channel belt deposits (Thomas *et al.*, 1987). Active vertical sorting is the result of dunes that mix the sediment vertically, by grain-size dependent sediment transport processes at the lee side (Kleinhans, 2001; Blom & Parker, 2004). There are three main active lee side sorting mechanisms according to Reesink & Bridge (2007): sorting by grain-size selective deposition of particles that are transported over the lee side, by movement of sediment in the flow-separation zone behind the bedform crest, and by presorting of sediment that is supplied to the lee side, for example, by superimposed bedforms. Grain-size selective deposition causes coarser particles to be deposited further downslope the lee side, which results in upward fining and possibly in

the formation of coarse bed layers beneath dunes when not all fractions are mobile (Kleinhans *et al.*, 2007; Frings, 2008). Both lateral and vertical sorting becomes more pronounced when the standard deviation of the sediment mixture is larger (Parker & Andrews, 1985; Blom & Parker, 2004; Kleinhans, 2005).

However, the relative importance between lateral sorting and vertical sorting is unknown, while their interaction and characteristic time-scales determine both the degree of sorting and the degree of morphological change. It is expected that larger bedforms at higher flow velocities have a relatively greater influence on bend sorting. In natural rivers, dune height scales with water depth and typically ranges between one-twentieth and one-third of the water depth (Yalin, 1964; Allen, 1984; Paola & Borgman, 1991). Additionally, large bedforms possibly enhance secondary flow patterns through their troughs (Dietrich & Smith, 1984; Kisting-Moller, 1993), which would influence the lateral sediment distribution.

Separately, several analytical and empirical relationships exist to describe lateral bend sorting and vertical lee side sorting. Blom & Parker (2004) developed an analytical model for vertical sorting at the dune lee side by grain-size selective deposition. This model redistributes the available volume of a sediment fraction that is transported over the dune crest over the lee side of that dune, as a function of sediment mobility. As a result, the model describes vertical sorting by bedforms with conservation of mass by size fraction, which is a critical requirement for application in numerical modelling. For lateral sorting there is not yet a model based on size fractions. Existing analytical solutions for lateral sorting focus on forces on individual sediment particles for active sorting during transport (Bridge & Jarvis, 1982; Parker & Andrews, 1985; Ikeda, 1989) or on differences in critical shear stress of individual grains (Odgaard, 1981). However, these equations were never directly incorporated in morphodynamic models. Ikeda *et al.* (1987) and Yen & Lee (1995) conducted a few experiments with a coarsely skewed mixture and developed an empirical relation that describes the change in median grain size over a cross-section along the bend radius, instead of considering grain-size fractions separately. However, these experiments were conducted in a flume with a fixed curvature, and therefore the effect of changing transverse bed slope was not directly quantified.

Furthermore, both of these experiments ignored the effect of bedforms and suffered from hiding exposure effects due to the large skewness of the sediment mixture. Moreover, these relations describe the effect of transverse bed slopes on sediment sorting, but it is unknown how sorting influences the magnitude of the slope itself. In conclusion, these analytical and empirical relations for lateral sorting are not yet suitable to be included in morphodynamic models.

Both lateral and vertical sorting and their interaction are poorly constrained in morphodynamic models. Spatial sorting on the large scale is approached with the active layer concept (Parker *et al.*, 2000; Blom *et al.*, 2008), which divides the bed into one active layer and immobile underlayers. The active top layer interacts with the flow and determines the amount of sediment transport, and there is only an exchange of sediment between the underlayers and the active layer in case of erosion or deposition. Therefore, the active layer determines the volume of each fraction that is available for sediment transport and, consequently, lateral sorting. As a result, spatial sorting and bed level changes are extremely sensitive to the user-defined thickness of this active layer, which sets the timescale of changes in bed composition. When the layer is relatively thin, sorting reacts fast to changes in the flow and will result in better developed sorting patterns. On the other hand, a relatively thick active layer results in slower adjustments, and therefore sediment sorting acts on the same timescale as morphological development (Sloff & Mosselman, 2007; Kleinhans, 2010).

Lateral sorting depends on the sediment that is available in the top layer of morphodynamic models, and is incorporated in the transverse bed slope predictor. This predictor adjusts the direction of sediment transport of specific grain sizes based on the bed slope. However, sediment deflection on slopes in general is poorly defined in morphodynamic models (e.g. van der Wegen & Roelvink, 2012; Schuurman *et al.*, 2013; Baar *et al.*, 2018) and grain sorting due to lateral gradients is even more simplified. Vertical sorting by dunes is not included in the active layer concept. However, the thickness of the layer is often based on characteristic bedform height to simulate sorting processes on a timescale of multiple dunes migrating over the river reach (e.g. Ribberink, 1987; Armanini & Di Silvio, 1988; Sloff & Mosselman, 2007). Therefore, to be able to accurately model average lateral sorting, it is

necessary to know the relative importance of vertical sorting on lateral sorting on the time-scale that is modelled.

The objective of this study is to develop a model for lateral sorting in river bends based on size fractions, comparable to the relation of Blom & Parker (2004) for lee side sorting, and to determine the relative importance of vertical sorting by dunes on this relation. To this end, experiments were conducted with poorly sorted sediment in a rotating annular flume, in which the transverse bed slope and dune dimensions can be systematically varied (Baar *et al.*, 2018). As a result, bend sorting is described as an empirical function of grain-size fractions and magnitude of the transverse bed slope. Additionally, the feedback of sediment sorting on the transverse bed slope is analyzed, by comparing transverse bed slopes to experimental results with uniform sediment in the same flume. Finally, the resulting bend sorting model is compared with published field data.

METHODS

Experimental set-up and data collection

Experiments were conducted in a rotating annular flume (Fig 1A), which allows control of secondary flow intensity separately from the main flow velocity (Booij, 2003; Baar *et al.*, 2018). Both the lid and the floor of the flume can rotate separately over a continuous range of rotation velocities in both directions. Rotation of the lid of the flume drives the streamwise flow by applying shear on top of the water column, and drives the secondary flow by generating an outward directed centrifugal force. This centrifugal force causes a pressure difference between the inner and outer bend, which results in an inward directed bed shear stress near the bed, similar to the flow field observed in natural river bends. Rotation of the floor and attached side-walls of the flume adds an additional outward directed centrifugal force near the bed, resulting in a decrease of the pressure difference and thereby a decrease in secondary flow intensity. By varying the rotation velocities of the lid and the floor of the flume, and the ratio between them, the streamwise and normal flow velocity can be isolated and controlled (Fig 1A). As a result, different bend radii can be simulated from straight river reaches to very sharp bends, and as a result the transverse bed slope that

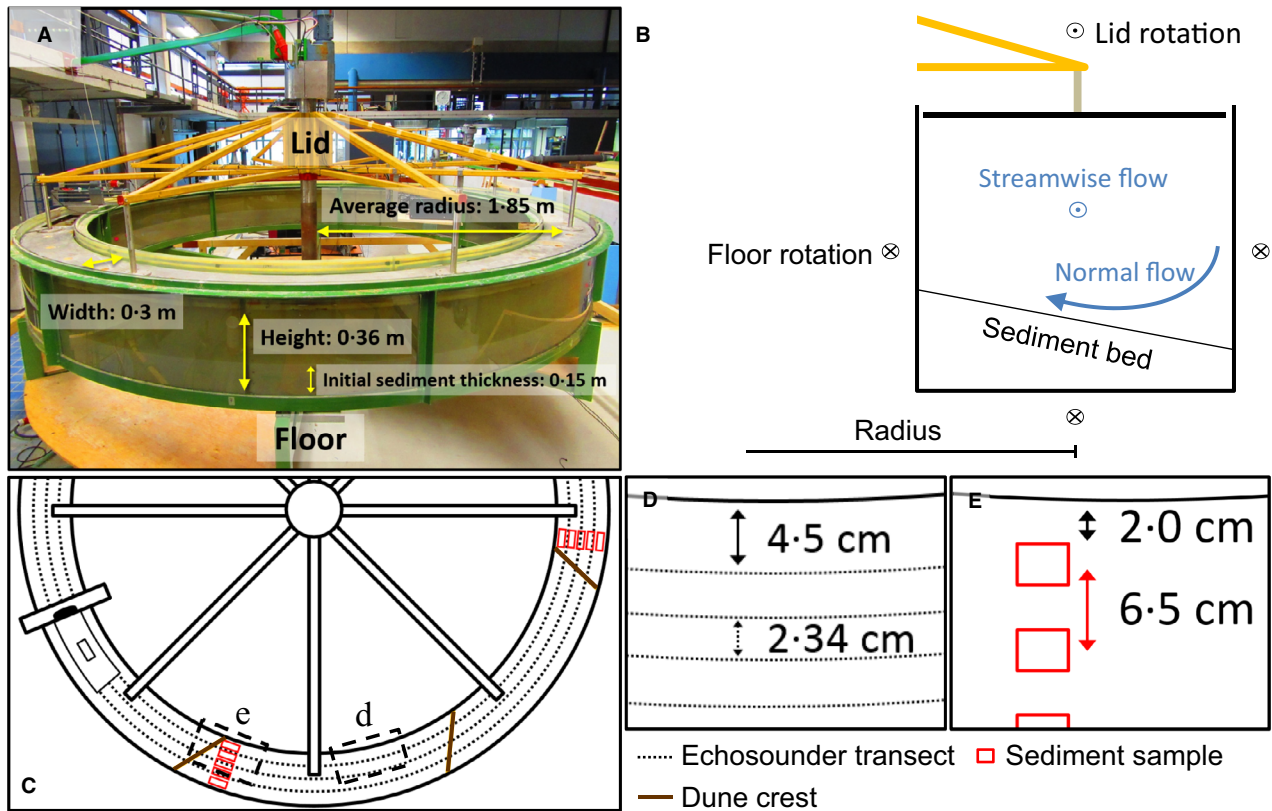


Fig. 1. Experimental setup. (A) The dimensions of the rotating annular flume. The lid rotates independently from the floor and attached side walls. (B) Schematic drawing of the flow vectors and rotation directions. The floor and attached side walls rotate in the opposite direction of the lid, which allows control of the centrifugal forces in the flume and thereby the magnitude of the normal flow velocity. (C) Schematic top view of the measurement set up, with transects of the echo sounder, which measured bed elevation in still water, and the sampling locations of the bulk samples and surface samples on top of the dune crest. (D) Ten echo sounder transects were measured, each 2.33 cm apart in a transverse direction, starting at 4.5 cm from the walls. (E) Five sediment samples were taken along a cross-section, with their centres 6.5 cm apart, starting at 2 cm from the wall. Four times five (4×5) samples were taken both at the surface of a dune crest and at the surface of a dune trough, and five samples over the entire height of the dune (bulk samples). This resulted in a total of 45 samples per experiment.

develops towards the inner bend can be controlled. Baar *et al.* (2018) derived an analytical model based on flow velocity measurements describing near-bed streamwise and normal flow velocity as a function of lid and floor rotation and flume dimensions. Furthermore, these authors describe the relation between secondary flow intensity, i.e. the ratio between streamwise and normal flow velocity, and the transverse bed slope that develops.

Since the objective of this study is to determine the relative influence of transverse bed slope and dune dimensions on bend sorting, a series of 22 experiments was conducted with slopes varying between 0 m and 0.38 m m^{-1} , and sediment mobility varying between $\theta = 0.025$ and 0.63, which determines the dune

dimensions (van Rijn, 1984). Here, sediment mobility, i.e. the non-dimensional shear stress, is defined as:

$$\theta = \frac{\tau}{(\rho_s - \rho)gD_{50}} \quad (1)$$

where τ = shear stress [N m^{-2}], ρ_s = specific density of the sediment, g = gravitational acceleration [m s^{-2}] and D_{50} = median grain size [m]. Both sediment mobility and transverse bed slope were varied by systematically changing the ratio of lid and flume rotation, which determines the magnitude of streamwise and transverse bed slope. These ratios were based on the results of Baar *et al.* (2018). The sediment mixture was

chosen such that dunes dominated and ripples were rare, and that all sediment fractions were mobile over a wide range of average mobilities, to avoid selective transport, hiding exposure effects and bed armouring. This resulted in a sediment mixture with a median grain size of 0.78 mm and a standard deviation of 0.73 mm.

Experiments started with a flat and a well-mixed sediment bed, and with a water depth of 0.21 m, and were run until both the transverse bed slope and the bedform dimensions were in equilibrium with the flow conditions. It was assumed that this equilibrium was reached when transverse bed slope, bedform length and height were stable over time. Generally, an experiment ran for two to three days. After the experiment ended, the equilibrium morphology was registered by an echo sounder in still water over ten transects in a streamwise direction (Fig. 1C and D). The bed levels along each transect were reduced to a median bed level, and the average transverse bed slope was obtained by fitting a linear trend through these values. To determine whether sediment sorting also influences the average transverse bed slope compared to bends with uniform sediment, the average transverse bed slopes were compared to experiments with a uniform grain size of 1 mm in the same flume (Baar *et al.*, 2018). In order to compare equilibrium transverse bed slopes, the average transverse bed slope (dz/dy) of each experiment was divided by the characteristic secondary flow intensity (u_n/u_s) and plotted against relative sediment mobility (θ/θ_c). This ratio represents the transverse bed slope effect (B):

$$\frac{\partial z_b}{\partial y} = B \frac{u_n}{u_s} \quad (2)$$

After slowly draining the water, the bed of 13 of the 22 experiments was sampled based on the magnitude of the transverse slope and dune dimensions. Samples were taken at the surface of four dune troughs and dune crests, and over the entire depth at the location of dune crests (Fig. 1C), which enabled comparison of the relative contribution of dunes to observed bend sorting. At each location, five samples were taken over the cross-section, with the centre of the samples 6.5 cm apart (Fig. 1E). As a result, for each experiment there were four samples that were taken at the same relative location over a cross-section and along a dune. These samples were combined into one sample, to get an

average value per experiment. Additionally, in two experiments, vertical lee side sorting was quantified by sampling each centimetre over the dune height. The grain-size distribution of each sediment sample was determined by sieving in 15 size fractions between 0.16 mm and 3.96 mm. The volume of each sediment fraction was used as input for the bend sorting model.

Development of the bend sorting model

The bend sorting model described in this study is consistent with the dune lee face sorting model of Blom & Parker (2004). The sorting function herein for lateral sorting redistributes the available volume of a sediment fraction over the cross-section as a function of transverse bed slope. This sorting model will be calibrated with the bulk samples of the experiments that were taken over the entire depth of the dune (bulk samples). Therefore, this relation will describe an average bend sorting pattern over a longer time period, i.e. longer than the migration of a few dunes. Then, the resulting bend sorting model is compared with the surface samples at the dune troughs and crests, which show the local bend sorting pattern. If there is a large deviation between the bulk and surface samples, for example, local bend sorting patterns at the surface are much more pronounced than in the bulk samples, this means that vertical mixing by dunes is significant and needs to be included in the bend sorting model.

The bend sorting model predicts the volume (F) of a specific sediment fraction (i) at a certain location (R) along a transverse bed slope (dz/dy), relative to a reference volume ($F_{i,\text{ref}}$). It is assumed that the logarithm of the relative fraction increases or decreases linearly over the cross-section:

$$\log\left(\frac{F_i}{F_{i,\text{ref}}}\right) = \delta_i R_{\text{rel}} + \gamma_i \quad (3)$$

A schematic representation of the model is visible in Fig. 2. The reference volume depicts the volume of a sediment fraction that would theoretically be present at each location if the sediment was well-mixed over the cross-section. This volume is therefore defined as the sum of the volume fractions over the cross-section, divided by the number of samples (N) along that cross-section:

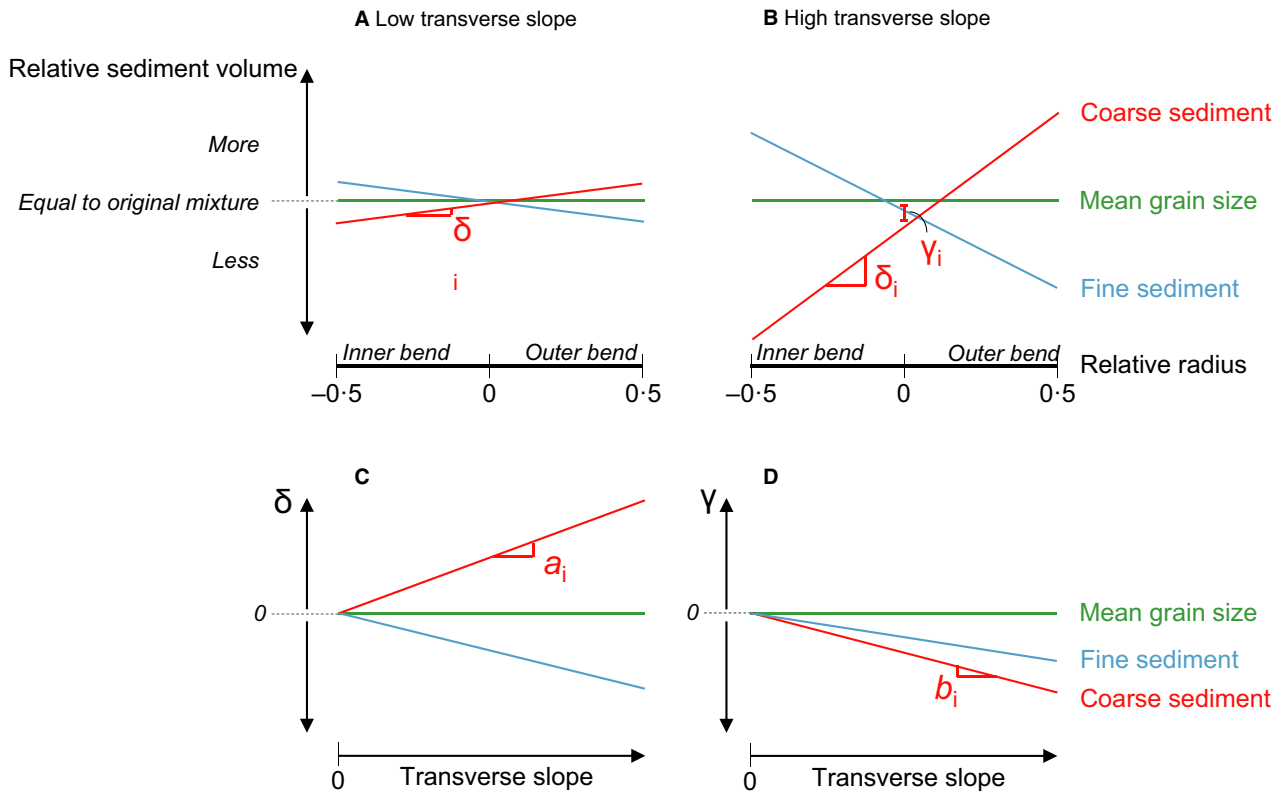


Fig. 2. Schematic representation of the bend sorting model (Eq. 2). (A) Theoretical change in relative volume over the cross-section of fractions that are coarser and finer than the median grain size. The volume of coarser sediment increases towards the outer bend due to the pull of gravity, while finer sediment will be transported towards the inner bend by the secondary flow: δ and γ represent the parameters in Eq. 2. (B) An increase in transverse bed slope will cause more pronounced sorting and therefore a larger change in volume of the fractions (δ) over the cross-section, and a larger offset at the channel centreline (γ). The relation of the parameters δ and γ with transverse bed slope is visible in (C) and (D) (Eqs 6 and 7).

$$F_{i,\text{ref}} = \frac{\sum_R^N F_i}{N} \quad (4)$$

R_{rel} is the relative location along the cross-section, which is used to make the location non-dimensional and relative to the centre of the cross-section:

$$R_{\text{rel}} = \frac{R - R_{\text{mean}}}{W} \quad (5)$$

where R_{mean} is the radius at the centreline of the channel, and W is the width of the cross-section. The width should be measured from the lowest point at the outer bend to the water line at the inner bend, since it is assumed that all sediment fractions present along the cross-section are mobile and available for sorting. Since the location is relative to the centre of the flume, this means that when sediment is perfectly linearly

sorted over the cross-section of the flume, the volume of a sediment fraction at the centreline is equal to the initial sediment mixture.

The parameter δ_i in Eq. 3 determines the change in relative volume over the cross-section, while γ_i denotes the relative volume at the centreline (Fig. 2A and B). These parameters depend on slope and grain size, since coarser fractions will be deposited downslope, resulting in an increase in relative volume towards the outer bend and thus a positive δ_i , while finer fractions are mainly deposited at the inner bend and therefore will have a negative δ_i . A larger slope is expected to result in a larger change in volume of a certain fraction over the cross-section, which results in a larger absolute magnitude of δ_i (Fig. 2C). When γ_i is zero, the volume of a sediment fraction at the centreline is equal to the initial sediment mixture and the sorting is perfectly linear over the cross-section. However,

when sorting is more distinct, the offset at the channel centreline is higher and γ_i will be lower than 0. This offset will therefore also depend on grain-size fraction and transverse bed slope (Fig. 2D). A constraint for the model is that when the transverse bed slope is equal to zero, i.e. in a straight river section, fractions are equally distributed over the cross-section, and thus δ_i and γ_i are equal to zero.

The resulting definitions are as follows:

$$\delta_i = a_i \frac{\partial z}{\partial y} \quad (6)$$

$$\gamma_i = b_i \frac{\partial z}{\partial y} \quad (7)$$

where:

$$a_i = c_1 \frac{\psi_{i,\text{rel}}}{\sigma} \quad (8)$$

$$b_i = c_2 \left(\frac{\psi_{i,\text{rel}}}{\sigma} \right)^2 \quad (9)$$

where σ is the standard deviation of the initial mixture, defined as:

$$\sigma = \sqrt{\sum_i^n \Psi_{i,\text{rel}}^2 F_{i,\text{ref}}} \quad (10)$$

$\Psi_{i,\text{rel}}$ is the relative grain size in the Ψ scale, defined as:

$$\psi_{i,\text{rel}} = \psi_i - \psi_{\text{mean}} \quad (11)$$

which relates to grain size as follows:

$$\psi_{i,\text{rel}} = {}^2 \log \frac{D_i}{D_{\text{mean}}} \quad (12)$$

where D = grain size in millimetres. In this study, the mean grain size is determined by:

$$\psi_{\text{mean}} = \sum_i^n \psi_i F_{i,\text{ref}} \quad (13)$$

where n = the number of sediment fractions. The relative grain size is divided by the

standard deviation to be able to use the sorting function for different sediment mixtures. The Ψ scale is used so that sediment fractions that are finer than the median grain size are negative, and coarser sediment fractions are positive.

The resulting equation for relative volume per sediment fraction at a location along the cross-section then reads:

$$\frac{F_i}{F_{i,\text{ref}} \sum_i^n F_i} = \exp \left[\left(c_1 \frac{\phi_{i,\text{rel}}}{\sigma} R_{\text{rel}} - c_2 \left(\frac{\phi_{i,\text{rel}}}{\sigma} \right)^2 \right) \frac{dz}{dy} \right] \quad (14)$$

where the parameters c_1 and c_2 are constants that determine the change in volume fraction over the cross-section and offset at the channel centreline, which will be determined with the experimental data. The relative volume of each grain-size fraction is divided by the total volume of all fractions, to make sure that the sum of all fractions is 1.

Field data

To study natural deviations in the sorting patterns compared to the experimental data, the model is tested against scarce field data that is available in literature. Grain-size distributions from three previous studies are used, with different median grain sizes, channel dimensions, and transverse bed slopes (Table 1).

Firstly, Bridge & Jarvis (1976) studied the flow and sedimentation in the small meandering river South Esk (UK) during a discharge peak, from bankfull conditions to low water. These authors sampled along several cross-sections along the bend, but here the focus is on the cross-section at the bend apex, to minimize possible effects of flow adaptation on sediment transport processes. Here, the transverse bed slope was 0.1 m m^{-1} . During high water dunes were

Table 1. Characteristics of field sites and measured sediment distributions found in literature.

	D_{50} [mm]	σ [mm]	W [m]	$\partial z/\partial y$ [m m ⁻¹]
South Esk	1.36	2.89	7.5	0.100
Severn	63.40	1.88	10.0	0.050
Rhine	2.25	3.67	280.0	0.010
Pannerdensch	3.67	3.54	70.0	0.035
Kanaal				

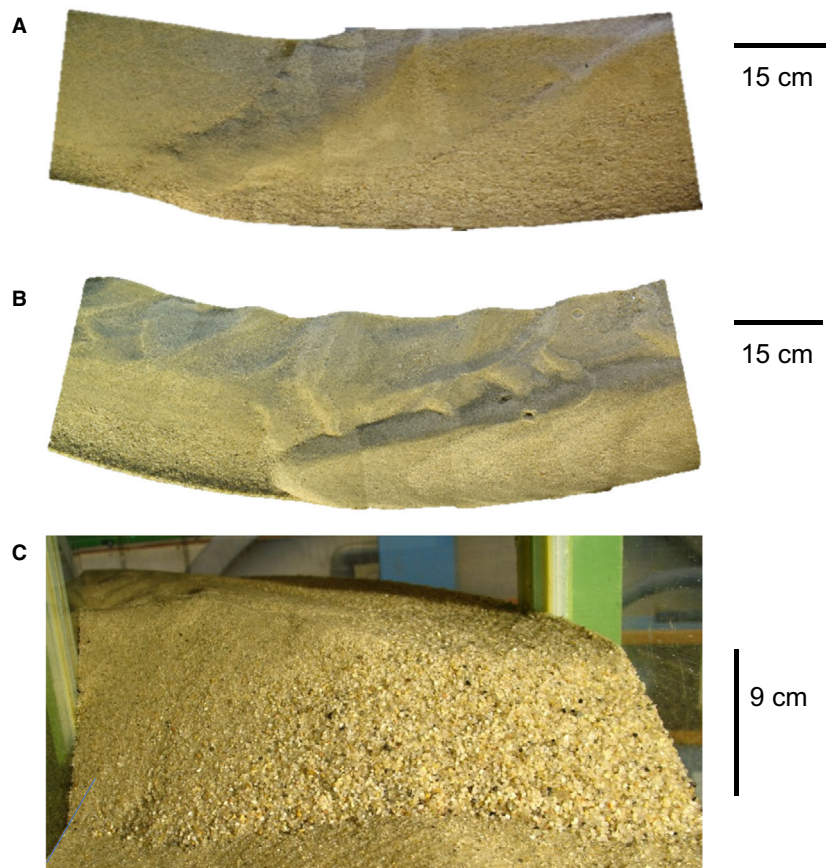


Fig. 3. Examples of equilibrium morphology and sorting patterns of experiments visible on photomosaics with: (A) high transverse bed slope; and (B) low transverse bed slope in combination with low sediment mobility. The flow direction in (A) and (B) is towards the left. (C) Frontal view on a dune crest and slipface, where coarse sediment is located in the outer bend (right) and fine sediment in the inner bend (left).

present over the entire cross-section, while during falling discharge these dunes disappeared and ripples started to form near the inner bend and expanded towards the pool at the outer bend.

Secondly, data from a gently curved reach with a transverse bed slope of 0.06 m m^{-1} in the gravel bed river Severn (UK), as described by Hey (1991), is used to test the bend sorting model with larger grain sizes (Table 1). These authors sampled the bed load transport four times during two months, to study the shear stress distribution over the cross-section with varying discharge. On one occasion, all fractions were mobile over almost the entire cross-section, in contrast to the other three measurement campaigns when only the silt to fine gravel fractions were in transport, and only at the centre of the channel. The bend sorting model is compared to all measurement campaigns.

Thirdly, the model was tested on data from the lower Rhine river (NL), a gravel–sand bed river with protected banks. Data was collected at a meander bend located upstream the bifurcation of the Rhine river into the Waal river and the Pannerdensch Kanaal (NL). This data was obtained by Guijters *et al.* (2001), who took samples along a total of 15 cross-sections in all three rivers (also see Kleinhans, 2001). For this study the grain-size data is used for the first 40 cm of the bed, along the cross-section just upstream of the bifurcation and along the first cross-section of the Pannerdensch Kanaal just after the bifurcation. This case is extremely relevant for morphodynamic modelling, since this bend upstream of the bifurcation determines the sediment size distribution over the bifurcates. The Waal river is located at the inner bend and therefore receives a larger volume of the finer fractions, while the Pannerdensch Kanaal is

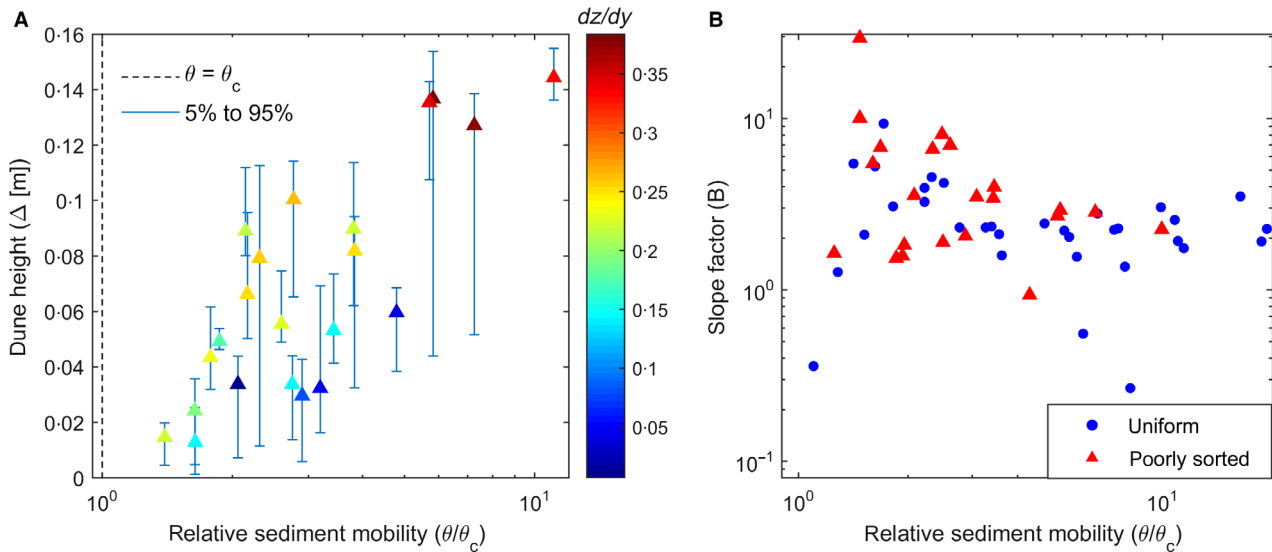


Fig. 4. (A) Average dune height (Δ) of all experiments against relative sediment mobility (θ/θ_c), including the variation in dune height in each experiment. Colour scale indicates average transverse bed slope (dz/dy). (B) Slope factor B (average transverse bed slope divided by the average secondary flow intensity) against relative sediment mobility, for the experiments in this study with a sediment mixture and experiments with uniform sediment with comparable grain size from Baar *et al.* (2018).

located at the outer bend and receives a larger volume of the coarser sediment. However, the bend radius of the upstream bend is relatively large, and therefore transverse bed slopes are relatively low. The transect in the Rhine has a transverse bed slope of 0.01 m m^{-1} , while the transect just downstream of the bifurcation has a slope of 0.035 m m^{-1} .

RESULTS

Observations in the experiments

After the start of experiments, the outer bend eroded and this eroded sediment was transported by sediment lobes towards the inner bend under the influence of secondary flow. These lobes of sediment extended laterally as they moved towards the inner bend and thereby gradually transformed into dunes. Experiments were run until the dune dimensions were in equilibrium with the flow conditions, which was reached faster in experiments with relatively high sediment mobility. For experiments with low sediment mobility and relatively weak secondary flow, dunes did not expand over the entire cross-section, and instead ripples formed near the inner bend, where sediment mobility was below the ripple-dune transition (Fig. 3B).

Dune height increased with increasing sediment mobility, displaying a smaller increase with transverse bed slopes lower than about 0.1 mm^{-1} (Fig. 4A).

While these bedforms were forming, a transverse bed slope developed towards the inner bend, and sorting became more pronounced. Mainly finer sediment was transported in the lobes of sediment over the dune towards the inner bend by the secondary flow (Fig. 3A). Relatively coarse sediment rolled downslope under the influence of gravity, and the coarsest fractions remained in the dune troughs. At the end of most experiments a clear sorting pattern could be observed with fine sediments in the inner bend and coarse sediment at the outer bend (Fig. 3B). Average transverse bed slopes showed the same trend with increasing sediment mobility as uniform sediment experiments (Fig. 4B).

These sorting patterns caused by transverse bed slopes and dunes were quantified by the sieve data. The bulk samples taken over the entire depth of the dune show that median grain size is about equal to or slightly lower than the original mixture at the channel centreline, and increases rapidly towards the outer bend for transverse bed slopes larger than 0.15 m m^{-1} , while for lower transverse bed slopes this increase seems more gradual (Fig. 5A). A more

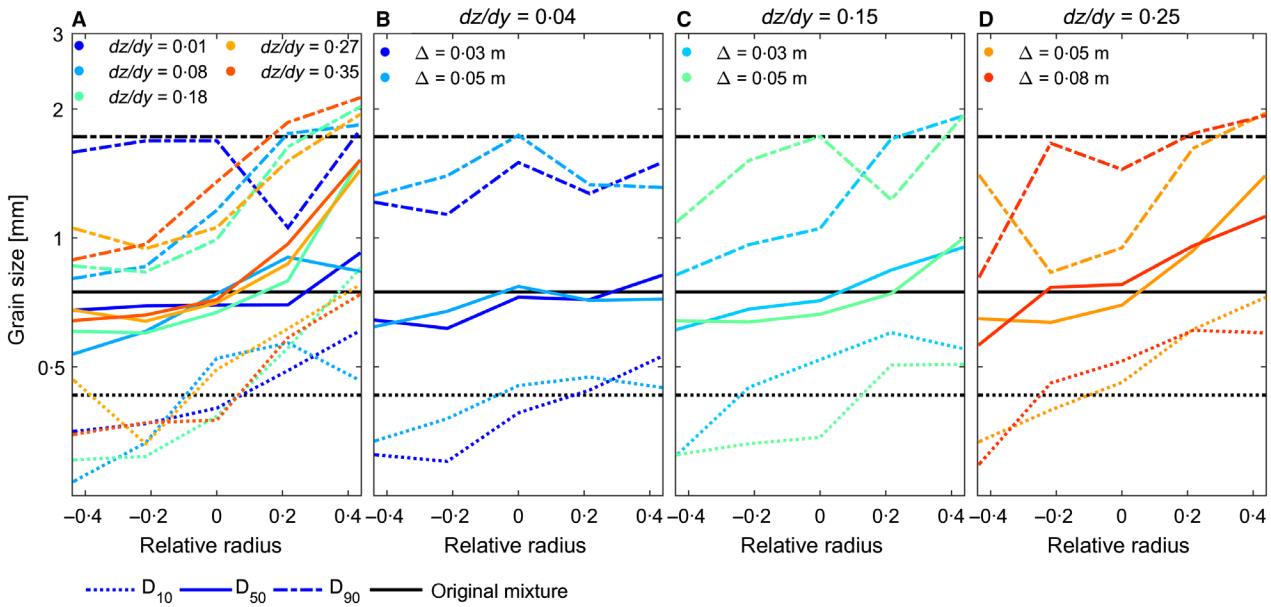


Fig. 5. Bulk sediment distribution of D_{10} , D_{50} , D_{90} , over the entire cross-section of the flume for bulk samples in experiments with varying transverse bed slope (dz/dy) and dune height (Δ). Black lines indicate values from the original mixture at the beginning of the experiment. Radius is relative to the centre of the flume (0).

gradual decrease in median grain size is observed towards the inner bend, and this is less dependent on average transverse bed slope. Comparing experiments with different bedform height but equal transverse bed slopes showed no significant effect of dune height on the

sorting patterns, since the trend in median grain size does not differ significantly (Fig. 5B to D). However, dunes mainly affected both the D_{10} and D_{90} , which showed a larger variation over the cross-section with varying bedform heights. Nevertheless, lateral sorting by slope effects is

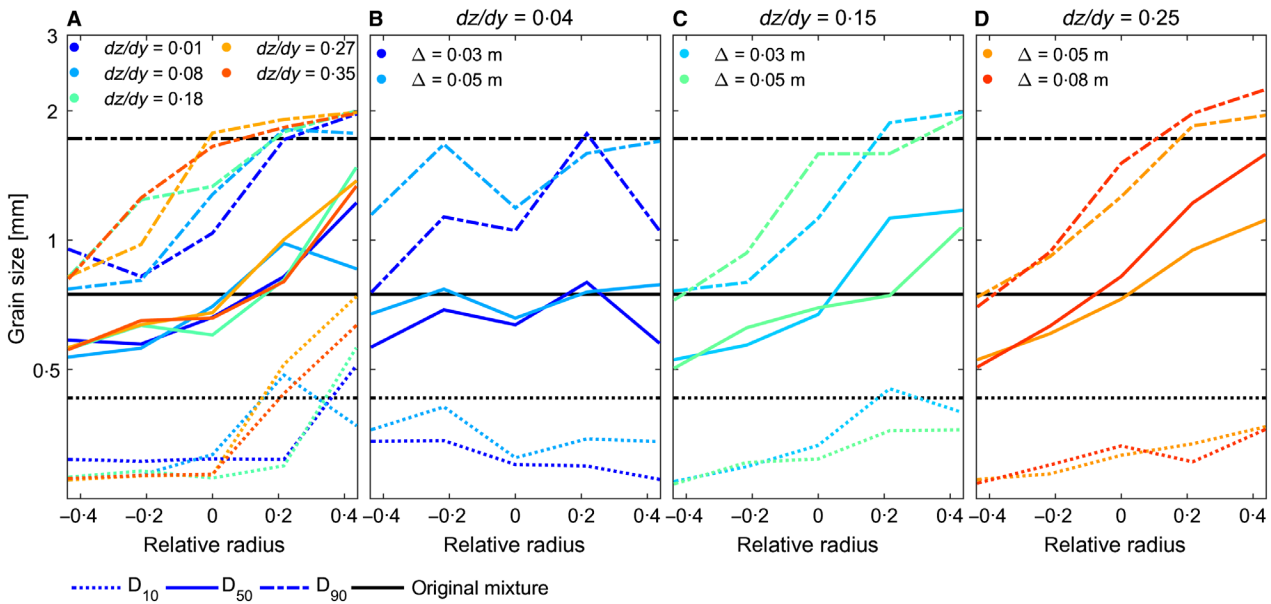


Fig. 6. Dune trough distribution of D_{10} , D_{50} , D_{90} , over the cross-section of the flume for surface samples in dune troughs in experiments with varying transverse bed slope (dz/dy) and dune height (Δ). Black lines indicate values from the original mixture at the beginning of the experiment. Radius is relative to the centre of the flume (0).

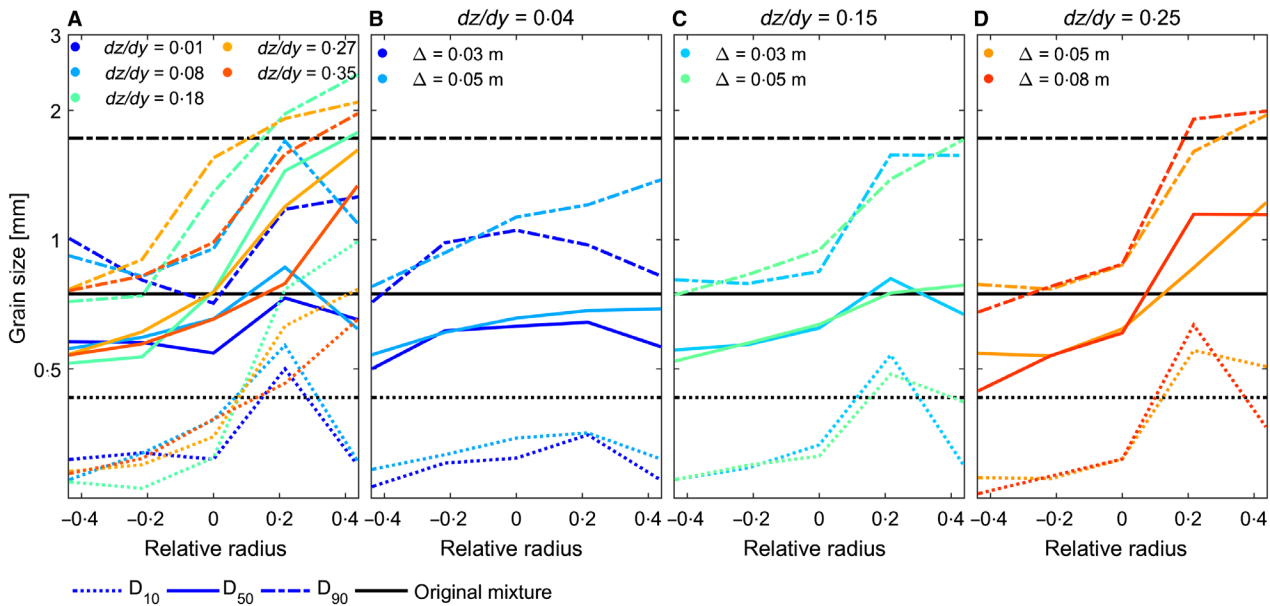


Fig. 7. Dune crest distribution of D_{10} , D_{50} , D_{90} , over the cross-section of the flume for surface samples at dune crests in experiments with varying transverse bed slope (dz/dy) and dune height (Δ). Black lines indicate values from the original mixture at the beginning of the experiment. Radius is relative to the centre of the flume (0).

clearly the dominant mechanism, as the general trend related to the transverse bed slope is always visible.

Surface samples in dune troughs and on dune crests show in general the same trend in sorting with increasing transverse bed slope (Figs 6 and 7). However, samples in dune troughs show the same sharp increase in median grain size towards the outer bend for all transverse bed slope magnitudes, and also the trend in D_{10} and D_{90} shows a more distinct sorting for low transverse bed slopes than in the bulk samples. Furthermore, for both trough and crest samples, sorting is even less dependent on dune height with increasing transverse bed slope, since also the D_{10} and D_{90} show the same trend for experiments with the same transverse bed slopes but different dune height.

The variation in D_{10} and D_{90} between experiments is caused by small deviations in the most fine and coarse fractions that alter the trend in percentiles over the cross-section, and also the sharp increase in median grain size towards the outer bend is the result of a couple of coarse grains that are more likely to end up in the outer bend. This shows that the only way to describe and predict bend sorting is by using grain-size fractions instead of percentiles.

The degree of vertical sorting was quantified by comparing the volume change of grain-size

fractions over the height of a dune with the lee side sorting model of Blom & Parker (2004) as calibrated by Blom *et al.* (2006). The lee side sorting model accurately predicts the relative volume change compared to the initial mixture (Fig. 8), which means that the dunes in the experiments were efficiently vertically sorted by grain-size selective deposition.

Testing of bend sorting model on experimental data

The sieving data of the bulk samples were used to calibrate the bend sorting model. Figure 9 shows four examples of the relative volumes of the sieved fractions over the cross-section and the fitted linear function through these volumes to determine coefficient δ_i , which is the slope of the fitted function, and γ_i , which is the offset at the centre of the channel (Eq. 2). For fractions coarser than the median grain size, relative volumes increase towards the outer bend, resulting in positive values for δ_i . On the other hand, fractions finer than the median grain size show a decrease in relative volume towards the outer bend, corresponding to negative values for δ_i . Furthermore, the offset of the relative volume of all sediment fractions is always negative, but this offset generally increases, i.e. becomes more negative, towards the finer and coarser fractions. These

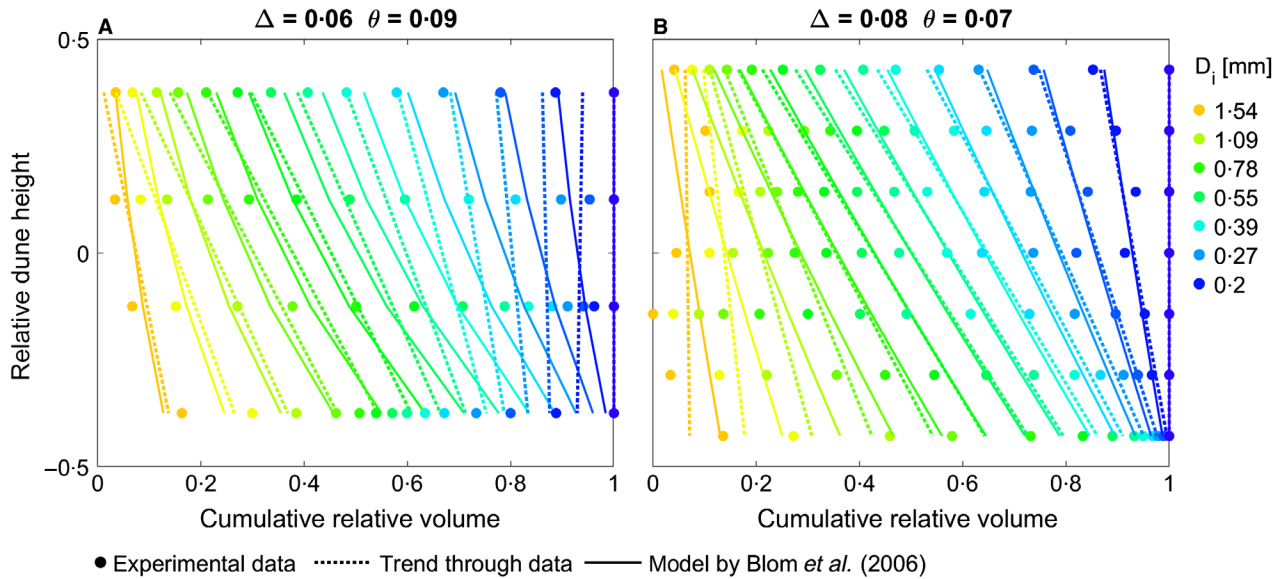


Fig. 8. Sorting along the lee side of a dune in two experiments with different dune height (Δ) and sediment mobility (θ). The graphs show the measured cumulative volume of grain-size fractions (scatter) over the lee side of the dune and the fitted linear function through these volumes (dotted lines). Colour scale represents the grain size of the fractions (D_i). The solid lines represent the lee side sorting model of Blom & Parker (2004) which was calibrated by Blom *et al.* (2006).

trends increase with increasing slope, while the effect of sediment mobility is not significant.

The change of δ with increasing transverse bed slope for specific fractions is characterized by the variable a_i (Eq. 6), and the change of γ by b_i (Eq. 7). These variables are plotted in Fig. 10 for each grain-size fraction, together with their values for the samples that were taken in the dune trough and on the dune crest. For the bulk samples, coefficients c_1 and c_2 (Eq. 14) can be determined by fitting a function through the trend in a_i and b_i against grain-size fraction according to Eqs 8 and 9, which are input for the bend sorting model (Eq. 14). These fitted functions result in a c_1 of 5.5 and a c_2 of -0.5 . Both the coarsest and finest sediment fractions show a slight deviation from the bend sorting model. However, these fractions have a much smaller total volume than the fractions near the median grain size, as shown by the sediment distribution of the initial mixture (Fig. 10). Furthermore, using more complex functions, for example polynomial functions, to describe these trends did not result in a more accurate prediction of the resulting sediment volumes.

For trough and crest samples, the curves show a slightly different behaviour. For a_i the trend is steeper towards the coarser fractions and more constant towards the finer fractions. This means that the volume change over the cross-section

with increasing transverse bed slope is larger for coarser grains, and thus sorting is more pronounced, while the volume change of finer sediment over the cross-section does not change significantly for increasing slope. The more pronounced sorting of coarser grains is also visible in the curve of b_i , which is steeper towards the coarser fraction, which means that the offset is increasingly larger at the centre of the flume. Again, the offset of sediment volumes of the finer fractions are less influenced by increase in slope.

The bend sorting model, with the coefficients c_1 and c_2 computed based on the experimental data, predicts the measured volumes well (Figs 11 and 12), with a R^2 of 0.85. However, for low sediment mobilities, predicted relative volumes can be significantly higher than measured (Fig. 12B), especially in combination with high slopes (Fig. 12A). Furthermore, the model underpredicts low volumes of fine sediment.

DISCUSSION

Interaction between lateral and vertical sorting

The experimental data showed that lateral sorting strongly increases with transverse bed slope. The average transverse bed slope shows the

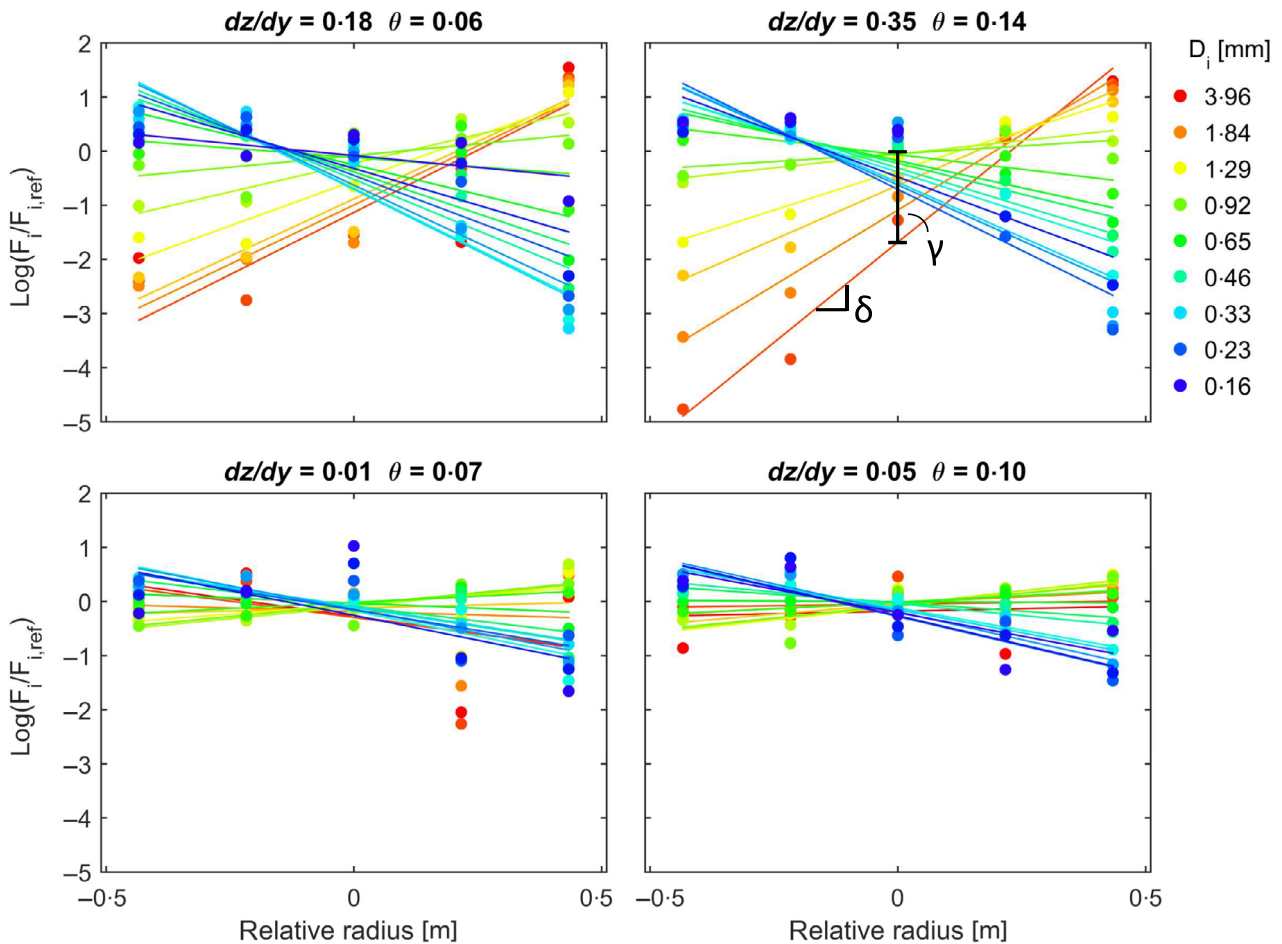


Fig. 9. Measured relative volume of grain size fractions (scatter)($\log(F_i/F_{i,ref})$) over the cross-section in four experiments with different average transverse slope (dz/dy) and sediment mobility (θ). Colour scale represents the grain size of the fractions (D_i). The lines represent the fitted linear function through these volumes to determine coefficient δ_i , which is the slope of the fitted function, and γ_i , which is the offset at the centre of the channel (Eq. 2; Fig. 2)

same trend with secondary flow and sediment mobility as the experiments with uniform sediment (Baar *et al.*, 2018) (Fig. 4B), showing that the transverse bed slope effect is unaffected by transverse sorting in experiments where all fractions are mobile. The sharp increase in median grain size and D_{90} towards the outer bend, especially for slopes steeper than 0.15 m m^{-1} , and the more gradual decrease towards the inner bend shows the greater tendency of coarser grains to travel downslope due to gravity than the finer sediment upslope due to secondary flow (for example, Fig. 5A). This difference is more enhanced for steeper slopes. Qualitatively, the experimental observations are in agreement with Parker & Andrews (1985), who observed the locus of sediment coarser than the median grain size to be at the channel centreline at the bend apex.

Vertical sorting over the entire height of the dunes was well predicted by the dune lee side sorting model of Blom & Parker (2004) (Fig. 8), which means that grain-size selective deposition was the dominant sorting mechanism at the lee side of the dunes in the experiments. Small deviations between the experimental data and the lee side sorting model could be related to other mechanisms of lee side sorting, for example by presorting of sediment that is supplied to the lee side or by flow in the separation zone behind the dune crest (Reesink & Bridge, 2007). For example, Fig. 8A shows a larger volume of the finest fractions over the entire dune. However, these processes had no significant effect on the general lee side sorting pattern.

The difference between bulk samples and surface samples tells us the relative importance of lateral sorting by the transverse bed slope and

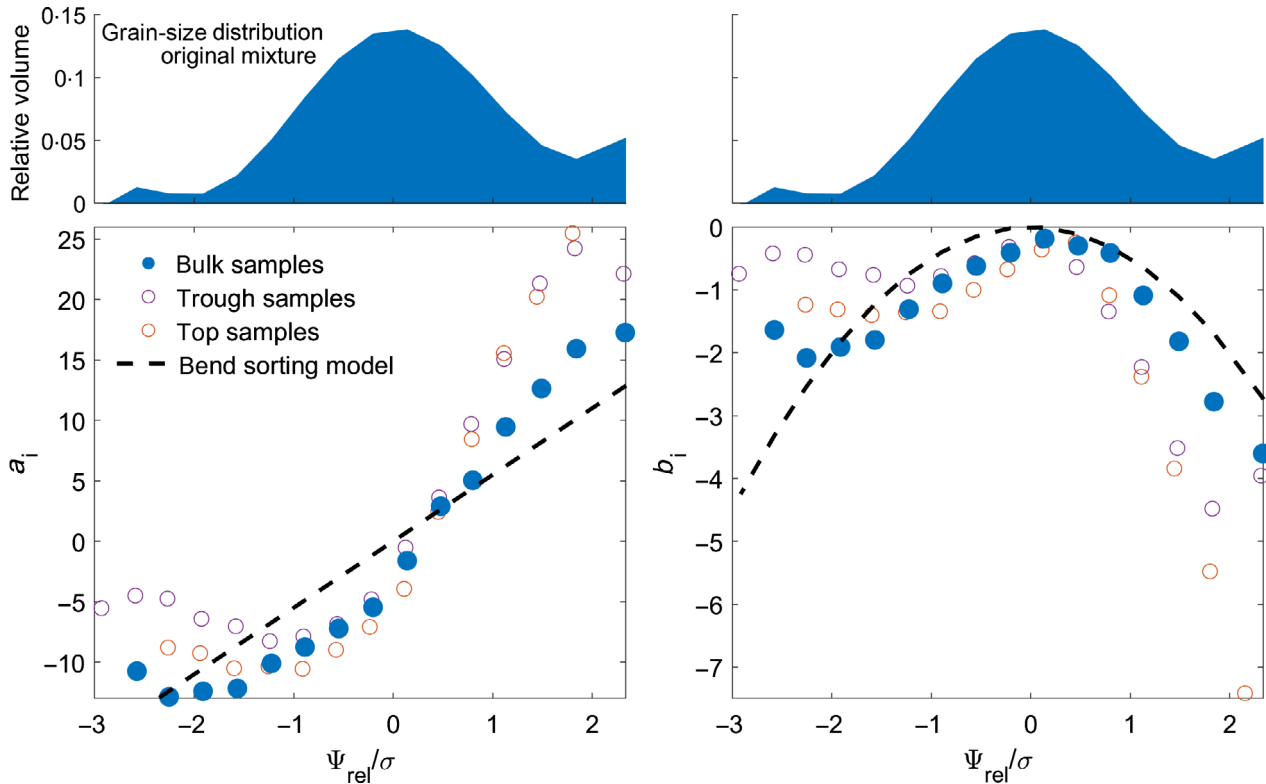


Fig. 10. Change in parameters a_i (Eq. 8) and b_i (Eq. 9) with increasing relative grain-size fraction (ψ_{rel}/σ), for bulk and surface samples (scatter) and the trend described by the bend sorting model (dashed lines): a_i represents the change in volume change over the cross-section with increasing transverse bed slope, while b_i represents the change in offset at the channel centreline with increasing transverse bed slope. The grain-size distribution on top shows the relative amount of grain-size fractions present in the initial mixture.

vertical sorting by dunes. Bulk samples show a sorting pattern averaged over a longer time, since this pattern is the result of multiple dunes passing, and thereby filter out local or temporal variations. Surface samples show local trends that depend on their location on the dunes. Dunes determined the availability of sediment fractions in the surface samples. In dune troughs, secondary flow was likely enhanced and as a result local transverse bed slopes were steeper than the average slope, and sorting was more efficient than in the bulk samples (Fig. 10). In contrast, finer fractions showed a smaller change with increasing slope at the surface, possibly due to lateral mixing by suspension. Comparison between the surface samples and the bulk samples therefore showed that vertical sorting by dunes dampens lateral sorting of the coarsest fractions and slightly enhances sorting of the finest fraction. However, the overall trend of dependency on transverse bed slope between bulk and surface samples is similar, and the influence of vertical mixing by dunes

on the lateral sorting was not sufficient to depend on dune height or sediment mobility. Therefore, the relative influence of vertical sorting by bedforms on lateral bend sorting appears to be relatively low, and does not need to be included in the bend sorting model that was calibrated on the bulk samples collected from the experiments.

The bend sorting model based on the bulk samples thus accurately describes the lateral sorting trend as a function of transverse slope, even though there was distinct vertical sorting by dunes with a dune height between one tenth and one half of the water depth (Fig. 4A). Some of the dunes in the experiments were therefore larger than in nature (Yalin, 1964; Allen, 1984) and covered the entire width of the channel. Since in nature dunes are generally smaller and not in equilibrium with the flow conditions, it is expected that the influence of vertical sorting on the average lateral sorting is even smaller. However, local variations at the surface could differ depending on dune dimensions, and also

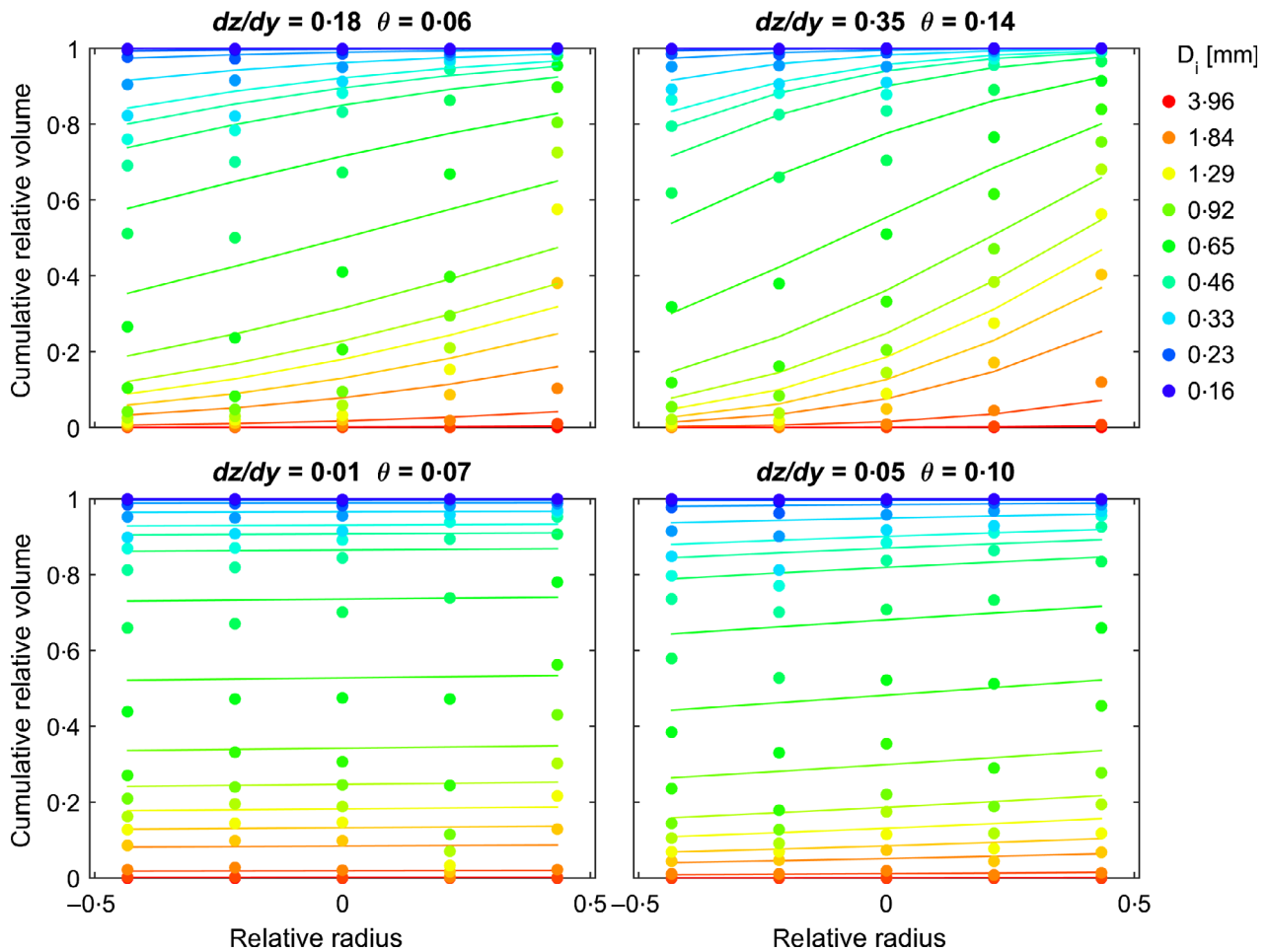


Fig. 11. Comparison between measured (scatter) and predicted (lines) relative grain-size fractions (D_i , colour scale) over the cross-section of the flume, for four examples of experiments with varying transverse bed slope (dz/dy) and sediment mobility (θ).

different lee side sorting processes could have an effect on these local sorting patterns.

Application of the empirical bend sorting model to field data

Comparison of the bend sorting model with field data shows a generally good agreement, since it redistributes all sediment that is available over the cross-section. The trend in volume change over the cross-sections of specific fractions is similar to that of the experiments. Nevertheless, deviations from the model are observed. In general, Fig. 13 shows that the model can overestimate lower relative volumes. This overestimation is larger than that observed from the experimental data. Other deviations can be explained by differences in field and experimental conditions.

Firstly, the bend sorting model redistributes available sediment assuming that all fractions are mobile, while this was not the case when discharge was lower in the gravel bed river Severn (Fig. 14), and at the inner bend at the lowest discharge in the river South Esk (Fig. 15). When only the finer sediment fractions were in motion, the volume of fine sediment fractions at the inner bend is considerably larger than the bend sorting model predicts. The measured volumes of the coarser fractions at the outer bend did not change compared to when all fractions were mobile, but since the model redistributes the fractions that are present, it now underestimates these volumes.

Secondly, in case of the Severn and the South Esk surface samples were taken, and therefore show interaction with bedforms and present flow conditions. Just like the surface samples in the

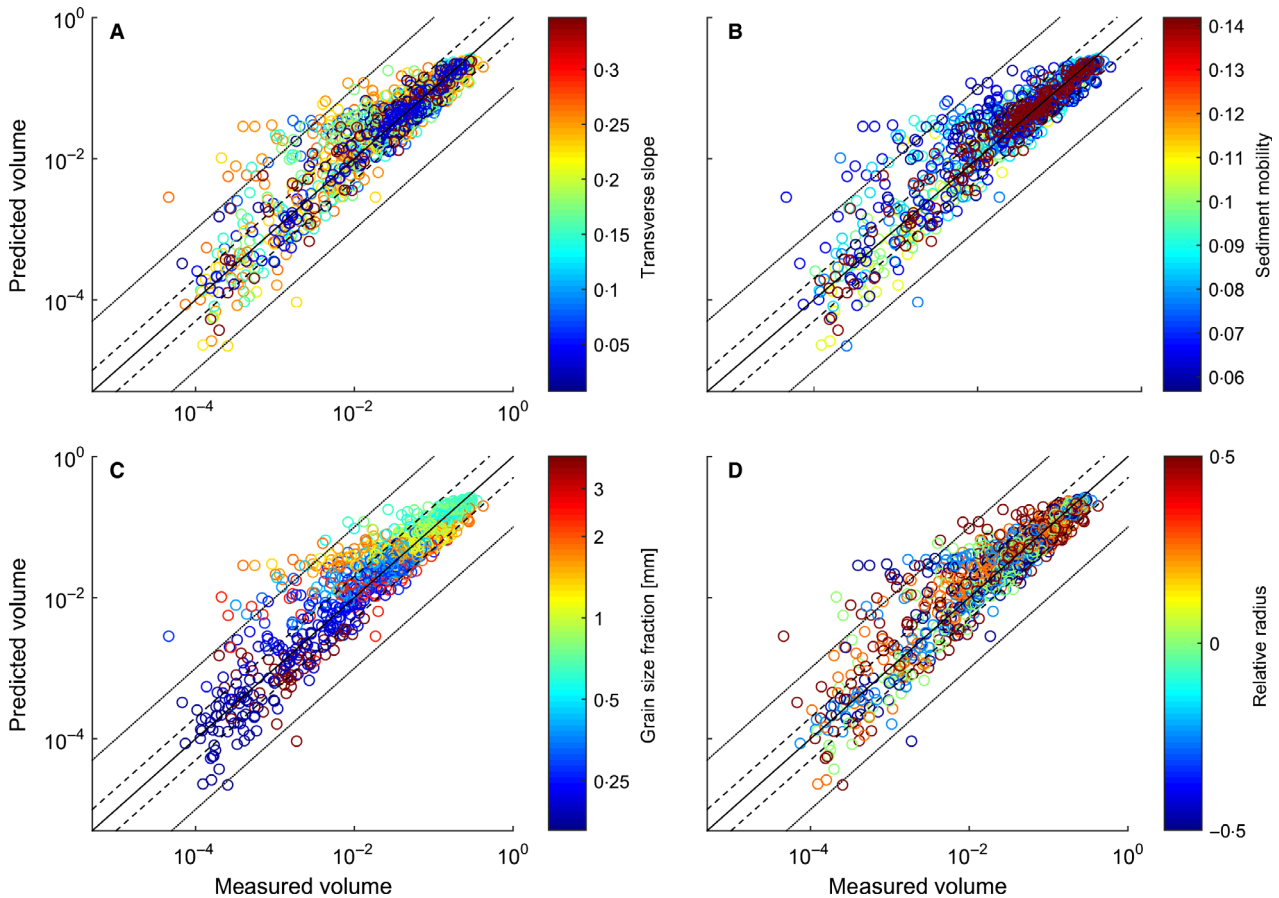


Fig. 12. Predicted against measured volumes of all grain size fractions from all bulk samples. Colour scales show: (A) the average transverse bed slope; (B) sediment mobility of the experiment during which the sample was taken; (C) grain-size fraction in millimetres; and (D) the cross-sectional location of the sample.

experiments, data from the South Esk show relatively more fine sediment in the inner bend and a larger amount of coarser sediment at the outer bend when all fractions were mobile. The data of the Severn show a slight deviation when all fractions were in transport because of a bar that was located in the middle of the cross-section.

Thirdly, sorting patterns of the Rhine river seem to be more pronounced in the data compared to the model (Fig. 16). Furthermore, the river Rhine is heavily managed, which might influence local sediment characteristics near the banks due to groynes that alter the flow. Grain-size samples from the Rhine river just upstream of the bifurcation into the Waal river and the Pannerdensch Kanaal show that sorting is gradual over the cross-section in the first 40 cm of the bed, since there is only a mild transverse bed slope. Nevertheless, the volume of coarse sediment fractions is indeed larger in the

Pannerdensch Kanaal, which is the bifurcation originating in the outer bend of the Rhine river.

In nature flow and sediment transport patterns are often more complicated, for example due to upstream morphology or due to more complicated secondary flow patterns, like the presence of a reverse secondary flow cell near the outer bank that directs near-bed flow towards the centre of the channel (Thorne *et al.*, 1985). Upstream bends and other morphological features determine the location of the thalweg and the availability of sediment fractions. Furthermore, it is unknown until which width to depth ratio compared to bend radius the model is valid. Large bends with a large width to depth ratio have a low water surface slope and therefore a weak secondary flow towards the inner bend McLelland *et al.* (1999); Parsons *et al.* (2007), and in these bends bedforms can play a more important role. It would therefore be

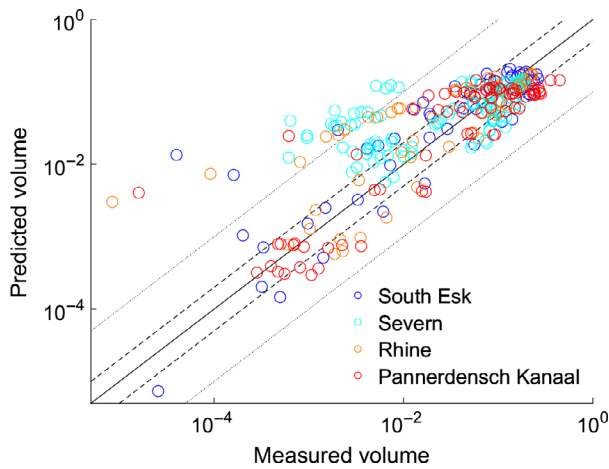


Fig. 13. Predicted against measured volumes of all grain-size fractions from field data found in literature. Colour indicates the river that was sampled.

interesting to study the limits of the bend sorting model in the future.

Static sorting

The bend sorting model redistributes available sediment assuming that all fractions are mobile, but as the field data shows this is not always valid. When not all fractions are mobile, static sorting can occur due to differences in critical sediment mobility, since larger particles are less mobile than finer grains and need higher shear stresses to be entrained (e.g. Odgaard, 1981; Ashworth & Ferguson, 1989). This can lead to vertical sorting by armouring of the bed when selective entrainment removes all fines from the bed and supply is limited (e.g. Powell, 1998; Kleinhans, 2001), and also hiding exposure effects become important when coarser grains shelter finer particles from the flow (e.g. Wilcock & Crowe, 2003). When coarser fractions are immobile, lateral sorting is hampered. However, static sorting is most prominent in gravel-bed rivers with wide sediment distributions, and therefore selective entrainment presumably has less influence on sorting patterns than active sorting during transport (e.g. Hoey & Ferguson, 1994).

Differences in critical sediment mobility and resulting static sorting will have an influence on the transverse bed slope and consequently on bed morphology. In case all fractions are mobile, the river bend responds to changes in shear stress by adjusting the bed level, and in this case the transverse bed slope. In case of

selective entrainment, the river will adjust to a gradient in shear stress by adjusting the sorting pattern before it can adjust the bed level (Dietrich & Whiting, 1989). This will thereby result in a different bed slope than when all fractions were mobile, and influences the dynamics of river bars and the amount of bed and bank erosion (Ikeda, 1989). Due to both differences in sorting patterns and bed morphology, the bend model in this study that only describes active sorting is less applicable in model cases where sorting due to selective entrainment plays an important role. Rather, the empirical model best represents the end member case of fully mobile sediment mixtures in infinitely long bends.

The effect of size selective entrainment was almost absent in the experiments due to the choice in sediment mixture. However, comparison between measurements and the bend sorting model showed that sorting was less pronounced with low sediment mobility, especially in combination with steep transverse bed slopes, which indicates that sediment was not mobile enough to fully develop the sorting pattern. However, this effect was only minor, and the two experiments for which this was the case did not influence the trend in the bend sorting model.

Implications for modelling bend sorting

The relatively simple bend sorting model can be used for multiple applications, since it can be included in any model that already predicts transverse bed slope and flow conditions. For example, it can be an addition to analytical models that predict bifurcation dynamics based on upstream transverse bed slope (Bolla Pittaluga *et al.*, 2003; Kleinhans *et al.*, 2008). Furthermore, an existing transverse bed slope predictor based on bend radius can be used to predict the slope of lateral accretion surfaces in a point bar, after which the bend sorting model can predict grain-size distribution along this surface (van de Lageweg *et al.*, 2014). The current model predicts lateral sorting along the transverse bed slope at the bend apex, but this pattern can have a large influence on morphology by different trajectories of the different grain sizes through the bend and towards bends downstream (Parker & Andrews, 1985). The current bend sorting model could therefore be a starting point to predict spatial distribution of sediment fractions along a given bend, and thereby improve predictions of sediment transport, bed level elevations and point bar

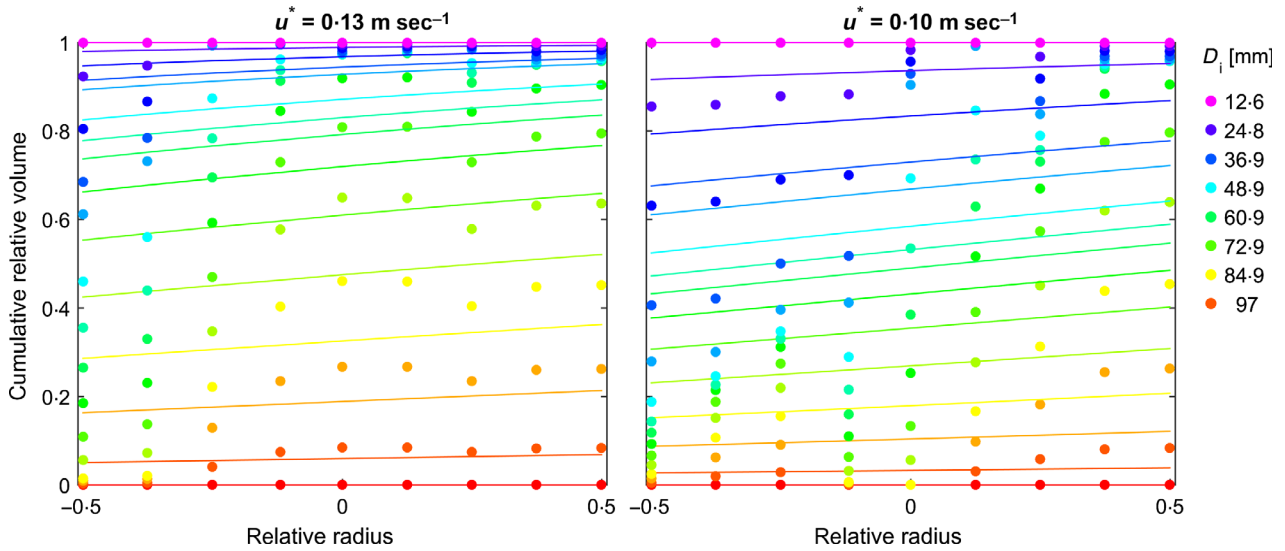


Fig. 14. Comparison between measured (scatter) and predicted (lines) relative grain-size fractions (D_i , colour scale) over the cross-section of the river Severn (Hey, 1991) at different flow conditions (u^* = shear velocity).

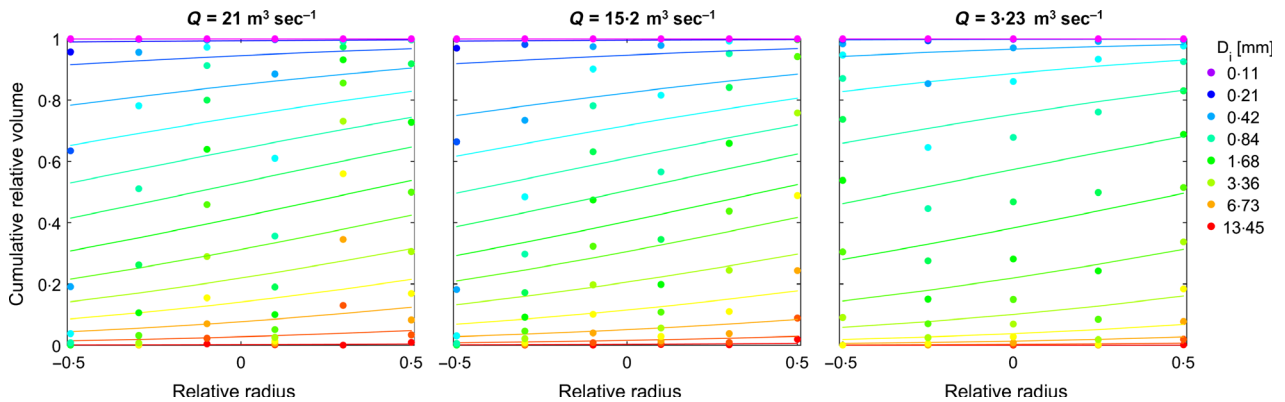


Fig. 15. Comparison between measured (scatter) and predicted (lines) relative grain-size fractions (D_i , colour scale) over the cross-section of the river South Esk (Bridge & Jarvis, 1976), during falling discharge (Q).

connectivity models by predicting the dimensions and spatial distribution of stratigraphic units (Willis & Tang, 2010).

The relatively low influence of vertical sorting on the trend in lateral sorting has important implications for morphodynamic models with the active layer concept. These findings show that over a longer time period, i.e. longer than the migration of a few dunes, the effect of vertical sorting can be ignored. This shows that the use of the active layer is still valid when modelling lateral sorting, which should make it easier to model sediment transport processes realistically. However, before lateral sorting can be described accurately, a more physics-based

predictor needs to be implemented to calculate the deflection of the available grain-size fractions in the active layer as a function of transverse bed slope (Sloff & Mosselman, 2012). In model scenarios where the active layer concept is not sufficient, for example when the objective is to look at smaller scale processes at a shorter timescale, recent studies suggested replacing the active layer by a continuous bed distribution, and including the entire particle size distribution (Powell, 1998; Parker *et al.*, 2000; Blom *et al.*, 2008; Frings, 2008). In this case, the fraction-based lateral sorting function of this study can be a useful addition to the already existing formulations for streamwise (Parker *et al.*, 2000)

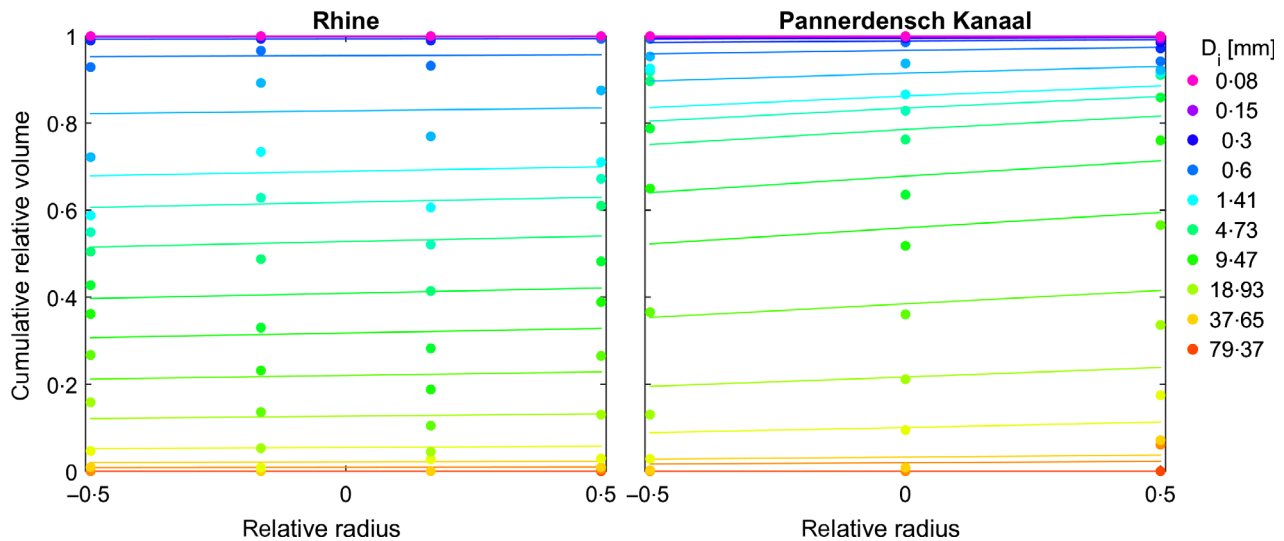


Fig. 16. Comparison between measured (scatter) and predicted (lines) relative grain-size fractions (D_i , colour scale) over the cross-section of the Rhine and Pannerdensch Kanaal. The transect of the Rhine is just upstream of a bifurcation, while the transect at the Pannerdensch Kanaal is the first after the bifurcation.

and vertical sorting (Blom & Parker, 2004). However, these more advanced continuous sorting models have not yet been applied in two-dimensional horizontal modelling because of its mathematical and numerical complexity (Chavarrías *et al.*, 2018).

CONCLUSION

The trend in lateral sorting of grain-size fractions is experimentally determined as a function of transverse slope, and described the relative influence of vertical sorting by dunes. All sediment fractions that are mobile are efficiently sorted along the transverse bed slope, where the volume change over the cross-section of specific fractions increases with grain size and magnitude of the slope. There was no feedback between sorting and the magnitude of the slope itself.

Bulk samples that were taken over the entire height of a dune showed minor effects of vertical sorting along the lee side of dunes, since the differences with surface samples were small, even though dunes were efficiently vertically sorted by grain-size selective deposition. Only the coarsest fractions were distributed more evenly over the cross-section as a result of dune migration, while sorting of the extremely fine fractions was enhanced. Therefore, lateral sorting can be modelled independently of active

vertical sorting by dunes, which allows application of the active layer concept in morphodynamic models.

A bend sorting model is developed that redistributes the available sediment over the cross-section as a function of transverse bed slope and grain-size fraction. This model is calibrated with the bulk samples, which show an average trend over a longer time period, instead of local trends that depend on interactions with bedforms and present flow conditions. Comparison with field data showed that the model is only valid when all grain-size fractions that are sampled are mobile under the present flow conditions, and therefore the model is less applicable in rivers with wide sediment distributions. The resulting bend sorting model can be used in any analytical model that predicts the transverse bed slope, and is a reference for morphodynamic models that predict sediment sorting patterns of mobile sediment in bends.

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Supporting Information

Additional information may be found in the online version of this article:

Table S1. Characteristics of all experiments and sieve curves of all samples.