SEDIMENT SUPPLY-LIMITED BEDFORMS IN SAND–GRAVEL BED RIVERS

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Abstract: The stability of bedforms in mixtures of gravel and sand is not well understood. Two bedform types are characteristic: flow-parallel sand ribbons and flow-transverse barchans. Flume experiments and field data presented here show that gradual transitions exist from sand ribbons to barchans, and from barchans to fully developed dunes. Barchans and sand ribbons occur when not enough transportable sediment is available for the formation of fully developed ripples or dunes. The reason is that a part of the bed sediment is immobile, e.g., with an armor layer, which limits the sediment supply and thus the volume of sediment available for the formation of bedforms.

Bedform stability diagrams are shown to be extendable to sediment supply–limited bedforms in sand–gravel sediment, if the particle parameters of the diagrams are derived from the transported sediment instead of the bed sediment. Barchans and forms transitional to fully developed dunes plot in the dune stability fields. Sand ribbons, on the other hand, plot in the ripple, lower plane bed, and dune fields.

In the case of sediment supply limitation, bedforms are partly or completely related to the characteristics of the sediment supply from upstream. The sediment underlying the bedforms may be a stable armor and the exchange of sediment between this armor and the bedforms may be small or non-existent. Consequently, bedform characteristics in sand–gravel mixtures in supply–limited conditions often are not predictable from the local hydraulics and sediment characteristics.

Introduction

The stability of bedforms in sandy material is well understood. Many bedform stability diagrams for uniform sand have been proposed in the past decennia, e.g., Simons and Richardson (1965), Allen (1984), Southard and Boguchwal (1990), and Van den Berg and Van Gelder (1993, 1998). Bedforms in sediments with both gravel and sand have received attention only recently. An outstanding property of (bimodal) sand and gravel mixtures is that the larger grains become practically immobile during some critical lower flow stage, while the smaller grains are propagating downstream as bedforms (Wilcock 1998; Carling et al. 2000a; Carling et al. 2000b). The effect of this partial mobility of sediment on bedform characteristics and morphology is not well known.

The objectives of this paper are (1) to describe the bedform types that occur in sediments with sand and gravel, (2) to test the applicability of existing bedform stability diagrams to sediment mixtures, and (3) to determine the effect of sediment supply on bedform morphology. Flume experiments presented herein provide bedform data for conditions ranging from extremely transportable sediment-supply-limited to supply-unlimited. Furthermore, new data are presented for bedform types in natural rivers with (bimodal) sand–gravel sediment. These data and data from the literature are used to infer the main factors determining bedform stability and morphology in sediment supply–limited conditions, and are applied to existing bedform stability diagrams to extend their applicability.

Review

Dinehart (1989, 1992) observed active gravel dunes in the North Fork Toutle river, proving that dunes do exist in very coarse sediment. Superimposed on and migrating over these dunes, features were found that seemed to be transitional forms between bedload sheets and small dunes. Carling (1999) presented an overview of published data on bedforms in coarse sediments and applied those to the bedform stability diagrams of Allen (1984) and Southard and Boguchwal (1990). The stability fields of bedforms in sand could be extended into the gravel grades. However, the data used by Carling refer mostly to unimodal sand or gravel sediments; bimodal mixtures were not considered.

The effect of sediment sorting on bedform stability was experimentally determined by Chiew (1991). Lognormally distributed sediments with a D50 of 0.6 mm and a Trask sorting coefficient varying from 1.2 to 5.5 were subjected to steady flows of 0.3 to 2 m/s in a small recirculating flume. Chiew found that differences from uniform sand were: the armor tendency, the absence of antidunes, and the fact that bedform sizes at intermediate flows were dependent on the availability of fine sediment at the bed-surface. Chiew did not provide information on detailed bedform morphology and sediment transport.

Three bedform types appear in literature as typical for sand–gravel sediment: bedload sheets, flow-parallel sand ribbons, and flow-transverse barchans. Bedload sheets are thin accumulations of bedload sediment about two grain diameters thick and ~ 0.5–2 m long, and are recognizable mainly by their flow-transverse sorting with the coarse grains at the leading edge. Sand ribbons are created by near-bed helical flow cells in combination with selective transport of bed sediment (e.g., Allen 1970; McLelland et al. 1999). The sand is concentrated in flow-parallel ribbons and transported over the immobile gravel. The spatial segregation of fine and coarse sediment enhances this flow structure, providing a positive feedback for formation of sand ribbons (Colombini 1993; McLean 1981; McLelland et al. 1999). Barchans have a crescent shape with the horns pointing downstream, and they migrate over an immobile base. They are well known features in subaerial settings and have a stable form; here, barchans were observed to preserve their form while migrating over long distances (McKee 1979; Pye and Tsoar 1990; Hesp and Hastings 1998). The supply of transportable sediment is limited, either because the base is wet and thus cohesive due to a high groundwater table, or because the base is more or less immobile, in the case of a desert pavement or sabkha. Individual barchans are separated from each other by the immobile substrate. With increasing supply of mobile sediment barchans may coalesce to barchanoid transitional forms between barchans and dunes.

The first mention of barchans in the fluvial literature known to the authors is by McCulloch and Janda (1964), who observed barchan dunes migrating over an immobile gravel lag in an Alaskan river. They suggest that subaqueous barchans are formed in response to a limited sand supply due to the immobility of the coarser grains. Recently, Carling et al. (2000a) and Carling et al. (2000b) described large sandy barchans migrating over an armor layer in the river Rhine (Germany) downstream of a hydropower dam, which limits the upstream sediment supply. In addition, researchers mention barchans migrating over armor layers in flume experiments (Klaassen 1986; Rosza and Jozsa 1999).

Compared to their subaqueous counterparts, subaerial dunes are not limited in height because of an infinite air “depth,” whereas dunes in flumes or shallow rivers react strongly to changes in water depth (e.g., Southard and Boguchwal 1990). An important similarity is that the height of subaerial barchans is often limited by sediment supply, although the limitation of sediment supply does not necessarily mean that barchans become smaller.
as the sediment supply diminishes. Instead, the number of barchans simply declines because of the declining availability of mobile sediment for bedform formation. This agrees with the observation of Rubin and Topping (2001) that in case of extreme winnowing, coarsening of the bed may be accompanied by reduction in surface area of transportable sediment patches on the river bed. Thus, subaerial dunes can be limited in height only by sediment supply, whereas subaqueous dunes can be limited in addition by water depth.

The phrase “supply-limited” here refers to a limitation of available, transportable sediment from which the bedforms are molded. With a fully mixed bed as the initial condition, this could also be seen as a flow limitation. The critical shear stress for the larger grains in the bed is not exceeded by the flow, which leads to coarsening of the bed, and less sediment in transport than would have been the case in fully mobile bed conditions. Thus the limit on entrainment is strongly related to the critical shear stress of all grain-size fractions. This effect is different for different sediment mixtures. In bimodal sediment the finer grades are much more mobile than in unimodal sediment, whereas in both cases the mobility of the finer grades is less than in uniform sand (Wilcock 1998). In the case of an armor layer formed during a previous discharge wave or period of low flow, however, sediment-supply limitation is not seen as a flow limitation, because that condition does not relate to the present flow. Such an armor layer (history effect) inhibits the entrainment of finer sediment from the underlying bed, which otherwise would have been entrained in the present flow.

An important question is how the supply limit relates to the stability and morphology of subaqueous bedforms. Belderson et al. (1982) observed migrating sand ribbons, sand barchans, and dunes over a clay substrate on the continental shelf. They presented a semiquantitative model of bedform morphology with the availability of sediment for bedload transport as the main factor. Likewise, McKee (1979) presents a qualitative model to illustrate the continuous sequence of subaerial transverse dunes to transitional forms to barchans with unidirectional wind and diminishing sand supply. No model is available for bedforms in rivers.

In the case of supply limitation, bedforms apparently are related partly or completely to the characteristics of the sediment supply from upstream. Therefore, in contrast to the unimodal case, bedform characteristics in (bimodal) mixtures at supply-limited conditions may therefore be unpredictable from the local hydraulic and sediment characteristics. This hypothesis is tested herein.

FIG. 2.—Sequence of the experiments of Blom and Kleinhans (1999) (after Kleinhans 2000).

**Table 1.—Experimental conditions (Blom and Kleinhans 1999; Kleinhans 2000).**

<table>
<thead>
<tr>
<th>Experiment Condition</th>
<th>Water Depth** (m)</th>
<th>Discharge** (m³/s)</th>
<th>Flow Velocity** (m/s)</th>
<th>Water Surface Slope (10-4)</th>
<th>D50 Transport* (m)</th>
<th>Thickness of Transport Layer (m)</th>
<th>Final Bed State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bed was remixed and bed slope installed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T0 incipient motion</td>
<td>0.20±0.20</td>
<td>0.13±0.13</td>
<td>0.40±0.44</td>
<td>−4.48</td>
<td>0.073</td>
<td>0.001</td>
<td>0.62</td>
</tr>
<tr>
<td>T1 transitional flow</td>
<td>0.20±0.37</td>
<td>0.13±0.33</td>
<td>0.42±0.59</td>
<td>−4.48</td>
<td>0.102</td>
<td>0.001</td>
<td>0.62</td>
</tr>
<tr>
<td>T2 arming</td>
<td>0.37±0.37</td>
<td>0.33±0.33</td>
<td>0.59±0.60</td>
<td>−5.22</td>
<td>0.056</td>
<td>0.000</td>
<td>1.33</td>
</tr>
<tr>
<td>T3a fast gradual flow rise</td>
<td>0.37±0.46</td>
<td>0.33±0.50</td>
<td>0.59±0.73</td>
<td>−4.53</td>
<td>0.001</td>
<td></td>
<td>flat armored bed</td>
</tr>
<tr>
<td>T3b fast gradual flow rise</td>
<td>0.49±0.61</td>
<td>0.60±0.78</td>
<td>0.78±0.87</td>
<td>−7.06</td>
<td>0.002</td>
<td></td>
<td>small barchans over armor layer</td>
</tr>
<tr>
<td>T4a top speed</td>
<td>0.49±0.52</td>
<td>0.60±0.60</td>
<td>0.77±0.82</td>
<td>−6.38</td>
<td>0.193</td>
<td>0.008</td>
<td>small barchans over armor layer</td>
</tr>
<tr>
<td>T4b incipient motion</td>
<td>0.38±0.35</td>
<td>0.33±0.33</td>
<td>0.59±0.64</td>
<td>−4.88</td>
<td>0.134</td>
<td>0.008</td>
<td>small dunes over armor layer</td>
</tr>
<tr>
<td>bed was remixed and new bed slope installed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T5 incipient motion</td>
<td>0.21±0.25</td>
<td>0.22±0.26</td>
<td>0.68±0.73</td>
<td>−14.72</td>
<td>0.170</td>
<td>0.008</td>
<td>small barchans over armor layer</td>
</tr>
<tr>
<td>T6 transitional flow</td>
<td>0.24±0.33</td>
<td>0.26±0.38</td>
<td>0.70±0.79</td>
<td>−14.62</td>
<td>0.217</td>
<td>0.017</td>
<td>dunes over armor layer</td>
</tr>
<tr>
<td>T7 top speed</td>
<td>0.34±0.36</td>
<td>0.41±0.43</td>
<td>0.77±0.81</td>
<td>−15.20</td>
<td>0.241</td>
<td>0.028</td>
<td>large dunes over armor layer</td>
</tr>
<tr>
<td>T8 transitional flow</td>
<td>0.35±0.27</td>
<td>0.42±0.30</td>
<td>0.79±0.70</td>
<td>−15.71</td>
<td>0.029</td>
<td></td>
<td>large dunes over armor layer</td>
</tr>
<tr>
<td>T9 lower flow</td>
<td>0.25±0.27</td>
<td>0.26±0.28</td>
<td>0.68±0.72</td>
<td>−16.94</td>
<td>0.204</td>
<td>0.027</td>
<td>large dunes over buried armor layer</td>
</tr>
<tr>
<td>T10 incipient motion</td>
<td>0.14±0.19</td>
<td>0.14±0.19</td>
<td>0.49±0.60</td>
<td>−11.06</td>
<td>0.126</td>
<td>0.002</td>
<td>small barchans over armor layer</td>
</tr>
</tbody>
</table>

Notes: Water temperature in all experiments: 14°C.
** To obtain constant flow velocities during an equilibrium test, both the water depth and discharge were adapted. Therefore these parameters are given as a range.
*** The flow velocity in the equilibrium experiments was constant, the given range is twice the standard error. The average velocity was used in the graphs.
**** The water-surface slope approximates the average bed slope.
FLUME EXPERIMENTS

Description of the Experiments

The experiments were done with slightly bimodal sediment (Fig. 1) from the uppermost reach of the river Waal, a distributary of the Rhine in the Netherlands. Herein, only the results with respect to bedform morphology are given. Kleinhans (2000) presents an overview of all results. The experiments were started with a mixed bed, installed at a bed slope equal to the water-surface slope. The flow was started slowly (over 15 minutes) to prevent bed damage and was maintained until the system was in equilibrium (Fig. 2). The equilibrium phase was pragmatically defined as the time at which changes in flow roughness, bedform dimensions, and sediment transport became smaller than the measurement variability. After draining the flume, the bed was photographed and sampled, and the sampling pits were repaired with original sediment. Next, a different bed shear stress was applied until equilibrium was again reached (Fig. 2) (Blom and Kleinhans 1999; Kleinhans 2000). The rising and waning flow stages between the equilibrium experiments are referred to as transitional experiments. The conditions of most experiments were near incipient motion for most diameters, but some experiments had shear stresses well above critical for most diameters (Table 1). Sediment transport in suspension was negligible.

It is assumed that the bedload transport depends on the grain-related bed shear stress (grain shear stress) (Van Rijn 1984; Van den Berg and Van Gelder 1993). The grain bed shear stress is herein defined as $\tau_g = \rho g (u/C)^2$, in which $\rho = \text{density of water (1000 kg/m}^3$), $g = \text{gravitational acceleration (9.81 m/s}^2$), $u = \text{depth-averaged flow velocity (m/s)}$, and $C = \text{Chezy (m}^{0.5}/\text{s})$ roughness related to grain friction (explained later). It was assumed that the roughness coefficient related to grains $C'$ (skin friction) remained constant in the experiments. On the basis of this assumption, Kleinhans and Van Rijn (2002) successfully hindcasted the sediment transport with a bedload predictor for these flume experiments, which suggests that the assumption is reasonable.

$C'$ was calculated using the White-Colebrook equation and assuming a Nikuradse grain-related roughness $k_95 = D_{90}$ (m) in which $D_{90} = 90$th percentile of the original sediment mixture: $C' = 18\log(12h/k')$ in which $h = \text{water depth (m)}$. Alternative methods, which subtract bedform-related roughness from total roughness to obtain grain roughness, are subject to...
large uncertainties related to the measurement of the total roughness and the determination of the bedform roughness.

In order to keep the grain-related shear stress for each experiment at a constant value, the flow velocity ($u = Q/A$, with $Q =$ flow discharge (m$^3$/s) and $A = hW$ cross-sectional area (m$^2$), $W =$ width of the flume (m)) had to be kept constant while bedforms developed. This cannot be established with a constant flow discharge, because the growing bedforms lead to increasing form roughness and hence to decreasing grain bed shear stress. Therefore both the water depth (controlled by a downstream weir) and discharge had to be adjusted iteratively while maintaining uniform flow. It is acknowledged that the assumption of constant $C$ may not hold in changing surface compositions of sediment mixtures in different conditions, but the alternative of keeping the flow discharge constant would have led to a much less constant $u$.

The experiments were conducted in the straight sediment-recirculating sand flume in the Delft Hydraulics Laboratory, which is 50 m long and 1.5 m wide (Bakker 1984). The water temperature was kept constant at 14°C. Bed-surface and water-surface levels are automatically recorded at every centimeter along the centerline of the flume with electromagnetic water-surface and bed-surface profilers. The total bed shear stress was calculated from the bed-surface and water-surface profiles and corrected for flume sidewall roughness with the method of Vanoni and Brooks. All bed profiles were detrended and analyzed with the computer program Dunetrack 2D (Wesseling and Wilbers 1999). The output of this program is a number of bedform parameters: height, length, volume, and number of bedforms.

During the experiments the sediment transport rate was measured in the recirculation system. In experiment T2, the sediment was not recirculated, in order for an armor layer to develop. The sediment transport per grain-size fraction was determined from the bulk transport (kg/s). Samples from the transported sediment were analyzed by sieving and settling tube to determine the grain-size distributions.

**Results of the Flume Experiments**

In Figures 3 and 4, the observed bedform types are given as a function of depth-averaged flow velocity and bedform height. The flow-parallel ribbons occurred at the lowest flow velocities (T0 and T2). Between the ribbons the bed surface consisted mainly of gravel. The sand in the ribbons migrated downstream in the form of small ripples, which sometimes had barchanoid forms. Barchans occurred in experiments T3b, T4a, T5, and T10. Dunes occurred in experiments T4b and T6–T9. Furthermore, sheets were observed to migrate over the dunes. The sheets had the height of ripples but were somewhat longer and sometimes showed a longitudinal sorting with the coarser grains at the leading edge. The sheets resembled both sand ribbons and bedload sheets.

The findings are interpreted as follows. During low flow, armoring almost inhibits bedload transport and only a very small portion of the bed is covered by bedload sediment in sand ribbons, bedload sheets, or barchans. At rising stages the armor layer remains unbroken up to a certain point. This point is determined by the threshold of motion of the imbricated particles and pebble clusters in the armor layer. In this case, the armor layer was broken up by the turbulence in the bedform troughs, as was also found by Klaassen (1986), and mixed into the bedform sediment. Consequently, more sand becomes available from below the armor layer and the bedforms may eventually evolve into dunes.

The history of sorting in the bed partly determines the outcome of the experiments. In the absence of an initial armor layer, a higher shear stress mobilizes more sediment and larger grains, leading to the observed transition from sand ribbons to barchans to dunes (cf. T0, T10, T5, and T7). The outcome of T7 would have been the same for a fully mixed bed as initial condition, because the turbulence in the troughs of barchans and dunes becomes strong enough to override the armoring tendency, as was also observed by Klaassen (1986). When an armor layer is allowed to develop (as in T2) by cutting off the upstream sediment supply, however, then the critical shear stress for mobilizing the armor layer is much larger. Once the armor layer is mobilized, the same transitions from sand ribbons to barchans and dunes occur (in T3 and T4), though at much higher shear stresses, and probably within a much narrower range of shear stresses. Consequently, although the experiments represent only a subset of all possible realizations, they range from the endmembers of a strong armor layer to a fully mixed bed as initial conditions.

Summarizing, during low flow most of the sediment is immobile, leading to strong sediment supply-limited conditions with sand ribbons. With increasing flow strength and sediment transport, sand ribbons evolve into barchans, barchanoids, and finally dunes.
with discharges of 20–40 m$^3$/s. Bedforms consisting of sand with a $D_{50}$ of 0.5 mm migrated over the armored bed. Bedform dimensions (height, width, length) and the surface area covered by the bedforms were measured. Vertical velocity profiles and water depths were obtained at several locations above and near the bedforms with an electromagnetic flow device (EMF) mounted on a portable frame. The flow velocity was measured at the following levels above the bed: 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.40, 0.50 and 0.70 m. From these values, data on depth-averaged flow velocities, bed shear stress, and roughness length were obtained at the location of the bedforms. The bed and bedforms at the measuring location were sampled after the measurements and sieved for grain-size analysis.

Several types of bedforms were observed (Table 2): sand ribbons, barchans, and dunes, often concurrent in the same stretch of the river. Barchans varied in height between 0.01 and 0.05 m, and dune heights were between 0.05 and 0.25 m. The sand coverage of the bed varied from 0 to 100%. Relict gravel dunes were found on the surface of bars above the low-flow water surface.

Meander pools often contained fine sand fills between 0.1 and 1 m thick. These are probably waning-flow or low-flow deposits as described by Lisle and Hilton (1999). During the fieldwork period, a small peak in the discharge occurred, which allowed a wave of sand to detach from the sand deposit in the pool (Fig. 6). The wave of sand provided a spatially varying sediment supply for bedforms in equal flow conditions. Near the pool, dunes with sinuous crests occurred, and these gradually changed into barchanoid features downstream. Farther downstream barchans occurred concurrently with sand ribbons, and only sand ribbons occurred even farther downstream. At the front end of the wave of sand the armor was fully exposed. In time the volume of sand in the wave decreased, as the downstream-propagating sand infiltrated into the armor layer.

At other locations, downstream migrating waves of sand of a few square meters to a few hundred square meters in area were found with the same pattern and order of bedform types, originating from the sand deposits in pools or from bank failures. In the surveyed sand wave (Fig. 6), the bedform pattern was mirrored in both the upstream and the downstream direction. For all locations and bedform types the flow conditions were more or less equal and the armor layer was stable.

Summarizing, a large range of bedform types were found in the river Allier at flow conditions in which the gravel was immobile. These bedform types were the same as found in the flume experiments. In contrast with
the experiments, the flow conditions were about the same for all bedform types, and the armor layer was not broken up. The main factor causing the differences in bedform type was the availability of mobile sand for the formation of the bedforms.

**Field Measurements in the River Waal (The Netherlands)**

The measurement location was the upstream section of the river Waal (Fig. 7). For navigation purposes and bank protection, both sides of the river have a system of groins. The average width of the river (between the groins) is 240 m. Here, the water depth varies between 3 and 12 m. The mean discharge of the Waal is 1350 m³/s with peaks up to 8000 m³/s. At high discharges bedforms develop with lengths over 10 to 20 m and heights over 0.5 m over the full width of the river (Wilbers 1999).

Dunetrack 2D (Wesseling and Wilbers 1999) software was used to calculate bedform dimensions and statistics. The observed bedform type was straight-crested transverse (two-dimensional) dunes. The bedforms attained their maximum height one day after the discharge peak (Fig. 8, Table 3). After the peak discharge, smaller dunes emerged that propagated over the immobile and gradually disappearing large dunes. Allen and Collinson (1974) attribute this superposition of small active bedforms on inactive large dunes to the fast change in discharge.

In conclusion, during discharge peaks in the river Waal the bedform type is two-dimensional dunes with no significant armor layers in the troughs. Supply-limited bedforms were not observed, but they might have been small to be seen with the echo sounder.

**BEDFORM STABILITY DIAGRAMS**

Hereinafter the hypothesis will be tested that the boundaries between bedform states as provided by the stability diagrams should simply be extrapolated into the coarser grades (Carling 1999). A disadvantage of most of the existing diagrams is that they require information on the energy gradient of the flow, or, alternatively, the total hydraulic roughness (comprising bedform and skin friction) in order to calculate the bed shear stress. In rivers these parameters generally are not measured with the required accuracy.

The bedform stability diagram of Van den Berg and Van Gelder (1993) does not have this disadvantage, because bedforms are plotted as a function of a grain shear stress–related dimensionless mobility number versus a dimensionless grain number. The mobility, or skin friction–related Shields parameter, is θ = τ/[(ρ_s - ρ) D_{50}], with D_{50} = median diameter of the bed sediment, g = gravitational acceleration, ρ_s - ρ = submerged density of sediment, and τ = grain-related bed shear stress. The grain, or Bon-

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**Table 3. Summary of the collected bedform, flow, and sediment data in the river Waal.**

<table>
<thead>
<tr>
<th>Date</th>
<th>Bedform Type</th>
<th>Discharge (m³/s)</th>
<th>Water Temp (°C)</th>
<th>Water Depth (m)</th>
<th>θ Transport</th>
<th>Dune Height (m)</th>
<th>Dune Length (m)</th>
<th>Dune Volume (m³)</th>
<th>Thickness of Transport Layer (m)</th>
<th>D₅₀ Transport (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>31-Oct-98</td>
<td>small dunes</td>
<td>3993</td>
<td>12</td>
<td>9.2</td>
<td>0.313</td>
<td>0.09</td>
<td>3.22</td>
<td>0.20</td>
<td>0.063</td>
<td>0.94</td>
</tr>
<tr>
<td>02-Nov-98</td>
<td>small dunes</td>
<td>5032</td>
<td>12</td>
<td>9.7</td>
<td>0.361</td>
<td>0.19</td>
<td>7.02</td>
<td>0.83</td>
<td>0.118</td>
<td>0.92</td>
</tr>
<tr>
<td>03-Nov-98</td>
<td>dunes</td>
<td>5741</td>
<td>11</td>
<td>10.2</td>
<td>0.489</td>
<td>0.39</td>
<td>8.69</td>
<td>1.87</td>
<td>0.215</td>
<td>0.74</td>
</tr>
<tr>
<td>05-Nov-98</td>
<td>dunes</td>
<td>6097</td>
<td>11</td>
<td>10.7</td>
<td>0.521</td>
<td>0.47</td>
<td>10.93</td>
<td>2.86</td>
<td>0.261</td>
<td>0.74</td>
</tr>
<tr>
<td>05-Nov-98</td>
<td>dunes</td>
<td>5891</td>
<td>11</td>
<td>10.5</td>
<td>0.577</td>
<td>0.50</td>
<td>12.37</td>
<td>3.41</td>
<td>0.276</td>
<td>0.61</td>
</tr>
<tr>
<td>07-Nov-98</td>
<td>dunes</td>
<td>5114</td>
<td>10</td>
<td>10.1</td>
<td>0.316</td>
<td>0.46</td>
<td>18.86</td>
<td>4.68</td>
<td>0.248</td>
<td>0.86</td>
</tr>
<tr>
<td>09-Nov-98</td>
<td>small dunes</td>
<td>4198</td>
<td>10</td>
<td>9.4</td>
<td>0.287</td>
<td>0.28</td>
<td>6.53</td>
<td>0.98</td>
<td>0.150</td>
<td>0.89</td>
</tr>
<tr>
<td>10-Nov-98</td>
<td>small dunes</td>
<td>3899</td>
<td>10</td>
<td>9.2</td>
<td>0.344</td>
<td>0.28</td>
<td>6.53</td>
<td>0.98</td>
<td>0.150</td>
<td>0.70</td>
</tr>
<tr>
<td>12-Nov-98</td>
<td>small dunes</td>
<td>3407</td>
<td>9</td>
<td>8.7</td>
<td>0.392</td>
<td>0.28</td>
<td>6.19</td>
<td>0.95</td>
<td>0.154</td>
<td>0.56</td>
</tr>
<tr>
<td>03-Nov-98</td>
<td>small dunes</td>
<td>3372</td>
<td>9</td>
<td>8.6</td>
<td>0.390</td>
<td>0.28</td>
<td>6.08</td>
<td>0.92</td>
<td>0.152</td>
<td>0.56</td>
</tr>
</tbody>
</table>

* D₅₀ of transported sediment determined from Helley-Smith bedload trap samples, averaged over the width of the river.

<table>
<thead>
<tr>
<th>Date</th>
<th>Bedform Type</th>
<th>Discharge (m³/s)</th>
<th>Water Temp (°C)</th>
<th>Water Depth (m)</th>
<th>θ Transport</th>
<th>Dune Height (m)</th>
<th>Dune Length (m)</th>
<th>Dune Volume (m³)</th>
<th>Thickness of Transport Layer (m)</th>
<th>D₅₀ Transport (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>03-Nov-98</td>
<td>small dunes</td>
<td>3372</td>
<td>9</td>
<td>8.6</td>
<td>0.390</td>
<td>0.28</td>
<td>6.08</td>
<td>0.92</td>
<td>0.152</td>
<td>0.56</td>
</tr>
</tbody>
</table>

**Table 4. Summary of flume and field data of flow, sediment, and bedform types from literature.**

<table>
<thead>
<tr>
<th>Author</th>
<th>Condition</th>
<th>Bedform Type</th>
<th>Approx. Water Temperature (°C)</th>
<th>Water Depth (m)</th>
<th>θ Transport</th>
<th>Thickness of Transport Layer (m)</th>
<th>D₅₀ Transport (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bennett and Bridge</td>
<td>flume</td>
<td>bedload sheets</td>
<td>25</td>
<td>0.074–0.076</td>
<td>0.103–0.116</td>
<td>0.004–0.005</td>
<td>2.18–2.32</td>
</tr>
<tr>
<td>Blom et al. (2000)</td>
<td>flume</td>
<td>dunes</td>
<td>18</td>
<td>0.155</td>
<td>0.093–0.094</td>
<td>0.006–0.008</td>
<td>1.34–1.36</td>
</tr>
<tr>
<td>Carling et al. (2000)**</td>
<td>field</td>
<td>dunes</td>
<td>unknown</td>
<td>2.7–6.65</td>
<td>0.078–0.211</td>
<td>0.051–0.099</td>
<td>0.9–9.7</td>
</tr>
<tr>
<td>Chiew (1994)</td>
<td>flume</td>
<td>dunes</td>
<td>unknown</td>
<td>0.17</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dinehart (1992)</td>
<td>field****</td>
<td>dunes</td>
<td>8–10</td>
<td>1.40–2.24</td>
<td>0.105–0.245</td>
<td>0.079–0.226</td>
<td>22–36</td>
</tr>
<tr>
<td>Horton et al. (2000)</td>
<td>flume</td>
<td>bedload sheets</td>
<td>25</td>
<td>0.172–0.181</td>
<td>0.168–0.264</td>
<td>0.002–0.002</td>
<td>0.55–0.88</td>
</tr>
<tr>
<td>Carling et al. (1993)</td>
<td>low-relief bedforms (small dunes)*</td>
<td>25</td>
<td>0.173–0.181</td>
<td>0.217–0.264</td>
<td>0.004–0.006</td>
<td>0.55–0.88</td>
<td></td>
</tr>
<tr>
<td>Dinehart (1992)</td>
<td>sand ribbons</td>
<td>25</td>
<td>0.139–0.142</td>
<td>0.119–0.221</td>
<td>0.004–0.007</td>
<td>0.57–0.78</td>
<td>0.78–2.78</td>
</tr>
<tr>
<td>Hirano and Ohmoto (1988)**</td>
<td>flume</td>
<td>sand ribbons</td>
<td>unknown</td>
<td>0.050</td>
<td>0.077</td>
<td>0.002</td>
<td>0.70</td>
</tr>
<tr>
<td>McLelland et al. (1999)</td>
<td>flume</td>
<td>sand ribbons</td>
<td>unknown</td>
<td>0.100</td>
<td>0.044</td>
<td>0.0005</td>
<td>0.87</td>
</tr>
</tbody>
</table>

* Low-relief bedforms and bars are here interpreted as small dunes.
** For additional data, Carling and Goelz (1993) was used.
*** In McLelland et al. (1999)
**** North Fork Toutle river
SEDIMENT SUPPLY-LIMITED BEDFORMS

FIG. 10.—Data on bedforms in non-uniform sediment plotted in the diagram of Chiew (1991). The $D_{50}$ and $D_{90}$ are determined from the bed sediment.

For the Chiew (1991) diagram (Fig. 10), streampower is plotted against the $D_{90}/D_{50}$ of the bed sediment. For the Chiew data it is assumed that the

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FIG. 9.—Data on bedforms in non-uniform sediment plotted in the Southard and Boguchwal (1990) bedform stability diagram for 10 C-equivalent quantities and subcritical flow conditions: A) Flume and field data, $D_{50}$ determined from bed sediment. B) Flume data, $D_{50}$ determined from transported sediment. C) Field data, $D_{50}$ determined from transported sediment. Labels for regions: I, no movement on plane bed; II, ripples; III, lower-plane-bed; IV, dunes; V, upper-plane-bed.
Fig. 11.—Data on bedforms in non-uniform sediment plotted in the Van den Berg and Van Gelder (1993) bedform stability diagram. A and B are flume and field data, respectively, $D_{50}$ and $D_{90}$ determined from bed sediment. C and D are flume and field data respectively, $D_{50}$ and $D_{90}$ determined from transported sediment.

sediment was lognormally distributed and the $D_{90} = D_{50} \sigma^{1.3}$, in which $\sigma$ is the Trask sorting as given by Chiew. The data mostly plot in the fields as indicated by Chiew, confirming his conclusion that the bedform stability is independent of sediment sorting.

The Van den Berg and Van Gelder stability diagram is given in Figure 11. Note that the $D_{50}$ and $D_{90}$ of the bed or transported sediment are incorporated in the Shields parameter related to grain roughness. In Figure 11A (flume) the bedform types plot in the correct stability fields, but the field data in Figure 11B plot extremely low in the lower-plane-bed field. In Figure 11C and D, in which the $D_{50}$ and $D_{90}$ of the transported sediment are used, the bedform types plot reasonably well within the correct bedform stability fields. The only exception is the Dinehart data, which apparently plots partly in the lower-plane-bed field. The sand ribbons plot in the lower-plane-bed field as well as in the ripple and dune fields. Again, the classification is successful when size parameters of the transported sediment (instead of the bed sediment) are taken.

Note that ripples from the Horton dataset (Table 4) would have plotted in the dune range at grain-sizes larger than 0.7 mm, whereas Costello and Southard (1981) noted that ripples do not exist for grain-sizes larger than 0.7 mm. Horton (personal communication) indicates that the ripples consisted of sand with grain-sizes smaller than 0.7 mm, which migrated over the other bedforms, as has often been observed in the flume experiments and in the Allier. Data on superimposed ripples in the dune regime have therefore been excluded from the diagrams.

There has been some discussion in literature about the nature of bedload sheets (e.g., Whiting et al. 1988; Iseya and Ikeda 1987; Bennett and Bridge 1995), particularly their relation with ripples or dunes. The bedload sheets and low-relief bedforms in the Bennett and Horton datasets plot in the dune fields. Dinehart (1989, 1992) and Whiting et al. (1988) observed bedload sheets that were superimposed on dunes. Just like the ripples of Horton, these sheets would also plot in the dune stability field because the bed is in the dune phase, but this does not mean that they are in the dune phase as well. Anyhow, bedload sheets seem not to be supply-limited because they do not occur when the coarser grains are immobile, and thus are probably not very relevant in the present discussion of supply-limited bedforms.
In conclusion, the extended bedform stability diagrams describe the observed bedforms in non-uniform sediment reasonably well, provided that the grain-size parameters are derived from the transported sediment instead of the bed sediment, bed surface, or substrate. This proviso is the consequence of the sediment-supply limitation. Bedload sheets and barchans plot almost without exception within the dune stability fields, whereas sand ribbons plot within the lower-plane-bed field, as well as in the ripple and dune stability fields. Thus the bedform stability diagrams have a limited predictive capacity to discriminate between the different bedform types in supply-limited conditions.

EFFECT OF THE SUPPLY LIMITATION ON BEDFORM MORPHOLOGY

Transitions between Types of Supply-Limited Bedforms

Until now the focus of this paper has been on the classification of sediment-supply limited bedform types. In reality, however, gradual transitions exist between these types. Barchans and transitional forms (here called barchanoids) to fully developed dunes plot in the dune stability fields of bedform stability diagrams, indicating that the sediment supply limitation determines the bedform morphology. It is interesting to note that barchan forms may occur in the ripple and in the dune stability fields. It suggests that this form is not limited to a certain bed state, but that a supply limit of sand may cause both a ripple and a dune to acquire a barchan form.

Sand ribbons are stable in both the ripple regime and the dune regime. Thus the dominant factor determining the occurrence of sand ribbons is a strong limit of the sediment supply, even more so than in the case of barchans.

The transitions are illustrated with the experiments. In experiment T4b the flow velocity and the bedform height are lower than in T4a. The bedforms in T4b became lower as a response to the lower flow velocity and water depth (flow-depth limitation). Thus sand became available for the transition from barchans to dunes (Fig. 12). The same principle lies behind the difference in bedform types between T5 and T9, which have almost equal flow velocities. In T5 there was not enough sand available for dunes because of the armor layer, so the type was barchanoid. In T7, however, much more sand was entrained because it was winnowed from the bed below the armor layer. In T9 this sand was still available, so the type was two-dimensional dunes.

To summarize (Fig. 12), the bedform type transitions are gradual, from barchans to barchanoids, to barchanoids with increasing slipface lengths, to dunes with barchanoid characteristics like crescentic slipfaces and tails, to dunes with irregular slipfaces, to more or less two-dimensional (transverse) dunes.

Prediction of Morphology of Sediment Supply-Limited Bedforms

The question now is how the bedform morphology in this continuum can be predicted, incorporating the sediment supply. Belderson et al. (1982) presented their semiquantitative model for the continental shelf with flow velocity as the only parameter. In decelerating flow the sand settled from suspension and the supply for bedload increased, leading to a development from ribbons to dunes. Thus the main factor is the sediment supply in disguise. In many riverine conditions, however, the reason for the sediment-supply limitation is not that all the sediment is suspended but that the sediment on the bed surface cannot be entrained. Therefore their qualitative model is not generally appropriate for rivers. The qualitative model of McKee (1979) illustrates the continuous sequence of subaerial transverse dunes to barchanoids to barchans with unidirectional wind and diminishing sand supply, but offers no quantification.

The problem might be approached by comparison with the uniform-sediment case. The available bedload transport predictors (e.g., Meyer-Peter and Müller 1948) for uniform sediment neglect the armoring which is the cause of the supply limitation. Therefore a comparison between predicted transport and measured transport will reveal whether the sediment is supply-limited. In Figure 13 the bedforms of the flume dataset (Kleinhans 2000) are plotted against the $\theta'$ (related to the grains of the transported sediment) and the ratio of predicted and measured (dimensionless) transport. For perfect supply-unlimited bedload predictions, the latter ratio is unity. The bedload transport was predicted with the Meyer-Peter and Müller (1948) predictor, on the basis of the (measured) transport sediment parameters and the $\theta'$ instead of the original $\theta$ combined with the original ripple factor (Kleinhans and Van Rijn 2002). The different bedform types are reasonably separated. So, if the sediment transport rate is predictable and the true transport has been measured, then the bedform type is predictable.

This is confirmed by Van der Zwaard (1974), who followed a comparable approach for determining the bedform-related flow roughness in the case of unimodal sand moving over an immobile coarse gravel layer. While increasing the sand feed-rate in a flume, a transition was observed of barchans to fully developed dunes for which the sediment transport and flow roughness were the same as in experiments without the gravel. From the measured sediment feed rate, Van der Zwaard was able to hindcast the flow roughness.

Unfortunately, this approach is impractical for the present purpose because the true transport rate must be measured. In the field, these mea-
measurements are difficult and expensive to do (Kleinhans and Ten Brinke 2001). A cheap mapping of the bedforms with echosounders would directly answer the question about bedform morphology. Moreover, the prediction of the sediment transport rate provides a problem in rivers with an armor layer, where the sediment supply is often unrelated to the local flow and bed sediment composition. Waves of sediment may propagate through the system, which are derived from sudden collapse of upstream river banks during floods and other non-steady and history effects. This almost erratic sediment supply can in no way be predicted.

As an alternative to the transport rate, the availability of sediment for the formation of bedforms could be expressed in a thickness of the transport layer. Roughly, this is the thickness of the layer of transported sediment that is obtained after distributing the sediment of the bedforms evenly over the bed. The thickness is computed by estimating the volume of sediment in each bedform, multiplying this by the fraction of the bed that is actually covered by the bedforms, and dividing the result by the total area in which the bedform dimensions were collected. For fully developed dunes that cover the armor layer, the volume per meter width (here equivalent to thickness of the transport layer) for regular triangular dunes is \( 0.5H \) (\( H \) = bedform height) by definition, and up to \( 0.7H \) for more convex dunes (e.g., Havinga 1983). Here, \( 0.55H \) is taken, assuming nearly triangular forms (Shinohara and Tsubaki 1959; Jinchi 1992). For plane-bed conditions the \( D_{90} \) of the bedload sediment was taken as the thickness.

The thickness of the transport layer does not alone determine the bedform morphology, because the water depth also was shown to have a large effect. A tentative approach is to rely on the relation between bedform height and flow depth, because most predictors of dune height depend on the flow depth in some way (Van Rijn 1993). As a first approximation the transport-layer thickness is simply divided by the water depth to obtain a dimensionless parameter for sediment availability. The flume and field datasets must then be considered separately, because dunes are higher in flumes (30% of flow depth as a rule of thumb) than in rivers (15% of flow depth).

A bedform-height predictor for uniform sediment might be applied to the same flow conditions, but such predictions are even more uncertain than the prediction of bedload transport. Furthermore, bedforms in non-uniform sediment plot correctly in bedform stability diagrams only if the parameters of the transported sediment are used instead of the bed sediment. We expect that using the transported sediment is also necessary for
SEDIMENT SUPPLY-LIMITED BEDFORMS

Fig. 15.—Conceptual explanatory (but not predictive) model for the occurrence of bedforms in sediment supply-limited conditions.

a correct prediction of bedform height, but that depends again on the unreliable prediction of bedload transport.

A plot (Fig. 14) of the dimensionless transport layer thickness \( TL^* \) (thickness divided by water depth) against the \( \theta' \) for transported sediment shows a reasonable division between the bedform types in flumes and in rivers. The barchans plot to the left of the dunes, and the sand ribbons are even farther to the left. Heights of both ripples, sand ribbons, and bedload sheets are unrelated to the water depth, which explains their scatter in the plot (Fig. 14A). The dunes of the Waal dataset plot in the barchan range (Fig. 14B), which is not correct. This deviation may have to do with the delayed response of large dunes to changes in the flow, because the dune height in the Waal dataset is much larger than in the other datasets.

Two alternative dimensionless parameters (not shown here) did not give any consistent outcome when plotted on the horizontal axis of Figure 14. The first was the transport-layer thickness divided by the \( D_{90} \) of the transported sediment, with the idea that the ripple and sand ribbon height might be related to the \( D_{90} \) of the sediment. The second alternative was the square of the \( D_{90} \) of the transported sediment divided by the product of transport-layer thickness and water depth, with the idea that the ripples and sand ribbons are related to the surface area of the grains (and the drag force that acts on that surface), and to low water depth combined with small transport-layer thickness.

A block diagram (Fig. 15) based on the \( TL^* \) against the \( \theta' \) is given to illustrate the bedform morphology as derived from visual observations in the flume experiments and the river Allier. This diagram is an explanatory but not a predictive model, because the \( TL^* \) is partly dependent on the mostly unpredictable upstream sediment supply. The upper bound \( TL^* = 0.2 \) is given by the maximum (equilibrium) height that a dune can attain in rivers, which is about 20% of the water depth.

In flume experiments and some rivers the sediment supply may be limited because of some (relatively weak) armoring, whereas with increasing flow velocities more sediment may be entrained to counteract the sediment-supply limitation. In other rivers with stronger armor layers that cannot be broken up, the sediment may be supplied only by upstream inputs like bank failures. Furthermore, sand stored in meander pools (and comparable areas in braided rivers) may be entrained by a small increase in discharge, forming a sand wave that provides the sediment for the local bedforms. In conclusion, armoring, sand storage in pools, and bank erosion may play roles to some extent in one and the same river. Only if these processes were fully understood and the boundary conditions well known, might a prediction of the sediment supply be feasible.

CONCLUSIONS

Sand ribbons and barchans are supply-limited bedforms that may occur frequently in rivers with non-uniform sediment, i.e., in flows below the critical threshold of motion of the coarser grains in or on the bed.

Bedform stability diagrams from the literature can be extended to coarser sediment. For bedforms in sediment mixtures, the particle parameters must be derived from the transported sediment instead of the bed sediment, as a consequence of the supply limitation of sediment.

The sediment-supply limitation determines the morphology of the bedforms. Sand ribbons occur both in the ripple and in the dune regime, and are extremely sediment supply-limited in the dune regime. With increasing sediment availability, barchans emerge, and then grow together into barchanoid dunes up to fully developed dunes. The sediment supply depends mostly on upstream sources and cannot be predicted from the local conditions of flow and bed sediment.

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REFERENCES


Belderson, R.H., Johnson, M.A., and Kenyon, N.H., 1982, Bedforms, in: Cultivation and Management (RIZA) and the Directorate Eastern Netherlands of Rijkswaterstaat in the Netherlands financed and carried out the measurements in the rivers Waal and Bovenrijn. The sand flume experiments were financed by (1) the Transport and Mobility of Researchers III program of the European Commission and (2) the consortium of Twente University, the Institute for Inland Water Management and Waste Water Management (RIZA) and WL/Delft Hydraulics. Joanne Horton (of Leeds University) is gratefully acknowledged for providing her data on bedforms in sand-gravel sediments and for discussions. Ward Koster, Gerrit Klaassen, Jan Alexander, John Southard, and an anonymous reviewer are thanked for their useful and stimulating comments.


Sinha, K., and Turbati, T., 1959, On the characteristics of sand waves formed upon the beds of open channels and rivers: Kyushu University, Research Institute for Applied Mechanics, report, p. 15-45.


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