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Opposite hysteresis of sand and gravel transport upstream and downstream of a bifurcation during a flood in the River Rhine, the Netherlands

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Abstract

At river bifurcations water and sediment is divided among the downstream branches. Prediction of the sediment transport rate and division thereof at bifurcations is of utmost importance for understanding the evolution of the bifurcates for short-term management purposes and for long-term fluvial plain development. However, measured sediment transports in rivers rarely show a uniquely determined relation with hydrodynamic parameters. Commonly a hysteresis is observed of transport rate as a function of discharge or shear stress which cannot be explained with the standard sediment transport predictor approach. The aim of this paper is to investigate the causes of hysteresis at a bifurcation of the lower Rhine river, a meandering river with stable banks, large dunes during flood, and poorly sorted bed sediment. The hydrodynamics and bed sediment transport were measured in detail during a discharge wave with a recurrence interval larger than 10 years. Surprisingly, the hysteresis in bedload against discharge was in the opposite direction upstream and downstream of the bifurcation. The upstream clockwise hysteresis is caused by the lagging development of dunes during the flood. The counter-clockwise hysteresis downstream of the bifurcation is caused by a combination of processes in addition to dune lagging, namely 1) formation of a scour zone upstream of the bifurcation, causing a migrating fine sediment wave, and 2) vertical bed sorting of the bed sediment by dunes with avalanching lee-sides, together leading to surface-sediment fining and increased transport during and after the flood. These findings lead to challenges for future morphological models, particularly for bifurcations, which will have to deal with varying discharge, sediment sorting in the channel bed, lagging dunes and related hydraulic roughness.

Keywords: bedload transport, bifurcation, hysteresis, sandy gravel-bed river, sediment sorting, suspended bed sediment transport

Introduction

Most predictors of sediment transport assume a unique relation between a flow parameter and the transport rate. Transports measured in the field, however, commonly differ much from predictors. One important source of systematic deviations is hysteresis of the transport rate, e.g. different transport rates occur before and after the peak discharge under similar hydraulic conditions, which is graphically visualised as an open loop in a plot of transport rate versus discharge. Hysteresis is defined as a clockwise loop if the sediment transport is larger before the discharge peak and smaller after the discharge peak, and vice versa for counter-clockwise hysteresis. A number of causes have been cited for hysteresis, commonly development of bedforms (e.g. Allen & Collinson, 1974, Ten Brinke et al., 1999, Wilbers & Ten Brinke, 2003) and armour layers (e.g. Reid et al., 1985, Beschta, 1987, Klaassen, 1991, Kuhnle, 1992, Garcia et al., 1999). Moreover, the sediment sorting created in antecedent discharge waves may be preserved to some extent and may thus influence sediment transport in the next discharge wave (Klaassen, 1991, Kleinhans, 2001, 2005a). This 'history effect' may cause hysteresis during a discharge wave, and may also cause considerable differences in transport between two discharge waves. Finally, upstream erosion during floods may create a sediment wave of fine sediment, of which the timing of passage may cause both clockwise and counter-clockwise hysteresis (e.g. Lisle et al., 2001). Note that explanations for wash load hysteresis are not applicable because such fine sediment is often limited in upstream supply related to hillslope processes; the present study is focussed on sand-size or coarser bed sediment which is abundantly present, even if immobile, in the river bed.

Here we present detailed measurements of bed sediment transport exhibiting extreme hysteresis. The data were collected during a large flood in 1998 at a bifurcation in the river Rhine where the bed sediment consists of sand and gravel and large dunes develop during floods. The relevance of transport hysteresis is considerable at this bifurcation, because a change in the sediment division over the bifurcates could cause morphological change and, consequently, a potentially runaway change in the discharge division (Wang et al., 1995, Bolla Pittaluga et al., 2002, Kleinhans et al., 2007, Schielen et al., 2007), affecting the downstream flooding and drought risks.

Until now, the dune dynamics, sediment transport and the hydraulic roughness were reported and well explained for the upstream river (Julien et al., 2002, Wilbers & Ten Brinke, 2003) but not for the major downstream bifurcate. The objective of this paper is to identify the mechanisms responsible for hysteresis of bed sediment transport at the eastern bifurcation of the Dutch Rhine. Data of two additional bifurcations in the Rhine, acquired much later, are analysed in Frings & Kleinhans (2007). We focus on the striking difference in transport hysteresis upstream and downstream of the bifurcation. First we introduce the field site and the data collection method. Then we present the data on flow conditions, sampled bed sediment transport and sorting in the river bed, and we validate the bedload transport measurement methods. Next we discuss three likely explanations for the observed hysteresis. The last subsections of the discussion are devoted to consequences for the stability of the bifurcation and to specific challenges derived from our interpretations for future modelling, as state-of-the-art modelling of bifurcations has captured only some of the observed phenomena (Bolla Pittaluga et al., 2002, Mosselman & Sloff, 2005, Kleinhans et al., 2007).

Measurement methods

Field site and general conditions

The lower river Rhine at the German-Dutch border is a large sand-gravel bed river with fixed banks and low sinuosity. The average discharge of the Bovenrijn is 2350 m^3/s, with peaks up to 12,000 m^3/s. The water surface slopes are of the order of 10^{-4} m/m. The river is heavily shipped, and the banks are protected with groynes.

The measurement area ranged from upstream to downstream of the bifurcation point Pannerdensche Kop, the Netherlands (Fig. 1), at which the upstream reach, the Bovenrijn, bifurcates into the Pannerdensch Kanaal (the minor bifurcate) and the Waal (the major bifurcate). The average bedload-transporting width of the river Bovenrijn between the groynes is 315 m, of

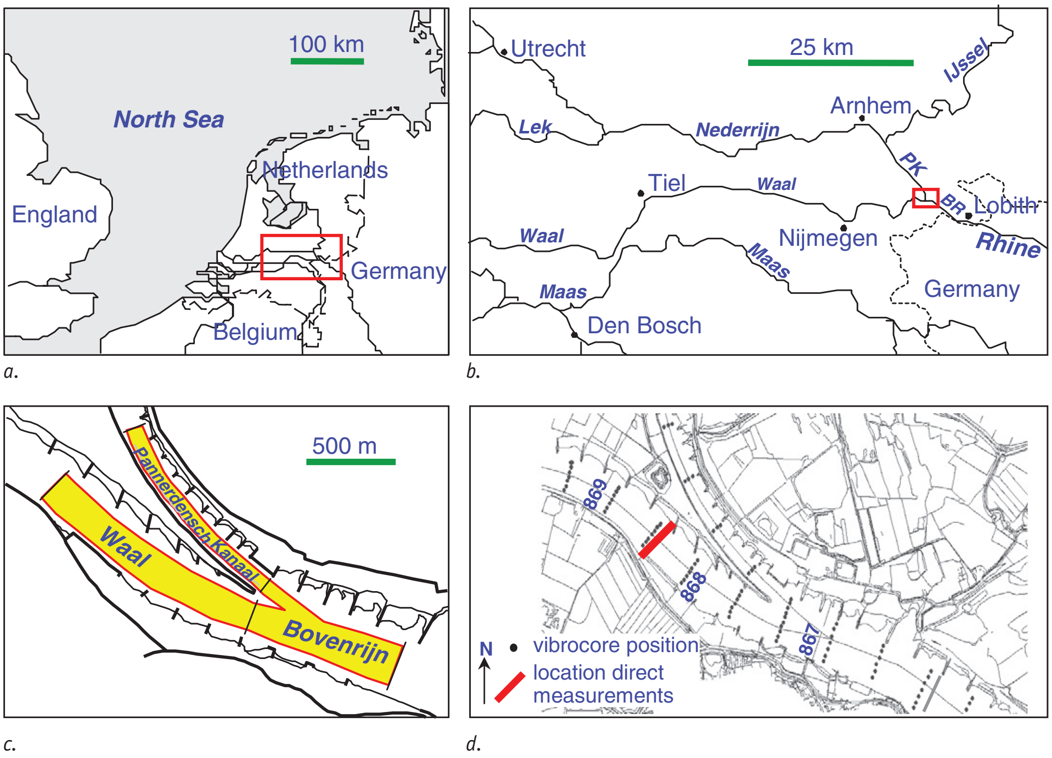

Fig. 1. Maps of the measurement positions of direct sampling of the sediment transport and flow in the river Waal, as well as the vibracore positions. The grey area in (c) was mapped with multibeam echosounders for dune-tracking. The numbers at cross-sections are river kilometres. BR = Bovenrijn, PK = Pannerdensch Kanaal.

the Waal is 247 m and of the Pannerdensch Kanaal is 115 m, and the water depth varies between 3 and 14 m at low and high discharges respectively. The Pannerdensch Kanaal discharges one-third of the water of the Rhine, and the Waal discharges two-thirds (Hesselink et al., 2006, Schielen et al., 2007). The sediment transport division is more asymmetrical: 90% of the bedload enters the Waal and 10% enters the Pannerdensch Kanaal (Wilbers et al., 2003, Wilbers, 2004, Frings & Kleinhans, 2007, this paper).

Process measurements

Flow and sediment transport measurements were done in October and November 1998 (Kleinhans, 2001, 2002, 2005a, Wilbers & Ten Brinke, 2003, Wilbers, 2004, Frings & Kleinhans, 2007). A maximum discharge of about 9600 m^3/s in the Bovenrijn, 6400 m^3/s in the Waal and 3200 m^3/s in the Pannerdensch Kanaal was reached on 5 November (Fig. 2), which has a recurrence interval of >10 years.

Direct sediment transport measurements with bedload and suspended load samplers were done in the river Waal at km 868.5 (Fig. 1), whereas the bedload transport was calculated from dune migration (dunetracking) in the upstream river reach and both downstream bifurcates (Wilbers, 2004). Bedload sediment is pragmatically defined as the sediment measured with a bedload sampler or the sediment moved by the migration of dunes. The two measures for bedload will be compared later. The instruments, the strategy of the direct measurements, data processing and accuracy of the resulting data are described by Kleinhans & Ten Brinke (2001). The details of the field data can be found in Kleinhans (2002, process measurements) and Wilbers (2004, bedforms).

The cross-section of the river was divided in 7 subsections centered at the river axis and 33 m, 67 m and 100 m from the axis at both sides following the guidelines of Kleinhans & Ten Brinke (2001). In each subsection, 20 bedload transport samples and 2 - 3 suspended sediment concentration profiles were collected (method described below), while the dunes migrated downstream approximately one dune length in that period. The sediment transport was integrated over the width of the channel with an uncertainty of the width-integrated transport rate of about 5 - 20%.

The bedload transport was sampled with an adapted version of the classical Helley-Smith bedload sampler: the Helley Smith for sand-gravel sediment (HSZ) (Kleinhans & Ten Brinke, 2001). The dimensions of the sampler orifice are the same as in the original: 7.62 cm wide and high. The mesh bag had a mesh diameter of 250 μm, which is smaller than the 10% diameter percentile of the bed material, and has a 500 μm patch on top near the orifice to prevent blocking by fines and organic material. The bedload transport sediment was collected and sieved to determine the grain size distributions. The calibration of the bedload sampler is a factor of 2.7 which is based on laboratory calibrations of our and the original Helley Smith samplers (Kleinhans, 2002). This factor indicates that the sampler undersamples the moving sediment and has a trapping efficiency of 1/2.7.

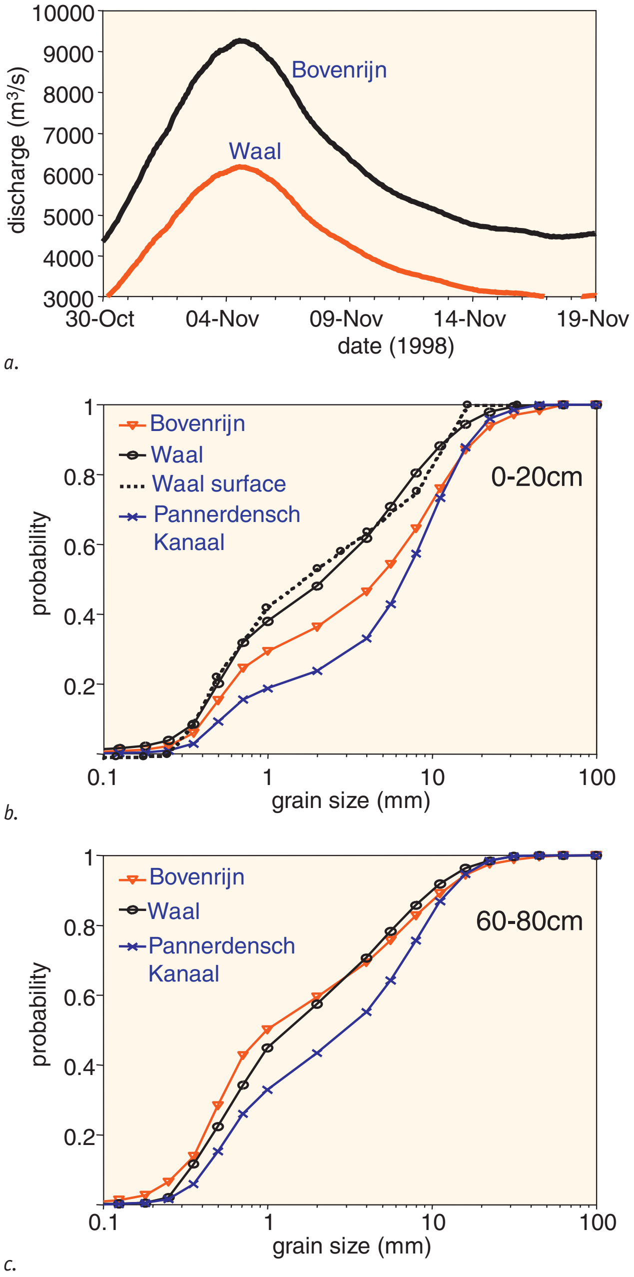

Fig. 2. a. The discharge wave. b. Average grain size distribution of the bed sediment of the Bovenrijn, Waal and Pannerdensch Kanaal at depths of 0 - 0.2 m. The Waal surface composition is the width-averaged data collected by Kleinhans & Ten Brinke (2001). c. Same, at depths of 0.6 - 0.8 m.

Echo soundings of the bed were done with a multibeam echo sounder in the river Bovenrijn and in the river Waal, yielding on average 10 - 15 points per m^2, fully covering the river bed that is shown in Fig. 1c (Wilbers, 2004). The soundings in the Pannerdensch Kanaal were done with a single-beam echo sounder (see Wilbers (2004) for a discussion of the comparability of the methods). The echosoundings were done twice a day to be used for one transport calculation for that day. Software especially designed to characterise dunes and their migration rates, was used to calculate bedload transport by dunetracking (Ten Brinke et al., 1999) for the whole width of the river in subsections of 1 m wide (10 m in the Pannerdensch Kanaal). The sediment transport was integrated over the width of the channel by summing the average transport of each subsection. The uncertainty of the cross-channel averaged sediment transport rates is calculated to be 10 - 20% (Kleinhans & Ten Brinke, 2001).

The flow velocity and suspended sediment concentration were measured simultaneously with an Acoustical Sand Transport Meter (ASTM): three times at the levels 0.2, 0.5 and 1 m above the bed, and one time at 2, 3, 4 m &c. above the bed up to the water surface. A pressure sensor in the ASTM was used to determine the water depth (h) and the height of the sensor. The suspended sediment transport was calculated by time-averaging the instantaneous (2 Hz sampled) product of velocity and concentration. The suspended transport was integrated between the top of the bedload sampler and the water surface for depth-integration. The suspended sediment was sampled with pump sampling close to the measurement volume of the ASTM. The sampling nozzle was directed into the current and the sampling flow velocity was 0.3 - 0.5 m/s. The grain size distribution was determined in a calibrated settling tube. Sediment finer than 0.063 mm was excluded because its abundance by weight in the bed sediment is far less than 1% while its settling velocity is very low, so it can be considered wash load. Kleinhans & Ten Brinke (2001) discussed the field calibration of the ASTM.

The water surface slope was measured daily with gauges several hundreds of metres upstream and downstream of the measurement location, and used for the computation of the total bed shear stress as $\tau = \rho ghi$ with ρ = density of water, g = gravitational acceleration, h = water depth and i = water surface slope. This reach-averaged total shear stress is affected by the roughness of the banks, groynes and the floodplain, and therefore is not an appropriate measure for local flow energy dissipation by dunes. Logarithmic velocity profiles ('law of the wall') were fitted to the measured vertical velocity profiles to obtain the shear velocity, which is related to the shear stress as $\tau = u^{*2}$. This is considered a more local measure of the shear stress than the depth-slope product. Although a logarithmic profile is only applicable to the lowest 20% of the flow (turbulent boundary layer), it was found to be an accurate description up to the water surface. Finally, the grain shear stress (related to skin friction), commonly used for sediment transport prediction (Van Rijn, 1984a,b), was calculated as $\tau' = \rho g(u/C')^2$, where u = depth-averaged flow velocity from the fitted profiles and $C' = 18\log(12h/k_s')$ is the empirical White-Colebrook equation to estimate the Chézy roughness, with k_s' = skin friction, here k_s' = D75 which is the 75% diameter percentile of the mass-distribution of bed grain size (Kleinhans & Van Rijn, 2002). For the discussion it is convenient to refer to the nondimensional grain shear stress, or sediment mobility (Shields number) defined as $\theta = \tau'/[(\rho_s-\rho)gD_{50}]$ with ρ_s = sediment density.

Vibracores

Vibracores were collected from the river bed of the Bovenrijn and Waal (Gruijters et al., 2001, Kleinhans, 2001) in the area where the sediment transport measurements of 1998 were done (Fig. 2). In each cross-section, 7 cores were collected at distances of 140, 100, 50 and 0 m off the river axis in the Bovenrijn, 100 m, 67 m, 33 m and 0 in the Waal and 35 m and 0 m in the Pannerdensch Kanaal. In the Bovenrijn and Pannerdensch Kanaal, this was done in 5 cross-sections and in the Waal in 6 cross-sections, all 400 m apart. Particle size analysis was done for samples taken from the cores at 0.0 - 0.2 m and at 0.6 - 0.8 m below the bed surface as available from Gruijters et al., presented in cross-sectionally averaged form here. Thinner layers sampled at heights based on visual classification of the sediment in the cores would have been preferred but are unavailable as the cores were sampled for other purposes. For comparison the cross-sectional average composition of the surface sediment will be shown (from Kleinhans & Ten Brinke (2001) who used a leaden bucket to scrape the sediment off the bed).

Results

The flow and sediment transport data are presented in Figs 2a, 3 - 5, 7 and 8. After 31 October – the start of the measurements – the whole bed of the Waal (major bifurcate) near the measurement position was covered with dunes that became larger as the discharge rose (Fig. 3a). The maximum dune height was reached 1 day after the peak discharge. From 6 November (during falling discharge) secondary dunes appeared superimposed on the primary dunes that were still present after peak discharge. The dune length of the primary dunes still increased up to its maximum on 7 November. After 7 November the secondary dunes were no longer destroyed as they arrived at the top and lee side of the primary dunes, and the primary dunes decayed. The dimensions of the secondary dunes decreased as discharge fell. On 19 November, the whole bed of the Waal was still covered with secondary dunes.

As in the Waal, the dunes in the Pannerdensch Kanaal (minor bifurcate) grew with the rising discharge (Fig. 3c). During falling discharge the dune height remained constant until 19 November when it had decreased near the threshold of observation (threshold defined by the echo sounding accuracy of about 0.05 m). The dune length on the other hand decreased gradually with decreasing discharge. It is not entirely clear whether the Pannerdensch Kanaal had secondary dunes. These appeared and took over the transport on 12 of 19 November.

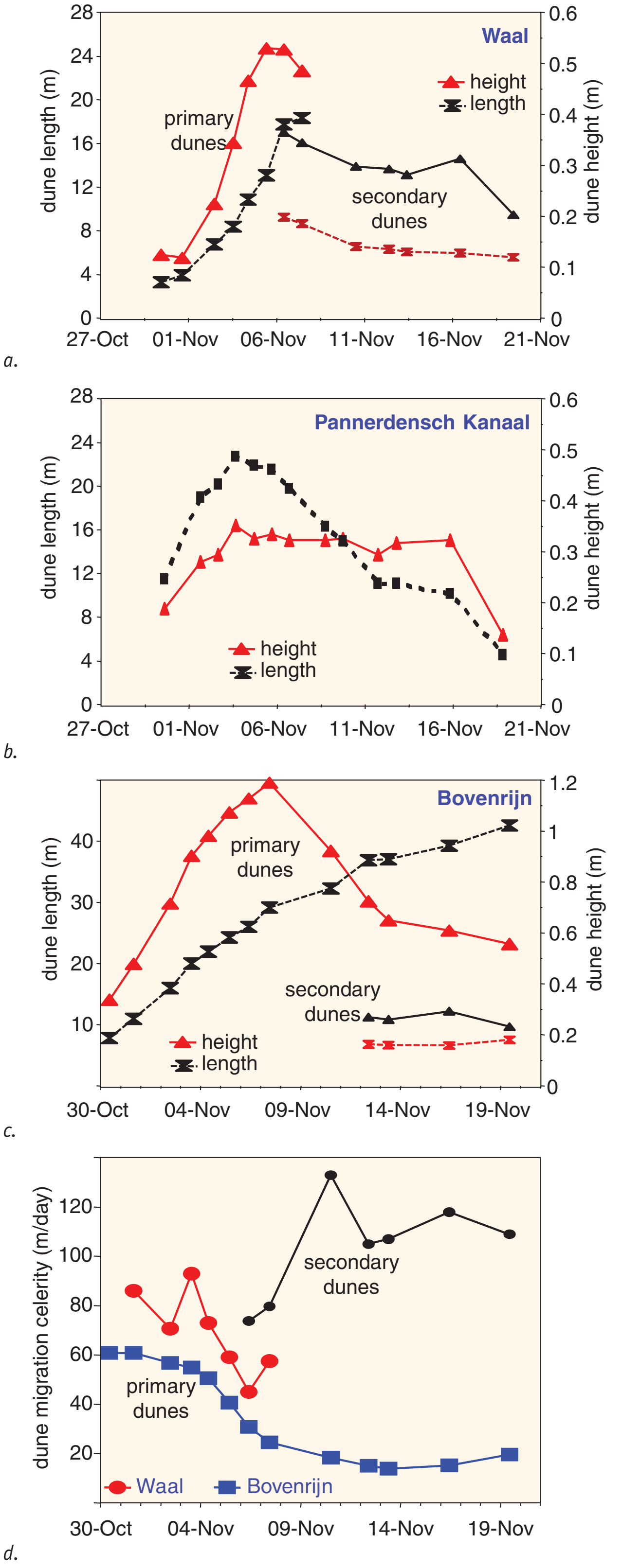

Fig. 3. Dune height and length in the river Waal (a), Pannerdensch Kanaal (b), Bovenrijn (c), and migration rate in Waal and Bovenrijn to illustrate contrast between primary and secondary dunes (d). Large symbols refer to the primary dunes, and small symbols to the secondary dunes. The error due to noise in the dune height is less than 0.1 m, while the standard deviation of the dune height is about 10 - 15%.

In the Bovenrijn (upstream river) dune development showed more or less the same temporal development as in the Waal (Fig. 3b). Contrary to the Waal bed, the bed of the Bovenrijn was already completely covered with dunes before 31 October. Apparently, the dunes formed and decayed when river discharge was below 4000 m^3/s, indicating larger sediment mobility than in the Waal. The maximum dimensions of the dunes in the Bovenrijn were reached 2 days after the peak discharge. The secondary dunes are destroyed at the lee side of the primary dunes until the end of the measurements.

The bedload transport rates in the river Waal measured with the HSZ and the dunetracking method are similar. Given the fundamental differences between the methods, this is a very good result. Both methods show the same trend of low transport at rising stages and higher transport at falling stages. However, the finer wiggles in the measured bedload transport rate trend are not significant.

The bedload transport versus discharge is counter-clockwise in the Waal and Pannerdensch Kanaal (Fig. 4), particularly in the Waal, while the hysteresis is clearly clockwise in the Bovenrijn. The bedload in the Waal at rising stages consisted of 60% sand and 40% gravel, while it became sandier during the discharge wave, with the sand content rising to 75% near the end of the discharge wave (Fig. 5a and b). The suspended sand transport in the Waal showed a clockwise hysteresis (Figs 5c and d) and was about 3 - 4 times as high as the bedload transport rate until the peak discharge and afterwards decreased rapidly in importance. The grain size distribution of the suspended sand shows some coarsening during the discharge wave, with the coarsest sediment transported in the falling limb. The suspended sediment had a median diameter of 0.3 mm and a slightly positively skewed lognormal distribution with a D95 below 0.8 mm.

The bed levels at the start and the end of the measurement period (Fig. 7) show significant erosion upstream of the bifurcation near river km 867, and deposition just downstream of the bifurcation and downstream of km 868 in the Waal (near the sediment transport sampling site).

The total bed shear stress in the Waal as determined from the product of water depth and slope shows no hysteresis against discharge. The water surface slope was larger before the discharge peak than after the peak due to the passage of the discharge wave, but this hysteresis was fully balanced by the opposite hysteresis in water depth. The total bed shear stress determined from the shear velocity on the other hand shows a complicated hysteresis (Fig. 8) with a clockwise hysteresis during peak discharge and counter-clockwise hysteresis after the discharge peak. The grain shear stress is smaller than the total shear stress as expected and shows a small clockwise hysteresis (Fig. 8).

The data derived from the vibracores are presented in Figs 2b, c and 6. The bed surface sediment (Fig. 2) of the Waal is finer than of the Bovenrijn. Both the surface and subsurface

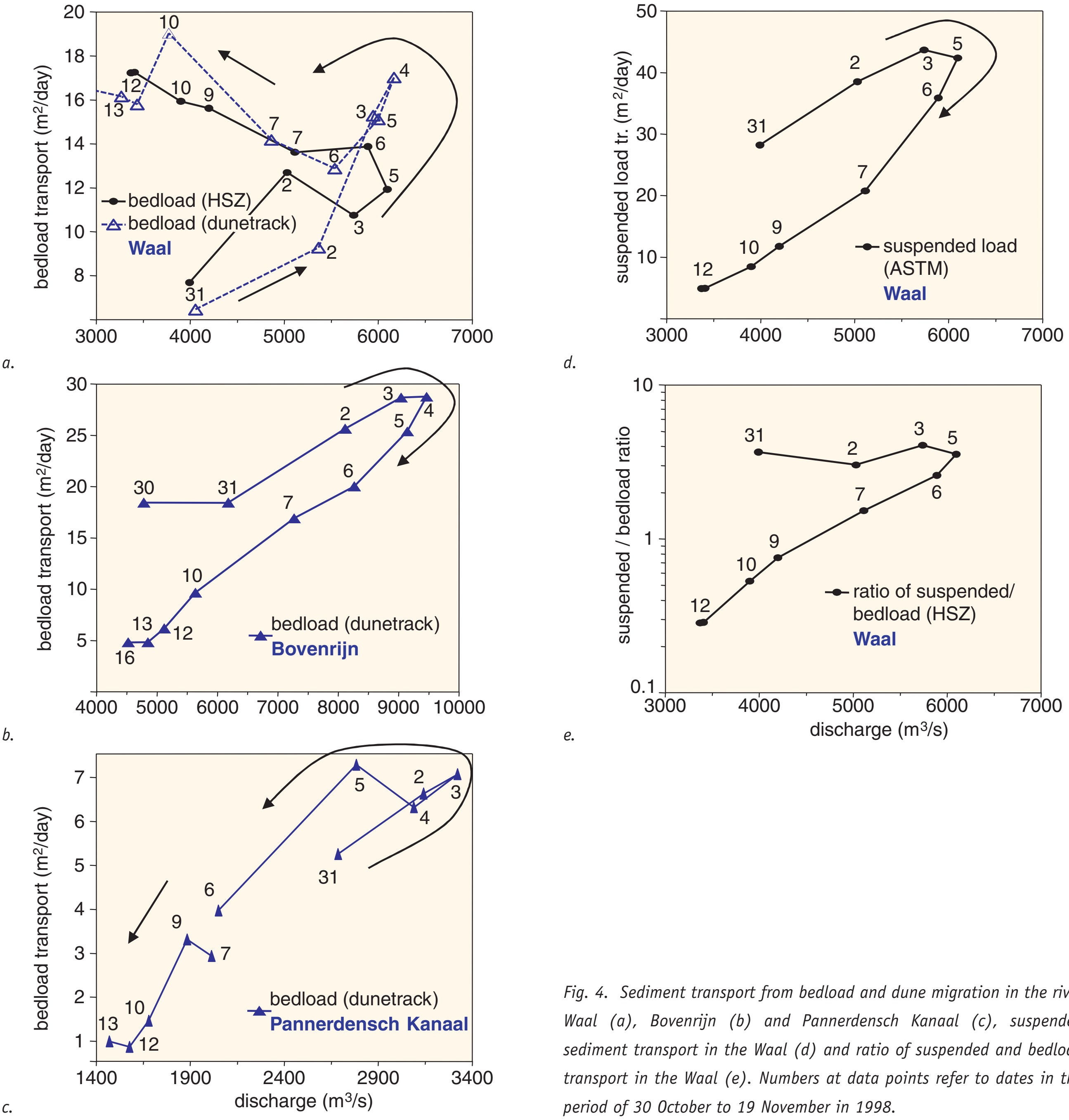

Fig. 4. Sediment transport from bedload and dune migration in the river Waal (a), Bovenrijn (b) and Pannerdensch Kanaal (c), suspended sediment transport in the Waal (d) and ratio of suspended and bedload transport in the Waal (e). Numbers at data points refer to dates in the period of 30 October to 19 November in 1998.

sediment of the Pannerdensch Kanaal is coarser than of the upstream Bovenrijn. This asymmetry in composition is caused by the meander bend-sorting just upstream of the bifurcation, so that the coarse outer-bend sediment enters the Pannerdensch Kanaal and the finer sediment enters the Waal, and by historical erosion of the Pannerdensch Kanaal into older subsurface deposits following its opening in 1707 AD.

Interpretation and discussion

First the likely combination of causes of the hysteresis of bedload transport are discussed (a conceptual addition of these effects is presented in Fig. 9). Other hypotheses for the explanation of the hysteresis were rejected by Kleinhans (2002). Next, the causes of hysteresis of the suspended load transport are discussed. Then, potential consequences of the observed processes for the stability of the bifurcation are addressed. The final part of the discussion is devoted to the shortcomings and challenges for mathematical morphological models.

Hysteresis of bedload transport

There are three crucial observations in the data which indicate the causes of hysteresis of bedload:

1. the bedload transport in the river Waal becomes much sandier during falling stages;

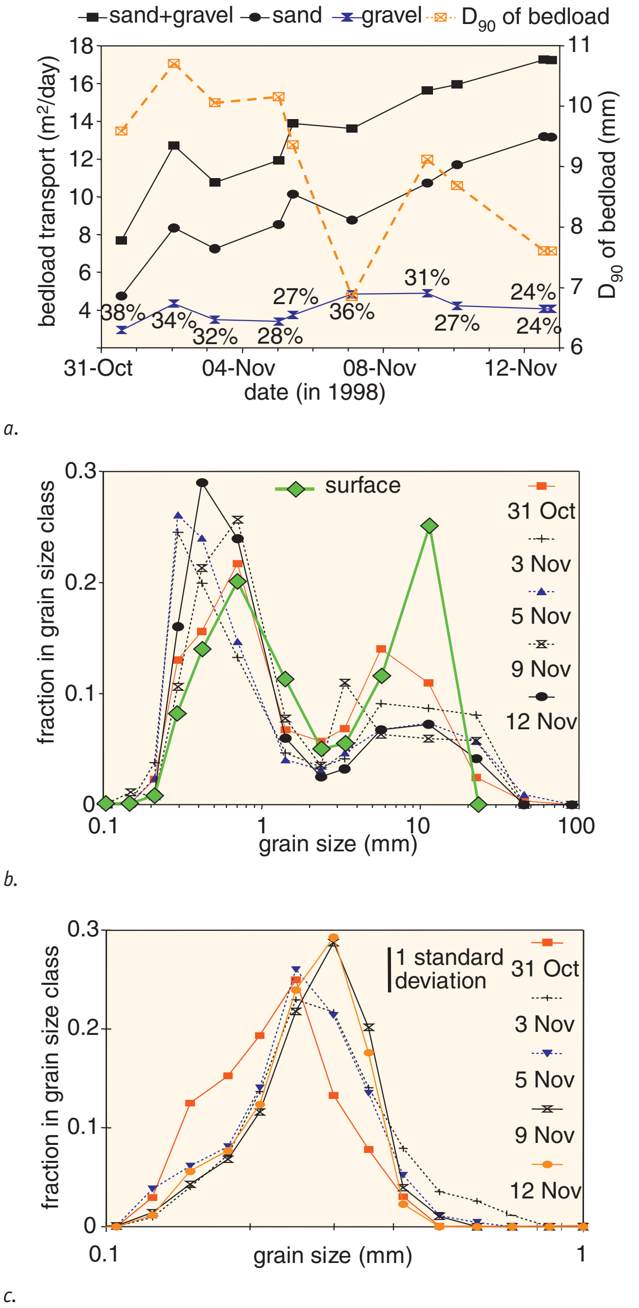

Fig. 5. a. Bedload transport in the river Waal by the HSZ, and the D90 of the bedload sediment. The percentages refer to the precise gravel fraction. b. Grain size distributions of the bedload sediment. 'surface' refers to the surface bed sediment composition determined by Kleinhans & Ten Brinke (2001) (also shown in Fig. 2b). c. Grain size distributions of the suspended load sediment.

2. hysteresis of bedload transport against discharge in the Waal (major bifurcate) and Pannerdensch Kanaal (minor bifurcate) is opposite to that in the Bovenrijn (upstream river), while this hysteresis in the Bovenrijn and in the Pannerdensch Kanaal is less pronounced than in the Waal; and
3. the bed erodes in the Bovenrijn and this sediment partly migrates downstream into the Waal where aggradation takes place.

Three mechanisms may explain the observed hysteresis:

1. the temporal varying hydraulic roughness and grain shear stress due to lagging dune height;
2. the vertical sediment sorting process by dunes causing the bedload sediment to fine after the discharge peak; and
3. erosion of a fine-grained area in the Bovenrijn every flood and subsequent filling during low flow, supplying a fine-sediment wave to the Waal.

We will argue that none of these three mechanisms can alone explain the observations, but they are not mutually exclusive and it is very likely that they act together (Fig. 9). These hypotheses will be tested elsewhere on new data of two additional bifurcations in the Rhine river (Frings & Kleinhans, 2007).

Hysteresis due to lag in dune height development

Turbulence generated by dunes is in fact a dissipation of the flow energy at the expense of the energy available for bedload transport (Van Rijn, 1984a, McLean et al., 1999). The energy that is available for bedload transport is the difference between the total energy (total bed shear stress) and the dissipated energy by dunes. In general, higher dunes are hydraulically rougher and therefore generate more turbulence (Julien et al., 2002, see review in Wilbers, 2004).

Large dunes adapt slowly to changing flow conditions, simply because it takes time to transport the large volumes of sediment involved. Consequently the dune height is larger after the discharge peak than before (Figs 2a, 3b). This is even more the case for the dune length (Figs 2a, 3b), which continues to increase until the dunes have disappeared (Wilbers & Ten Brinke, 2003). The celerity of the dunes is inversely related to their height (Fig. 3c) (Wilbers, 2004), which has been observed in many rivers (e.g. Allen & Collinson, 1974).

The dunes in the Bovenrijn are larger after the discharge peak than before the peak (Figs 2, 3b). If the dune-related

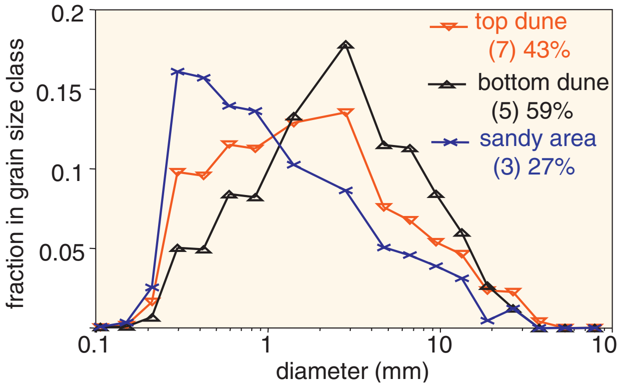

Fig. 6. Grain size distributions of selected samples of the sediment in the top and base of dunes in the Waal, and the fine surface sediment in the scour area of the Bovenrijn. Number of samples between brackets; gravel (>2 mm) percentage indicated.

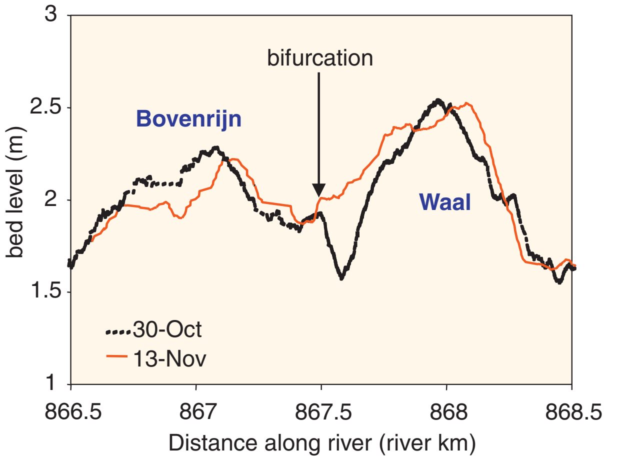

Fig. 7. Width-averaged bed level development (above arbitrary datum) during the discharge wave. Note the scour area in the Bovenrijn.

shear stress is indeed larger after the peak, then it is expected that the bedload transport is large before the discharge peak and small after (clockwise hysteresis). This is indeed the case in the Bovenrijn (Fig. 4b) (Wilbers & Ten Brinke, 2003).

The opposite hysteresis is observed in the Waal and Pannerdensch Kanaal just downstream of the bifurcation (Figs 2a, 3a, 4a). In the Waal, this is correlated with the early decay of the primary dunes (compared to the Bovenrijn dunes) and the dominance of the secondary dunes after the discharge peak. This means that there is no significant flow separation at the lee-side of the primary dunes and therefore the hydraulic roughness of the primary dunes is negligible. As the development of the secondary dunes is delayed, they are still small so their roughness is small. As a consequence, their celerity is large (Fig. 3c), the dune-related shear stress is smaller and the bedload transport is larger after the discharge peak than before in the Waal (Figs 4a, 9b). In the Pannerdensch Kanaal the dune dimensions decreased more rapidly after the discharge peak, presumably because they were smaller than elsewhere during the peak. The presence of primary dunes is questionable, and in agreement with the hypothesis discussed above the hysteresis in bedload transport is much less pronounced than in the Waal.

Based on this hypothesis, the calculated grain-related shear stress in the Waal should be larger after the discharge peak than before. Surprisingly, the reverse is true (Fig. 8) because the flow velocity is larger before the discharge peak than after the peak. However, the grain roughness was assumed constant, but in reality is likely to decrease in reality (decreasing the grain shear stress as well) because the bed surface sediment (in the dunes and captured in the bed load sampler) fined in time. However, the correct separation of grain and bedform related shear stress from the total shear stress still provides an important challenge so our reasoning may be flawed. Nevertheless, the opposite sediment transport hysteresis in the Bovenrijn and the Waal clearly correlates with the differences of development lag of dune height and timing of emergence of the secondary dunes between the Bovenrijn and the Waal.

Hysteresis due to vertical sediment sorting and bed sediment fining

The bedload sediment in the Waal became finer in the course of the discharge wave. Since finer sediment is more easily transported than coarse sediment, this fining will have contributed to the pronounced hysteresis in the Waal. The fining in the bed is caused by vertical sorting of sediment in dunes, combined with the decay of the dunes The sediment is sorted vertically in the process of grain flowing at the lee side of the dunes, and in the dune troughs additional sorting takes place by winnowing of fines. As a result, coarse sediment is present in the lower part of the dunes while fine sediment is in the higher part of the dunes. When dunes decrease in height, the coarser sediment is left increasingly immobile below the active sediment layer (Kleinhans, 2001, 2002 Chapter 10, 2005a,b). The burying and immobilisation of gravel happens particularly in the major bifurcate where the large dunes immobilise while small superimposed dunes only rework the finer sediment in the tops of the large dunes (Fig. 9c). Since sandier sediment is more easily transported, this may lead to larger sediment transport after the peak, that is, counter-clockwise hysteresis.

Gravelly layers were indeed identified in the vibracores at depths of more than 0.5 times the maximum height of the dunes formed in the discharge waves of 1995 and 1998 (Kleinhans, 2001, 2005a). Also the grain size data clearly indicate upward fining (Fig. 6, gravel % in legend). Of the available grain size data (Gruijters et al., 2001), only the samples that coincided with gravelly layers and fine overlying sediment were selected (number of samples given in legend of Fig. 6).

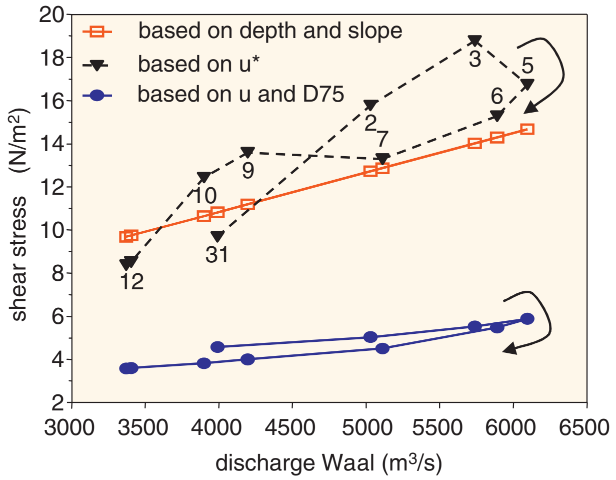

Fig. 8. Estimates of the shear stress from the regional depth-slope product, the local shear velocity and the depth-averaged velocity combined with an estimate of the grain-related roughness.

The effect of sediment fining on bedload transport has been estimated by Kleinhans (2001, 2005a) based on the Kleinhans & Van Rijn (2002) sediment transport predictor for sand-gravel mixtures. The sediment transport rate in waning flow was predicted 27% larger with the upward fining effect than without. However, the observed hysteresis is still much larger than predicted with the fining, whereas the gravel abundance of the predicted bedload transport is still smaller than in reality. Moreover, vertical sorting was found in the Bovenrijn as well, while the hysteresis in the Bovenrijn occurred in the opposite direction. Yet, the general sediment mobility in the Waal clearly is smaller than in the Bovenrijn so the coarse sediment detrainment was probably more significant in the Waal (Fig. 9c). We conclude that vertical sorting plays a significant role in the hysteresis and fining of bedload transport in the Waal but that it cannot alone explain the observations fully.

Hysteresis due to unsteady morphological change by size-selective transport

A scour zone developed in the Bovenrijn (km 866.7 - 877.2) at high discharge (Fig. 7). Contrary to the mechanisms of lagging dunes and sediment sorting by dunes, this mechanism is entirely caused by boundary conditions, namely a constriction of the channel or locally concentrated outflow from the northern embanked floodplain. This will have happened in previous discharge waves as well, and later the scour zone gradually filled in with the fine sediment that is mobile in low flow. The vibracores (Gruijters et al., 2001) at kms 866.5 and 866.9 indeed contain sandy deposits at or just below the surface (Fig. 6). So, when the event repeats itself in subsequent discharge waves, relatively fine sediment is released during peak discharge. The fine sediment wave will migrate downstream and disperse (Lisle et al., 2001). With an increasing downstream distance from the source, clockwise to counter-clockwise hysteresis will be observed depending on the time of arrival and migration celerity of the sand wave at the observation site. A good estimate of the sediment celerity is that of the dunes. The total distance that the dunes travelled from 31 October to 12 November was about 2000 m. This means that the potential source area for sediment arriving at the measurement location could be located up to 1 km upstream of the bifurcation. This mechanism may therefore have caused part of the hysteresis; clockwise in the Bovenrijn and counter-clockwise in the Waal (Fig. 9d).

The fate of the sand wave is further determined by the bend sorting just upstream of the bifurcation, where finer sediment is deflected towards the inner-bend to which the major bifurcate is connected. The sediment mobility in the major bifurcate is smaller than in the upstream reach, so that the transport rate decreases and the sand accumulates, in this case at the measurement location in the major bifurcate (Fig. 7).

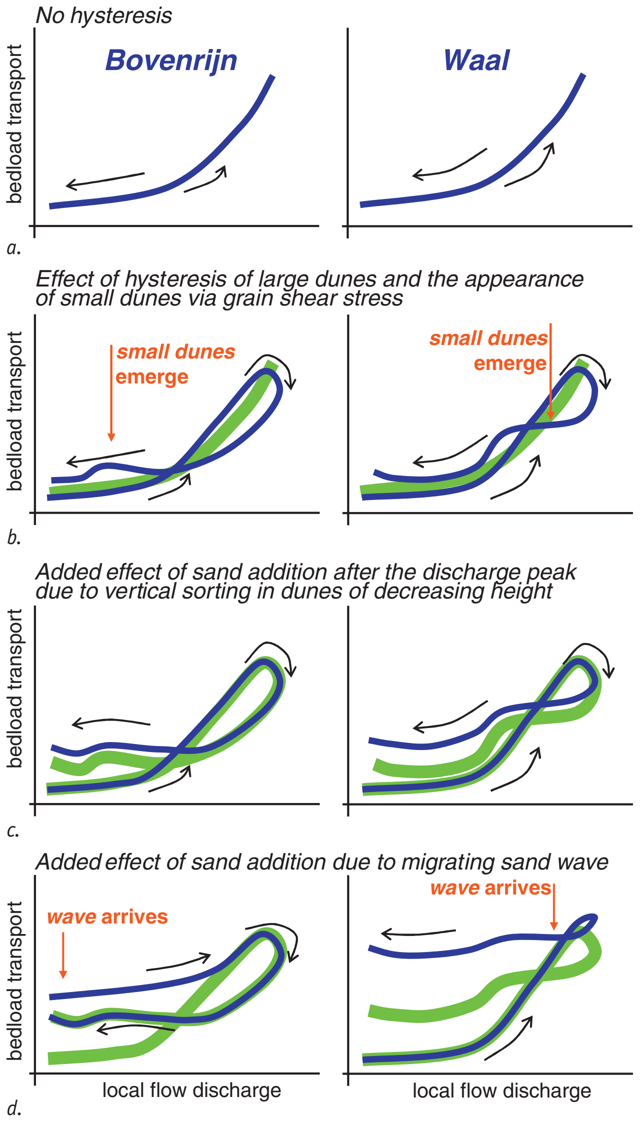

Fig. 9. Sketched relations between bedload transport and discharge illustrating the added effects of the discussed mechanisms on hysteresis in the Bovenrijn (upstream river) and Waal (major bifurcate). The Pannerdensch Kanaal is similar to the Waal except that the fine sediment wave (d) does not arrive here because of bend sorting, and that the existence of secondary dunes (b) is uncertain. The fat green lines in b - d are copies of the blue lines in a - c to illustrate the effect of adding a mechanism.

Hysteresis of suspended load transport

The suspended load transport in the major bifurcate was observed to have a significant clockwise hysteresis. This is opposite to, and less pronounced than the hysteresis observed in the bedload transport rates in the Waal. This is a counter-intuitive result, because so far we argued that the increasing sand content lead to counter-clockwise hysteresis of the bed-load transport.

A suspended load transport predictor like that of Van Rijn (1984b) is based primarily on the shear velocity for the Rouse suspension number, and also on the grain shear stress for sediment entrainment (reference concentration near the bed). Hence the suspended bed material transport rate depends in a complicated way on both near-bed conditions, grain size and general flow conditions. The measured suspended load transport followed the pattern of the grain shear stress based on D_{75} grain roughness. Also the total shear stress as based on the shear velocity largely followed a clockwise trend for Waal flow discharges above 4000 m^3/s (Fig. 8). The Van Rijn model therefore predicts the same hysteresis trend as measured (not shown here), which indicates that the observed trends in shear stress explain the observed trend in suspended load transport. However, the absolute magnitude of the suspended transport prediction by the Van Rijn model differs from the observations and the predicted hysteresis is less pronounced. One reason for this is, as in the bed load prediction, that the bed surface sediment composition from which the suspended sediment is derived was not varied in time. The shear stress based on flow velocity profiles has a counter-clockwise hysteresis in the final part of the discharge wave (Fig. 8), but apparently this is counteracted by the (clockwise) decreasing grain shear stress so that the suspended transport trend remains clockwise.

We conclude that the hysteresis of suspended load transport is explained partly by the observed flow dynamics. The explanation, in turn, of the hysteresis in shear stress is clearly related to the dune evolution during the discharge wave as discussed above.

Bifurcation stability

In view of planned modifications to the Rhine branches in the Netherlands for flood risk mitigation, understanding of bifurcation dynamics is urgently needed. Stability analyses by Wang et al. (1995) and Bolla Pittaluga et al. (2002) suggest that bifurcations can both be stable and unstable. Bifurcations become unstable when the sediment division over the bifurcates differs from the discharge division. As a result, the sediment supply to the bifurcates does not match the sediment transport capacity in the bifurcates so that one bifurcate deepens (and widens in the absence of bank protection) while the other shallows. Kleinhans et al. (2007) found that even very gentle meander bends just upstream of a bifurcation have a strong unbalancing effect, because flow is mostly conveyed through the outer bend whereas the sediment, particularly the finer sediment, is deflected towards the inner bend. In this paper we show the importance of upstream unsteady morphodynamics and sediment sorting dynamics, in this case causing a fine sediment wave that, at the bifurcation, is mostly routed into the major bifurcate due to bend sorting processes. This analysis would predict that the Pannerdensche Kop bifurcation is unstable, but observations show that the bifurcation has been stable for more than 200 years (Hesselink et al., 2006). There are two potential explanations for this contradiction.

First, Kleinhans et al. (2007) demonstrated that the upstream bend effect can be counteracted by a downstream slope difference. The bifurcate connected to the upstream inner bend is prone to closure, but if its gradient is larger this may compensate for the larger sediment input with a larger sediment mobility. As a result the bifurcation can remain quasi-stable for hundreds of years. However, in this case the other bifurcate (Pannerdensch Kanaal) has a larger gradient, so that an unbalanced bifurcation is expected. Moreover, their model does not account for sediment mixtures (see next section).

Second, Bolla Pittaluga et al. (2002) show that bifurcations can also be stable if the sediment in one bifurcate is generally immobile. Allowing for simplifications in their model, this may represent the condition of the minor bifurcate. The sediment mobility in the bifurcates and upstream reach clearly differed. For the upstream reach and the minor bifurcate no measured flow data are available but the dune dynamics and the bedload transport rates are indicative. The appearance and disappearance of the dunes in the minor bifurcate at a discharge (in the Bovenrijn) of about 5000 m^3/s, and the overall much lower sediment transport rates per unit width both indicate a sediment mobility near the critical Shields value (confirmed in more detailed analyses in Frings & Kleinhans, 2007). The mobility in the Waal is higher and that in the Bovenrijn the highest. One obvious reason of differing mobilities is that the combined downstream width of the bifurcates is larger than the upstream channel width. Additionally, the much lower sediment mobility and transport rate in the Pannerdensch Kanaal is caused by the much coarser sediment in the bed. In short, the sediment in the Pannerdensch Kanaal is immobile during most of the time except during relatively large floods, while the sediment transport rates in the Waal are considerable. Two-thirds of the discharge is conveyed throught the major bifurcate, while it conveys 90% of the sediment delivered by the Bovenrijn (Wilbers et al., 2003, Wilbers, 2004, Frings & Kleinhans, 2007). Thus the bifurcation may be stable because the sediment in the minor bifurcate is nearly immobile (see also Sloff & al, 2001).

If this is true, it has implications for future flood risk mitigation works in view of climate change in the hinterland of the Rhine. Schielen et al. (2007) describe how acceptable flooding risks are proposed to be divided over the downstream Rhine branches by controlling the distribution over the bifurcates of extreme flood discharges. Controlling the discharge division allows the accommodation of different demands and risk levels along the downstream branches. More importantly, the discharge division can not only be controlled by the planform and morphology of the bifurcation, which is impractical, but also through backwater effects from obstructions (or removal thereof) in the bifurcates. At present, 2D flow model calculations suggest that the Pannerdensch Kanaal will receive too much flow during an extreme event so this has to be changed by adjustable spillways (see Schielen et al., 2007). They further infer that the morphology will hardly be affected by the spillways because extreme flood events occur infrequently and because the river bed is armoured in many places. From our results we infer, in contradistinction, that large floods are potentially much more important than their magnitude versus frequency suggests. Under high shear stress the coarse gravel of the Pannerdensch Kanaal will be mobilised and transported in dunes. During extreme floods the dunes may become so large that they excavate deeper sediment layers with different compositions (as Schielen et al. remark elsewhere in apparent contradiction to their earlier statement and as based on the work of Gruijters et al. (2001), Blom & Parker (2004) and others). This is potentially amplified by bed degradation and by the dynamic response of the bed in meander bends to floods (Sloff et al., 2001). It is at present nearly impossible to predict the morphodynamic and sedimentological response to these processes, but there is a risk that large floods unbalance the bifurcation by entraining coarse sediment of the minor bifurcate. If that were to happen, the minor bifurcate would erode, convey more discharge and potentially undercut the bank protection works. It is therefore fortunate that future engineering works are aimed at decreasing flood discharge through the Pannerdensch Kanaal for other reasons (mentioned in Schielen et al., 2007). To progress beyond the stage of hypothesis, more quantitative and detailed understanding of dynamics of bifurcations with sediment mixtures in the channel bed is urgently needed, to be tested on the actual measured sequence of events at the Rhine bifurcation in 1998 and to be used for robust explanation and prediction.

Mathematical modelling challenges

The observed hysteresis in sediment transport upstream and downstream of the bifurcation is caused by mechanisms that strongly affect the morphology, the sediment division and composition thereof at the bifurcation. The outcome of the complex interactions between the mechanisms cannot be comprehended without a mathematical model for morphodynamics, but unfortunately several essential processes are not yet included in the available models (e.g., Sloff et al., 2001; Blom & Parker, 2004; Mosselman & Sloff, 2005; Kleinhans et al., 2007; Frings PhD thesis, in prep.). Specifically, challenges for future morphodynamic models relevant to bifurcation issues in the Netherlands are vertical sorting, varying discharge, lagging dunes and related hydraulic roughness.

To start with the latter, hysteresis in dune development is usually not considered in mathematical models. This could be done based on an adaptation time scale calculated from the sediment volume involved in changing the dune height compared to the sediment transport rate (Allen, 1976). Furthermore, the relation between hydraulic roughness and the dune dimensions needs to be included in such a way that the hysteresis of roughness indeed follows from a relevant parameter, but which parameter and what relation is unknown because the hydraulic roughness of growing and decaying and superimposed dunes is poorly understood.

To predict sediment transport of mixtures, a continuous sorting model is imperative (Blom & Parker, 2004) in contradistinction to a simpler active layer model (Hirano, 1971) which simplifies the dune sorting too much to represent the observed mechanisms. In poorly sorted sediment, two counteracting adaptations take place in response to changing shear stress: morphological change and grain-size change. For an increased shear stress, a meandering river may increase the bar height and pool depth, but may also increase the grain size in the surface layer which dampens the morphological change (Dietrich & Whiting, 1989, Mosselman & Sloff, 2005). In duned beds the situation is even more complicated: the dunes entrain and deposit sediment from various depths depending on their trough-depth distribution, while dune height is affected by the local water depth in the bends. The presence of coarse or fine layers at deeper trough levels thus leads to a change in surface bed composition, in addition to the dune sorting effects explained earlier. The presence of meander bends and bars will considerably affect the sediment dynamics but how has not experimentally been studied in flumes large enough for significant dunes. To cover the morphodynamics, the size-selective transport and mobility variations and the dune heights and hysteresis, the discharge must obviously be varied during a model run (e.g., Parker et al., 2005).

To complicate things further, the composition of the sediment supplied upstream strongly affects the sediment sorting and transport process downstream (Kleinhans, 2005b). Therefore morphological models should not only be validated for bed level (change), but also for grain size composition (change). Consequently, the specification in models of upstream sediment supply and composition thereof cannot simply be based on measurements only; it is intricately coupled to the modelled morphological and compositional change.

Conclusions

During a flood in the Dutch River Rhine, striking hysteresis was observed in the measured bedload and suspended bed material transport rates upstream and downstream of an asymmetrical bifurcation with poorly sorted bed sediment. Upstream of the bifurcation the hysteresis of bedload transport plotted against discharge is clockwise whereas downstream it is counter-clockwise, particularly in the major bifurcate. The bedload sediment in the major bifurcate fined considerably during the flood. Three combined mechanisms likely explain the opposite hysteresis pattern in sediment transport: 1) the effects of lagging dune height development and emergence of secondary dunes on hydraulic roughness and grain shear stress; 2) the vertical sediment sorting process by dunes causing the bedload sediment to fine after the discharge peak; and 3) a migrating fine sediment wave originating from a persistent scour zone.

1. The primary dunes lag behind the changing discharge, become relics and then secondary dunes appear. This happens late in the upstream reach but early in the major bifurcate relative to the peak discharge because of the lower sediment mobility (due to the larger added river width downstream of the bifurcation). Since small dunes have a small roughness, the shear stress on grains is relatively large so that the bedload transport increases in the major bifurcate (counter-clockwise hysteresis), whereas the larger dunes in the upstream branch cause smaller bedload transport after the discharge peak (clockwise hysteresis).
2. Dunes and selective transport cause upward fining sorting of the bed sediment. The sorting leads to sandier sediment transport after the peak discharge because the gravel is immobilised below the retracting dune troughs, especially in the major bifurcate where the large dunes become inactive. Since sand is more easily transported, this leads to larger sediment transport after the peak (counter-clockwise hysteresis).
3. Erosion in the upstream reach releases the fine sediment that accumulated there in a previous discharge peak (and will accumulate again after the new discharge peak). This fine sediment migrates about 2 km with the dunes during one event and is preferably deposited in the major bifurcate because the sediment mobility is lower, leading to clockwise hysteresis in the upstream branch and counter-clockwise hysteresis in the downstream branch.

The suspended sand transport in the downstream branch shows a clockwise hysteresis, contrary to the bedload transport, because the shear velocity, which determines the suspension rate, has a clockwise hysteresis due to lagging dunes with its effect on hydraulic roughness. As a result, it is about 3 - 4 times as high as the bedload transport rate until the peak discharge but rapidly decreases in importance afterwards.

The division of sediment transport over the bifurcates is more asymmetrical than the division of flow discharge, which would lead to an unstable bifurcation, but the bifurcation is stable because the sediment in one of the bifurcates is nearly immobile except during large floods. Mobilisation of this sediment potentially unbalances the bifurcation which would greatly increase flooding risks in one of the bifurcates. In accidental agreement with policy, our results suggest that future modifications of the discharge division should decrease the flood discharge through bifurcate with the immobile sediment to reduce entrainment.

It is not yet possible to test the combined mechanisms in state-of-the-art morphological models. Anticipated experiments and model improvements should focus on the vertical sorting process by dunes and horizontal sorting in bends in varying discharge, lagging dunes and related hydraulic roughness.

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