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Incipient meandering and self-formed floodplains in experiments

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ABSTRACT: Meandering rivers have partly been explained from theories that predict bend and bar formation and migration, whilst assuming a simplistic erosion formulation for the bank opposite to where bars form. However, floodplains are highly heterogeneous in composition and vegetation density and bank erosion consists of a set of complicated processes. Our objective is to understand the formation and heterogeneity of experimental self-formed floodplains and test a forced bar theory on the self-formed meandering channel. We did experiments in a 1.25x7.5 m flume with an initially straight and narrow channel in a bed of river sand and silica flour. We measured the evolving channel location and the resulting stratification within the floodplain. Our experimental and theoretical alternate bar wave length agree within 25 percent. Despite the simplicity of the setup and the limited dynamics of meandering, the stratification in the floodplains was quite complicated, reflecting a rich history of stratification, suspended sediment deposition onto the floodplains and unexpected erosion processes in the cohesive floodplain cover. The latter affected channel planform formation and success of chute cut-offs. We conclude that the bar theory provides a reasonable general estimate of bar length, but the exact channel location and curvature were affected by the heterogeneity of bank erodibility.

Keywords: Heterogeneous floodplains, Meandering, Bar theory, Flume experimentation, Chute cut-offs

1 INTRODUCTION

The present experimental study focuses on interaction between incipient meandering and self-formed floodplains. Meandering can partly be explained by bar theories (Struiksma et al., 1985; Johannesson and Parker, 1989). So far, these bar theories and numerical models have replicated many aspects of meandering behaviour. However, the detailed shape of meanders is commonly not well predicted because a simplistic formulation is used for river bank erosion of the outer bank (e.g. Camporeale et al., 2007). These theories ignore the heterogeneous in sediment composition and vegetation of floodplains, while bank retreat is the result of a whole suite of processes. Here, we will test the 'forced bar' theory of Struiksma et al. (1985) on an experimental self-formed meandering channel.

The channel pattern is affected by bank strength (Ferguson, 1987; Kleinhans, 2010). To maintain a relatively narrow and deep channel, like a meandering river, appreciable bank strength is required. Earlier experiments, aimed at recreating (incipient) meandering, confirm this insight: 1) Static meanders formed in cohesive sediment (Friedkin, 1945; Schumm and Khan, 1982; Smith, 1998). 2) One small dynamical meandering channel formed in sediment ranging from fine gravel to silt (silica flour), in which the silt caused some added bank strength (Peakall et al., 2007). And 3) Alfalfa seeded to an initially braided experimental river formed in non-cohesive uniform sediment during low flow. The roots provided strength to the banks and higher hydraulic resistance to the flow during floods, though not enough to create single-thread meanders with levees (Gran and Paola, 2001; Tal et al., 2004). Alfalfa sprouts increased floodplain sedimentation of fines, resulting in a meandering system with a low sinuosity (Braudrick et al., 2009).

The aim of this study is to understand the formation and heterogeneity of an experimental self-formed floodplain and the effect on incipient meandering. Our experiments form a heterogeneous floodplain of river sand and silica flour. To quantify bank strength, auxiliary experiments on bank erosion and bank failure were conducted (Kleinhans et al., this volume). The characteristics and dimensions of the experimental meandering channel are compared to the bar theory of Struiksma et al. (1985) to test whether this theory can be used to interpret bar formation of a heterogeneous floodplain.

2 FORCED BAR THEORY

Bars form due to instability in the interaction of an erodible channel bed and unsteady flow. Forced bars form from a fixed perturbation, such as a variation in channel width or channel curvature. Free bars can occur at any location in the river and they migrate through the river. Forced bar theory can also be used to predict bar mode, or, effectively, braiding index, in cases with mid-channel bars. This study focuses on the lowest mode, wherein the over- and underdamped regimes are associated to meandering. Excitation indicates that higher modes may appear (Crosato and Mosselman, 2009).

The behaviour of alternating bars in response to a perturbation is simplified by four length scales: λ_w, λ_s, L_P, L_D.
The adaptation length of the flow; λ_w:

$$\lambda_w = \frac{C^2 h}{2g} \tag{1}$$

where g=gravity acceleration (m/s^2), C=Chézy roughness coefficient (N/m^2), h=depth (m).
The adaptation length of the bed; λ_s:

$$\lambda_s = \frac{1}{\pi^2} h \left(\frac{W}{h}\right)^2 f(\theta) \tag{2}$$

where W=width (m), and $f(\theta)$=transverse bed slope effect $9(D_{50}/h)^{0.3}\sqrt{\theta}$, D_{50}=median grain size (m), and θ=dimensionless shear stress (-). For flume studies the transverse slope effect was empirically calibrated as $1.7\sqrt{\theta}$ by Talmon et al. (1995).
The wave length of a bar; L_P:

$$2\pi\frac{\lambda_w}{L_P} = \frac{1}{2}\sqrt{(n+1)IP^{-1} - \left(IP^{-2}\right)^2 - \left(\frac{n-3}{2}\right)^2}\ , \tag{3}$$

and the damping length; L_D:

$$\frac{\lambda_w}{L_D} = \frac{1}{2}\left(IP^{-1} - \frac{n-3}{2}\right), \tag{4}$$

where IP=the interaction parameter as ratio between λ_s and λ_w (Struiksma et al., 1985), and n=the degree of non-linearity of sediment transport versus depth-averaged flow velocity; sand-bed rivers (n=4) and gravel-bed rivers (n=10) (Mosselman, 2005; Crosato and Mosselman, 2009). A higher n, the stronger the tendency is to form bars and islands (Mosselman, 2005). For experiments the threshold of motion is lower, therefore calculations are done with values related to gravel-bed rivers. The stability of a bar depends on the resonance of the system (L_D) (Mosselman et al., 2006), which is subresonant by overdamping and underdamping conditions, while superresonant by spatially growing (excitation) of the bars downstream. The corresponding ranges for the IP are:

$$IP \leq \frac{2}{n+1+2\sqrt{2n-2}} = 0.103\,, \text{ - overdamped}$$

$$\frac{2}{n+1+2\sqrt{2n-2}} < IP \leq \frac{2}{n-3}\,, \text{ - underdamped} \tag{5}$$

$$IP > \frac{2}{n-3} = 0.286\,. \qquad \text{ - excitation}$$

The IP depends mostly on the width-depth ratio $(W/h)^2$ and less on hydraulic roughness (g/C^2) and sediment mobility ($\sqrt{\theta}$).

This study focuses on incipient meandering induced by underdamped spatial bars at the lowest bar mode interacting with a self-formed heterogeneous floodplain. To further assess the effect of heterogeneity, theoretical and measured bar wave length L_P and IP values are compared.

3 METHODS

3.1 *Flume set-up*

The experimental conditions were designed using the dimensionless Froude number, Shields mobility number, the interaction parameter and the bank strength (see Kleinhans et al., this volume). The experiments were conducted in a 7.5 m long and 1.25 m wide flume. The experiment started with an initial bed of 0.05 m thick and a slope of 0.005 m/m. Initially a straight trapezoidal narrow channel (0.07 x 0.015 m) was cut in the centre of the flat bed surface, with an inflow angle of 30 degrees to initiate meandering. During the experiment the discharge was kept constant at 0.9 L/s ($9.0\cdot10^{-4}$ m^3/s) and water was recirculated. At the inflow sediment was added at 1.65 kg/hr. Each experiment was run for at least thirty hours. Flow velocity, width and depth were measured hourly along the channel. The width was taken at the section where (active) sediment transport took place.

We counted active and inactive channels based on sediment transport at every section with an interval of 0.2 m (every two hrs) to determine active braiding index (*ABI*) and total braiding index (*TBI*). Grain sizes were sampled in sections across the entire flume.

3.2 *Sediment mixture*

Two sediment mixtures were used. In the control experiment poorly sorted noncohesive river sand was applied, whilst for the second experiment a fine-grained tail was added by mixing eighty volume percent of the river sand with twenty volume percent of silica flour (Table 1; see also Kleinhans et al., this volume). The main focus of these two experiments was to analyze the effectiveness of adding a fine-grained fraction; on the formation of a heterogeneous floodplain; on the bank strength; and to obtain an incipient meandering channel.

Table 1. Sediment grain sizes (in μm).

Sediment	D_{10}	D_{50}	D_{90}
Silica flour	4	32	95
River sand	228	418	1203
River sand and silica	32	353	1016

4 RESULTS

4.1 *Experimental channel and floodplain*

This section compares the evolution of the channel and floodplain in the plain river sand and the same sand with added floodplain-forming silica flour.

4.1.1 *Processes*

Bank erosion by the inflow at an angle with the initial straight channel led to the formation of a forced alternate bar (Figure 1). The finer (silica) fraction was transported predominantly in suspension and settled on top of the alternate bar. Episodic accretion of unit bars resulted in a continued growth of a point bar. Once a point bar formed, subsequent development occurred by accretion of parts of downstream-migrating unit bars, while the bars lengthened until an equilibrium meander wave length of 3±0.5 m was reached (Figures 2-4).

The conceptual development of a meandering pattern is shown in Figure 2. The initial inflow angle translated the straight channel (Figure 2.1) into a first bend (Figure 2.2). Curvature of the first bend forced a (submerged) bar on the opposite side (Figure 2.3), which expanded (Figure 2.4), slightly rotated and translated downstream (Figure 2.5). The second bend initiated a new forced bar at the downstream and of the flume (Figure 2.5). This third bend was abandoned by a chute cut-off; as a result the bar wave length equilibrium was around three meter in the control and the heterogeneous experiments (Figure 2.6).

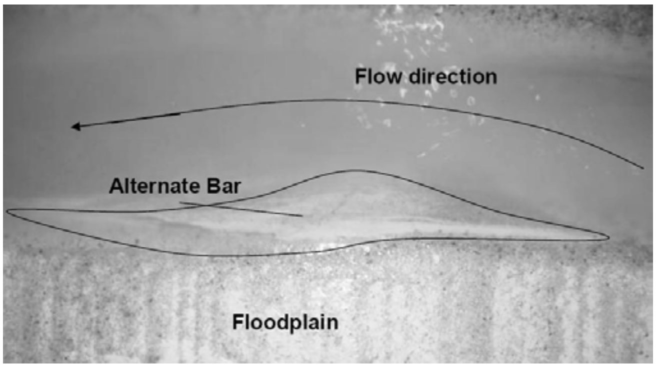

Figure 1. Initial inflow angle results in forced (alternate) bars downstream with silica deposited on top.

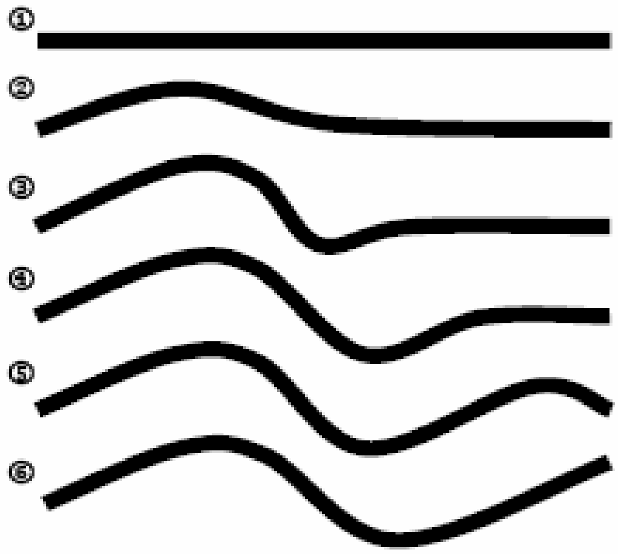

Figure 2. Meander development from an initial angle into three bends by expansion and rotation, which were cut-off by chutes after 24 hours of flow. The meander length equals approximately the flume length.

The river sand experiment evolved towards a dynamically braided pattern characterized by a pronounced multi-thread channel with extensive bar complexes (Figure 3). The river sand and silica experiment, in contrast, evolved into a dynamic single-thread channel (Figure 4) with temporary chute cut-offs that were filled up again. Thus the pattern was on the transition between meandering and weakly braided. This is common for low-sinuosity meandering rivers on the transition to braiding, such as the river Allier in France.

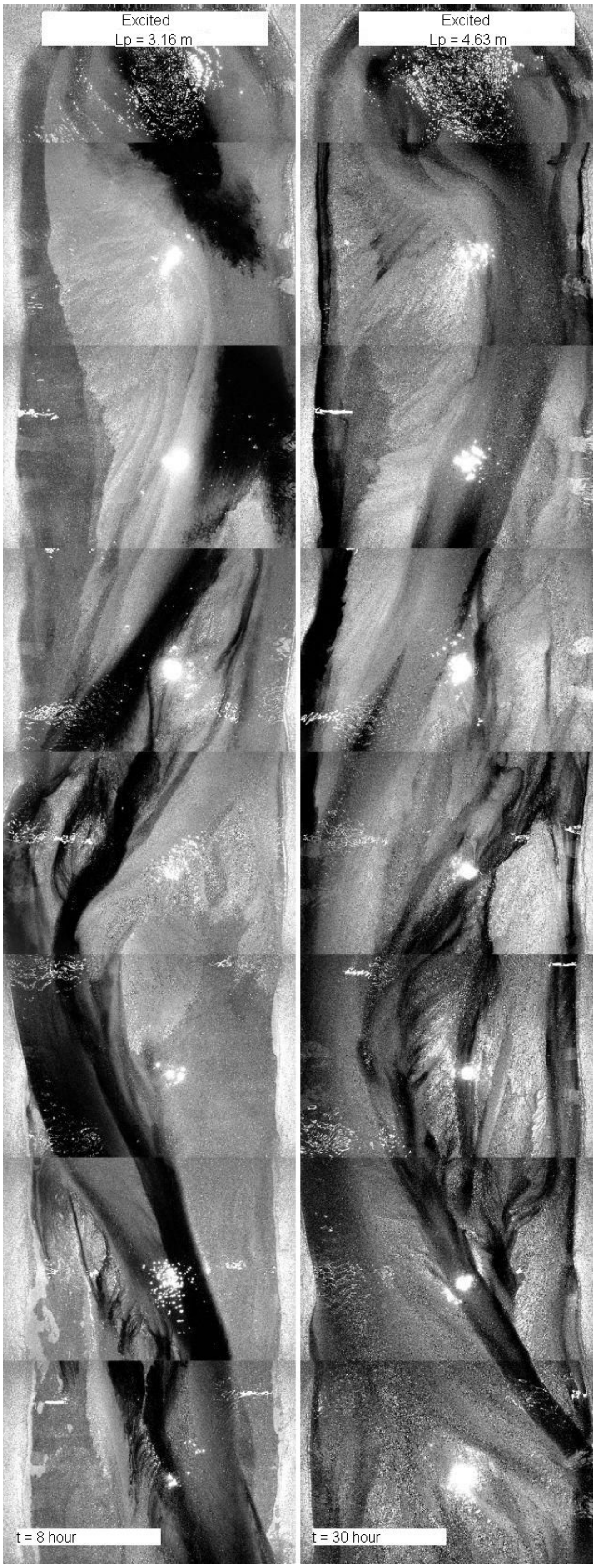

Figure 3. Two snapshots of the river sand experiment with a homogeneous floodplain. The flume is 7.5 m long and 1.25 m wide, and water (darker) flows from top to bottom of the page. Image shows a contrast-enhanced blue layer of the RGB photograph of a standard digital compact camera.

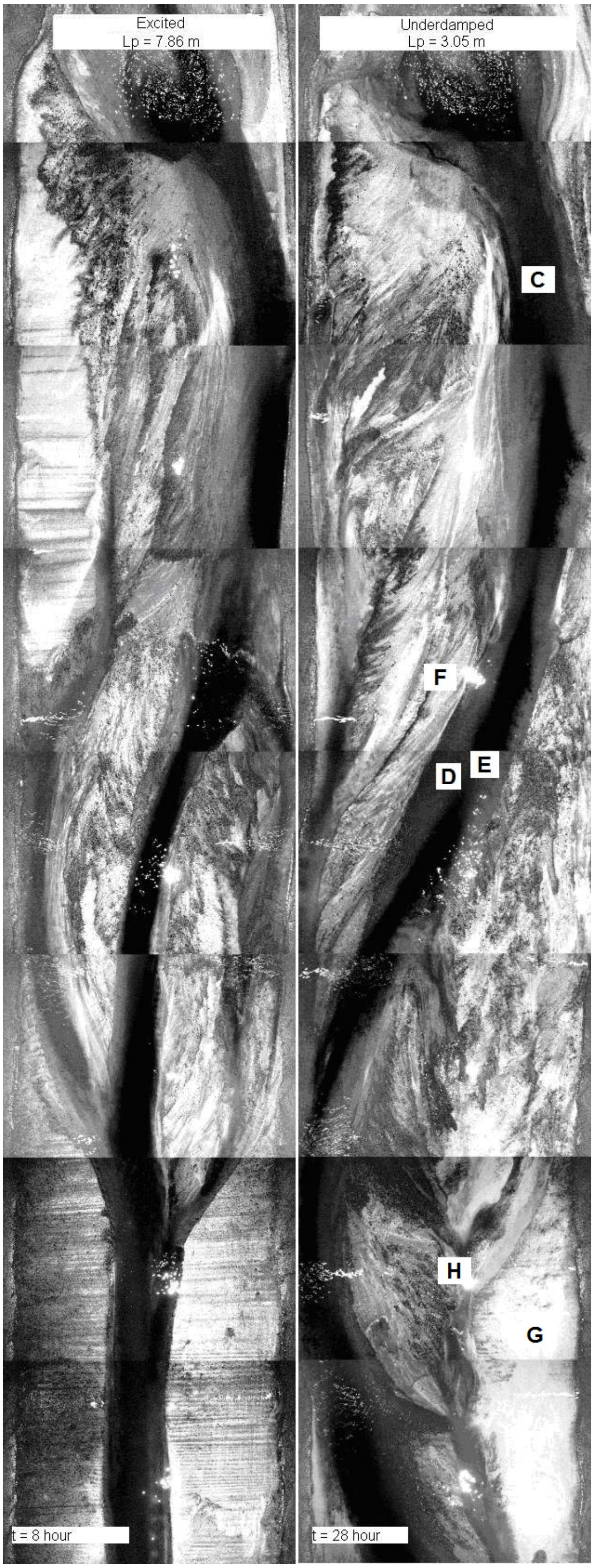

Figure 4. Snapshots of river sand and silica experiment with a heterogeneous floodplain. See Figure 3 for comparison. C-H indicates the position of sediment sampling (see sec. 4.3).

4.1.2 *Measured and predicted bar properties*

The Interaction Parameter (*IP*) (Eq. 1) was calculated for both experiments. The *IP* values stabilised after twenty hours of flow. The river sand experiment had an *IP* of 0.35-0.45, indicative of bar excitation for the lowest mode. For the sand-silica mixture the *IP* decreased from the excitation regime to the underdamped bar regime over time with an *IP* of 0.43 to 0.27. This shows that the silica flour indeed causes sufficiently narrower and deeper channels to change the bar regime.

The *IP* value is highly sensitive to the non-linearity of sediment transport (n), which renders the prediction of bar length rather uncertain. Fortunately, the length as a function of n shows a minimum at reasonable values of n. Sand bed rivers, such as our experiment, are very mobile with n=4. Gravel bed rivers are near incipient motion, as are our experiments, so that n=10 is more reasonable (Crosato and Mosselman, 2009). The effect is that gravel-bed rivers are predicted to have a shorter bar wave length: L_p=4.0 m for width-depth ratio of the river sand and L_p=3.5 m for the river sand with silica (Figure 5).

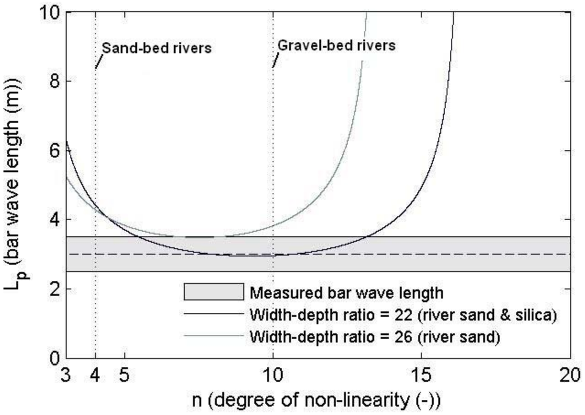

Figure 5. Effect of non-linearity of sediment transport on predicted bar wavelength at width-depth ratios of the two experiments. The range of measured bar wave length is indicated by the gray area.

4.2 *Effect of silica flour on erosion processes*

We observed three typical erosion processes caused by the addition of silica, namely chute cut-offs, upstream migrating backward steps and bank retreat by failure.

4.2.1 *Chute cut-offs*

As the overall channel widened, chute bars developed downstream of initial chute channels. As a result, flow velocity in the main channel reduced and sediment was deposited. This happened after reaching the maximum sinuosity (Figure 2.5). Observations during the experiment suggested that further development of the chutes into chute cut-offs was often preceded by blockage of the old channel because of the deposition. The presence of a sediment plug inside the channel forced the flow increasingly onto the point bar and into the chute channel, leading to a full cut-off.

Formation of these chutes were frequently observed in this study and led (temporary) to a transition from a single-thread towards a multi-thread system. Abandonment or closing of a channel occurred gradually. In the experiment with silica flour the chute channels were partially filled with the finer silica particles, which reduced the frequency of chute cut-offs from four times for the control experiment to only three times for the heterogeneous experiment during the 30 hours. Therefore the overall *ABI* and *TBI* values decreased for the experiment with silica (Table 2).

Table 2. Average parameter values for *W*, *ABI* and *TBI*.

	W (m)	*ABI*	*TBI*
River sand	0.28	1.66	2.43
River sand and silica	0.26	1.42	2.12

4.2.2 *Upstream migrating backward steps*

A characteristic process of the heterogeneous bed was the occurrence of widespread upstream migrating backward steps on the floodplain and channel. Upstream migrating backward steps were characterized by an irregular erosion step which marked the cohesive properties of the silica flour (Figure 6). The upstream migrating backward steps in the channel were mostly observed during the first hours, because the initial bed contained silica. Upstream migrating backward steps were initiated on the floodplain where water accelerated from the floodplain into a (downstream) channel and are characteristic for cohesive materials. Therefore in the channel these steps could only exist when silica was available in the bed.

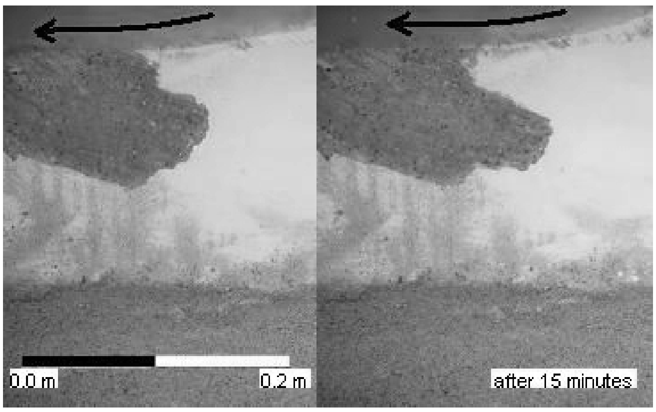

Figure 6. Upstream migrating backward steps, the right part shows the increase in the step after 15 minutes.

4.2.3 *Bank retreat*

Important erosion processes at the channel banks were mass failure processes, and bank toppling failure. The sand and silica mixture was capable of attaining a large angle of internal friction until mass failure occurred (see also Kleinhans et al., this volume). This made undercutting of the channel bank (bank toe erosion) an important erosion process.

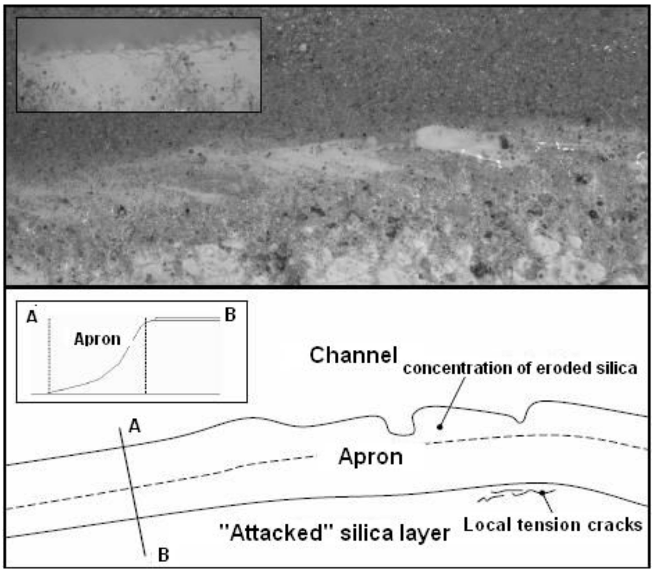

Figure 7. Bank erosion processes of the finer silica layer. Top: Greyscale image of the apron with (left top) water and without water (large image). Bottom: Drawing with geomorphologic indications at the apron as deviation of the channel and bank.

Most silica was deposited on the floodplain where the flow velocity was lowest. Bank erosion at floodplain areas with silica flour occurred in several stages. The silica layer on top of the banks was first removed while afterwards the apron with on top deposited sediments was gradually eroded through grain-by-grain erosion. The apron of eroded sediments characteristic for bank erosion of floodplain areas is shown in Figure 7. It was observed that the apron mainly consisted of a mixture of river sand and silica. At the toe of the bank a concentration of eroded silica was found.

4.3 *Alluvial architecture of a heterogeneous bed*

During the experiment the amount of silica deposits was influenced by the distribution of the flow. Kleinhans et al. (this volume) described the influence of silica in the bed on bank failure and bank erosion. This section describes where silica concentration was the highest.

4.3.1 *Depth of activity*

Grain size analysis at channel cross-sections across the flume has shown valuable insights into alluvial substrate and corresponding sediment composition. Classification of alluvial activity was based on depth, in combination with dark-coloured active parts as visible in Figure 8 (Table 2).

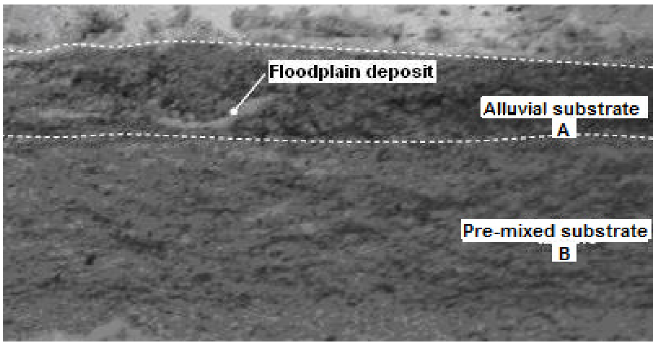

Figure 8. Channel activity can be distinguished by colour differences and depth at variety of cross-sectional profiles across the flume (A and B; see Table 3).

The alluvial substrate exhibited a much smaller grain size distribution than the pre-mixed substrate. Channels were defined as alluvial when the bed sediment was reworked by the flow, whereas the definition pre-mixed means that the flow had not (yet) reworked the initial sediment mixture. Figure 8 illustrates inactivity in the alluvial substrate by the presence of thin silica layers, marking the processes of floodplain deposition. An important aspect of meandering was the interaction between the heterogeneous floodplain and the channel. On the floodplain silica was deposited (Table 3) which increased the bank strength (see also Kleinhans et al., this volume). At appropriate bank strength, the outer bend eroded slower than the growth of the point bar in the inner bend, and incipient meandering developed, by decreasing the width-depth ratio.

4.3.2 *Sediment sorting at the alluvial substrate*

Differences in flow velocity led to sediment sorting in the flume. Observations of the flume bed showed distinct morphological units near the meander bend (Figure 9). A well-developed point bar with scroll bars can be observed in which lateral growth occurred by the presence of a unit bar near the inner bend. At the outer bend a steep (eroded) channel bank was visible whereas at the inner bend a gentler (depositional) bank was present. The relatively white colour of the unit bar near the inner bend suggested a considerable age of these deposits as significant portions of silica were already deposited on top. Locations of scroll bars were marked by a more dark-coloured appearance as less silica was deposited on top because of its relative height with respect to the lower-lying surrounding swales. Particle size analysis (Table 3) indicated that the outer bend contained a coarse (gravel) peak in its grain size distribution which was not present at other sample locations.

The pre-mixed sand and silica mixture consisted of finer material than most grain size analysis at channel cross-sections indicated (Table 3). Higher flow velocity resulted in a wash out of silica and less deposition of silica. When the flow velocity decreases the finer silica was deposited. Most silica was deposited on the floodplain (Table 3), where the flow velocity was the lowest. Relatively more silica was also deposited in the chute channel, this resulted in less chute cut-offs.

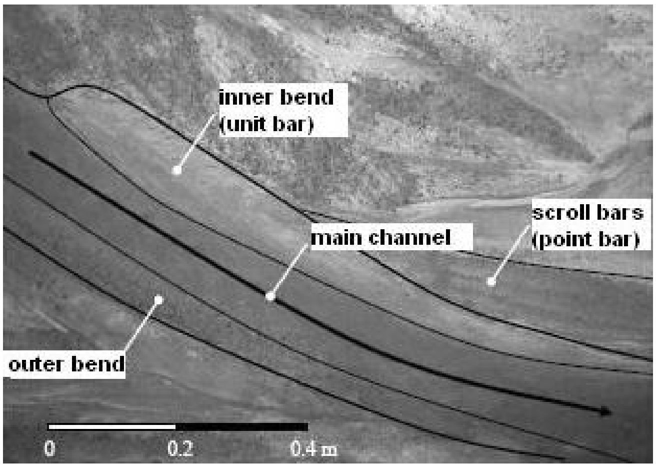

Figure 9. Morphological units in a meander bend at the end of the river sand and silica experiment.

Table 3. Sediment grain sizes during river sand and silica experiment (all in µm). Origins of sediment samples A-B are plotted in Figure 8 and locations of sediment samples C-H are given in Figure 4.

	D_{10}	D_{50}	D_{90}	< 45µm	
Alluvial Substrate	150	412	980	2.8%	A
Pre-mixed Substrate	29	376	1110	15.6%	B
Main Channel	130	500	860	3.1%	C
Inner Bend	20	280	940	24.9%	D
Outer Bend	350	1190	2190	1.3%	E
Scroll Bar	482	811	1488	2.7%	F
Scroll Swales	167	607	870	3.6%	F
Floodplain	20	400	1400	18.9%	G
Chute Channel	60	470	1080	8.7%	H

5 DISCUSSION

Morphological observations during the flume experiment with the sand and silica mixture shows dynamic point bar development in agreement with Peakall et al. (2007). Downstream of the skewed inflow a submerged (forced) bar developed and the opposite bank was eroded. Further downstream the same happened in the opposite transverse direction, resulting in the formation of a point bar and a meander bend. The self-formed relief on the floodplain resulted in the appearance of chute cut-offs and channel abandonment. Addition of silica led to more deposition of fine sediment in the chutes, which decreases the amount of chute cut-offs and eventually channel migration. Channel pattern evolution is caused by distinct patterns of in-channel deposition, which progressively result in channel abandonment and the capture of a new stream, and an increase in the channel slope.

The forced bar theory of Struiksma et al. (1985) can reasonably be used to design experimental studies. Therefore we need to predict the width-depth ratio. In this study addition of silica leads to narrower and deeper channels, which influence the *IP* value and bar regime. According to the forced bar theory the river sand and silica experiment is in the underdamped regime and not in excitation, while the initial river sand experiment is in the excitation regime for the lowest bar mode. This study shows that the theory can predict the bar wave length for heterogeneous floodplains quite accurate. The size of our flume is limited to the development of only one sinuous meander but at present we are conducting experiments in a much larger setup.

Understanding and prediction bank strength is essential for creating the conditions for narrower and deeper channels that are required for underdamped alternate bars and eventually dynamic meandering (Kleinhans, 2010). Bank strength was quantified by auxiliary experiments (Kleinhans et al., this volume). During the experiment the sediment deposition at the inner bend should exceed the erosion rate at the outer bend to get deeper channels. Pronounced sorting features (e.g. bend sorting, floodplain development) are observed in the flume which is indicative for stabilization of meandering (Clayton and Pitlick, 2007). Bend sorting results in armouring of the outer bend, which decreases sediment mobility and reduces the transverse slope (Mosselman and Sloff, 2007). Fine silica is deposited on the floodplain, in the inner bend and in chutes, and large particles are deposited mainly in the outer bend.

Vegetation is another method to increase the bank strength and to decrease width-depth ratio (van de Lageweg et al., this volume). A combination of both experiments will result in a more adjustable setting, where vegetation can capture more fine sediment onto the floodplain.

6 CONCLUSION

- Forced bar theory correctly predicts bar regime and length and demonstrates the importance of the width-depth ratio, bank stability and the non-linearity of sediment transport.
- Addition of silica flour to a poorly sorted river sand results in an increase in bank strength, a decrease in width-depth ratio and a single-thread channel in contrast to the multi-thread channel that formed in river sand in a control experiment.

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