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From nature to lab: scaling self-formed meandering and braided rivers

Maarten G. Kleinhans, Wout M. van Dijk, Wietse I. van de Lageweg,
Remko Hoendervoogt, Henk Markies and Filip Schuurman
Faculty of Geosciences, Universiteit Utrecht, The Netherlands

ABSTRACT: Traditionally, rivers were downscaled to the laboratory through similarity of the Froude, Shields and Reynolds numbers. This has worked well for rivers with fixed banks and for braided gravel-bed rivers. For self-formed dynamic meandering rivers in experiments, Froude scaling is incomplete without a constrained width-depth ratio. This aspect ratio should be small enough to obtain alternate bars and bank erosion should somehow be limited. Our objective was to develop a scaling and design strategy for experimental meandering that includes bank strength so that width-depth ratio, bar pattern and channel dynamics can be designed. Scale effects of water surface tension and of smooth boundaries were inferred from first principles. Bank strength cannot be predicted well and was experimentally evaluated with two fast, repeatable experimental setups for a range of sediments with additives and vegetation. With selected sediments, we produced moderately dynamic meandering rivers on a 1.25x7.5 m flume. A sediment mixture ranging from silt to fine gravel produces richer morphodynamics and less scale effects with adjustable slightly cohesive banks and self-formed floodplains. Width-depth ratio reduced and floodplain sedimentation prevented that chute cut-offs led to braiding. Different vegetation species and controlled conditions allow adjustable growth rate, bank strength and hydraulic resistance. With the appropriate theory and our preparatory experiments, a range of dynamic river patterns can now be designed for the laboratory with the essential characteristics of their natural counterparts.

Keywords: meandering, braiding, scale effects, river bank strength, river bank erosion, floodplain

1 INTRODUCTION

1.1 *Review and problem definition*

Natural rivers on plains and deltas can have distinctive planforms such as meandering and braided. Why these patterns emerge is only qualitatively understood. Their self-organisation involves feedbacks between channel morphodynamics and channel migration, and the evolution and subsequent erosion during floods of floodplains including the vegetated levees that flank the river as natural dikes.

The lack of quantitative understanding is demonstrated by the partial failure to reproduce a range of river patterns in laboratory experiments and in physics-based numerical models. Until now such models were made for either meandering or braiding, but not both (Kleinhans, 2010).

It also proved challenging to produce self-formed dynamic meandering in the laboratory, while braided channels are relatively easily reproduced in laboratory experiments (Friedkin, 1945). This either reflects a lack of understanding of the basic conditions in which a self-formed dynamic meandering river emerges, or reflects serious scale problems that, once understood, could lead to better experiments. Classical Froude scaling is incomplete as it requires width as an independent parameter, which it is not in self-formed channels. Furthermore, bar theory indicates that the width-depth ratio is essential in producing a bar.

Only three sets of experiments have reproduced aspects of dynamic meandering rivers with floodplains. Friedkin (1945), Schumm and Khan (1972), Jin and Schumm (1987) and Smith et al. (1998) produced meandering channels in cohesive sediment. These experiments demonstrated the importance of bank strength on channel pattern, but were unable to create self-formed and sustained dynamic meandering channels.

Peakall et al. (2007, also see van Dijk et al, this volume) produced one dynamical low-sinuosity meandering channel in sediment ranging from fine gravel to silt (silica flour), wherein the silt appeared to add strength to the banks. Many features of dynamic meandering rivers were observed in the experiment, which was a break-through. But how and why the silica flour addition strengthened the banks remained unclear and only one experiment was presented.

Tal and Paola (2007, also see van de Lageweg et al., this volume) seeded alfalfa to an initially braided experimental river in noncohesive uniform sediment during low flow. A dense vegetation resulted in a static stream or slowly wandering rivers, whereas less dense vegetation resulted in single-thread sinuous channels with some characteristics of meandering such as point bar formation and chute cutoff (Tal and Paola, 2007). Meandering has also been obtained from an intially straight channel using alfalfa and a light-weight sediment that filled in lower areas of the floodplain so that recapture was prevented (Braudrick et al., 2009). Apparently, the three combined factors leading to meandering probably were 1) the reduction of floodplain flow strength by the hydraulic resistance of vegetation and the concurrent increase of focus and strength of channel flow, 2) the increased strength of eroding banks, and 3) the filling of abandoned channels and lows by vegetation or light-weight floodplain sediment, so that multiple channels and reoccupation were prevented.

1.2 *Objective and approach*

So far, careful but slow tinkering with initial and boundary conditions such as concentration of silica flour or vegetation has led to the required result. Yet a quantitative predictive scaling method remains unavailable. A scaling methodology is required to design future experiments, quantify scale effects and quantify the key processes leading to the meandering pattern. The objective of this paper is to develop a scaling and design strategy for self-formed channels that includes bank strength so that width-depth ratio, channel pattern and dynamics can be designed.

First we will review shortcomings of classical Froude scaling and extend this scaling framework to self-formed channels from first principles based on the insights from the experiments. Then we will show our novel procedure involving two fast, repeatable experiments for quantitative determination of 1) bank erodibility and bank undercutting, and 2) bank material cohesion and strength, both for a range of sediments with additives and vegetation. To test the transferability of the small-scale bank stability experiments to an exploratory self-formed river experiment we selected conditions and sediments and produced moderately dynamic meandering rivers on a 1.25x7.5 m shallow flume.

2 SCALING THEORY

We will first summarize shortcomings of Froude scaling for self-formed laboratory rivers. Then we will extensively discuss the scale effects of very shallow flow typical in laboratory experiments. Finally we will add the requirements for an extended theory, make a first attempt to develop it, and discuss scale effects.

2.1 *Froude scaling, bed mobility and bars*

Froude scaling is well known (e.g. Struiksma, 1986; Peakall, 1996). In order to have similar flow conditions in a scale model with length L_S as in reality with L_R, the Reynolds (*Re*) and Froude (*Fr*) numbers should be equal in prototype and scale model. The Reynolds number is:

$$\mathrm{Re} = \frac{\rho h u}{\mu} \tag{1}$$

where ρ=density of water, h=water depth (or hydraulic radius), u=velocity and μ=dynamic viscosity. The Froude number is:

$$Fr = \frac{u}{\sqrt{gh}} \tag{2}$$

where g=gravitational acceleration. However, the first contains depth h whereas the second contains $\sqrt{h}$, so that it is impossible to fulfill both conditions to obtain the same velocity scale. The Reynolds number condition is usually relaxed under the assumption that inertia dominates over viscous effects, but that becomes problematic for very shallow flow such as on small-scale floodplains. In practice the Froude condition can be relaxed too as long as the flow conditions remain subcritical and more or less uniform.

For mobile bed experiments, the mobility of sediment must be similar. Mobility is expressed as the Shields number:

$$\theta = \frac{\tau_b}{(\rho_s - \rho) g D_{50}} \tag{3}$$

where ρ_s=sediment density, τ_b=$\rho g h \sin(S)$=bed shear stress, S=channel gradient and D_{50}=median particle size. This involves the scaling of particle size (D) with L_S/L_R. However, silt and finer sediment becomes cohesive, so that coarser sediment must be chosen. The concurrent decrease of mobility is usually counterbalanced by tilting (steepening) the model.

However, the hydraulic resistance scales with particle size (through h/D) and this scaling must be correct to reach similar flow conditions as well as similar (secondary) bend flow that drives the three-dimensional morphodynamics. These scale problems are further exacerbated as the particle Reynolds number (Re*) must be larger than the transition from hydraulic smooth to rough:

$$\mathrm{Re}^* = \frac{\rho u^* D}{\mu} > 11.63 \quad (4)$$

where u^*=shear velocity and D=particle size representative for the roughness. This is unknown: usually D_{50} is used but it can be argued that the D_{90} is more representative of near-bed roughness and disturbs the laminar sublayer sufficiently to create a hydraulically rough boundary. In smooth conditions ripples or scour holes form that do not scale with water depth and provide unrealistic morphology (Fig 1). In rough conditions the hydraulic resistance is large so that the model is distorted by further increase of gradient.


Figure 2. Scour hole in 0.2 mm sand. Flow depth was a few mm while scour depth is a few cm. Ruler in cm for scale.

To design bar dimensions and regime, we use theory for forced bars (Struiksma et al., 1985). Forced bars of the lowest and higher modes may be overdamped, underdamped and excited. The over- and underdamped regimes are associated to meandering. Bar regime (Fig. 1) depends on the ratio of adaptation length of flow (λ_w) and of sediment (λ_s) after a perturbation (such as a bend):

$$\frac{\lambda_s}{\lambda_w} \approx \frac{2g}{C}\left(\frac{W}{h}\right)^2\left(\frac{D_{50}}{h}\right)^{0.3}\sqrt{\theta} \quad (5)$$

with C=Chézy parameter and W=channel width. The last two terms are a transverse slope effect (Struiksma et al., 1985).

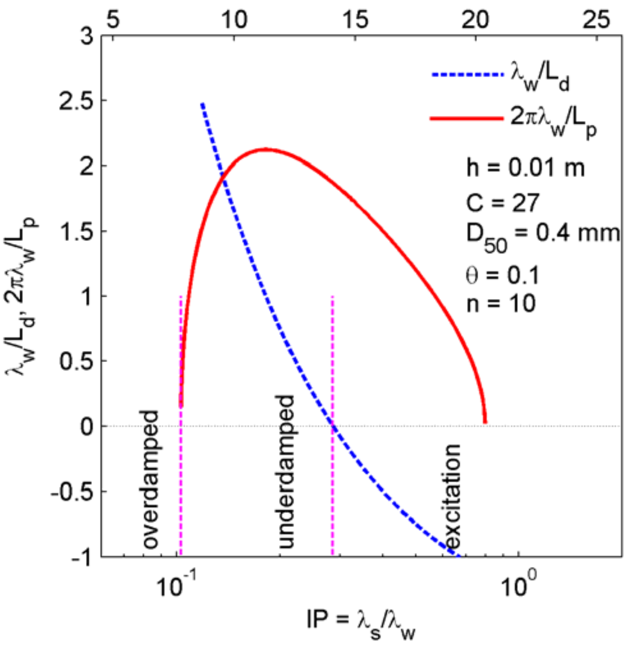

Figure 1. Bar regimes and dimensions (Struiksma et al., 1985) for typical flume conditions. Numbers at top of graph indicate the width-depth ratio W/h. L_p=bar wavelength and L_d=damping length (representing excitation when negative).

Thus bar regime depends primarily on width-depth ratio but also on sediment mobility and hydraulic resistance. Bar length is predicted with:

$$\frac{2\pi}{L_p} = \frac{1}{2\lambda_w}\sqrt{(n+1)\frac{\lambda_w}{\lambda_s} - \left(\frac{\lambda_w}{\lambda_s}\right)^2 - \frac{(n-3)^2}{4}} \quad (6)$$

where n=power in dependence of sediment transport q_b on flow velocity u as q_b::u^n where $n \rightarrow \infty$ towards beginning of motion. To obtain a meandering channel in the lab the bars must be in the underdamped regime and of reasonable short length (see van Dijk et al., this volume).

2.2 *Scaling of width of self-formed channels*

The review above indicates that scaling conditions can in principle not be satisfied and must therefore be relaxed. In the case of exploratory experiments in contrast to scale experiments this is fortunately not problematic at all as long as scale problems are considered in the interpretation.

The balance between floodplain formation and bank erosion determines channel width and depth. The width-depth ratio determines bar pattern (Eq. 5). The banks are eroded fastest at the pools between the bars, so that bar pattern provides a template for bank erosion. In principle alternate bars could then lead to meandering; however bars migrate rather fast so that erosion is not focused at a specific bank location for long enough to create meandering. Cohesive sediment, vegetation or armouring on the bars reduces bar migration (Kleinhans, 2010). Without cohesion, banks erode until a braided threshold channel has developed.

So, in order to have stronger banks that can be eroded, bank strength τ_f must be higher than critical shear stress τ_c for sediment motion, but not larger than the actual shear stress τ_b:

$$\tau_c < \tau_f < \tau_b \tag{7}$$

where bank strength can be described by the Mohr-Coulomb equation:

$$\tau_f = c' + \sigma'_f \tan \varphi' \tag{8}$$

where τ_f=shear strength at failure, c'=effective cohesion, σ'=effective stress at failure (dependent on bank height, weight and groundwater pressure) and φ'=effective angle of internal friction. Past attempts to increase bank strength were made by seeding vegetation (alfalfa), silica flour and clay. Clay proved far too strong because it has the same strength as bank material in the field whilst the flow shear stress is much weaker: $\tau_f >> \tau_b$. Results improved with vegetation or silt-sized silica flour.

The question is why banks in experiments are stronger when these materials are used. Several effects are important at this small scale:

1. laboratory vegetation produces natural polymere and organic material, which adds cohesion to the banks strengthened by roots (Tal and Paola, 2007);
2. electromagnetic forces between particles and between surface coating of fines add cohesion
3. van der Waals attractive forces add cohesion as a function of distance and particle shape (Lick et al., 2004);
4. capillary rising pore water adds cohesion to subaerial parts of the bank dependent on pore size and distribution;
5. the number of contact points between particles (‘coordination number’) determines sediment cohesion, and increases with poorer sorting;
6. slurry-type mass failure of the bank requires dilation, which requires groundwater inflow, which depends on pore size and distribution.

Obviously effects 2-6 become stronger for the mixtures with silica flour, but their quantitative contributions are at present unknown. Therefore we did experiments to quantitatively compare bank erosion rates for varying sediment mixtures, with other additions such as vegetation (see section 3 on experimental procedure).

2.3 *Effects of surface tension in very shallow flow*

Surface tension may affect experiments with very shallow flow because it modifies water surface elevation and gradient, which drives sediment transport. Peakall et al. (1996) suggest that the Weber number, defined as:

$$We = \frac{\rho u^2 h}{\gamma} \tag{9}$$

should be greater than 10. Here the denominator is the flow force per unit length and γ=surface tensile force per unit length (0.073 N/m for pure water). However, for typical experimental floodplain flow with u<0.1 m/s and h=O(0.001) m, We<1.

Theory for thin liquid films and capillarity may elucidate potential scale effects of surface tension. The exponential decay of surface perturbations is characterized by the capillary length. By comparing the Laplace pressure γ/L_c with the hydrostatic pressure $\rho g L_c$ (at depth L_c), the capillary length L_c can be calculated as (see de Gennes et al., 2004):

$$L_c = \sqrt{\frac{\gamma}{\rho g}} \tag{10}$$

For water this yields L_c=2.7 mm. Surface tension may modify water surface elevation when the capillary length is of the same order of magnitude as water depth. For example:

- A large particle or a plant stem on the floodplain will lift the water surface, which reduces the local flow velocity and bed shear stress. Hence the particle or plant stem may capture more suspended sediment than in (upscaled) conditions where surface tension is negligible.
- Surface tension over a backward step will pull down the water surface just upstream of the step and lift it up just downstream of the step. Upstream propagation of such steps is therefore relatively faster.

Surface tension can be modified by surfactants. Polymers in the flow may increase the surface tension, while soap may decrease it (de Gennes et al, 2004). Clearly experimentation and analysis on the effect of soap on shallow flow and sediment transport needs to be done before practical application is feasible.

3 EXPERIMENTAL PROCEDURE

The bank erosion process can conceptually be divided into sediment erosion, which may undercut the river bank, and the sudden fall of a block of bank material. The former is a fluvial sediment transport and removal process and the latter is a geotechnical failure process. Below we describe two simple experiments that we used for fast and systematic assessment of the behavior of a sediment mixture, possibly with vegetation (van de Lageweg et al., this volume). These experiments have also been used for experimental deltas in wide lakes (de Villiers et al., this volume).

3.1 *Sediment mixtures*

Based on the above scaling considerations, we selected a wide unimodal river sand with $D_{10,50,90}$ = {0.22,0.42,1.2} mm as the basic ingredient. For comparison, a similar mixture with a longer fine gravel tail with $D_{10,50,90}$ = {0.24,0.46,2.7} mm was used which presumably is hydraulically rougher (which is 'good') but may tend to armor (which is 'bad'). For hydraulic smooth conditions a uniform unimodal fine sand was chosen with $D_{10,50,90}$ = {0.14,0.21,0.32} mm. A varying volumetric concentration of silica flour was mixed into the river sands (for 20% $D_{10,50,90}$ = {0.03,0.35,1.0} mm). Furthermore vegetation was grown in the sediment (van de Lageweg et al., this volume).

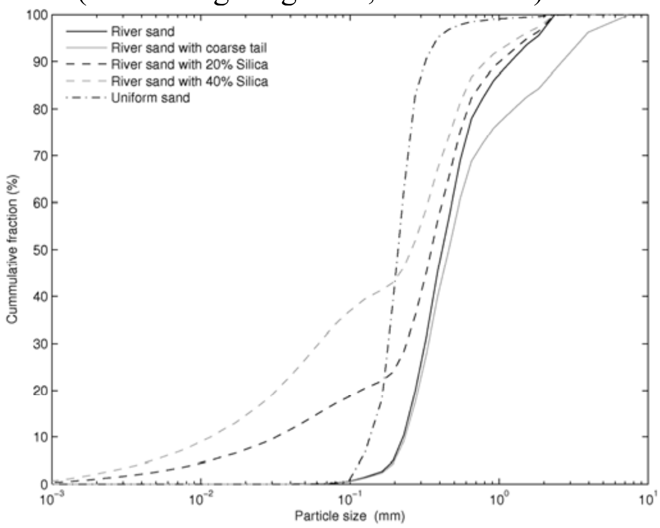

Figure 4. Particle size distributions.

3.2 *Bank erosion experimental setup*

We built a dedicated 'Friedkin' flume for this experiment (Fig. 4), named after Friedkin (1945) who did a similar experiment. The block of sediment was installed in a repeatable way using a mould. Progressive bank erosion was experimentally reproduced by focusing a uniform steady flow from a duct on a 0.1 m wide, 0.325 m long and 0.02 m thick block of sediment at an angle of 45°. Initial width of the channel was the same as of the duct: 0.05 m. The sudden bend forced the clear-water flow to erode the bank. Flow discharge was kept constant at 6-7 l/min by a constant head tank and recirculating flow. Flume gradient was kept constant at 8.8×10^{-3} m/m. We varied sediment mixture characteristics, silica flour concentration and vegetation density. At least three runs were done per mixture and averaged (except for the river sand with the coarse tail).

Orthogonal time-lapse photography and image processing was applied for automated recognition of the receding bank. Given the known initial block dimensions the volumetric erosion rate can be estimated accurately.

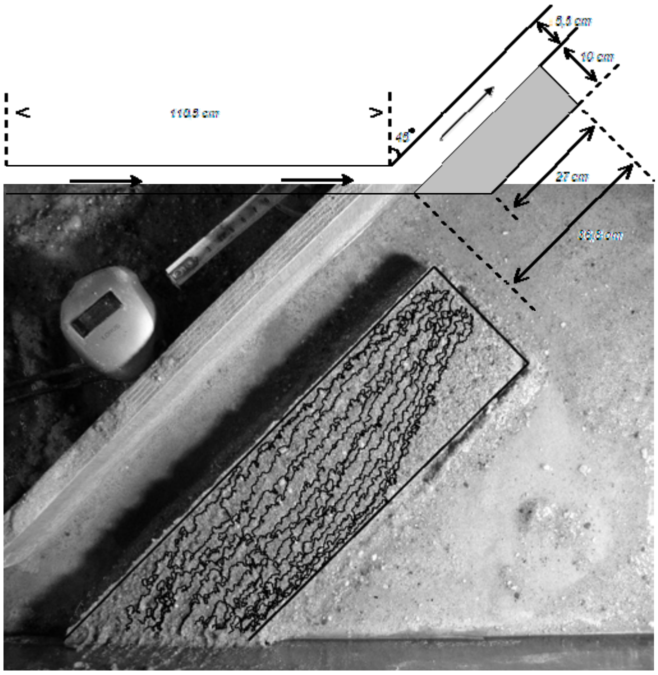

Figure 3. Friedkin experiment. Top: dimensions; sediment block in gray. Bottom: Flow is from the bottom left through the diagonal channel. Block of sediment and bank recognized lines of all time steps drawn in black. Stopwatch and ruler for time and length scale control.

3.3 *Direct shear tests representing bank failure*

The bank failure experiment was the well-known geotechnical direct shear experiment for drained materials. Samples of 0.06x0.06x0.02 m were submerged on a drainage plate and subjected to a normal force of 25-100 kPa. The top half of the sample was sheared at a constant rate. The required force peaks at material failure, which represents material strength. The Mohr-Coulomb equation (Eq. 8) was empirically solved to yield cohesion and angle of internal friction. Cohesion was inaccurately obtained from extrapolation to σ'_f=0. Lower normal forces, more representative of experimental banks, gave irreproducible results.

3.4 *Flume experiment*

A selection of sediments was used on a flume of 7.5 m long and 1.25 m wide to produce self-formed channels (van Dijk et al., this volume, van de Lageweg et al., this volume). These experiments are a first test of our scaling approach.

A sediment bed was carefully flattened on the flume floor at S=5×10^{-3} m/m. Constant discharge of 54 l/min was supplied through a constant head tank into a funnel at a 30° angle with the initially straight channel. Sediment was fed upstream at a rate such that neither net erosion nor net sedimentation took place.

4 EXPERIMENTAL RESULTS

4.1 *Bank erosion experiment results*

Initial erosion in the first minutes was fast as the vertical bank collapsed upon positioning the sample. The erosion decreased over time as the channel widened and got shallower despite the inner-bend bar that usually deposited on the opposite bank. The eroding bank usually became curved (Fig. 4) but with systematic shape differences between mixtures. The experiment was ended when the flow breached the channel wall, commonly near the middle of the sediment block.

The river sand breached in about half an hour in all cases and is used as control experiment to check constancy of conditions. The river sand with the coarse tail armored immediately at the bank toe so that erosion ceased entirely (Fig. 5). The fine uniform sand eroded slowly as expected from the hydraulic smooth conditions. The river sand with silica flour eroded markedly slower. There is hardly a difference in erosion rates between 20% and 40% by volume of silica flour. However, above 40% silica flour the sediment either hardened or, when deposited in as water-saturated sediment, entirely fluidized. This is expected from the fact that the pores of the sand, with porosity 37%, become entirely filled with silica flour which nearly blocks infiltration and exfiltration. In short, the experiments demonstrate that silica flour reduces bank erosion rate.

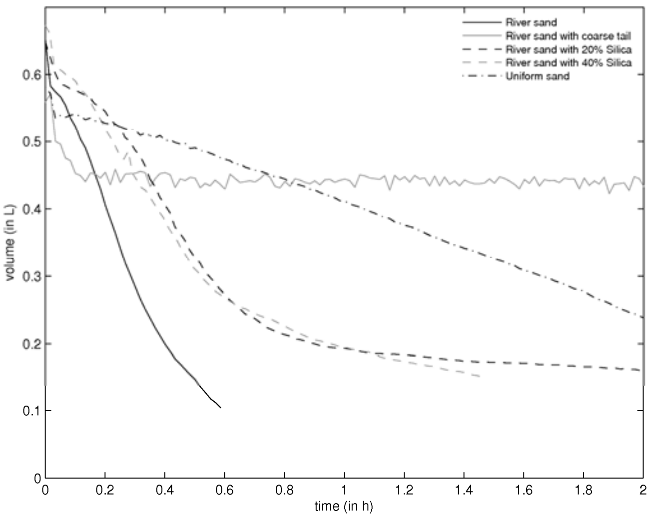

Figure 6. Results of Friedkin experiments presented as residual volume of sediment block over time. Initial volumes were identical. Experiment was ended when channel wall breached.

4.2 *Direct shear test results*

The results are rather scattered (Fig. 6) which indicates the difficulty in preparing a uniformly mixed sample of repeatable compaction. At least one replica was done per sediment mixture and normal stress. The cohesion of the river sand and uniform fine sand were not significantly different from zero, but river sand with silica flour was significantly cohesive. Surprisingly, the angle of internal friction decreased for this mixture.

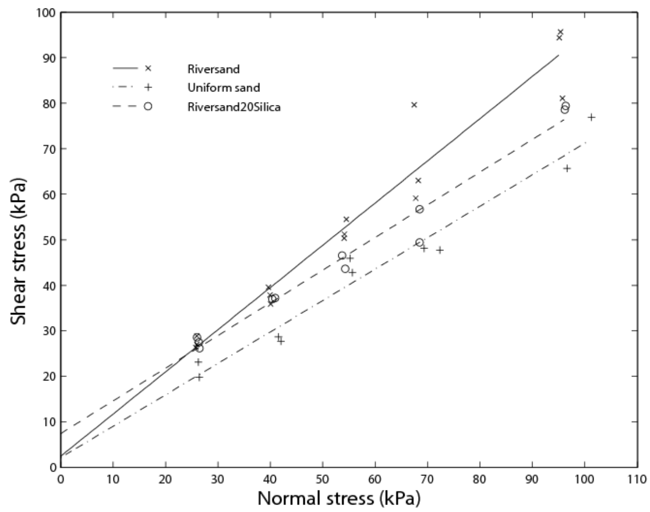

Figure 5. Results of direct shear tests. Intercept of straight regression line is cohesion; slope is angle of internal friction. The mixture with silica flour has significant cohesion.

4.3 *Flume results*

The fine uniform sand produced no clear channel; rather, the fluvial plane became covered in very shallow flow just below the threshold for motion. Local near-stationary trains of antidunes demonstrated that the flow was critical. A large number of scour holes formed with depths up to more than ten times the water depth. Seeding vegetation to this bed helped to focus flow, but the vegetation rapidly became too strong and dense for any channel mobility except in the sharpest bend (van de Lageweg et al., this volume).

The river sand with the coarse tail produced a single- to double-thread river with initial meandering and subsequent chute cutoff. The bed armored strongly in the channel so this experiment was terminated.

The better sorted river sand also produced a single- to double-thread channel with initial meandering and chute cutoffs. Strong armoring was not observed but bend sorting was obvious, fine sediment deposited on channel margins as initial levees and plugs formed in old channels. The absence of antidune trains and occasional presence of rhomboid ripples indicated slightly subcritical flow. The initially enlarging and migrating meanders stalled as their upstream feeding angle remained constant (van Dijk et al., this volume).

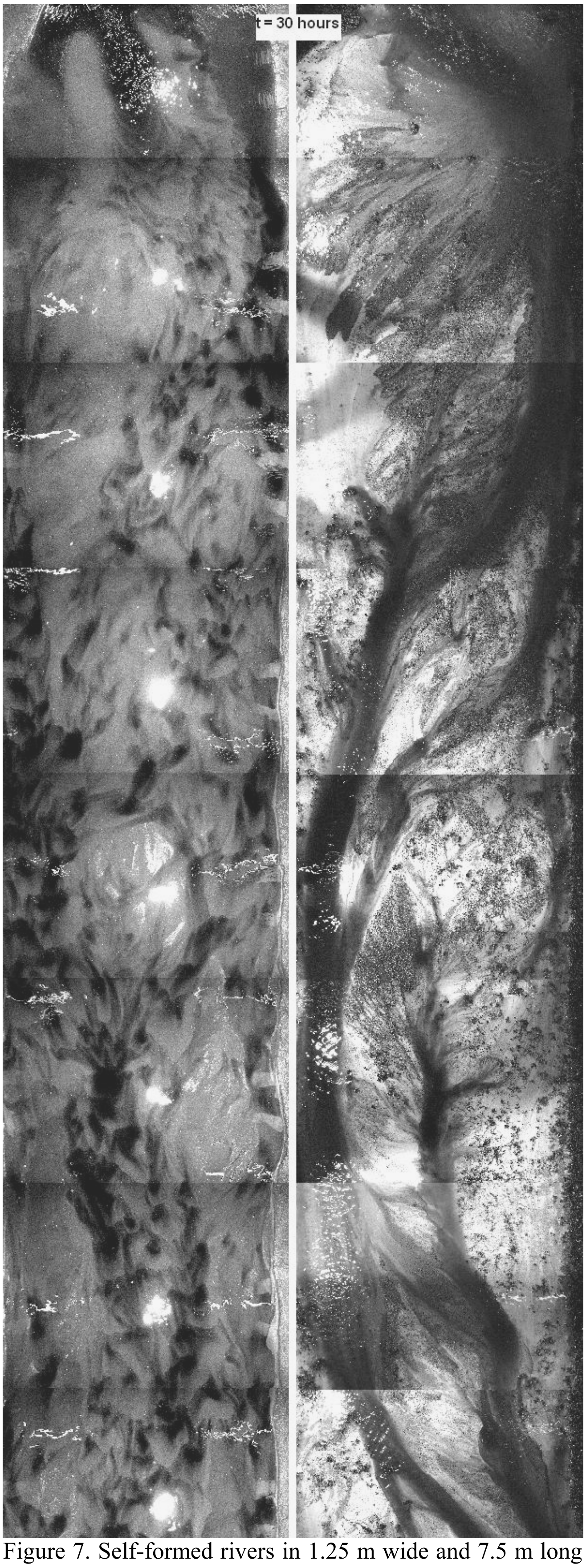

Figure 7. Self-formed rivers in 1.25 m wide and 7.5 m long flume. Flow (dark) from top to bottom. Left: fine sand with extensive unwanted scour holes. Right: river sand-silica flour mixture with low-density vegetation and chute channel.

The river sand with 20% silica flour produced similar morphodynamics as without this addition. The channels were about a tenth narrower and banks in the outer bends were steeper up to vertical. Notably, the silica flour was barely—if at all—present at the bed of active channels. A significant but unknown portion flushed through the channel without depositing.

Topographic lows in the floodplain gradually filled with silica flour settling from suspension (van Dijk et al., this volume). Upstream migrating backward steps through the silica top layer sometimes initiated chute cutoff.

Vegetation was sown at a density of 0.5 seeds/cm^2 over the river sand with 20% silica flour. This very low vegetation density had no measurable effect on channel width or hydraulic resistance. Plants settled preferably on higher bars.

Wall effects were found significant in all pilots, in particular concentrated scour formation. A sediment side ramp reduced wall contact but fed extra sediment upon erosion. Tal (pers. comm. 2009) tested groynes but these caused deep scours. We found that grown vegetation as natural roughness at the wall significantly reduced wall effects.

5 QUANTITATIVE SCALING FOR SELF-FORMED LABORATORY RIVERS

5.1 *Relaxed scaling*

Our general aim is to understand causes of different channel patterns and transitions between patterns through experiments, so we can safely relax a number of scaling requirements. The review above and our experiments yield general insights:

1. Reynolds and Froude scales can safely be relaxed as long as flow remains turbulent and subcritical. Flow on floodplains may become laminar so floodplain-forming sediment must be fine enough to maintain suspension.
2. Sediment mixture is crucial (see next section).
3. Surface tension effects remain negligible even when water depth is similar to capillary length, except at large particles, vegetation and backward steps where surface gradient is affected.
4. Vegetation adds strength to banks depending on rooting depth, density and production of organic material. Too dense or fast-growing vegetation inhibits channel migration (van de Lageweg et al., this volume). With about 300,000 plant species and the possibility to control growing conditions it should be possible to tune required plant effects on sediment strength and flow with a time scale of germi-

nation and growth appropriate for the morphological time scale and flood regime operation.

5.2 *Concocting a sediment mixture*

The composition of a sediment mixture is essential for all elements of the relaxed scaling approach. The entire mixture determines strength of river banks, spatial variation in roughness and hence bar dynamics and river pattern.

The coarse tail can be used to create hydraulically rough conditions with relatively fine sediment. This was demonstrated with the river sand versus fine unimodal sand experiments. Even though Re* for D_{50} is much below the transition to hydraulic rough conditions, neither ripples nor scour holes were observed (also see de Villiers et al., this volume), suggesting that Re* can be calculated using D_{90}. The coarse tail also increases the overall hydraulic roughness.

The sediment mixture should be unimodal. The large particles cause turbulence so that fines are suspended from the bed but, if not a separate mode, do not lead to flush-embedding of coarse particles by the fines so that flow becomes hydraulically smooth. Armoring tendencies increase if the mixture is more bimodal rather than unimodal.

The fine tail controlled the rate of levee formation. The size fraction that was incipiently suspended was deposited immediately adjacent to the channel, forming a levee.

The finest sediment flushed on towards the floodplain. These fines eventually controlled bank strength when this sediment was encountered in the outer bend of a mobile channel bank. In our experiments large areas of the floodplain were covered in silica flour and multiple layers were recognized in older floodplain deposits (van Dijk et al., this volume). The fines also fill abandoned channels and lows that otherwise would have promoted chute cutoffs.

The combination of scaling conditions, direct shear tests and bank erosion experiments led to the selection of a wide unimodal sediment mixture with about 20% of silica flour. Without the silica flour this mixture led to a moderately braided river. Combined with a low-density vegetation cover, we are now using this sediment in a 6x13 m flume (Eurotank) to create meandering channels.

6 CONCLUSIONS

We developed a quantitative scaling approach to design self-formed braided and meandering rivers in the laboratory. Required conditions are: mobile sediment, Froude number below unity, turbulent flow and hydraulic rough conditions based on mixture D_{90}. Mobility is low, implying that we simulate gravel bed rivers. A meandering channel requires underdamped alternate bars and a relatively narrow and deep channel. The sediment mixture is selected through several criteria including mobility, required hydraulic roughness and resulting bank strength. The mixture composition is tuned by auxiliary experiments on bank strength and erodibility so that banks remain erodible, though less than noncohesive sediment. The emerging width-depth ratio is sufficiently decreased to transition from braiding to weakly meandering. Our scaling approach promises to result in truly meandering experimental rivers.

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