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# Near-bed and surface flow division patterns in experimental river bifurcations

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**Abstract.** Understanding channel bifurcation mechanics is of great importance for predicting and managing multichannel river dynamics and avulsion in distributary river deltas. To date, research on river channel bifurcations has focused on factors determining the stability and evolution of bifurcations. It has recently been shown that, theoretically, the non-linearity of the relation between sediment transport and flow discharge causes one of the two distributaries of a (slightly) asymmetrical bifurcation to grow and the other to shrink. The positive feedback introduced by this effect results in highly asymmetrical bifurcations. However, there is a lack of detailed insight into flow dynamics within river bifurcations and the consequent effect on bedload flux through bifurcating channels and thus the impact on bifurcation stability over time.

In this paper, three key parameters (discharge ratio, width-to-depth ratio and bed roughness) were varied in order to examine the secondary flow field and its effect on flow partitioning, particularly near-bed and surface flow, at an experimental bifurcation. Discharge ratio was controlled by varying downstream water levels. Flow fields were quantified using both particle image velocimetry and ultrasonic Doppler velocity profiling. Results show that a bifurcation induces secondary flow cells upstream of the bifurcation. In the case of unequal discharge ratio, a strong increase in the secondary flow near the bed causes a larger volume of near-bed flow to enter the dominant channel compared to surface and depth-average flow. However, this effect diminished with larger width-to-depth ratio and with increased bed roughness.

The flow structure and division pattern will likely have a stabilizing effect on river channel bifurcations. The magnitude of this effect in relation to previously identified destabilizing effects is addressed by proposing an adjustment to a widely used empirical bed-load nodal-point partition equation. Our finding implies that river bifurcations can be stable under a wider range of conditions than previously thought.

## 1. Introduction

River deltas contain key nodes where fluid and sediment are partitioned into smaller channels and braided multi-channel river systems continually divide and bifurcate flow around mid-channel bars. The mechanisms governing the division of flow and sediment at these channel bifurcations essentially control downstream water and sediment partitioning and, in many cases, also results in an upstream backwater control [see *Slingerland and Smith*, 2004; *Kleinhans et al.*, 2013, for review]. The control of flow and sediment partitioning means that bifurcation evolution and stability is intrinsically linked with these mechanics over time [*Kleinhans et al.*, 2008] and, thus, play a significant role in the evolution of deltaic systems [*Wang et al.*, 1995; *Kleinhans et al.*, 2008; *Edmonds and Slingerland*, 2008]. Bifurcations are also a key control of braided river system behavior [*Repetto et al.*, 2002; *Bolla Pittaluga et al.*, 2003; *Federici and Paola*, 2003; *Bertoldi and Tubino*, 2005, 2007; *Miori et al.*, 2006; *Parsons et al.*, 2007]. Understanding river channel bifurcation behavior is hence of great importance for managing fluvio-deltaic and braided river plains, notably in prediction and management of flood risks and understanding the evolution of braided river systems and river delta environments in the face of environmental change.

The inherent instability of bifurcations has traditionally been explored and explained using numerical models and linear stability analysis [see review in *Kleinhans et al.*, 2013]. A qualitative description of the stability analysis is as follows. Given a nearly symmetrical bifurcation with one slightly deeper and one slightly shallower bifurcate, the slightly deeper bifurcate has a slightly higher discharge and flow velocity. As sediment transport is known to depend nonlinearly on flow velocity, the sediment transport rate in the deeper bifurcate is somewhat larger than in the shallower branch. However, in the absence of topographic or curvature-induced steering, the sediment supply in the upstream channel is partitioned between the downstream channels in proportion to the bifurcate widths [*Bolla Pittaluga et al.*, 2003]. Consequently, the upstream sediment supply to the slightly deeper bifurcate is smaller than the transport capacity, and this dominant channel incises. Channel deepening leads to a positive feedback wherein more water is drawn into the dominant bifurcate and more incision occurs, whilst the subordinate channel has reduced discharge and sediment transport capacity. As a result, the bifurcation is unstable and will become increasingly asymmetric [*Wang et al.*, 1995; *Bolla Pittaluga et al.*, 2003]. A key point of such linear stability analyses is that is evaluates the initial stability. As a consequence, in the above example the channel widths are constant and equal for both bifurcate channels. In erodible channels, the morphology will adapt to such cases over time. The study in this paper focusses on how the morphology might adapt.

Further research focused on the effect of bifurcation angle [*Klaassen and Masselink*, 1992], the influence of downstream water surface slope boundary conditions [*Wang et al.*, 1995; *Kleinhans et al.*, 2013; *Thomas et al.*, 2011], the morphological characteristics of bifurcations initiated by bar formation [*Bertoldi and Tubino*, 2005, 2007; *Federici and Paola*, 2003; *Repetto et al.*, 2002], the stability of bifurcations with erodible banks [*Miori et al.*, 2006] and their evolution [*Edmonds and Slingerland*, 2009; *Kleinhans et al.*, 2008, 2011], and the effect of bends upstream of bifurcations [*Kleinhans et al.*, 2008]. A curved channel upstream of the bifurcation causes helical flow, which strongly affects the sediment transport direction [*Kleinhans et al.*, 2008] and thus controls sediment partitioning. All these effects point to the importance of secondary flow structures, which modify the sediment partitioning between the two bifurcates. This suggests that a perturbation of the detailed flow structure at a perfectly symmetrical bifurcation may also trigger the destabilization of the bifurcation. Moreover, if a perfectly symmetrical bifurcation is not perturbed at the bed but within the inherited flow field, the detailed flow structure determines the partitioning of bed load transport and the initial aggradation or erosion of the downstream channels.

The objective of this paper is to investigate the detailed flow structure in a perfectly symmetrical bifurcation that is perturbed by a slight difference in discharge conveyance in the two bifurcate channels. We focus particularly on the near-bed flow direction as this drives the sediment transport at the onset of bifurcation destabilization. The methodology is to perform detailed measurements in a symmetrical bifurcating flume. Here the discharge partitioning can be unbalanced by adjusting the downstream weirs in both bifurcate channels, which has the consequence that flow at the bifurcation is preferentially curved towards the channel with the highest discharge. Helical flow intensity is inversely proportional to the bend radius relative to the channel width and depth, and inversely proportional to the Nikuradse roughness length (bed roughness) relative to channel depth. Therefore, we further vary bed roughness and width to depth ratio. To isolate the effect of the bifurcating planform from changes in depth or gradient advantages, we also performed control experiments where the water depths were kept equal in the upstream channel and both downstream channels.

Previous work with a similar setup by *Thomas et al.* [2011] showed that secondary flow cells develop in the bifurcate channels which flow towards the inner bank at the surface. Their work mainly investigated the effect of the internal bifurcation angle on the partitioning of the flow, which had little to no influence, and the flow structure in the bifurcate channels as result from a range of discharge divisions. An interesting observation in those experiments is that near-bed flow seemed to be steered stronger into the bifurcate channel with the highest discharge. Here we study this effect of flow steering just upstream of the bifurcation in detail in order to explore implications for sediment partitioning and bifurcation stability. In addition to similar flow measurements as in *Thomas et al.* [2011], we utilize Particle Image Velocimetry to elucidate the flow structure very near the bed. Building on these data we study overall flow structure and near-bed flow steering for a wide range of variables known to be relevant to bifurcation stability, namely discharge division, width-to-depth ratio and bed roughness.

## 2. Methods and Materials

### 2.1. Experimental Setup

We conducted a series of experiments to systematically investigate the flow structure in relation to three key variables. First, we varied the width-to-depth ratio (WDR) of the incoming channel by lowering flow discharge and reducing downstream weir height to maintain uniform flow conditions at the system scale. As wider, shallower, channels tend to have lower secondary flow intensities the experiment was targeted at examining the importance of WDR on flow partitioning at bifurcations. Second, within the WDR experiments we also varied downstream water levels in the bifurcate channels in order to introduce a gradient advantage for one channel. This led to asymmetric discharge partitioning and strengthened secondary flows, allowing us to examine the interaction of secondary flow with WDR under asymmetric conditions. Third, we varied bed roughness by running experiments initially with a smooth bed and subsequently with an immobile gravel bed. This set of experiments was designed to capture the dampening influence of increased roughness on secondary flows and how this interacted with WDR in governing the mechanics of partitioning.

The experiments were conducted in a transparent Perspex bifurcation scale model (Fig. 1a,b), with a 1.6 m-long, 0.5 m-wide inlet channel upstream of a bifurcation which splits the flow into two 0.25 m-wide, 1.6 m-long, distributaries [the same model as the 54° setup used by *Thomas et al.*, 2011]. The entire setup was tilted at a slope of $1 \cdot 10^{-3}$. Water was pumped from a reservoir into a header tank. This header tank was filled at a controlled rate from below and contained a layer of rocks at the bottom to break any flow structure present from the water flowing in. From the header tank, the water flowed downstream through a series of flow straightening baffles into the upstream channel of the flume. The inlet flow was tested and adjusted to ensure the best possible upstream boundary conditions as will be demonstrated with measurements.

The water level and water surface slope were controlled by two weirs, one at the downstream end of each of the bifurcate channels. The water plunged over the control weirs from the bifurcate channels into a reservoir. The flow rate was adjusted until uniform flow conditions were achieved within the system. This was achieved by equalizing the water depths in the inlet channel and downstream distributaries just upstream and downstream of the bifurcation, respectively.

A total of eight experiments were performed (Table 1), varying three parameters: width-to-depth ratio (WDR), discharge ratio ($Qr$) and bed roughness. Experiments were conducted with two different WDRs namely 6.3 and 14.3, the latter representing conditions found in natural systems such as the Cumberland Marshes, Canada [*Edmonds and Slingerland*, 2008] and the Columbia River, Canada [*Kleinhans et al.*, 2012]. For these ratios, water depths of 80 and 35 mm were used, abbreviated as 80xxx and 35xxx herein. Both equal (nnEQ) and unequal (nnNEQ) discharge divisions were examined; discharge ratios of Qr=1 and about Qr=1.5 were used. Downstream weirs were used to control discharge ratio and water depth in each bifurcate. For the equal discharge division runs, discharge and weir heights were adjusted to acquire the required water depth and uniform flow conditions. Experiments with unequal discharge division were always run with the same discharge as their equal counterparts; in these runs uniform flow was acquired by varying weir heights. The backwater adaptation length (*Ribberink and Van Der Sande* [1985]; *Parker* [2004] also see *Kleinhans et al.* [2013] for importance in bifurcations, sometimes named backwater length or backwater effect), estimated by $\lambda_{bw} = h/3S$ ($h$ is water depth, $S$ channel slope), equals 27 m for the low width-to-depth ratio, and 12 m for the high width-to-depth ratio experiments. These values are longer than the entire flume, justifying using downstream weirs to control the division of water at the bifurcation. Individual runs were repeated to allow data collection with different techniques.

All the experiments described above were conducted with a smooth bed as well as with a rough bed; experiments with a rough bed are indicated with the suffix _S for sediment. For the experiments with a rough bed, a 15 mm-thick immobile layer of 3-8 mm ($D_{50} = 5$ mm) white gravel was installed at the bed of the model. The same water depths and discharge ratios were used for the runs with sediment; water levels were measured relative to the top of the gravel bed to retain the same width-to-depth ratio. To ensure uniform flow, but to retain the same WDR, experiments 35EQ_S and 35NEQ_S and experiments 80EQ_S and 80NEQ_S were run at about 60% and 80% of the discharge of their smooth bed counterparts, respectively. This reduced discharge is caused by slower flow induced by the increased roughness.

## 2.2. Data Acquisition

### 2.2.1. Flow Velocity Vectors (UDVP)

A series of measurements were taken from a total of 4 cross-sections distributed throughout the model domain (Fig. 1c). 1D flow velocities were measured sequentially in the streamwise $Ux$, cross-stream $Uy$ and vertical $Uz$ directions at each cross-section (Fig. 1c) using an ultrasonic Doppler velocity profiling (UDVP) system [*Takeda*, 1991, 1995]. A Met-Flow UVP-XW ultrasonic velocity profiler was used to record a multiplexed signal from an array of 4 MHz ultrasonic transducers. The locations of the measurements were chosen such that the individual signals could be combined into time-averaged 3D flow velocity vectors for each cross-section. The positions of the transducers are described in detail in the following paragraphs (also see Fig. 1d).

For the measurement of both $Ux$ and $Uy$, 7 UDVP transducers were used. These transducers were placed at a distance of 10 mm from each other. For the lower WDR runs (runs 80xxx), all 7 transducers were used to measure flow velocities. For the higher WDR runs (runs 35xxx) only 3 transducers were submerged due to the shallower water depth. For the measurement of cross-stream velocities, the transducers were mounted on the outside of the Perspex flume wall and sounded the flow using acoustic coupling gel to prevent distortion of the acoustic signal through the flume walls. In the upstream section, the cross-stream measurements were repeated from both sides. Streamwise velocities were measured by inserting the stack of probes in the flow 100 mm downstream of the actual position of the cross-section in order to minimize the influence of the probe on the measured flow field. Measurements for $Ux$ were taken at 16 locations per cross-section in the upstream channel (see Fig. 1d) and at 8 locations per cross-section in the bifurcate channels (effectively splitting the measurement location shown in Fig. 1d). For the measurement of $Uz$, 16 UDVP transducers were used in the upstream channel and 8 in the bifurcate channels. Transducers were mounted to be only slightly submerged. Locations corresponded with the location of $Ux$ measurements.

The measured streamwise flow velocities $Ux$ were in the range of 40 to 240 mm/s for the low-WDR runs and 10 to 200 mm/s for the high-WDR runs. The majority of cross-stream flow velocities $Uy$ were in the range of -10 to 10 mm/s for the low-WDR runs and -5 to 5 mm/s for the high-WDR runs. Vertical flow velocities $Uz$ were in the range of -4 to 4 mm/s for the low-WDR runs and -1 to 1 mm/s for the high-WDR runs. These fell well within the measurable range (Table 2), $Ux$ and $Uy$ were high compared to the flow velocity resolution. Values for $Uz$ come quite close to the minimum measurable value in the high-WDR runs.

For every measurement location, a total of 512 samples were collected, this value was determined using a method to estimate the optimal record length for turbulent flow, as described by *Buffin-Bélanger and Roy* [2005]. By analysis of convergence of the measured velocity to a mean value. Each transducer was set to record 1D velocities in a profile at 64 distances from the probe. These profiles spanned different lengths for the different measurement orientations and locations: 510 mm for cross-stream measurements in the upstream channel, 256 mm for cross-stream measurements in the downstream channels, 200 mm for streamwise measurements and 98 mm for vertical measurements (see Table 2 for full set of properties). Streamwise measurements were obtained at a distance of 100 mm upstream from the probe, which matched the locations of the cross-stream velocity measurements, which is the actual location of the cross-section. This then allowed co-located time-averaged velocity vectors to be combined along each of the cross-sections. For the cross-sections in the upstream channel, the cross-stream velocity was measured from both sides of the channel subsequently. At every vector location in each section, the two available values for the cross-stream component taken from either side were compared. If the difference of the two values was within one standard deviation of all cross-stream values, the mean of these values was used. Otherwise, the value with highest magnitude was used. This procedure was followed because in the cross-stream data, vertical bands with zero flow velocities were present in some of the data. It is likely that acoustic reflections from the opposite flume boundary caused these bands. An occasional large difference in the two values is likely to be the result of this effect.

### 2.2.2. Near-bed and Surface Flow Fields (Particle Image Velocimetry)

For all model runs Particle Image Velocimetry (PIV) [see *Adrian*, 1991, 2005] was used to record 2D near-surface flow velocity vectors in the streamwise $Ux$ and cross-stream $Uy$ directions. This was achieved through introduction of about 15,000 floating particles ($\rho_s = 660\,\mathrm{kg\,m^{-3}}$, $d = 2.0 - 2.5\,\mathrm{mm}$). Additionally, for runs with a smooth bed, near-bed velocities were also measured using PIV using about 10,000 denser ($\rho_s = 1360\,\mathrm{kg\,m^{-3}}$, $d = 2.5\,\mathrm{mm}$) particles. In contrast to classic PIV techniques with neutrally buoyant small particles and laser sheets, we applied PIV methods to slightly larger floating surface particles and sinking particles at the channel bed (c.f. *Jodeau et al.* [2008]; *Blanckaert et al.* [2013]). Note that the PIV data were collected in repeated runs and not simultaneously with the UDVP data. For both the near-surface and near-bed measurements PIV involved uniformly feeding black particles into the inlet channel over a period of about 10 s. A digital SLR camera with High Definition (HD) video capabilities (Canon EOS 550D) with a low-distortion wide angle lens (Canon EF-S 10-22 mm @ 20 mm) was used to record the movement of the particles during the run. The camera was mounted perpendicular to the flume in the centre of the channel just upstream of the bifurcation head (Fig. 1c). The camera was set to shoot HD video (1080×1920 at 29.97 fps). Three 500 W halogen lamps, shielded to prevent reflections at the water surface, illuminated the measurement section. Single frames were extracted from 15-20 s of video from each run, resulting in 450-700 individual frames. For all runs, images of different water levels were used to create image masks to remove areas outside the actual flow field. These masks represent the with of the flume for the different water levels, and effectively correct for vertical relief-displacement. As the water surface is near-flat, the camera was positioned level and centered above the flume, and the used lens features minimal distortions, no further lens corrections were applied to the image to maintain image sharpness. The main source of optical distortion in these images is at the sides in the runs where we filmed bed-particles through the water. This distortion is minimal straight below the camera, which is the area just before the bifurcation. A rectangular region centered on the inlet channel with the bifurcation head as a fixed point was cropped out of the masked image. The resulting image was converted to 8-bit grayscale, inverted and a pixel value threshold was then applied to remove irregularities introduced by the bed and walls. Lighting irregularities were minimal relative to the high contrast between the black particles and white background.

For every pair of consecutive images, flow velocities were calculated using the Mean Quadratic Difference method. This method was chosen as it gives better results in recordings with a high particle density [*Gui and Merzkirch*, 1996; *Merzkirch and Gui*, 2000]. Velocity vectors were calculated in MATLAB using a bespoke toolbox [based upon *Mori and Chang*, 2003] using sampling windows of 32×32 pixels. This method uses a sub-pixel estimate of particle location based on pixel values. The pixel size is about 0.5 mm which, with a 30 fps frame rate, yields a theoretical minimum velocity resolution of $0.05\,\mathrm{mm\,s^{-1}}$. Vectors were spaced such that each dataset contains 32 vector per channel width, which corresponds to a vector spacing of 32 pixels for the low WDR runs (80xxx) and 30 pixels for the high WDR runs (35xxx, Table 1), resulting in overlap of 1 pixel at each side of the sampling window in the high WDR runs. The magnitude of the vectors were corrected for the different field of views for the different water heights. Filtering was applied to the velocity time series at every vector location, resulting in all spurious vectors outside a range of 2 standard deviations from the local mean being removed from the dataset. This filtering resulted in the removal of about 10% of the vectors in the surface measurements for the smooth-bed runs and about 35% of the rough-bed runs. For the near-bed measurements of the smooth-bed runs, about 5% of the vectors were filtered. The quality of this method seems related to artifacts introduced by visible shadows as result from the gravel in the setup. The mean values per time series were used in further analysis. Note that no spatial filtering or any form of interpolation was performed on the data.

## 2.3. Data Analysis

### 2.3.1. Discharge and (Depth-) Averaged Velocities

The measured UDVP data were used to calculate cross-sectional discharge and average flow velocity vectors. The average flow velocity was calculated for each measured cross-section $cs$ and at each measured depth profile $y$. The cross-sectional discharge $Q_{cs}$ (m$^3$/s) was calculated by summing the products of stream-wise flow velocity measurements $Ux$ (m/s) and their effective area $a$ (m$^2$):

$$Q_{cs} = \sum_{y=1}^{n_y} \sum_{z=1}^{n_z} (Ux_{y,z} \cdot a_{y,z}) \tag{1}$$

Where $a$ is calculated from the distances from the centers between measurement locations or the flow boundaries at the outer edges. The cross-sectional averaged velocity $U_{av,cs}$ (m/s) is the discharge through that cross-section ($Q_{cs}$) divided by cross-sectional area $A = W \cdot H$ (m$^2$).

$$U_{av,cs} = Q_{cs}/A \tag{2}$$

The discharge passing through the upstream sections CS01, CS02 and CS03, and the summed discharge of both downstream sections CS04L and CS04R were evaluated for continuity by calculating the root-mean-square (RMS) deviation from the mean discharge $\bar{Q}$ of all four sections.

$$Q_{rms} = \sqrt{\frac{1}{n} \sum_{cs=1}^{n} \left(\bar{Q} - Q_{cs}\right)^2} \tag{3}$$

At each measured vertical profile $y$ the discharge per unit width $qx_y$ (m/s) was calculated in a similar way as the cross-sectional discharge:

$$qx_y = \sum_{z=1}^{n_z} (Ux_{y,z} \cdot h_z) \tag{4}$$

where $h_z$ is the effective height of each measurement. For the depth-averaged flow velocity vectors $Ux_{av,y}$, the discharge per unit width $qx_y$ was divided by the flow depth $H$:

$$Ux_{av,y} = qx_y / H \tag{5}$$

Equations 4 to 5 were also applied to attain depth-averaged cross-stream flow velocities $Uy_{av,y}$ by substituting streamwise flow velocities $Ux$ by cross-stream flow velocities $Uy$.

### 2.3.2. Streamwise Circulation and Planar Vorticity

UDVP measurements were used to calculate the streamwise circulation at each cross section. PIV data were used to calculate the planar vorticity field for both the surface as well the near-bed measurements.

The streamwise circulation $\Gamma$ of a flow is a measure of the amount of rotating secondary flow field in a cross section. The circulation is calculated by taking the area integral of the two-dimensional vorticity ($\omega$, in the y-z plane) per cross section:

$$\Gamma = \int_z \int_y \omega \, dydz \tag{6}$$

where $\Gamma \, (\mathrm{m^2 s^{-1}})$ is the circulation and $\omega \, (\mathrm{rad \cdot s^{-1}})$ is the vorticity which is defined as the curl of a vector field:

$$\omega = \nabla \times \vec{\mathbf{u}} \tag{7}$$

where $\vec{\mathbf{u}}$ is a 2D vector field of cross-stream and vertical flow velocities $Uy$ and $Uz$ from UDVP measurements.

In order to compare the circulation for different cross sections, the circulation is computed using the absolute values of the vorticity ($\omega = |\omega|$ in Eq. 6). The vorticity is normalized using the method of *van Balen* [2010, p.77]:

$$|\hat{\Gamma}| = |\omega| H/(A \cdot U_{av,cs}) \tag{8}$$

where $|\hat{\Gamma}|$ is the absolute normalized circulation and $A$ is the cross-sectional area.

Details of the secondary flow structure are also shown by the planar vorticity (in the x-y plane) using Eq. 7, but using cross-stream flow velocities ($Uy$) and downstream flow velocities ($Ux$) for vector field $\vec{\mathbf{u}}$, taken from PIV measurements of the surface flow and near-bed flow.

## 2.4. Data Quality

### 2.4.1. Development of turbulence

We analysed the UDVP data at CS01 to see whether a turbulent flow developed. Turbulent flow conditions result in a logarithmic velocity profile. We tested if such profile existed in the measured flow velocities. At each vertical profile $y$ we applied a logarithmic regression to predict the stream-wise flow velocity $\hat{Ux}$ from the height above the bed $z$:

$$\hat{Ux}(\log(z)) = a_0 + a_1 \log(z) \tag{9}$$

We analysed these profiles visually and we indicate how good the data fits the model with the coefficient of determination $R^2$, which is calculated as:

$$R^2 = 1 - \frac{\sum \left( Ux(z) - \hat{Ux}(z) \right)^2}{\sum \left( Ux(z) - \overline{Ux} \right)^2} \tag{10}$$

where $\overline{Ux}$ is the average flow velocity in the profile under consideration.

### 2.4.2. Scaling assessment

We used the Froude number, Reynolds number and Weber number to evaluate the hydraulic behavior of our experiments. We evaluated these values from UDVP measurement in the upstream section of the experiment. The Froude number ($Fr$) determines if the flow is affected by downstream or only by upstream disturbances, respectively subcritical ($Fr < 1$) or supercritical ($Fr > 1$) flow. Subcritical flow conditions are desirable.

$$Fr = \frac{U}{\sqrt{gH}}, \tag{11}$$

where, $g$ the gravitational acceleration (9.81 $\mathrm{m}^2$/s). The Reynolds number (Re) indicates if the flow is turbulent ($Re > 2000$) or laminar ($Re < 500$), with a transition zone in between:

$$Re = \frac{UR}{\nu}, \tag{12}$$

where $R$ is the hydraulic radius (m), $R = (H \cdot W)/(2H + W)$, $\nu$ is the kinematic viscosity of water ($\mathrm{m}^2$/s), $\nu = 4 \cdot 10^{-5}/(20 + t)$, where $t$ is the temperature ($18°C$ for the current experiments). We aim for turbulent flow in our experiments.

The Weber number (We) shows the relation between inertia and surface tension forces [*Peakall and Warburton*, 1996]. Critical values for the Weber number are uncertain and vary from 10-100, so we aim for values above this range.

$$We = \frac{U^2 \rho H}{\sigma}, \tag{13}$$

where $\sigma$ is the surface tension. We used an estimate of $\sigma = 6 \cdot 10^{-3}\,\mathrm{N/m}$ in our experiments as opposed to the value of $7 \cdot 10^{-2}\,\mathrm{N/m}$ for water because we used soap in the water to reduce the surface tension.

## 3. Results

### 3.1. General Flow Structure

The following key flow field properties were derived from UDVP data (Table 3): (1) all equal weir runs had equal (50/50) discharge division; (2) all unequal weir runs had a discharge division close to 40/60. The measured discharge was less uniform for the shallower runs with a rough bed ($Q_{RMS}$, Table 3), which is probably due to the higher levels of noise present in the UDVP measurements for these runs.

### 3.2. Effect of Flow Division on Flow Structure

In the low WDR smooth bed runs with equal discharge division (Run 80EQ), the high velocity core was positioned in the center of the channel (Fig. 2). In the unequal discharge division case (80NEQ), the flow velocity core was located to the right-hand side in the two downstream cross-sections (Fig. 3), the side with the gradient advantage and largest discharge. In both the equal and unequal cases (80EQ, 80NEQ), two opposed secondary flow cells were present in the channel upstream of the bifurcation. These cells flowed towards the center of the channel at bed level and towards the banks at the water surface (Fig. 2a-b, 3a-b). However, in the unequal discharge division case, the cell at the side of the channel with the highest discharge was smaller (Fig. 3a-b). In both cases, the division of flow becomes visible in CS02 and dominates the flow structure in CS3. In the latter, the rotational flow cells are almost absent (Fig. 2c, 3c). For a large portion of the width (about 80%) in the unequal discharge division case, the flow structure caused the near-bed velocities to be oriented towards the channel with the water surface gradient advantage (Fig. 3c Fig. 6b). Note that a flow direction towards the right channel does not mean that this flow indeed enters the right channel as we will discuss later.

In both bifurcate channels, most velocity vectors were consistently directed towards the inner bank while the near-bed vectors were directed towards the outer banks (Fig. 2d-e, 3d-e). This flow structure had an inverse direction of rotation compared to the flow cells upstream of the bifurcation.

The PIV vectors obtained for the near-surface and near-bed flow reveal a more detailed flow field in the horizontal plane than the UDVP data (Figs. 7 and 8), especially in the area just upstream of the bifurcation (the downstream-most UDVP section (CS03) is located at x=431 mm in Fig. 7 and 8). In this zone, the flow divergence and steering into the bifurcate channels becomes even stronger than at the locations observed with UDVP data (Fig. 7). Moreover, near-bed flow accelerates closer to the bifurcation (Fig. 8b,d). Indeed, just upstream of the bifurcation (x = 550 mm, Fig. 8) the near-bed velocity vectors were almost perpendicular to the outer banks in both cases with unequal discharge division (nnNEQ).

Flow division lines (Fig. 9) were derived from the near-surface (Fig. 7) and near-bed velocity vectors (Fig. 8). These lines indicate the spatial location of the division of incoming near-surface and near-bed fluid into the two bifurcate channels. Important observations from these divisions include: 1) in symmetrical bifurcations both the discharge ratio, $Q_{right}/Q_{total}$, and the near-bed division ratio, $q_{bed,right}/q_{bed,total}$, were about 50%; 2) in asymmetrical bifurcations $q_{bed,right}/q_{bed,total}$ (71%) was much greater than $Q_{right}/Q_{total}$ (62%) (Table 3); and 3) the majority of this division of near-bed flow occurred within a distance of about one channel width upstream of the bifurcation (Fig. 9b).

### 3.3. Effect of Width-to-depth Ratio on Flow Structure

Similar flow features described above were also observed in the higher WDR runs 35EQ and 35NEQ (see Fig. 4,5 and 6c-d), although some differences exist. There is no high flow velocity core in the middle of the channel, but the highest flow velocities are spread over a larger part of the channel (Fig. 4c). There are actually two locations with higher velocities in the left and right part of the upstream channel, which can be related to the highest velocity core in the bifurcate channels. Also in the unequal discharge case, the stream-wise velocities develop toward one core of flow velocity on the side of the channel with the largest discharge (Fig. 5c). The secondary flow structures upstream of the bifurcation consists of two counter-rotating flow cells in the middle of the channel flowing towards the banks near the bed (Fig. 4a). Additionally, a third and fourth flow cell seems to be present near the banks which flow towards the banks near the water surface (Fig. 4a). The secondary flow structure in the middle of the channel in opposite direction as observed in the low-WDR runs. However, this flow structure has the same structure in respect to the cores of highest flow velocity, which are two in the high-WDR case on either side of the channel and just one in the middle in the low-WDR runs. These flow cells were not observed in the unequal discharge division high-WDR run 35NEQ (Fig. 5). The rotation of these cells is mostly inferred from the cross-stream flow as vertical flow is close or even under the measurement limit. The splitting flow structure closer to the bifurcation and flow cells in the bifurcate channels are comparable to the structure observed in the low-WDR runs and suppress the flow cells closer toward the bifurcation (Fig. 4b-c).

There was no clear difference in the direction of near-bed and depth-averaged flow (Fig. 6c-d). However, a divergence of surface water was observed in the zone just upstream of the bifurcation (between x=400 mm and the bifurcation) in both the low-WDR runs (80EQ, 80NEQ, Fig. 7a-b) and high-WDR runs (35EQ, 35NEQ, Fig. 7c-d), but this diversion extended farther upstream and was significantly more pronounced in the low-WDR runs. Indeed, near-surface velocities are affected by the unequal discharge distribution at a distance of about one channel width upstream of the bifurcation in the low-WDR run (80NEQ, Fig. 9b) and about half a channel width in the high-WDR run (35NEQ, Fig. 9b). Interestingly, the low-WDR has less impact upon near-bed cross-stream flow velocities than on the near-surface flow. This effect is shown in terms of flow division (Fig. 9, Table 3): in the high WDR run (35NEQ), a larger proportion of the near-surface flow enters the bifurcate channel with a gradient advantage ($q_{surf,right}/q_{surf,total} = 62\%$) whereas in the low WDR run this is somewhat lower ($q_{surf,right}/q_{surf,total} = 56\%$). The same holds for near-bed flow, but with a smaller difference observed between the two runs ($q_{bed,right}/q_{bed,total} = 71\%$ and $q_{bed,right}/q_{bed,total} = 68\%$ for runs 80NEQ and 35NEQ, respectively).

### 3.4. Flow Circulation

Upstream of the bifurcation, there were two counter-rotating flow cells with upwelling flow in the middle of the channel in the low-WDR runs. These cells were symmetrical in the symmetrical bifurcation (Fig. 2a) and were unequal in size in the asymmetrical bifurcation (Fig. 3b). In the high-WDR runs, two counter rotating flow cells with downward flow in the middle and two weaker flow cells with downward flow near the banks on either side were observed in the symmetrical run (Fig. 4a), but this structure was not observed in the unequal discharge run (Fig. 5a). In all cases these flow cells were suppressed by splitting flow closer to the bifurcation. Downstream of the bifurcation, a single flow cell was present in each bifurcate channel with flow towards the outer bank near the channel bed (Fig. 2d-e,3d-e,4d-e,5d-e). The magnitude of circulation consistently increased downstream of the bifurcation in all runs (Fig. 10). Earlier results [*Thomas et al.*, 2011] already show the inversion of direction and increase in magnitude of flow rotation in the bifurcate channel. This effect is attributed to super-elevation of the water surface at the bifurcation point.

The low WDR runs (80xx) had a higher relative circulation than the high WDR runs (35xx) (Fig. 10). For unequal discharge division cases, the subordinate left channel (gradient disadvantage and thus lower discharge) had a 20-50% larger intensity of normalized circulation than the dominant right channel (Fig. 10). In the equal discharge division cases, there were differences in circulation between the bifurcate channel, however these were small and not always stronger in the same channel (Fig. 10). Perhaps the most notable difference was for 80NEQ, which is likely to have the strongest transverse flow velocities because of the low WDR and smooth bed.

The planar vorticity of the flow field show the presence of rotating cells in the smooth bed runs (Fig. 11a-d). The general pattern corresponds with the flow structures observed in the UDVP data, with the presence of two counter-rotating flow cells in the low-WDR runs (Fig. 11a-b) and the presence of two additional cells in the high-WDR runs (Fig. 11c-d). The main vorticity pattern in the low-WDR runs corresponds with a high flow velocity core in the middle of the channel and slow flow on the sides, which results in rightward vorticity on the right-hand side of the channel and towards the left on the left-hand side. In the high-WDR runs, there is no concentrated velocity core in the middle of the channel, the high velocity is more spread over a larger area. In this case, the planar vorticity pattern shows the pattern of the the secondary flow structure, which are multiple cells of rotating flow cells. In both cases, the planar vorticity pattern follows the streamline curvature. The pattern of planar vorticity in the near-bed flow (Fig. 12) also shows a banded pattern. However, there are more small-scale features. These patterns do not resemble the pattern of flow cells observed in the surface data. Additionally, these patterns also show dividing and splitting circulation bands.

Spatially averaged vorticity (Fig. 13) shows the average planar vorticity pattern in the upstream reach. The large-scale vorticity pattern for the low-WDR runs is consistent for both the equal and unequal discharge division and both smooth and rough bed runs (Fig. 13a). This pattern is the result of a high-flow velocity core in the center of the upstream channel which curves towards the outer banks and is consistent with the flow structures observed in the cross-section. The vorticity pattern in the high-WDR runs shows local vorticity patterns superimposed on a large-scale vorticity pattern (Fig. 13b). This pattern is consistent with local flow structures, as also observed in cross-section data (Fig. 4, 5). Vorticity of the near-bed flow show a local pattern without a large-scale structure (Fig. 13c,d).

### 3.5. Effect of Bed Roughness on Flow Structure

In the runs with a rough bed (nnxxx_S), the deviations of the near-bed velocity from the depth-averaged velocity in the low-WDR rough bed experiments were similar as their smooth-bed counterparts (Fig. 6e,f, 80EQ_S, 80NEQ_S). Flow velocities were lower in the rough-bed cases. Additionally, the decrease in flow velocity towards the bed is stronger for the rough bed cases. The general flow structures were similar to those in their smooth-bed counterparts but were lesser in magnitude (Fig. 7e-h).

The high WDR, rough bed experiments (Fig. 6g,h, 35EQ_S, 35NEQ_S) showed significant levels of noise induced by acoustic interference between the rough bed and the UDVP. In the rough bed runs, the upstream influence of the bifurcation extends for only half the distance observed in their smooth bed counterparts. Near-surface flow is divided more equally between the distributaries (Fig. 9, Table 3, $q_{bed,right}/q_{bed,total} = 55\%$ for run 80NEQ_S) and almost equal in the higher WDR run ($q_{bed,right}/q_{bed,total} = 51\%$ for run 35NEQ_S). Unfortunately, the near-bed flow field could not be quantified using PIV because of entrapment of particles in the bed sediment. Compared to the smooth bed runs, similar vorticity patterns are visible in the rough bed cases, although these are noisier (Fig. 11e-h). The effect of bed roughness is dependent upon the WDR: in the low WDR runs, both the smooth and rough beds show similar banding of comparable magnitude (Fig. 13a) whereas in the high WDR runs the rough bed shows similar banding, but at about a 2-4 times higher magnitude (Fig. 13b, pale colored lines). This comparison shows that stronger flow structures emerged preferentially in channels with a larger width-to-depth ratio, but is reduced in channels with a larger ratio of roughness length to water depth.

## 4. Discussion

### 4.1. Scaling Assessment and Robustness of Methods

In all experimental runs, the flow was subcritical with Froude numbers between 0.1 and 0.3 (Table 3). The Reynolds number was well above the threshold for turbulent flow

(Re> 2000) in all low-WDR runs and in the smooth bed high-WDR runs. Re values for the high-WDR runs with rough bed, equal discharge division (35EQ_S) are closer to, but still above 2000. Run 35NEQ_S had a Reynold number slightly below 2000 (Table 3). The same is shown by the flow velocity profiles at the most upstream cross-section: the measured flow velocity profiles show a well-developed logarithmic profile in all low-WDR runs (Fig 14a) and in the high-WDR, smooth bed runs (Fig 14b, closed symbols). The high-WDR, rough bed runs show more scattered velocity profiles (Fig 14b,c open squares), which is most probably due to noise in the measurements due to the high amount of acoustic scattering on the rough bed and the limited water depth. Nevertheless the Reynolds number is in the upper end of the transitional regime and the velocity profiles show no indication of laminar flow so we believe these experiments to have had fully turbulent flow.

Deviations from the logarithmic profile are apparent close to the flume wall (Fig 14a, profile 1). The deviation from a logarithmic profile is visible in all measurements and most prominent in the smooth bed, low-WDR runs (Fig 14c, closed circles). This wall friction effect is expected and is perhaps even more important in natural channels.

In small-scale experiments, surface tension might have an effect on the dominant acting processes. In our experiments, however, the relative importance of the fluid's inertia to the surface tension is very low as the Weber number is above the critical value of 100 for most runs and well above 10 for the high-WDR, rough bed cases. Note that the reported critical values are not consistent [*Peakall and Warburton*, 1996].

We compared the streamwise velocity from UDVP measurement closest to the water surface to the surface PIV data at the same location (Fig. 15). Please note that these two things do not measure the same flow, but this provides a way to see whether there are issues with any of the data. Most measurements are close to being equal, with a tendency of the PIV data to be slightly higher. The main difference are the rough bed high-WDR runs. As stated above, we consider the UDVP data for these runs to be noisy.

### 4.2. Implication for Bifurcation Instability

Flow structure at bifurcations is determined by (1) flow forcing by streamline curvature, angular divergence upstream and through a bifurcation and related zones of flow separation [e.g. *Ramamurthy et al.*, 2007]; (2) the width-to-depth ratio and flow field inertial and momentum forces [e.g. *Bradbrook et al.*, 2001; *Parsons et al.*, 2007]; (3) flow field super-elevation and related pressure gradient terms [e.g. *Shettar and Keshava Murthy*, 1996]; (4) backwater surface slopes; and (5) topographic forcing by the bed [e.g. *McArdell and Faeh*, 2001; *Bolla Pittaluga et al.*, 2003; *Kleinhans et al.*, 2008]. In this paper, two independent flow measurement techniques have been used to quantify flow fields in a morphologically symmetrical experimental bifurcation. Flow structures develop that can significantly modify the near-bed flow direction at a distance of up to one channel width upstream of the bifurcation head. The character of the flow was turbulent and highly subcritical with strong backwater effects. Data obtained from control experiments with equal discharge partitioning do not show asymmetric near-bed flow but do have some flow structures that contain counter-rotating transverse-vertical cells upstream of the bifurcation in addition to a clear signal of the bifurcating flow closer to the bifurcation. In the experiments with unequal discharge partitioning the near-bed transverse flow was directed towards the bifurcate channel which had the gradient advantage and largest discharge. About 80% of the near-bed flow entered the larger channel. Furthermore, as expected, the transverse flow component is larger for channels with larger water depth relative to channel width and relative to the characteristic length of bed roughness. This flow structure upstream of the bifurcation is caused by flow curvature towards the bifurcate channels at the bifurcation. Such upstream influence is also observed in curved channels and may be the result of the actual flow curvature itself [*Jamieson et al.*, 2010], or the result of backwater effects [*Blanckaert et al.*, 2013]. Downstream of the bifurcation, the flow structure shows a pattern that is consistent with plunging water resulting from super-elevation at the bifurcation point, as shown by *Thomas et al.* [2011].

In classical analyses of the stability of a perfectly symmetrical bifurcation, a perturbation to the bed level or water depth is introduced either in one of the distributaries or just upstream of the bifurcation [*Wang et al.*, 1995; *Bolla Pittaluga et al.*, 2003; *Kleinhans et al.*, 2008]. Such a perturbation may grow or dampen depending on the channel width-to-depth ratio and sediment mobility. A growing perturbation may eventually lead to the closure of one of the bifurcate channels, i.e. the bifurcation is unstable. In the present paper, we document laboratory flume experiments in which we perturbed the bifurcation by changing the energy gradient in the bifurcate channels. Theoretically, this should always lead to the enlargement of the channel receiving the most discharge when the bifurcation is otherwise symmetrical. However, our experimental findings suggest that the destabilization of a morphologically perfectly symmetrical bifurcation has a pronounced influence on the near-bed flow over a distance of about one channel width upstream of the bifurcation, which may influence the bifurcation stability. This length scale is in agreement with the length scales and model concepts of *Bolla Pittaluga et al.* [2003] and *Kleinhans et al.* [2008]. However, in these models, the upstream length of bifurcation influence is assumed to be the result of an upstream extension of topographic forcing by the bed [e.g. *McArdell and Faeh*, 2001; *Bolla Pittaluga et al.*, 2003; *Kleinhans et al.*, 2008], which was absent in our experiments. In our case, the dividing line between near-bed flow that enters the dominant channel and near-bed flow that enters the subordinate channel is strongly curved (Fig. 9). Thus, the fraction of upstream channel width that contributes water to the dominant bifurcate channel is much larger than expected on the basis of the relative discharges of the bifurcate channels. This novel result is not included within the depth-averaged model concepts used in both *Bolla Pittaluga et al.* [2003] and *Kleinhans et al.* [2008]. The implication is that linear stability analyses of perturbed bifurcations based on depth-averaging requires modification for the flow structure induced by discharge asymmetry, which is the result of a perturbation in one of the downstream channels..

The observed near-bed flow structure upstream of perturbed bifurcations has an unexpected ramification for the breakdown of symmetry of river bifurcations. In our experiments, near-bed flow is directed towards the dominant bifurcate. Such flow structure may cause an increase of sediment supply into this dominant channel. For example, for experiments where the dominant bifurcate received about 60% of the total discharge, about 70% of the near-bed flow was going into this bifurcate (Fig. 9). We expect a similar effect on bedload partitioning in bifurcations.

Morphologically, we suggest that the impact of this accentuated asymmetry in near-bed flow partitioning could be a negative feedback on the destabilized bifurcation: the dominant bifurcate channel could receive so much more sediment that it aggrades, reducing its conveyance and thus forcing the bifurcation towards symmetry. In other words, the net effect opposes the initial degradation of the dominant bifurcate channel, particularly in the case of narrow and deep rivers with stronger transverse flow. Curvature in the flow just upstream of the bifurcation will initially lead to sedimentation in the dominant channel because of flow convergence, but also sedimentation upstream of the subordinate channel distributary because of flow divergence. As a result, the dominant channel may aggrade initially, even if it eventually enlarges [e.g. *Bertoldi and Tubino*, 2007; *Bolla Pittaluga et al.*, 2003; *Edmonds and Slingerland*, 2008; *Federici and Paola*, 2003; *Kleinhans et al.*, 2008; *Miori et al.*, 2006]. The flow structure observed in our experiments may thus cause stabilization of a symmetrical but perturbed bifurcation. This negative feedback has not been described before.

The question is: how important is this negative feedback in natural bifurcations? It could be argued that the sediment transport capacity of the dominant bifurcate channel would increase nonlinearly with discharge. However, the analyses of *Wang et al.* [1995] and *Bolla Pittaluga et al.* [2003] demonstrate that the ratio of sediment transport in the two bifurcates $Q_{s,right}/Q_{s,left} = (Q_{right}/Q_{left})^k$, where $k$ is unity in the absence of a transverse bed slope and planimetric perturbation. In principle, k is to be determined empirically, but three-dimensional flow and sediment transport modeling has demonstrated that $k$ is approximately unity for much of the lifetimes of bifurcations formed in mobile beds [*Kleinhans et al.*, 2008]. Here, $k = 1$ means that sediment is partitioned over the downstream channels proportionally to their widths. This work was based on modeling idealized but asymmetrical bifurcations with an initially flat bed [*Kleinhans et al.*, 2008]. There were indeed fluctuations in discharge partitioning after the start of all model runs, particularly in runs where the bifurcate channels were nearly balanced by, on the one hand, a gradient advantage for one channel, but on the other hand an advantage for the other channel caused by an upstream bend with helical flow upstream of the bifurcation that favors the subordinate channel. The models show that initially sediment always deposited in one of the channels such that k is offset as the dominant bifurcate channel initially receives relatively more sediment despite the presence of a bend [*Kleinhans et al.*, 2008, their Fig. 9]. This can be expressed empirically as:

$$Q_{s,right}/Q_{s,left} = a\,(Q_{right}/Q_{left})^k \tag{14}$$

where $a < 1$. In the numerical modeling the ultimate bifurcation condition was asymmetrical in the manner expected from gradient or upstream bend advantage, but the evolution towards this state was delayed by the negative feedback of flow structure.

In short, previous numerical modeling work supports our hypothesis that bifurcations with subcritical flow perturbed by asymmetrical downstream discharge conveyance have a flow structure that may result in elevated sediment transport into the dominant channel, providing a negative feedback on the onset of bifurcation destabilization. Given that the transverse bed slope upstream of the bifurcation only overcomes the initial flow and sediment attraction of the advantaged channel in a later stage, we hypothesize the following. The balance is subtle and the transverse bed slope readily develops, so the condition where balancing potentially occurs is when the transverse bed slope development is limited whilst the imbalance between channel width and flow discharge is large. In other words, balancing flow attraction and sediment attraction is most likely to occur where there is a large gradient or bend advantage for one channel, leading to higher discharge, whilst the other channel is equally wide or wider but has a lower discharge. Other important factors are the roughness of the channel and the width-to-depth ratio of the channel, as these suppress the transverse flow and therefore the sediment attraction of the dominant channel.

The hitherto unidentified effect could lead to unexpected sedimentation in engineered bifurcations, for example in small streams with newly created side channels. Altered sedimentation patterns will be especially present in cases of low roughness. Furthermore, the flow structure and the inherited mixing of flow propagating into the downstream branches may be relevant for the aquatic chemistry of small bifurcating streams as commonly found in lowland areas, because it modifies the supply of dissolved oxygen, nutrients and organic matter. In addition, the reported effects of bifurcation perturbation on near-bed flow affect the biologically important benthic boundary layer.

## 5. Conclusions

The effect of flow structure on the stability of geometrically symmetrical bifurcations was studied in fixed-bed experiments under a range of conditions, including both a smooth and rough bed case, over two width-to-depth ratios and either symmetrical or asymmetrical flow division forced by downstream water surface gradient.

Upstream of the bifurcation, counter-rotating flow structures emerged. In high width-to-depth ratio channels, the number of flow cells increased. These flow cells were equal in size for bifurcations with equal discharge division, but asymmetrical for the bifurcation with unequal discharge division. These flow cells diminished in strength with higher width-to-depth ratio and bed roughness. Closer to the bifurcation, flow splitting suppressed these flow structures.

The experiments demonstrate that, under unequal discharge division, the flow is strongly curved towards the channel with the highest discharge over a length of about one channel width. The near-bed flow curvature was considerably larger than the surface flow curvature, with the strongest curvature just upstream of the bifurcation. These effects diminish with increasing width-to-depth ratio and increasing bed roughness.

These results imply that a disproportionately large amount of sediment can be transported into the downstream channel with the largest discharge. This could provide a negative feedback on bifurcation destabilization because the enhanced sediment input would reduce the expected erosion rate in that channel. This modifies the usual hypotheses that sediment division in a symmetrical bifurcation is proportional to channel width. This mechanism would act as a stabilizing effect on perturbed river bifurcations, which is not been taken into account in current theory.

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**Figure 1.** (a) Photograph of the model set-up, (b) schematic illustration of the model set-up, (c) bifurcation model detail with locations of UDVP measurements cross-sections and PIV area. (d) Illustration of the locations and directions of UDVP transducers in the upstream part of the bifurcation at low WDR. In the bifurcate channels 8 measurements per channel width were used. In the high WDR runs, 3 vertical measurement locations were used.

**Figure 2.** 3D velocity components (UDVP data) for run 80EQ, at cross-sections a) CS01, b) CS02, c) CS03, d) CS04L and e) CS04R. Color contours show stream-wise velocity ($Ux$), black arrows show cross-stream ($Uy$) and vertical ($Uz$) velocity components. White arrows indicate the bulk flow structure, dashed line shows the approximate location of flow division ($Uy = 0$). Axis orientation is such that the 'flow goes into the paper' / looking downstream. Vertical axis and vertical flow velocities are 2 times exaggerated in respect to cross-stream axis and flow velocity.

**Figure 3.** 3D velocity components (UDVP data) for run 80NEQ, see Fig. 2 for caption.

**Figure 4.** 3D velocity components (UDVP data) for run 35EQ, see Fig. 2 for caption.

**Figure 5.** 3D velocity components (UDVP data) for run 35NEQ, see Fig. 2 for caption.

**Figure 6.** Depth-averaged (DA, light-green) and near-bed (NB, dark-red) flow velocity vectors (UDVP data) at all measured cross sections. Axis labels were removed where they are the same as the adjacent graphs. Secondary flow structures caused the direction of the near-bed flow to deviate from the depth-averaged flow. This effect was more pronounced in the low WDR, asymmetrical runs (80NEQ / 80NEQ_S). The high WDR, rough bed runs are noisy due to acoustic resonance in the flume.

**Figure 7.** Near-surface velocity vectors (PIV data, arrows). Cross-stream flow velocities are emphasized with colored contours, which indicate the magnitude of cross-stream flow $Uy$ relative the upstream channel. Red contours indicate flow to the right, blue /dashed contours indicate flow to the left, first contour $= 5\,\mathrm{mm\,s^{-1}}$, contour interval $= 10\,\mathrm{mm\ s^{-1}}$. For clarity, only every third vector in the downstream direction is shown.

**Figure 8.** Near-bed velocity vectors (PIV data, arrows), see Fig. 7 for caption.

**Figure 9.** Division of flow at the bifurcation derived from PIV flow fields. a) equal discharge division runs (read legend as xx=EQ), and b) unequal discharge division runs (read legend as xx=NEQ). Solid black lines show the boundaries of the bifurcation model. Solid lines denote the division between surface water entering the left and right channels for the smooth bed runs, dashed lines show the surface water division for the rough bed runs. Dotted lines denote the division of incoming near-bed flow between the left and right channels.

**Figure 10.** Absolute normalized circulation derived from UDVP data for all a) smooth bed runs and b) rough bed runs plotted against downstream coordinate y. For the most downstream location, the lines spit for the left and right bifurcate channel. Blue lines represent the low-WDR runs, green the high-WDR runs. Dark colors represent equal discharge division runs, pale colors the unequal discharge division runs.

**Figure 11.** Surface flow vorticity derived from PIV data. Blue indicates counter-clockwise circulation and red indicates clockwise circulation. White lines are streamlines derived from PIV data.

**Figure 12.** Near-bed flow vorticity derived from PIV data. Blue indicates counter-clockwise circulation and red indicates clockwise circulation. White lines are streamlines derived from PIV data.

**Figure 13.** Average vorticity in the upper straight part of the bifurcation ($0 < x < 320$ mm) plotted against normalized channel width (0=left bank, 1=right bank) for surface flow (a,b) and near-bed flow (c,d). a and c show the low-WDR runs, b and d the high-WDR runs.

**Figure 14.** Measured streamwise velocity profiles (symbols) and logarithmic fit (lines) at CS01 at probe location 1 (next to wall), 4 and 8 (near-center) for all low WDR runs (a) and high WDR runs (b). Probe 4 and 8 are plotted with offset. Open symbols show the experiments with rough bed, pale colors are the unequal discharge division runs. c) The coefficient of determination ($R^2$) for the logarithmic fit of flow velocities for all probes in CS01, shown against normalized distance to the wall. Where the flume wall is at 0 and the center of the channel at 0.5. Symbols are plotted with slight offset for clarity.

**Figure 15.** Measured near-surface streamwise velocity from UDVP data plotted against surface streamwise velocity from PIV data.

**Table 1.** Experimental runs.[a]

| Run abbr. | WDR (-) | h (m) | Qr (-) | bed |
|---|---|---|---|---|
| 80EQ | 6.3 | 0.080 | 1 | smooth |
| 80NEQ | 6.3 | 0.080 | 1.5 | smooth |
| 35EQ | 14.3 | 0.035 | 1 | smooth |
| 35NEQ | 14.3 | 0.035 | 1.5 | smooth |
| 80EQ_S | 6.3 | 0.080 | 1 | rough |
| 80NEQ_S | 6.3 | 0.080 | 1.5 | rough |
| 35EQ_S | 14.3 | 0.035 | 1 | rough |
| 35NEQ_S | 14.3 | 0.035 | 1.5 | rough |

[a] Showing the width-to-depth ratio (WDR), the corresponding water depth (h) in the entire flume measured from the top of the bed, the desired discharge ratio ($Qr = Q_{right}/Q_{left}$) and the type of bed (no sediment / smooth or with gravel / rough). Upstream flume width is 0.5 m.

**Table 2.** UDVP settings and parameters.[a]

| | x | y up | y down | z |
|---|---|---|---|---|
| Sample bins | 64 | 64 | 64 | 64 |
| First sample distance (mm) | 4.995 | 4.995 | 4.995 | 4.995 |
| Sample length (mm) | 194.4 | 496.5 | 247.6 | 99.7 |
| Sample distance (mm) | 2.96 | 7.68 | 3.79 | 1.48 |
| Sample width (mm) | 2.96 | 2.96 | 2.96 | 2.96 |
| Sampling period (ms) | 8 | 8 | 8 | 16 |
| Intra-sample delay (ms) | 15 | 15 | 15 | 15 |
| Number of probes in cycle | 7 | 7 | 7 | 8 |
| Sampling frequency (Hz) | 6.21 | 6.21 | 6.21 | 4.03 |
| Maxium depth, Lmax (mm) | 228.29 | 912.79 | 912.79 | 983.46 |
| Min U (mm/s) | 0.00 | -74.99 | -74.99 | -69.60 |
| Max U (mm/s) | 299.84 | 74.99 | 74.99 | 69.60 |
| Velocity resolution $\Delta$U(mm/s) | 1.17 | 0.59 | 0.59 | 0.54 |

[a] for streamwise (x), cross-stream in upstream channel (y up), cross-stream downstream channels (y down) and vertical (z) velocities.

**Table 3.** Flow properties for all runs.[a]

| | | Run | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Property | Location | 80EQ | 80NEQ | 35EQ | 35NEQ | 80EQ S | 80NEQ_S | 35EQ_S | 35NEQ_S |
| WDR | | low | low | high | high | low | low | high | high |
| Symmetry | | symm | asymm | symm | asymm | symm | asymm | symm | asymm |
| Bed | | smooth | smooth | smooth | smooth | rough | rough | rough | rough |
| $H$ (m) | CS01-04 | 0.080 | 0.080 | 0.035 | 0.035 | 0.080 | 0.080 | 0.035 | 0.035 |
| $Ux_{av}$ (m s$^{-1}$) | CS01-03 | 0.18 | 0.18 | 0.16 | 0.15 | 0.14 | 0.15 | 0.09 | 0.06 |
| | CS04L | 0.18 | 0.14 | 0.16 | 0.10 | 0.14 | 0.12 | 0.07 | 0.04 |
| | CS04R | 0.18 | 0.23 | 0.16 | 0.18 | 0.15 | 0.17 | 0.06 | 0.06 |
| Fr (-) | CS01-03 | 0.20 | 0.20 | 0.28 | 0.26 | 0.16 | 0.17 | 0.15 | 0.10 |
| Re (-) | CS01-03 | 10298 | 10358 | 4720 | 4396 | 8320 | 8605 | 2524 | 1765 |
| We (-) | CS01-03 | 426.6 | 431.5 | 152.8 | 132.5 | 278.5 | 297.9 | 43.9 | 21.6 |
| $Q$ (m$^3$s$^{-1}$ 10$^{-3}$) | CS01 | 7.28 | 7.22 | 2.85 | 2.69 | 5.71 | 6.02 | 1.65 | 1.16 |
| | CS02 | 7.14 | 7.16 | 2.83 | 2.62 | 5.74 | 6.00 | 1.41 | 1.10 |
| | CS03 | 7.03 | 7.21 | 2.81 | 2.60 | 5.90 | 5.91 | 1.49 | 0.92 |
| | CS04L+R | 7.08 | 7.25 | 2.78 | 2.49 | 5.80 | 5.87 | 1.17 | 0.91 |
| | CS04L | 3.56 | 2.71 | 1.37 | 0.88 | 2.85 | 2.40 | 0.61 | 0.36 |
| | CS04R | 3.52 | 4.54 | 1.41 | 1.61 | 2.95 | 3.47 | 0.55 | 0.55 |
| $Q_{rms}$ (m$^3$s$^{-1}$ 10$^{-3}$) | CS01-04 | 0.09 | 0.03 | 0.03 | 0.07 | 0.07 | 0.06 | 0.17 | 0.11 |
| $Q_{rms}$(%) | CS01-04 | 1.33 | 0.46 | 0.89 | 2.72 | 1.24 | 1.08 | 12.16 | 10.73 |
| $Qr$ ($Q_{right}/Q_{left}$) | CS04 | 0.99 | 1.67 | 1.03 | 1.83 | 1.03 | 1.45 | 0.90 | 1.51 |
| $Q_{right}/Q_{total}$ | CS04R | 0.50 | 0.63 | 0.51 | 0.65 | 0.51 | 0.59 | 0.47 | 0.60 |
| $q_{surf,right}/q_{surf,total}$ | PIT surface | 0.51 | 0.62 | 0.50 | 0.56 | 0.49 | 0.55 | 0.50 | 0.51 |
| $q_{bed,right}/q_{bed,total}$ | PIT bed | 0.52 | 0.71 | 0.50 | 0.68 | - | - | - | - |
| $\|\hat{\Gamma}\|$ (-) | CS01 | 15.4 | 12.8 | 5.5 | 0.9 | 8.5 | 9.0 | 2.1 | 4.0 |
| | CS02 | 14.6 | 10.8 | 1.2 | 1.0 | 6.0 | 8.1 | 1.3 | 4.3 |
| | CS03 | 12.7 | 10.3 | 0.9 | 1.5 | 6.8 | 10.0 | 2.9 | 4.5 |
| | CS04L | 18.0 | 29.9 | 9.9 | 7.1 | 24.4 | 31.5 | 8.4 | 8.5 |
| | CS04R | 13.1 | 16.3 | 8.2 | 4.0 | 27.6 | 23.9 | 5.4 | 10.2 |

[a] Derived from UDVP and PIV data. Flow division from PIV data were derived from the data in Fig. 9 and represent the location of division line in this Figure at $y/W = 1$.