

1 A novel mixing mechanism in sinuous seafloor channels: implications for submarine channel evolution

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7

8 **Abstract**

9 Previous experimental studies of density currents in sinuous seafloor channels have almost  
10 exclusively studied hydrodynamics either by considering time independent, instantaneous, flow  
11 measurements or by compiling time-averaged flow measurements. Here we present a novel study of  
12 the time dependent dynamics of a density driven flow in a sinuous channel fed by a source of constant  
13 discharge. The experiments show that whilst source conditions may be temporally steady, flow  
14 conditions are temporally unsteady with timescales of flow variation driven by flow interaction with  
15 channel topography. Temporal variations reveal that both downstream and cross-stream flows vary  
16 significantly from time average observations and predictions, across scales larger than those predicted  
17 for turbulence in equivalent straight channels. Large-scale variations are shown to increase the  
18 average production of turbulence across the height of the flow, providing a new mechanism for  
19 enhanced mixing of sediment within gravity currents. Further such large scale variations in flow  
20 conditions are recorded in the change in orientation of near-bed secondary flow, providing a plausible  
21 mechanism to reduce the cross-stream transport of bedload material and explain the ultimate  
22 stabilisation of sinuous seafloor channel systems.

23

## 24 **1 Introduction**

25 Density driven flows, such as turbidity currents, build and maintain sinuous channels on the seafloor  
26 that can extend for hundreds or thousands of kilometres (Wynn et al., 2007; Straub et al., 2008; Dorrell  
27 et al., 2015). Networks of these channels form the largest sedimentary landforms on the planet:  
28 submarine fans (Covault, 2011). The extent of mixing of suspended particulate material by turbulent  
29 flow is known to provide a key control on the degree to which the sediment suspension is stratified in  
30 these density-driven flows, yet stratification is also known to be a key control influencing the extent to  
31 which these flows may propagate over such large distances (Dorrell et al., 2014). As in rivers, the  
32 mechanisms of mixing include: shear generated turbulence; unstable buoyancy gradient generated  
33 turbulence; secondary (i.e., rotational) flow; particle-particle interaction; and, Brownian motion.  
34 However, in contrast to rivers (where the velocity tends to increase monotonically with distance from  
35 the bed), turbulence in straight-channel, steady-state density driven flows is observably reduced at the  
36 height of the downstream velocity maximum; because at this point shear generated turbulence  
37 production reduces to zero (Garcia and Parker, 1993; Kneller et al., 1999; Best et al., 2001; Buckee et  
38 al., 2001). This zone of reduced shear has been termed the slow diffusion zone and is postulated as  
39 being an internal barrier to sediment transport (Garcia and Parker, 1993; Kneller et al., 1999; Best et  
40 al., 2001; Buckee et al., 2001). Previous work has suggested that there are a number of mechanisms  
41 that operate in sinuous submarine channels that act to reduce the influence of this slow diffusion zone:  
42 i) induced secondary flow that mixes fluid vertically (Keevil et al., 2006); ii) flow run-up and  
43 superelevation that again act to move fluid vertically within the flow (Straub et al., 2011); and iii)  
44 internal hydraulic jumps within channels that generate large upward vertical velocities, redistributing  
45 mass and momentum (Dorrell et al., 2016). Here we demonstrate a new mechanism for mixing across  
46 the slow diffusion zone in density currents in sinuous submarine channels, linked to temporal changes  
47 in the structure of secondary flow fields. This novel mixing mechanism is believed to be unique to  
48 sinuous submarine channels, with no equivalent in river systems. Furthermore, these temporal  
49 changes in secondary flow have significant implications for bedload transport and channel evolution.  
50 Secondary flow, which rotates normal to the primary flow downstream, is ubiquitous in straight and  
51 sinuous channels (Nezu and Nakagawa, 1993; Peakall and Sumner, 2015). However, in sinuous

52 channels the magnitude of secondary flow, and thus its affect on flow dynamics is enhanced, by  
 53 centrifugal and pressure gradient forces driving recirculating flow. In sinuous open channels the near-  
 54 bed component of secondary flow is typically orientated towards the inner-bank of the channel bend  
 55 at bend apices (Rozovskii, 1957; Thorne et al., 1985). However, in density driven flows near-bed  
 56 secondary flow is more complex; here secondary flow at bend apices may be orientated towards the  
 57 inner- or outer-bank and may be composed of either single flow cells, or multiple, vertically stacked,  
 58 cells (Kassem and Imran, 2004; Corney et al., 2006, 2008; Keevil et al., 2006; Abad et al., 2011; Dorrell  
 59 et al., 2013). By redistributing suspended and bedload sediment, secondary flow plays a key role in the  
 60 morphodynamic evolution of sinuous channel systems (Peakall et al., 2007; Darby and Peakall, 2012;  
 61 Cossu and Wells, 2013; Peakall and Sumner, 2015).

62 In unstratified open-channel flow inner bank orientated secondary flow is driven by a balance of  
 63 outer-bank orientated centrifugal forces, reduced near the bed by friction, and an inner-bank  
 64 orientated pressure gradient, resulting from flow superelevation (Rosovskii, 1957). However, in  
 65 density driven flows this force balance is modified by density and velocity stratification (Corney et al.,  
 66 2006, 2008; Abad et al., 2011), enhanced superelevation, and associated flow overspill from the  
 67 channel (Dorrell et al., 2013; Ezz and Imran, 2014). Moreover, in large channels at high latitudes the  
 68 secondary flow is also significantly affected, and may be reversed, by Coriolis forcing (Cossu and Wells,  
 69 2010; Cossu et al., 2015).

70 Dorrell et al. (2013) demonstrated that secondary flow in temporally steady density currents is  
 71 dominated by flow superelevation, and overspill (if present), reflected in the magnitudes of the  
 72 dimensionless radial fluid,  $Q_f$  and radial material,  $Q_s$ , fluxes (Figure 1), defined by

$$73 \quad (1a) \quad Q_f = \frac{\int_0^h V dz}{h},$$

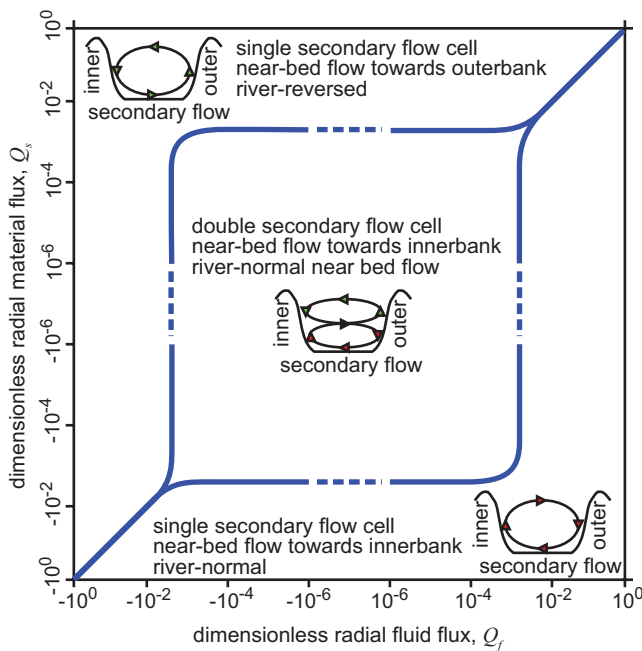
$$74 \quad (1b) \quad Q_s = \frac{\int_0^h V(\rho_f - \rho_a) dz}{\int_0^h (\rho_f - \rho_a) dz},$$

$$75 \quad (1c) \quad V = \frac{L\mu v}{\rho_a \left( \int_0^h u dz \right)^2}.$$

76 In Equation (1) the variables are defined as follows:  $L$ , the horizontal length scale of the flow (i.e.  
 77 radius of curvature);  $h$ , the vertical length scale of the flow (i.e. the flow depth);  $u$  and  $v$ , the down- and  
 78 cross-stream components of flow velocity, where  $V$  denotes the dimensionless secondary flow

79 velocity;  $\mu$ , dynamic fluid viscosity; and  $\rho_f$  and  $\rho_a$ , the density of the flow, and ambient fluid,  
 80 respectively. Due to differences in the mechanisms driving vertical density and velocity stratification  
 81 these fluxes may have significantly different magnitudes. As the concentration of suspended material  
 82 is known to increase towards the bed (Menard and Ludwick, 1951; Peakall et al., 2000a), and the  
 83 secondary flow peaks near the height of the downstream velocity maximum (Abad et al., 2011) the  
 84 depth-averaged radial material flux is likely to be greater than the radial fluid flux (Dorrell et al.,  
 85 2013). Consequently it has been speculated that basal drag, affecting elevation of the velocity  
 86 maximum, has a significant effect on secondary flow (Abad et al., 2011). Furthermore, as the density  
 87 difference between the flow and the ambient fluid is small in density currents, flow superelevation in  
 88 submarine channels is an order of magnitude, or more, larger than in open-channel flows (Imran et al.,  
 89 1997). This superelevation, in combination with flow overspill means that the relative magnitude of  
 90 both the radial fluid and material fluxes is significantly enhanced, preferentially towards the outer-  
 91 bank.

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93

94 Figure 1. The phase space solution for the dynamics of secondary flow, as a function of cross-channel  
 95 (radial) fluid and material fluxes (see Equation 1), modified after Dorrell et al. (2013).

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97 Stratified buoyancy driven gravity currents are known to be inherently unstable to topographic  
98 perturbations (Baines, 1998; Sakar and Scotti, 2017), in contrast to open-channel flows. Consequently,  
99 it is anticipated that the resulting large-scale temporal variations in gravity currents would lead to  
100 significant changes between instantaneous and time-averaged flow fields, for both primary and  
101 secondary flows. In turn, these fluctuations and in particular any divergences in flow direction  
102 between instantaneous and time-averaged flows would be expected to have important implications for  
103 flow, mixing, and sediment transport. Despite this, previous modelling of secondary flow within  
104 sinuous seafloor channels has exclusively focused on the mean flow dynamics of nominally steady  
105 state flows, and has consequently considered mixing processes solely in terms of these time-averaged  
106 flow dynamics. This paper seeks to use experimental observations to: i) examine the nature of  
107 temporal changes in secondary flow dynamics, and their role in mixing, ii) assess secondary flow  
108 dynamics as a function of net radial fluid-fluxes and basal drag, as parameterised by bed surface  
109 roughness, iii) provide a process-based model for temporal variations in secondary flow, and, iv)  
110 explore the implications of temporal variations in secondary flow and associated mixing, in terms of  
111 intra-channel sedimentation, submarine channel evolution, and flow runout.

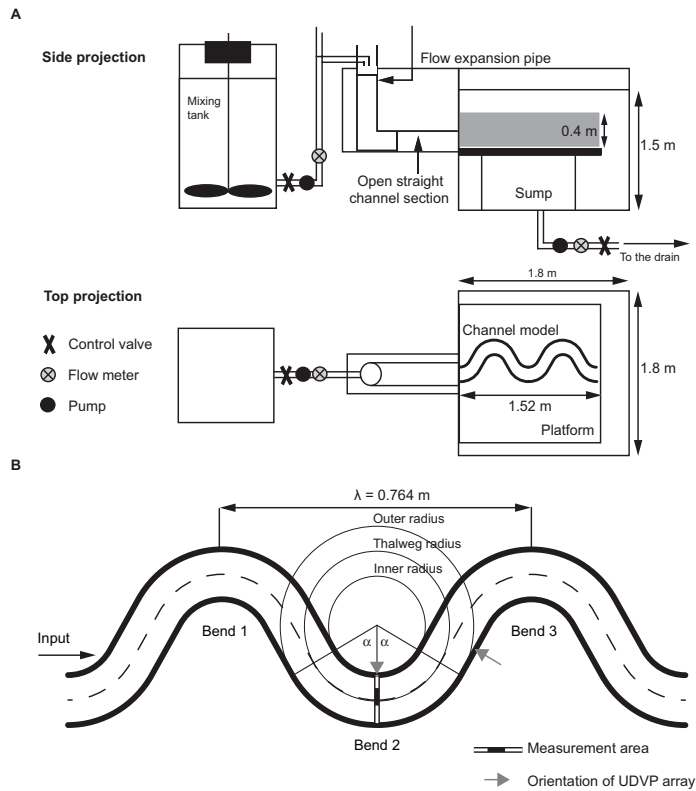
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## 113 **2 Methodology**

### 114 *2.1 Experimental Methodology*

115 A series of experiments were undertaken in a flume tank that is 1.8 m square, and 1.7 m deep, with a 2  
116 m straight inflow channel on the upstream face (see Figure 2). The tank has a false floor placed 0.4 m  
117 above the tank bottom to create a sump; consequently gravity currents reaching the end of the floor  
118 drop into the sump and do not undergo reflection from the sidewalls. A preformed channel model with  
119 a sinuosity of 1.36 was placed in the tank and connected to the inflow channel. The channel model  
120 consisted of bends of constant radius, over an arc of 120°, connected by straight sections (see Figure  
121 2), identical to the planform used in the gravity current experiments of Keevil et al. (2006, 2007). The  
122 planform setup of the channel was based on the UK Flood Channel Facility meanders (Greenhill and  
123 Sellin, 1993; Sellin et al., 1993). The channel model had a rectangular cross-section, with a width of

124 0.12 m, and sides that were 0.40 m high so that the flow was fully confined with an absence of  
 125 overspill.  
 126



127  
 128 Figure 2. (a) Schematic sketch of the experimental setup, illustrating the mixing tank and the position  
 129 of the channel model within the main flume tank. (b) Planform geometry of the channel model  
 130 illustrating all the elements in a single wavelength. The actual channel model consists of two complete  
 131 wavelengths, covering three bends; each bend has an angle of curvature ( $\alpha$ ) of  $60^\circ$ . The channel has a  
 132 sinuosity of 1.36 and a constant cross-sectional width; with an inner radius of 0.1 m, thalweg radius of  
 133 0.16 m and outer radius of 0.22 m.

134  
 135 A saline solution with a 2.5% density excess ( $1025 \text{ kg m}^{-3}$ ) was prepared in a  $1.8 \text{ m}^3$  mixing tank and  
 136 pumped into the model via the straight inlet channel at a flow rate of  $1.13 \text{ l s}^{-1}$ . As the dense fluid  
 137 entered the tank it passed through an expansion pipe to reduce the turbulence on the inlet, and then

138 through a straight channel, 0.12 m wide and with a development length of 1.3 m long, connected to the  
139 main sinuous channel.

140 Velocity measurements were taken at the second bend apex, using an array of ten 4 MHz ultrasonic  
141 Doppler velocity profiling (UDVP) probes, positioned at heights of: 6 (0.05h), 16 (0.09h), 26 (0.21h),  
142 36 (0.28h), 46 (0.36h), 56 (0.44h), 76 (0.60h), 96 (0.76h), 116 (0.92h) and 136 (1.08h) mm above the  
143 channel floor (parentheses denote the dimensionless depth of the UDVP probe in terms of the mean  
144 flow height, of  $h=126$  mm, see Table 1). Cross-stream flow was measured with the array positioned  
145 into and flush with the sidewall, with the probes positioned on the inner bank of the bend. Similarly  
146 downstream flow was measured by an upstream-facing array mounted in a bespoke PVC probe holder,  
147 and positioned 4 cm downstream of the bend apex, so that the UDVP profiles intersected the  
148 centreline of the channel at the bend apex.

149 UDVP measures single component velocity in the direction in which the probes are orientated and  
150 works by emitting ultrasonic pulses and then gating the return signal into a series of spatial bins (here  
151 128 bins), as the ultrasound backscatters off of small particles within the flow (Best et al., 2001). The  
152 probes operate individually, and are multiplexed enabling pseudo-instantaneous velocity fields to be  
153 constructed, in this case at a frequency of 3.33 Hz. Cross-stream and downstream velocities were  
154 measured in separate nominally identical runs, to avoid cross-talk between instruments. Cross-stream  
155 and downstream spatial return bin sizes were set at 1.48 mm, with downstream velocity averaged  
156 from the 5 bins central to the bend apex. To remove any velocity spikes, all the instantaneous velocity  
157 data were filtered by two standard deviations from a 11-point moving mean and the points were  
158 replaced with a 3-point moving mean (Buckee et al., 2001). As compiled datasets from the arrayed  
159 UDVP probes varied both spatially and temporally. Matlab's™ griddata function was used to  
160 interpolate spatial variation of the flow at fixed time, assuming a zero-slip velocity boundary condition  
161 on the height of the various bed roughnesses used in the experiments.

162 Eighteen experimental runs were undertaken in the flume with either the cross-stream or  
163 downstream UDVP probes active. In the subsequent analysis, each pair of repeat runs (downstream  
164 and cross-stream) is referred to as a single experiment, giving experiments I to IX. Three variations in  
165 bed roughness were chosen by building a fixed bed composed of: fine sand  $d_{50} = 186 \mu\text{m}$ , coarse sand

166  $d_{50} = 370 \mu\text{m}$  and very coarse glass spheres of 6 mm diameter. For each variation in bed roughness the  
 167 entire tank was set at either  $1^\circ$ ,  $2^\circ$  or  $3^\circ$  and the water level in the tank filled to 1.4 m. Velocity  
 168 measurements were started 30 s after the flow had traversed the length of the sinuous channel; 500  
 169 cycles were recorded, resulting in a relative sample time  $t = 0$  to 150 s, at which point the experiment  
 170 was stopped.

171 The planform channel setup and experimental slopes considered are not designed to mimic any  
 172 specific environmental setup. However, the deep channel sidewalls used mean the experiments are  
 173 most characteristic of sinuous incised channels (confined flows) found on continental slopes and in  
 174 some isolated deep-ocean channels on basin floors, or non-overspilling flows in aggradational  
 175 submarine fan channels (Peakall and Sumner, 2015).

176

177 **Table 1.** Flow parameters, time averaged for  $t=0$  to 150 s, for experimental runs I-IX.

Run	I	II	III	IV	V	VI	VII	VIII	IX
$d_{50}, \text{mm}$	0.19	0.19	0.19	0.37	0.37	0.37	6.00	6.00	6.00
$s$	$1^\circ$	$2^\circ$	$3^\circ$	$1^\circ$	$2^\circ$	$3^\circ$	$1^\circ$	$2^\circ$	$3^\circ$
$\tilde{u}, \text{mm/s}$	67.5	71.6	75.9	65.8	70.1	73.0	66.9	70.2	74.5
$\tilde{v}, \text{mm/s}$	8.28	12.9	14.4 s	7.39	10.4	14.2	11.6	12.6	15.4
$h, \text{mm}$	128	126	128	123	131	124	126	126	126
$C_d$	0.119	0.209	0.284	0.121	0.227	0.297	0.120	0.218	0.291
$Fr_d$	0.381	0.408	0.429	0.378	0.391	0.419	0.380	0.400	0.423
$Re$	8620	9000	9690	8130	9150	9050	8450	8830	9420

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## 180 2.2 Flow Analysis and Characterisation

181 Recorded downstream (primary),  $u$ , inner- to outer-bank cross-stream (secondary),  $v$ , and derived  
 182 vertical,  $w$ , flow velocities are separated into long-term average, denoted by overbar notation, and  
 183 fluctuating components, denoted by prime notation,

$$184 \quad (2) \quad u = \bar{u} + u', \quad v = \bar{v} + v' \quad \text{and} \quad w = \bar{w} + w'.$$

185 Observed velocities of each experimental run characterise individual experimental configurations, as  
 186 summarised in Table 1. To calculate the flow height from the separate one-component down- and  
 187 cross-stream velocity datasets two different methodologies are necessarily employed. When using the  
 188 downstream flow data, the flow height is defined by the height at which the downstream flow velocity  
 189 is zero (see Figure 3 and Dorrell et al., 2014); conversely when using the cross-stream velocity data



190 the flow height is defined by the position where the vertical gradient of the secondary flow velocity  
 191 profile is zero, i.e. the zero shear condition (see Figure 3 and Abad et al., 2011). The excess buoyancy of  
 192 the flow is defined as  $g' = g(\rho_f/\rho_a - 1)$ ; where the flow density  $\rho_f = 1025 \text{ kg m}^{-3}$  and the ambient fluid  
 193 density  $\rho_a = 1000 \text{ kg m}^{-3}$ . The densimetric Froude number of the flow (Baines, 1998; Kneller and  
 194 Buckee, 2000) is given by the dimensionless ratio of depth-averaged inertial to gravitational forces

$$195 \quad (3) \quad Fr_d = \frac{\tilde{u}}{\sqrt{g'h}},$$

196 where tilde notation denotes depth and time average velocity,  $\tilde{u} = \int_0^h \bar{u} dz / h$ , see Table 1. Given the  
 197 fluid viscosity,  $\mu$ , the Reynolds number defines the ratio of momentum to viscous forces,

$$198 \quad (4) \quad Re = \frac{\rho_a \tilde{u} h}{\mu},$$

199 As  $Re > 8000$  in the experiments conducted here, see Table 1, all flows are considered fully turbulent.  
 200 Further, the frictional drag,  $C_d$ , suffered by a flow with basal slope,  $s$ , is estimated by the Parker et al.,  
 201 (1987) frictional-entrainment-gravitational force balance

$$202 \quad (5) \quad s = \frac{C_d + E(1 + \frac{1}{2} Fr_d^{-2})}{Fr_d^{-2}},$$

203 where ambient fluid-entrainment,  $E$ , is calculated by the empirical formula of Fukushima et al., (1985)

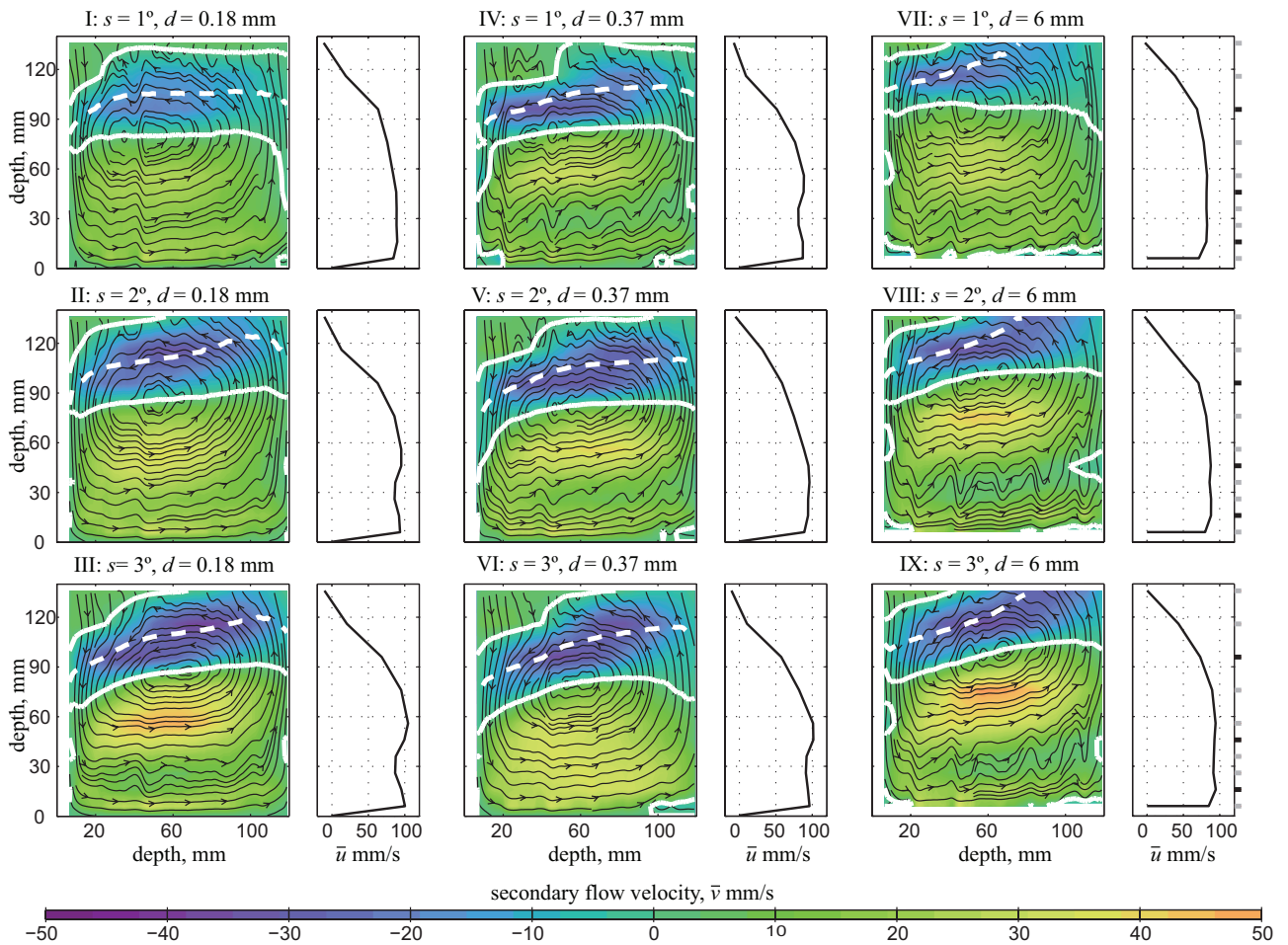
$$204 \quad (6) \quad E = \frac{0.00153}{0.0204 + Fr_d^{-2}}.$$

205 Finally, cross-channel vertical flow velocities are derived under the simplifying assumption that, at the  
 206 bend apex, downstream variations in the flow are negligible. Given the observed secondary flow field  
 207 at the bend apex, mass conservation implicitly defines vertical flow velocity by the leading order  
 208 differential equation,

$$209 \quad (7) \quad \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0,$$

210 which is solved subject to a no-slip boundary condition,  $w=0$ , at the bed roughness height  $z=z_0$  taken as  
 211 the diameter,  $d$ , of particles attached to the solid bed.

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Figure 3. The primary (downstream),  $\bar{u}$ , and secondary (cross-stream),  $\bar{v}$ , velocity flow fields in experiments I-IX, time averaged over  $t=0$  to 150 s (Table 1). Contour maps of secondary velocity are orientated from inner (left) to outer (right) bank. Outerbanks flow is described as positive. Downstream flow is derived from an average taken across the radial centreline of the apex. Black lines denote flow streamlines; solid white lines denote contours of zero velocity; dashed white lines denote contours of zero shear, used to define flow depth. Note the blanking distance at the base of experiments VII-IX caused by the 6 mm glass sphere bed-roughness elements. Grey and black tick marks on VII, VIII and IX denote UDVP location.

### 3 Results

#### 3.1 Temporally averaged secondary flow dynamics.

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The long-term time average flow velocities, taken over 150 s, of experiments I-IX are shown in Figure 3 and Table 1. The nine experiments show the effect of varying background slope and bed roughness on average flow structure. Contour plots are used to show the structure of the secondary (cross-

228 channel) flow velocity; whilst primary (downstream) flow velocity profiles are derived at the centre  
229 point of the bend apex. As noted above, primary and secondary flow velocities were recorded in  
230 separate experimental runs so are not quantitatively comparable.

231 From Figure 3 it is observed that around the midpoint of the flow depth, down towards the base of the  
232 flow, the average primary flow velocity is plug-like; with the velocity decreasing due to frictional shear  
233 close to the bed, and towards the flow-ambient fluid interface. The size of the plug-like region  
234 increases with decreasing bed roughness, (therefore with decreasing basal shear), and decreasing  
235 slope leading to reduced gravitational acceleration and associated turbulent mixing and frictional  
236 shear at the flow-ambient fluid boundary. The secondary flow velocity maps, Figure 3, also show that  
237 the maximum outer-bank orientated flow is located near the mid-point of the flow. Below this  
238 maximum there is a local minimum, where flow is still orientated towards the outer-bank, with the  
239 magnitude of flow towards the outer-bank then increasing again closer to the bed. Above the outer-  
240 bank orientated velocity maximum the secondary flow decreases, becoming negative and orientated  
241 towards the inner-bank. The lower, outer-bank orientated, and upper, inner-bank orientated, flow  
242 show that averaging leaves a single secondary flow cell rotating in the reverse direction to those of  
243 fluvial systems (Rosovskii, 1957). The long-term average rotation pattern of the secondary flow at the  
244 bend apex is emphasised by the estimation of vertical flow velocities (Equation 7), enabling flow  
245 streamlines to be determined.

246 Figure 3 shows that with increased bed-roughness, average near-bed flow may decrease and become  
247 inner bank orientated, i.e. river-normal (Abad et al., 2011; Dorrell et al., 2013). However, such river-  
248 normal near-bed flow was predominately observed to be located near the sidewalls, see, e.g., Figure 3  
249 I-VI. Although bed roughness was doubled between experiments I-III and IV-VI (the size of particles  
250 comprising the immobile bed increased from ~0.15% to ~0.30% of mean flow depth) cross-stream  
251 flow remained similar. However, near bed flow orientated towards the inner bank (located away from  
252 the sidewalls) was observed in the very coarse bed experiments, Figure 3 VII-IX, where the size of  
253 particles comprising the immobile bed was ~5% of the mean flow depth. Bed roughness has been  
254 suggested as a key parameter determining the orientation of secondary flow, as lower roughness is  
255 linked to a reduction in the height of the velocity maximum, therefore encouraging river-reversed

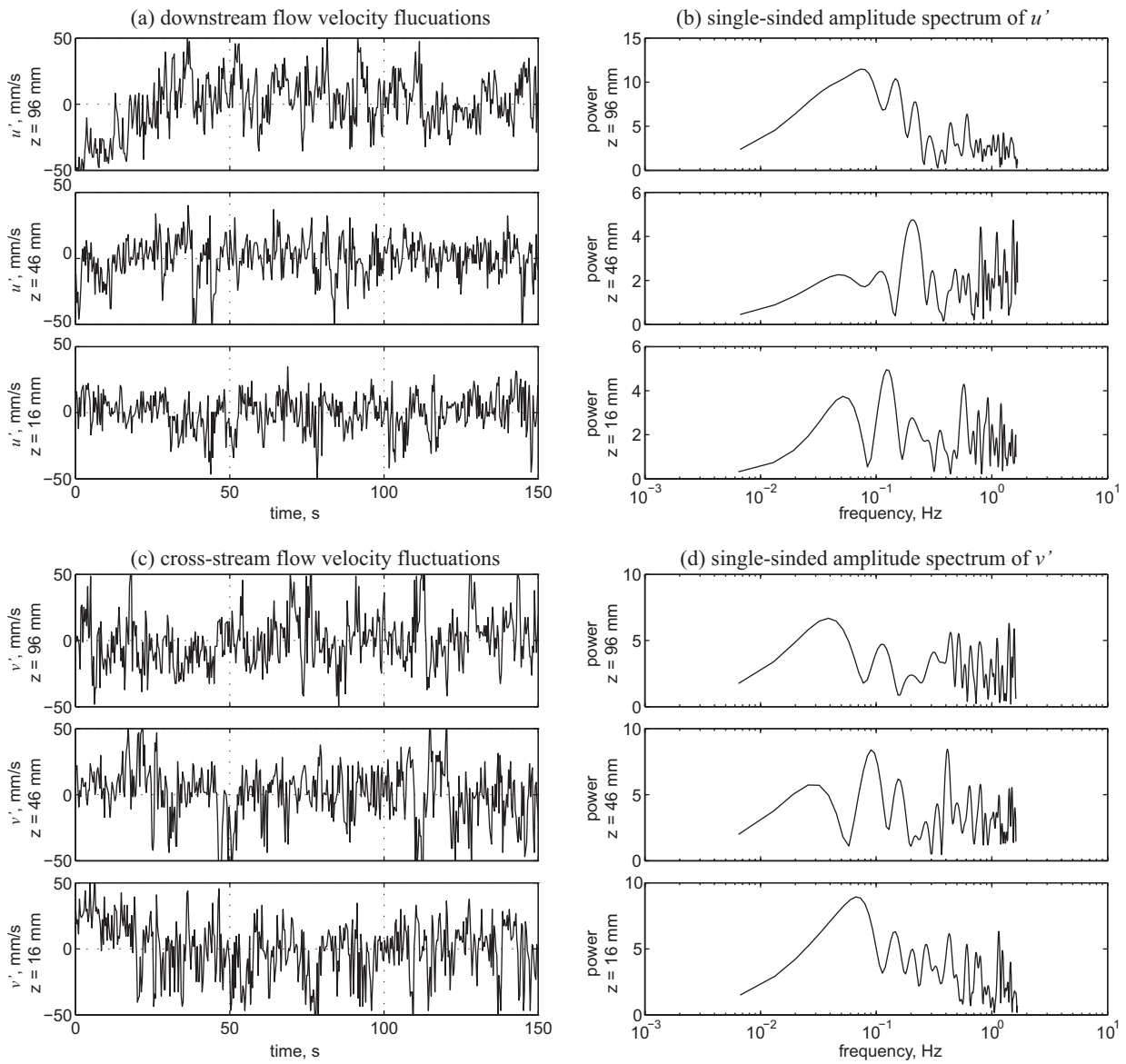
256 circulation (Abad et al., 2011). Smooth beds as used in some experiments (e.g., Corney et al., 2006;  
257 Keevil et al., 2006, 2007) were therefore argued to exhibit 'anomalous' river-normal secondary flows  
258 (Abad et al., 2011). However, here the results show that beds with grain-roughnesses (0.15-0.30%) far  
259 in excess of those expected for sand-bed channelized flows in natural systems, still exhibit river-  
260 reversed patterns, and that extreme roughness is required (~5% of flow depth) in the present  
261 experiments before roughness begins to alter the orientation of the basal flow velocities. This is in  
262 agreement with previous experiments which did not recognise bed roughness as an important  
263 parameter controlling secondary flow orientation (Ezz and Imran, 2014). Figure 3 also shows that  
264 with increased bed-roughness, and basal slope, the slope of the flow-ambient fluid interface increased.  
265 Moreover, with increased basal slope the centre of secondary flow circulation is observed to move  
266 towards the outer-bank (Keevil et al., 2007).

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### 268 *3.2 Temporally varying secondary flow dynamics.*

269 The difference between the flow velocity at a given point in time and its long-term average is the flow  
270 velocity fluctuation, Equation (2). In Figure 4 the velocity fluctuations of the downstream and cross-  
271 stream flow, recorded in run V, are presented for the UDVP located above the velocity maximum ( $z =$   
272 96 mm), near the velocity maximum ( $z = 46$  mm) and below the velocity maximum ( $z = 16$  mm)  
273 (locations UDVPs used in Figure 4 are highlighted in Figure 3). Velocity fluctuations for all 10 UDVP  
274 probes are presented in the supplementary material. The velocity fluctuations are chaotic, as expected  
275 due to turbulent fluid motion, but also show long-term periodic variations. Due to the low frequency of  
276 the UDVP array (~3 Hz) high frequency small-scale turbulent structures are not resolved. However, by  
277 taking a Fast Fourier Transform (FFT) of the velocity fluctuations low frequency forcing on both the  
278 primary and secondary flow fields are observed between 0.05-0.2 Hz.

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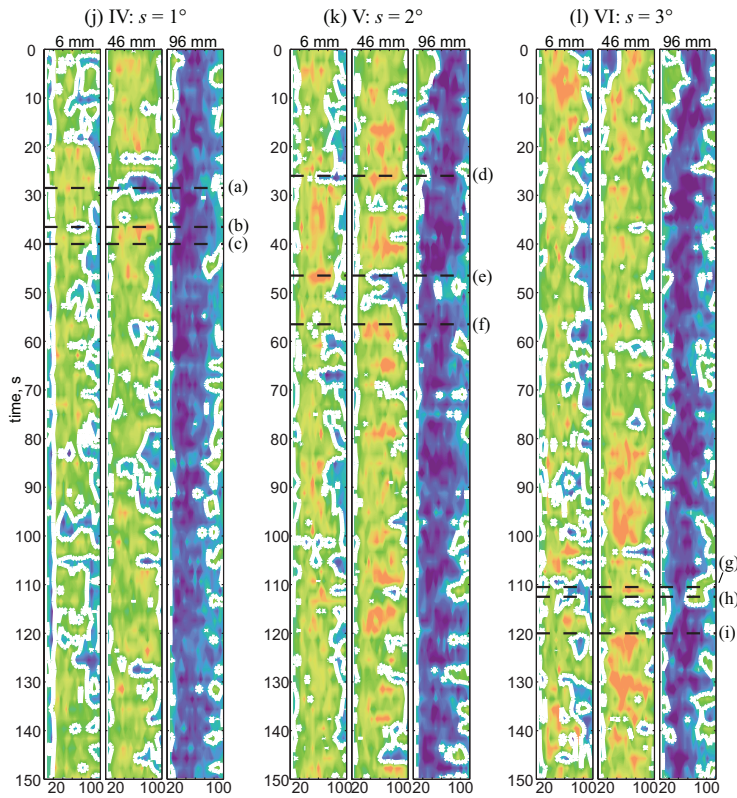
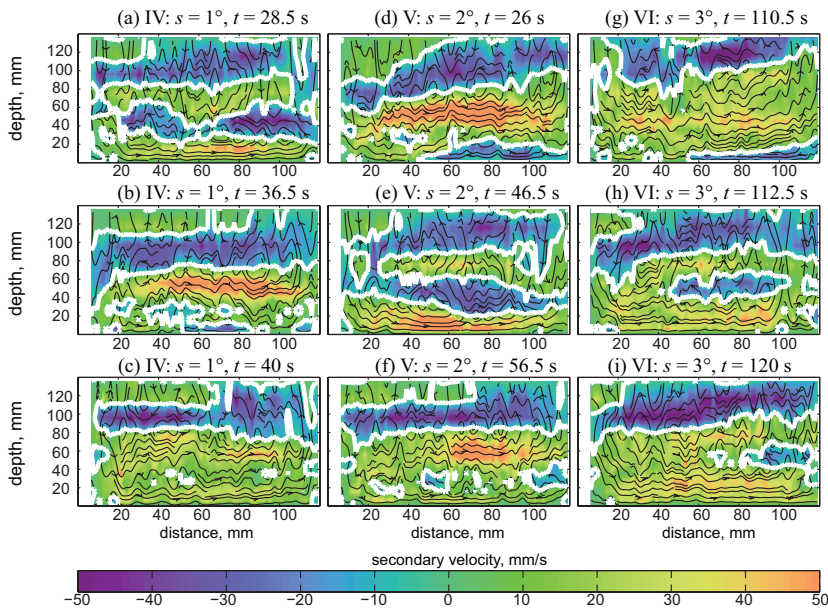
281 Figure 4. Primary,  $u'$ , and secondary,  $v'$ , flow velocity fluctuations (a) and (c) from run V, centred on  
 282 the midline line of the channel apex and derived from a 5-bin (6 mm) average to reduce instrumental  
 283 noise in the upper ( $z = 96$  mm), central ( $z = 46$  mm) and lower ( $z = 16$  mm) regions of the flow.  
 284 Associated single-sided FFT of primary and secondary flow velocity fluctuations signals, respectively  
 285 (b) and (d), showing the slow and fast scales of turbulent fluctuations observed. The three vertical  
 286 UDVP locations are denoted by black tick marks in Figure 3.

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288 It is important to note, that this low frequency forcing is not an artefact of the flow input, controlled by  
 289 an inverter-driven centrifugal pump with fixed discharge. Moreover, the low frequency forcing is  
 290 unlikely to be attributable to turbulent eddies at the largest vertical scale of the flow. Here turbulent  
 291 eddy timescales, determined by the ratio of flow depth to downstream flow velocity (Pope, 2000), are

292 ~2 Hz. The long-timescale variations, an order of magnitude larger ( $<0.2$  Hz), drive change in the  
293 primary (downstream) flow and thus result in transitions between different secondary flow cell  
294 configurations. The different secondary flow cell configurations are recorded in the instantaneous  
295 cross-channel measurements of secondary flow, see Figures 5-6 and in the online supplementary  
296 material a real-time animation of secondary flow covering 150 s of experimental runs I-IX.  
297 Observed cross-channel patterns captured in the instantaneous measurements of secondary flow are  
298 summarised in Figures 5a-i, as a function of basal slope, and Figures 6a-i, as a function of bed  
299 roughness. Also plotted is the temporal evolution of the secondary flow field at three different depths,  
300 see Figures 5j-l and 6j-l. As in Figure 3 the inner-bank orientated secondary flow was observed to be  
301 more predominant with increasing basal slope (Figure 5), or bed roughness (Figure 6). However, in all  
302 runs experiments were observed to transition between vertically stacked rotating flow cells with  
303 river-normal (towards the inner bank) (see, e.g., Figures 5d and 6g) and river reversed (towards the  
304 outer bank) near bed flow behaviour (see, e.g., Figure 5a and 6e). Single stack rotating flow cells were  
305 observed, but only with near-bed flow orientated towards the outer-bank. Interestingly the derived  
306 streamlines (based on Equation 7) further suggest that instantaneous secondary flow was at times  
307 composed of horizontal arrays of multiple rotating cells (see, e.g., Figures 5h and 6f). Steady horizontal  
308 arrays of rotating cells are commonly found in open channel flows (e.g., McLelland et al., 1999;  
309 Albayrak and Lemmin, 2011). However, although the discharge input is held constant in these density  
310 driven flows, the positioning and number of these cells vary temporally and thus are not observed  
311 when considering a time averaged description of the flow, Figure 3. The importance of the transition in  
312 the arrangement and rotation of secondary flow cells is highlighted in Figures 5j-l and 6j-l. Here it is  
313 seen that the magnitude, and orientation, of the near-bed flow velocity naturally vary with the same  
314 low frequency period recorded in the down- and cross-stream flow velocity fluctuations, Figure 4.

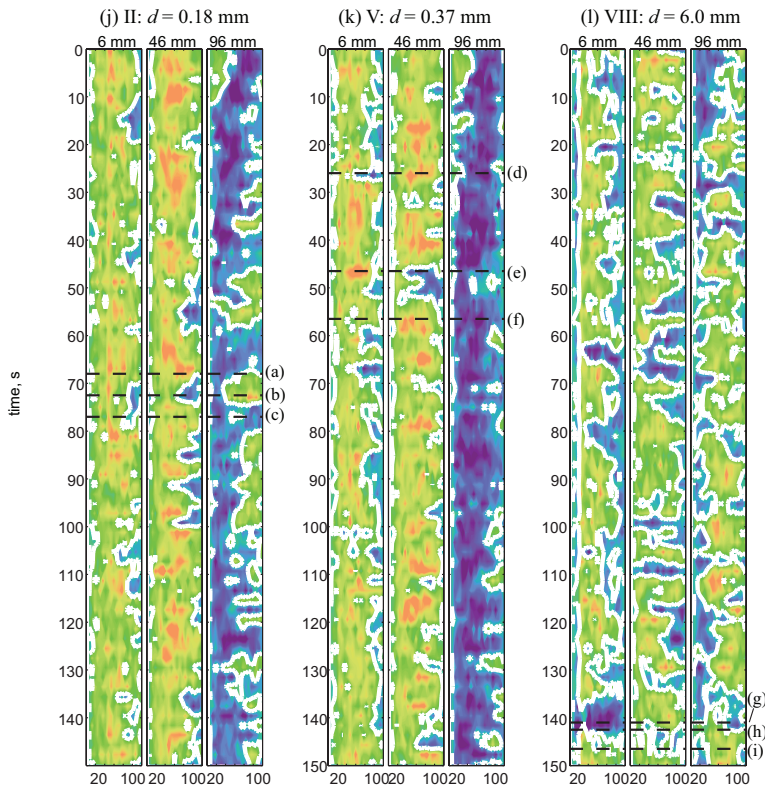
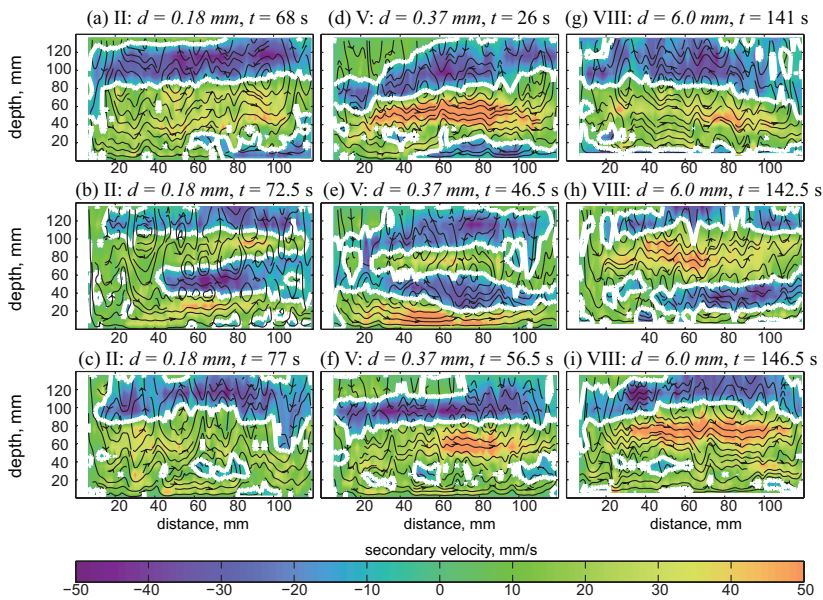
315



316

317 Figure 5. Instantaneous time-slices (a)-(i) and cross channel spatial-slices, (j)-(l) taken at 6, 46 and 96  
 318 mm above the bed respectively, of the secondary flow velocity field. Time and spatial slices contrast  
 319 slopes of 1, 2 and 3 degrees (Runs IV, V and VI respectively where bed particle size  $d=0.37\text{mm}$ ). Flow  
 320 directed from inner (left) to outer (right) bank is positive. Black lines denote flow streamlines,  
 321 Equation (7), whilst solid white lines denote contours of zero velocity. Black dashed lines on (j)-(l)  
 322 denote temporal locations of subplots (a)-(i).

323



324

325 Figure 6. Instantaneous time-slices (a)-(i) and cross channel spatial-slices, (j)-(l) taken at 6, 46 and 96  
 326 mm above the bed respectively, of the secondary flow velocity field. Time and spatial slices contrast  
 327 bed roughness, where bed particle size  $d = 0.19$ ,  $0.37$  and  $6$  mm (Runs II, V and VIII respectively on  
 328 slope  $s=2$  degrees). Flow directed from inner (left) to outer (right) bank is positive. Black lines denote  
 329 flow streamlines (Equation 7) whilst solid white lines denote contours of zero velocity. Note the  
 330 blanking distance at the base of experiment VIII caused by the  $6$  mm glass sphere bed-roughness  
 331 elements. Black dashed lines on (j)-(l) denote temporal locations of subplots (a)-(i).



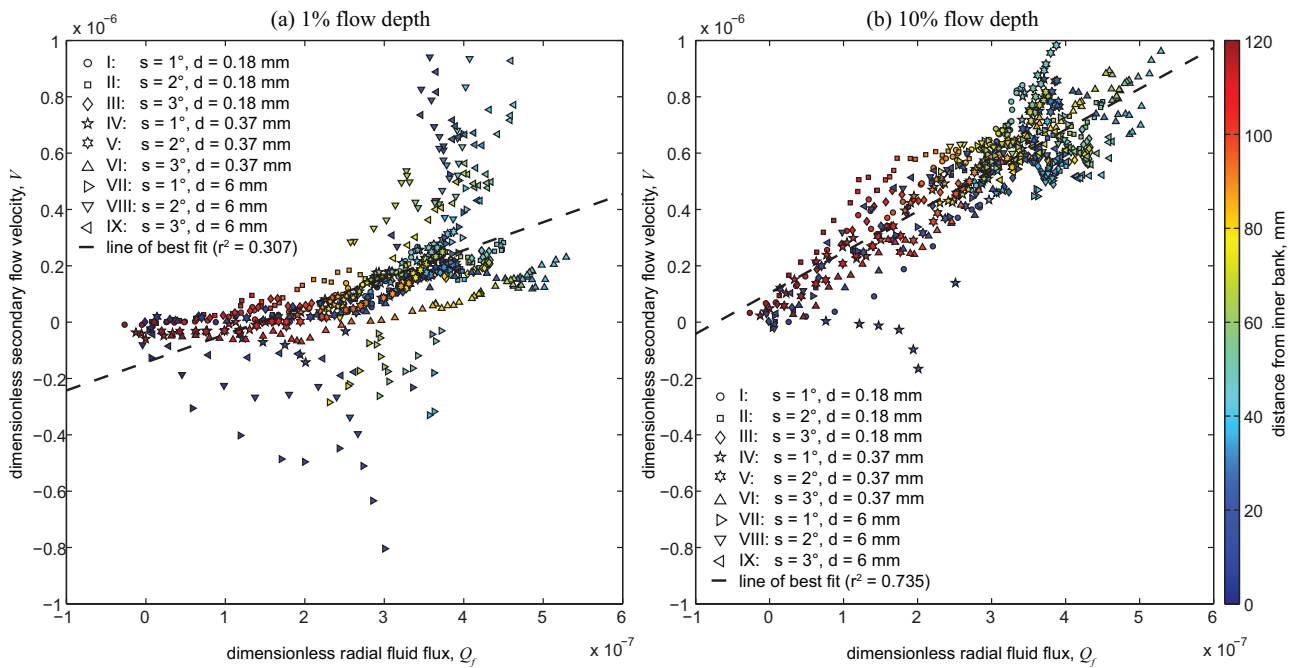
332

## 333 **4 Discussion**

### 334 *4.1 Correlation of net secondary flux and near bed secondary flow velocity.*

335 Based on the conservation of momentum in vertically stratified density driven flows, previous  
336 research has shown that near bed radial velocity, in steady flow conditions, is proportional to the net  
337 radial fluid flux, as a consequence of conservation of fluid mass, see Figure 1 and Dorrell et al. (2013).  
338 From the experimental data presented herein we directly investigate the relationship between the  
339 time average near bed flow velocity and radial flux, Figure 7. It is found that at 10% flow height there  
340 is a strong positive correlation between near-bed radial dimensionless flow velocity and radial fluid  
341 flux (see Equation 1), with a correlation coefficient,  $r^2$ , of  $\sim 0.7$  (Figure 7b). The positive correlation  
342 shows that with increasing flux the outer-bank orientated radial flow velocity increases, as predicted  
343 by Dorrell et al., (2013). However, at 1% flow height, Figure 7a, the positive correlation predicted by  
344 Dorrell et al., (2013) between radial flux and near-bed radial flow velocity, while still present is much  
345 weaker, and the correlation coefficient,  $r^2$ , drops to  $\sim 0.3$ . This decrease in correlation between the  
346 near-bed flow velocity and the net radial fluid flux may be explained by the observed instability of the  
347 flow. The observed secondary flow switches from single-cell near bed river-reversed to stacked-cell  
348 river-normal flow, e.g. helical couplets (see Figures 5-6, and supplementary online animation). This  
349 suggests that the flow is close to, but above, the upper transition curve in Figure 1, but that flow  
350 perturbations are sufficiently large to decrease the radial fluid and suspended material fluxes below  
351 the curve. The inference from the experiments is thus that, even under nominally steady flow  
352 conditions, the configuration of the secondary flow structure of density driven flow in sinuous  
353 channels may be unstable. The stability of the flow will depend on the magnitude of the perturbations  
354 made by the low-frequency forcings in river-normal to river-reversed phase-space, Figure 1. If the  
355 flow is close to a river-reversed to river-normal transitional point, small perturbations will have a  
356 large effect on secondary flow structure and thus turbulent mixing.

357



358

359 Figure 7. Dimensionless near-bed secondary flow velocity,  $V$ , at (a) 1% and (b) 10% of flow depth  
 360 above the bed roughness elements, as derived from interpolated UDVP data, plotted as a function of  
 361 dimensionless radial fluid flux  $Q_r$  (Equation 1).

362

363 From Figure 7 it is also noted that the magnitude of the, positive, radial flux (and thus near bed radial  
 364 velocity) decreases as a distance from the inner bank. This is an expected result as flow near the inner  
 365 bank is free to move towards the outer-bank, whilst flow near the outer-bank is limited by the fully  
 366 constraining sidewalls used in these experiments. In contrast to the experiments, for flows only  
 367 partially confined by a channel, there may be significant overspill and thus net radial transport may be  
 368 significant across the entire channel. However, even in confined channels there is significant flow  
 369 towards the outer-bank at the bend apex, meaning that superelevation is still increasing towards a  
 370 maximum past the bend apex. Post maximum superelevation radial fluxes must be reversed as the  
 371 flow-ambient fluid interface reverts to its normal position, and in partially confining channels overspill  
 372 is switched off. Therefore, regardless of channel type, the location of the superelevation maximum is  
 373 critical to understanding change in net radial flux around the bend, e.g. from inner bank to outer or  
 374 vice-versa, and thus the behaviour of the near-bed radial flow velocity. It therefore dictates the  
 375 reaches of the bend where sediment is transported towards the outer- and inner-bank respectively  
 376 and its average post apex location may explain why point bars are formed further along bends in

377 seafloor channels than in comparable fluvial systems (Peakall et al., 2007; Amos et al., 2010; Darby and  
378 Peakall, 2012; Peakall and Sumner, 2015). Moreover, temporal variations in the position of the  
379 superelevation maximum are directly linked to temporal variations of the radial velocity profile at the  
380 bend apex. For example, if the position of the superelevation maximum moves downstream away from  
381 the bend apex, radial flux, and thus the propensity for outer bank orientated secondary flow, is likely  
382 to increase. In contrast, upstream movement of the superelevation maximum will lead to a reduction  
383 in outer bank orientated secondary flow.

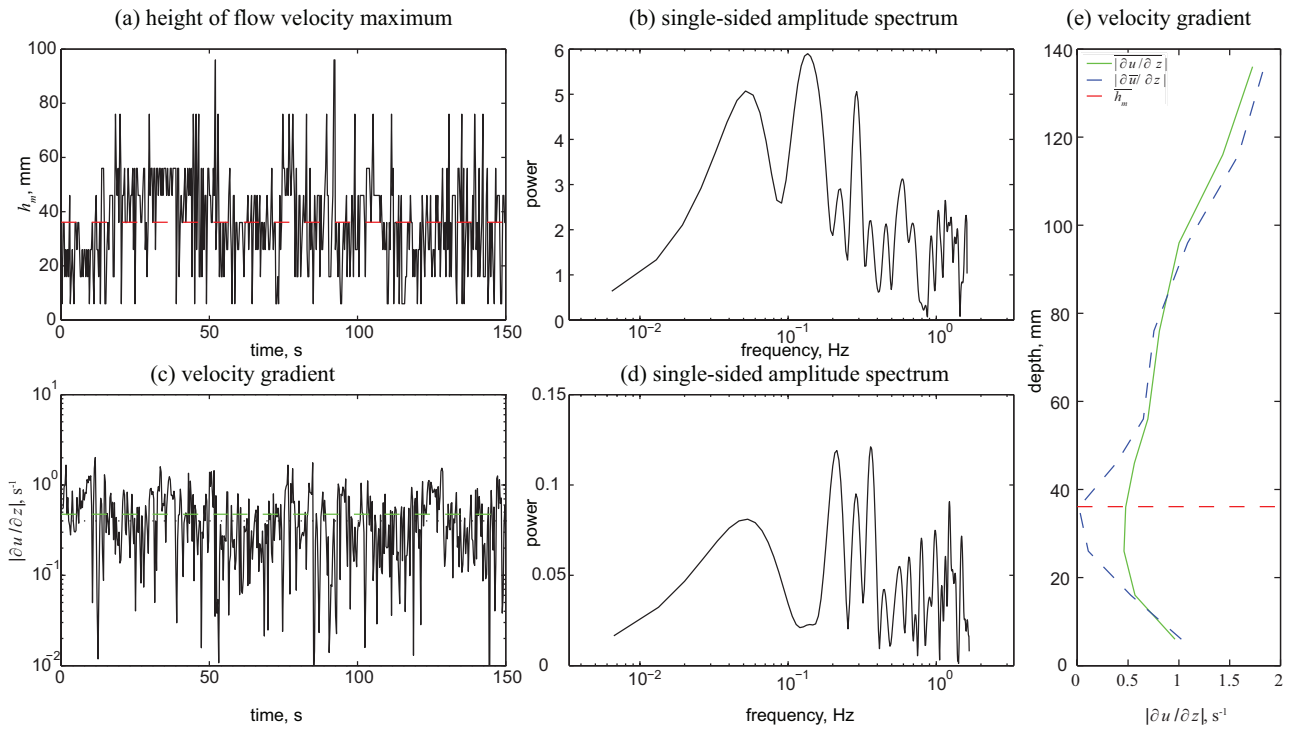
384

#### 385 *4.2 Implications of unstable secondary flow for mixing in sinuous channels*

386 A key implication of the observed instability of secondary flow cells for sinuous seafloor channels is  
387 enhanced turbulent energy production and, turbulent flow induced, vertical sediment mixing. This  
388 may be deduced from the long-timescale variations in primary and secondary flow velocity shown in  
389 Figure 4. It is noted that, because the flow transitions between different secondary flow cell  
390 arrangements, periodical variations in the cross-stream flow velocity fluctuations are not in phase.  
391 That is to say negative fluctuations lower in the flow may correspond to positive fluctuations higher up  
392 in the flow or vice-versa. A consequence of variation of cross-stream flow circulation is variation of the  
393 vertical position of the flow velocity maximum, Figure 8a. The cross-channel location of the flow  
394 velocity maximum is also likely to vary as a function of time, but is not recorded herein. The vertical  
395 location of the flow velocity maximum at the centreline of the channel at the bend apex is forced at the  
396 same frequency to the long-term fluctuations in primary and secondary flow, Figure 8b.

397 Production of turbulent kinetic energy, and thus mixing through turbulent fluid motion, is modelled by  
398 turbulent shear stresses, where shear may be assumed proportional to the velocity gradient (Pope,  
399 2000). In steady flows this may lead to a reduction of turbulence and turbulent mixing and diffusion  
400 (i.e. the slow diffusion zone) at the velocity maximum. However, although the experimental flows  
401 generated here have a steady state input the flows themselves have inherent temporal variations.  
402 These fluctuations mean that, whilst at an instance in time the velocity gradient is zero at the local  
403 velocity maximum, the velocity gradient at the average velocity maximum is not zero, Figure 8c.

404 Unsurprisingly the driving frequencies of variation in velocity gradient at the flow velocity maximum  
 405 are similar to the driving frequencies of primary and secondary flow fluctuation, Figures 4 and 8d.  
 406



407  
 408 Figure 8. Temporal variations, from experimental run V, of: the height of the velocity maximum,  $h_m$   
 409 (a); and the absolute velocity gradient estimated,  $|\partial u / \partial z|$ , at  $z = h_m$  (c). (b) and (d) respectively plot  
 410 the single-sided amplitude spectrum of the fluctuations of  $h_m - \overline{h_m}$  and  $|\partial u / \partial z| - \overline{|\partial u / \partial z|}$ . (e)  
 411 absolute values of the average velocity gradient,  $|\overline{\partial u / \partial z}|$  (green solid curve), compared to the gradient  
 412 of the average velocity,  $\partial \bar{u} / \partial z$  (blue dashed curve), as a function of flow depth. In (a) and (e) the  
 413 average depth of the flow velocity maximum is denoted by a red dashed curve.

414  
 415 A direct consequence of this is that, near the flow velocity maximum, the gradient of the average flow  
 416 velocity is not equal to the average flow velocity gradient. That is to say that unstable secondary flow  
 417 cells drive long-timescale variation in the zone of low shear and low turbulent mixing near the flow  
 418 velocity maximum, diffusing its effects over a wide central region of the flow, see Figure 8e and Keevil  
 419 et al. (2006). Furthermore, timescales over which sediment in suspension responds to changes in flow  
 420 conditions are large, scaling with flow depth over settling velocity (Dorrell and Hogg, 2011). Thus,  
 421 sediment response timescales may be much greater than hydrodynamic timescales associated with

422 unstable secondary flow. Therefore, enhanced mixing by unstable secondary flow will reduce  
423 stratification, and thus help to maintain sediment transport capacity of density driven flows (Dorrell et  
424 al., 2014). In particular, the implication is that this new mixing mechanism will work alongside those  
425 previously identified — stable secondary circulation (Keevil et al., 2006), run-up and superelevation at  
426 bends (Straub et al., 2011), and internal hydraulic jumps (Dorrell et al., 2016) — to reduce the vertical  
427 variation in sediment concentration and enhance run-out distances.

#### 428 429 *4.3 A new interpretation of secondary flow dynamics in submarine channels.*

430 Assuming the processes observed in the experiments reported herein are transferable to real oceanic  
431 density driven flows, it is proposed that the secondary component of density driven flow in sinuous  
432 seafloor channels varies dynamically. The dynamic variation in secondary flow structure is observed  
433 to occur at time-scales larger than natural, flow-depth scale, turbulent eddies. It is therefore proposed  
434 that the orientation of secondary flow cells within sinuous channel systems can be unstable.

435 A key question is what mechanism controls flow instability, and thus the perturbations between  
436 secondary flow cell states, observed within the experiments? One possible mechanism is that, as  
437 turbulent flow is drawn around the meander apex, large-scale coherent vortices are shed (Uijttewaal,  
438 2014) from horizontal recirculation zones, as observed in open-channel flow (Hickin, 1978; Ferguson  
439 et al., 2003). This vortex shedding naturally results in perturbations to the mean flow travelling  
440 around the meander bend. Moreover in the case of density currents, because of the low-density  
441 differences between the ambient fluid and flow, small perturbations may have relatively large impact  
442 on flow dynamics; see Figure 1 and Dorrell et al. (2013). Furthermore, separation zones are more  
443 likely in submarine channels than in rivers as a result of the prevalence of river-reversed secondary  
444 circulation that keeps flows outwardly directed for longer around the bend (Peakall and Sumner,  
445 2015). Such separation zones have been widely recognised in submarine channel experiments and  
446 simulations (Straub et al., 2008, 2011; Ezz et al., 2013; Janocko et al., 2013; Basani et al., 2014).

447 The vortex shedding frequency,  $f$ , of flow past an obstacle may be estimated

448 (8)  $f \approx 0.10 \frac{U}{r},$

449 where  $r$  is the radius of the flow obstacle and  $U$  the characteristic flow velocity past it (Bearman,  
450 1969). Taking  $r$  as the inner radius of the channel ( $r=0.1$  m, Figure 2) and considering experiment V,  
451 where the time and maximum flow velocity  $\sim 0.1$  m/s at  $\sim 46$  mm above the bed (Figure 3), the  
452 predicted vortex shedding frequency is  $f \sim 0.1$  Hz. This is in quantitative agreement to the observed low  
453 frequency in; the downstream and cross-stream velocity fluctuations (Figure 4); variation in the height  
454 of the velocity maximum (Figure 8); and turbulence production through shear (Figure 8). Scaling this  
455 to real-world channels and flows, where channel bend radii are  $\sim 0.5$ - $15$  km and flow velocities are  
456  $\sim 1$ - $10$  m/s (Pirmez and Imran, 2003; Peakall and Sumner, 2015), the shedding frequency is  $\sim 8$ - $2500$   
457 minutes.

458

#### 459 *4.4 Implications for sediment transport and submarine channel evolution*

460 A key implication of the observed fluctuations in the structure of secondary flow cells is that the  
461 reversals in basal flow direction lead to a net reduction in cross-stream sediment transport at a given  
462 point around the bend. Furthermore the analysis of these reversals in terms of the vortex shedding  
463 frequency,  $f$ , suggests that they will become more frequent in tighter bends; i.e.  $f$  increases as  $r$   
464 decreases, see Equation (8). Thus, vortex shedding is expected to progressively increase as bend  
465 amplitude increases from an initially approximately straight planform (e.g., see Peakall et al., 2000a,  
466 b). In this case, net cross-stream sediment transport will systematically reduce as bends grow, in turn  
467 suggesting that this may lead to a reduction in the rate of bend growth. This change in bend growth  
468 rate agrees with observations from submarine channel-levee systems where bend growth  
469 progressively decreases as a function of aggradation (Peakall et al., 2000a, b; Jobe et al., 2016).

470 Eventually submarine channels reach a point where there is a near cessation of planform movement  
471 (termed ossification) and are dominated by vertical aggradation (Peakall et al., 2000a; Wynn et al.,  
472 2007; Jobe et al., 2016). This contrasts with river channels that, although showing a rapid decrease in  
473 outer bend erosion rates as bend curvature tightens through outer bank flow separation (Blanckaert,  
474 2011; Blanckaert et al., 2013) and increased flow resistance (Hickin and Nanson, 1975), do not reach a  
475 point where bend migration ceases (Hickin and Nanson, 1975 and 1984). Peakall et al., (2000a) first  
476 postulated that additional processes in submarine channels, or variations in these processes, may

477 reinforce this fluvial-type stability criterion for bend stability, leading to the cessation of planform  
478 movement. Here we suggest that the observation herein that net sediment transport at a given point  
479 on a bend decreases with increasing bend curvature due to periodic changes in the structure of  
480 secondary flows, may provide the additional forcing for channel bends to reach stability. Peakall et al.,  
481 (2000a, p.446) earlier raised this possibility: “if the intensity or frequency of flow-cell reversal is  
482 linked to the curvature of the meander bend, there may be a negative feedback mechanism that serves  
483 to stabilize meanders”.

484 A number of other mechanisms have however been postulated for the near cessation of planform  
485 movement in submarine channels, including: i) clay hysteresis where the shear stress required to  
486 erode the clay is much higher than that to deposit, ii) climate-induced flow size reduction, iii) changes  
487 in flow type, and, iv) a balance between equilibrium flows depositing at the inner bank and  
488 disequilibrium flows depositing at the outer bank (Peakall et al., 2000a, Wynn et al., 2007; Kane et al.,  
489 2008; Nakajima et al., 2009; Amos et al., 2010). Jobe et al., (2016) identify that this reduction in bend  
490 growth is common to submarine channels irrespective of tectonic setting or other allogenic drivers,  
491 and thus suggest that the key control(s) is autogenic. This suggests that earlier hypotheses that  
492 planform cessation is related to climate induced flow size reduction, or to changes in flow type, are  
493 untenable. Similarly, variations in flow volume and thus equilibrium flows may be less important in  
494 sinuous submarine channels since the channels act to regulate the size of flows that traverse them  
495 through channel overspill at bends (Straub et al., 2008; Amos et al., 2010). Clay hysteresis will occur in  
496 a variety of systems such as rivers, tidal channels, and submarine channels, albeit that submarine  
497 channels and their associated levees can be an order of magnitude larger than in rivers (Konsoer et al.,  
498 2013) thus potentially strengthening the effect. Given the aforementioned analysis, the evidence  
499 presented here for changes in secondary flow cells and their influence on net sediment transport, as a  
500 function of bend curvature, appears the most plausible mechanism, in combination with the known  
501 increase in resistance to flow as bends tighten, for the observed stabilisation of submarine channel  
502 planforms.

503

504 An additional implication of the present work is that if the shedding frequency is low, and the net bed  
505 aggradation rate is high, then it may be possible for submarine channel bend deposits to preserve both  
506 inner bank and outer bank directed sedimentary structures (in and around the bend apex position),  
507 reflecting periodic changes between river-normal and river-reversed secondary flows. Significant  
508 variability in palaeocurrent directions, with inward and outward directed examples, has been  
509 recorded in submarine channel point bar deposits (Pyles et al., 2012).

510

## 511 **5 Conclusions**

512 Previous research, based on the analysis of individual time-slice or temporally averaged flow data, has  
513 lead to a model of stable secondary flow cells in submarine channel flows with continuous steady  
514 input. However, here novel experimental observations and analysis are presented that show that the  
515 velocity fields of these pseudo-steady density currents in sinuous channels can be temporally unstable.  
516 This flow instability is manifested as long-time scale variation in both primary (downstream) and  
517 secondary (cross-stream) flow fields measured at the apex of a channel bend. Further, it is  
518 demonstrated that these instabilities can enhance cross-channel flow and vertical mixing, and thus  
519 mitigate the previously proposed effects of the slow diffusion zone in inhibiting mixing past the  
520 velocity maximum in density driven flows. It is postulated that the temporal instability of such flows is  
521 driven by vortex shedding, in a similar manner as observed in turbulent flows past an obstacle. The  
522 importance of flow instability is highlighted by the flow switching between different secondary flow  
523 states, alternating between single secondary cells with outer bank directed basal flow and twin-  
524 stacked cells with either inner or outer bank directed basal flow. The proposed mechanism suggests  
525 that flow instability driven alternation of near bed secondary flow direction leads to a progressive  
526 reduction of net cross-channel bedload transport as a function of tightening bend curvature during  
527 bend growth. Ultimately we postulate that this may cause termination of net cross-channel bedload  
528 transport and therefore explain the eventual stabilisation of sinuous channels in subaqueous settings.

529

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535

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