EP51C-0568

Flow separation and morphology in sharp meander bends

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Research group
River and delta morphodynamics

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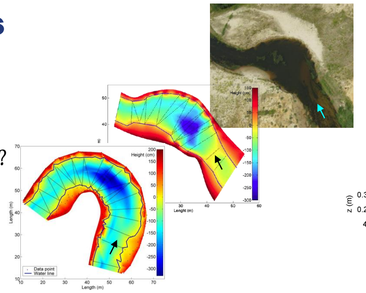
Research questions

- Spiral flow in gentle bends; flow separation over sharp edges... Where is the transition?
- When does flow separate in a bend? What are associated flow structures?

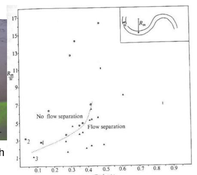
Relevance:
- sharp bends found in rivers of all sizes with strong banks



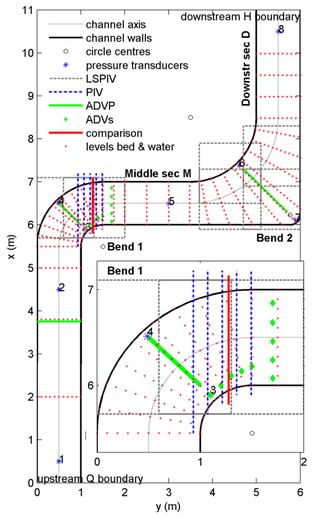
Hypothesis

- sharper bend R/h → onset flow separation → recirculation
- flow expansion → recirculation
- higher Fr → recirculation

Kleinhans et al. 2009 Geomorph



Leeder & Bridges 1976 Nature



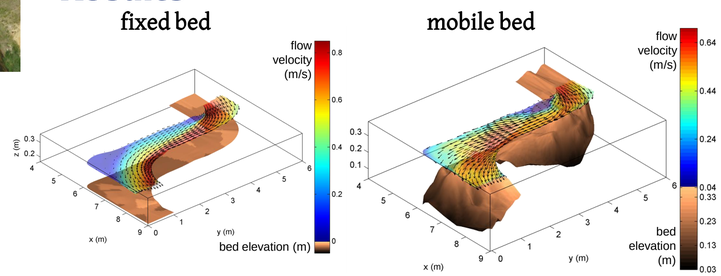
Methods

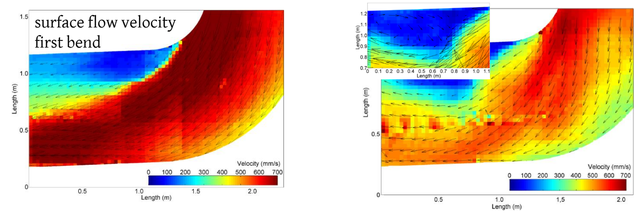
- facility
  - Total Environment Simulator Hull University
  - sharp bend R/W = 1
  - gentler bend with expansion
- conditions
  - see tables below
  - fixed bed varying depth and Fr
  - mobile bed coarse sand
- measurements
  - surface PTV
  - ADVP
  - 3DPIV
  - water and bed surface
  - ADVs for long time series

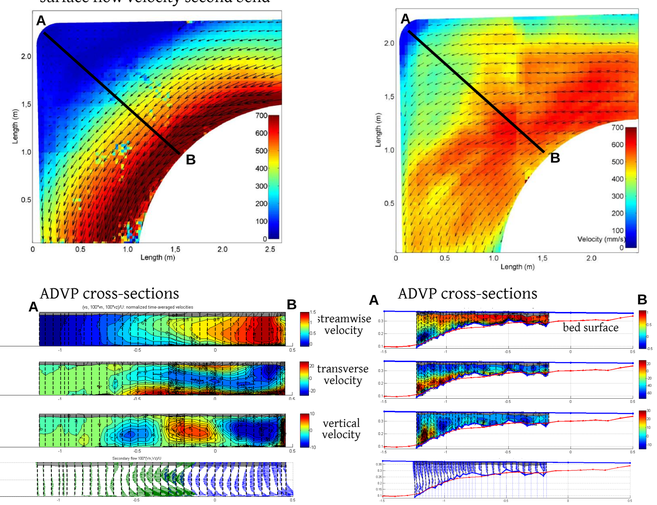
Fixed bed	*Q* [ls^{-1}]	*H* [m] ± **0.005**	*U* [ms^{-1}]	C_{bed} [m$^{1/2}$s^{-1}]	C_{com} [m$^{1/2}$s^{-1}]	$u_{*,in,bed}$ [ms^{-1}]	$E_{s,inflow}$ [10^{-4}]	*Re* [10^3]	*Fr* [-]	*B/H* [-]
Low H Low Fr	13.5	0.087	0.155	36.1	38.2	0.0135	2.2	13.5	0.168	11.49
Low H Medium Fr	30.5	0.087	0.350	36.1	38.2	0.0304	11.3	30.5	0.379	11.49
Medium H Low Fr	24.8	0.150	0.165	38.2	41.7	0.0135	1.4	24.8	0.136	6.67
Medium H Medium Fr	69.7	0.160	0.436	38.5	42.2	0.0354	8.8	69.7	0.348	6.25
High H Low Fr	32.4	0.215	0.151	40.4	45.2	0.0117	0.7	32.4	0.106	4.65
High H Medium Fr	117	0.215	0.545	40.4	45.2	0.0423	9.7	117	0.375	4.65
High H High Fr	125.4	0.220	0.570	40.6	45.4	0.0440	10.3	125	0.388	4.55

Mobile bed	*Q* [ls^{-1}]	*H* [m]± **0.005**	*U* [ms^{-1}]	C_{bed} [m$^{1/2}$s^{-1}]	C_{com} [m$^{1/2}$s^{-1}]	u_{*bed} [ms^{-1}]	E_s [10^{-4}]	*Re* [10^3]	*Fr* [-]	*B/H* [-]
Medium H medium Fr	49.0	0.121	0.40	22.8	25.1	0.0560	26	49	0.37	8.27

Results



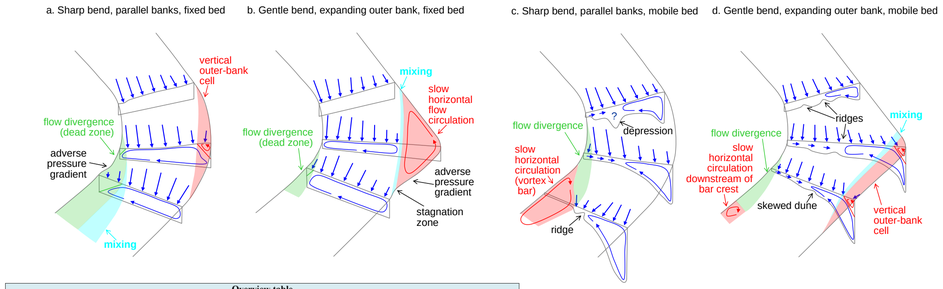




Flow structures

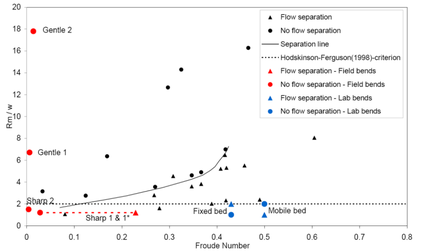
Fixed bed
- Sharpest bend: no flow recirculation; strong outer-bank cell; flow divergence *downstream* of bend
- Expanding bend: flow recirculation; weak divergence

Mobile bed
- Sharpest bend: flow recirculation over shallow bar *downstream* of bend
- Expanding bend: strong vertical flow cell near outer bank downstream of apex



Overview table

	Sharp bends with fixed bed in lab	Sharp bends with mobile bed in lab	Sharp bends with mobile bed and banks in field
Flow separation / divergence			
Bend 1	Divergence at inner bend downstream of the apex	Separation at inner bend downstream of the apex	Separation at inner bend upstream of the apex and outer bend at the apex
Bend 2	Separation at outer bend apex	Divergence at inner bend downstream of the apex	-
Main flow direction			
Bend 1	Crosses over from inner to outer bend	Crosses over from inner to outer bend	-
Bend 2	Stays at inner bend	Crosses over from inner to outer bend	-
Bed morphology			
Bend 1	-	Eroded bar at inner bend; Pool at outer bend bank	Eroded bar at inner bend; Pool in the centre
Bend 2	-	Eroded bar at inner bend; Pool at outer bend bank from apex till outflow	Eroded bar at inner bend; Pool in the centre of the channel
Highest velocity near the channel wall / Potential bank erosion patterns			
Bend 1	Outer bend, 1m downstream of the apex till outflow	Outer bend, 1m downstream of the apex till outflow	Outer bend and especially the stagnation point; Inner bend upstream of the apex
Bend 2	Outer bend, 1m downstream of the apex till outflow	Outer bend, from apex till outflow	Outer bend and especially the bare region downstream of the apex



Conclusions

Formative conditions for flow separation and horizontal flow recirculation:
- Flow separation in sharp bends downstream of about 60°
- Flow recirculation only in expanding bends: outer bend embayment, over shallow inner-bend bar
- *No* dependence on Froude number as found by Leeder & Bridges 1975
- Weak relation of bend curvature

Mobile bed responds strongly:
- deep outer-bank pools (partly due to smooth fixed walls)
- horizontal recirculation in outer bend embayment replaced by vertical cell near bank

Erodible banks (field cases) differ from experiment:
- deep scour not immediately at outer bank but more in the middle
- bank irregularities, i.e. high localised curvature causes flow recirculation

Acknowledgements
- Support by Lekan Owodunni for LSPIV analysis with his software; discussion by Stuart Lane, Richard Hardy, Jeff Peakall, Alex Sukhodolov, Carlo Camporeale, Kees Sloff and Rob Ferguson.
- Access to the TES at Hull University for 30 days was supported by European Community's Sixth Framework Programme through the grant to the budget of the Integrated Infrastructure Initiative HYDRALAB III within the Transnational Access Activities, Contract no. 022441. MGK was supported by The Netherlands Organisation for Scientific Research (NWO) (grant ALW-Vidi-864.08.007).

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