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Direct measurements of secondary currents in a meandering sand-bed river

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Natural channels often adopt a meandering course. Water flow in meander bends is three-dimensional, consisting of primary velocities which are tangential to the bend, and secondary velocities, which are in the radial plane. The pattern of secondary flow strongly affects the distribution of primary velocities. This in turn affects the distribution of erosion and deposition in the bend and the way in which the channel shifts and changes shape. Measurements of primary and secondary flows in a meandering gravel-bed river[1,2] show that, in addition to the widely recognized main secondary circulation driving surface water outwards and bed water inwards, there can be a small cell of reverse rotation at the outer bank. Further data have been collected in a sand-bedded river at low, intermediate and high discharges. The results confirm the existence of the main and outer bank cells but also indicate that in some bends the main cell does not extend to the inner bank. In fact, secondary flow at the inner bank of wide, shallow bends is directed radially outwards over the whole flow depth at all in-channel flows. This indicates that some models of bend flow and channel development may be significantly in error.

Secondary currents are defined as currents that occur in a plane normal to the axis of primary flow[3]. In meander bends, they develop by skewing of cross-stream vorticity into a long-stream direction[3,4]. The resulting skew-induced secondary circulation carries fast surface water towards the outer bank and slower bed water towards the inner bank.

At the outer bank, the primary flow, secondary circulation, and bank interact to produce a small cell of reverse rotation to the skew-induced cell. This cell occupies the channel to a distance one or two times the bank height away from the bank. Although this is a small proportion of the cross-section in most rivers, the outer bank cell is still important because it strongly affects the distribution of boundary shear stress, thereby influencing bank erosion processes[5,6].

In the central part of the channel, helical skew-induced flow produces inward velocities near the bed, which sweep bedload towards the inner bank. Sediment accumulation as a point bar at the inner bank gives the channel an asymmetrical cross-section. The balance between the transverse, upslope component of fluid drag on a bedload particle, and the transverse, downslope component of particle weight has been used as the basis for models of bed topography in bends[7,8]. This view of secondary flow-point bar interaction has been challenged recently[9]. Dietrich and Smith suggest that secondary flow above the point bar is directed radially outwards over the whole flow depth and that the helical skew-induced cell is confined to the deepest, or thalweg, portion of the cross-section. Sediment accumulation is then concentrated on a steep transverse slope called the point bar face, between the upper point bar (point bar platform) and the thalweg, where near bed flow converges and there is strong upwelling. Bridge[10] suggests that this pattern of flow and point bar building is a characteristic of point bar emergence at flows below about two-thirds bankfull. He suggests that at such low stages the point bar topography causes flow convergence at the bend entrance, but that such patterns are replaced by helical flow at formative (that is, bankfull) discharge.

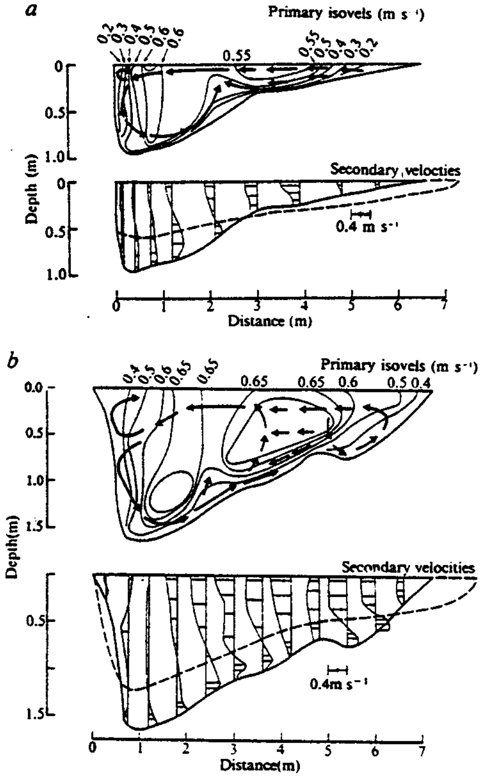

Fig. 1 Upstream bend apex, discharge: *a*, 1.7 $m^3 s^{-1}$; *b*, 4.0 $m^3 s^{-1}$. Dashed channel section represents that at the previous measurement section, ~6 m upstream.

To help to resolve this discussion, data were collected in this study over a range of discharges in meander bends of the Fall River in Rocky Mountain National Park, Colorado. The reach studied has a bankfull capacity of about 4 $m^3 s^{-1}$ and well developed meanders with a sinuosity of 2.2. The annual hydrograph is dominated by snowmelt runoff, resulting in long periods of almost steady bankfull flow in May, June and July. The gradient is ~0.1%. The bed material is sand, $D_{50} = 1.0$ mm, moving in dunes, ripples and as suspended load. Sediment availability has been greatly increased by erosion associated with the failure of Lawn Lake Dam on the Roaring River (an upstream tributary) on 15 July 1982. As a result, the bed is mobile at all discharges and point bars in the bends respond quickly to changes in flow stage.

Measurements were made at low, intermediate and bankfull stages, corresponding to discharges of 1.7, 2.8, and 4.0 $m^3 s^{-1}$. Long and cross-stream velocities were measured using an electromagnetic current meter capable of measuring two mutually perpendicular velocity components with an accuracy of ±3 mm s^{-1}. All measurements were made from temporary bridges aligned at right angles to the outer bank, and care was taken to work only over dune crests, avoiding separation zones on the lee side of dunes. Data were collected at 18 sections evenly spaced along the channel through two consecutive bends. The complete data set is available[11,12] but because of limitations of space, only data for the intermediate and high flow at the bend apices are reported here. However, these sections do typify the different patterns found in the two bends. The long and cross-stream velocities were resolved into primary and secondary components using the method based on three-dimensional continuity recommended by Dietrich and Smith[9]. The results are shown in Figs 1, 2.

At both sections and flows the salient feature of the secondary circulation is the helical, skew-induced cell. However, close to the outer bank, a small cell of reverse rotation is clearly present, especially at bankfull flow. These cells are associated with distortion of the primary isovels and depression of the maximum primary velocity below the free surface in the outer bank region.

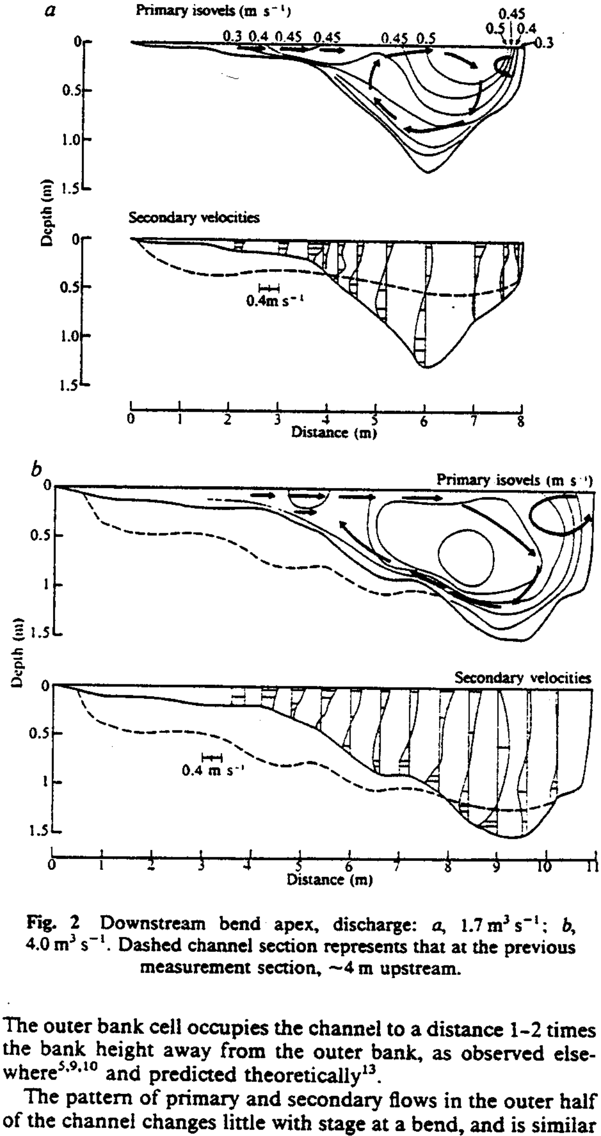

Fig. 2 Downstream bend apex, discharge: *a*, 1.7 m^3 s^{-1}; *b*, 4.0 m^3 s^{-1}. Dashed channel section represents that at the previous measurement section, ~4 m upstream.

The outer bank cell occupies the channel to a distance 1-2 times the bank height away from the outer bank, as observed elsewhere[5,9,10] and predicted theoretically[13].

The pattern of primary and secondary flows in the outer half of the channel changes little with stage at a bend, and is similar at both apices. This robustness is not present in the flow pattern in the inner half of the channel, where the two bends react differently to changing stage.

At intermediate flow, secondary flow over the point bar is directed radially outwards over the whole depth, as predicted and observed by Dietrich and Smith and by Bridge[9,10]. The reason for this is the dominance of the centrifugal force acting outwards over the hydrostatic pressure gradient, acting inwards. Also, the flow is shelving and narrowing in the longstream direction at the inner bank, as indicated in Figs 1*a* and 2*a* by the dashed lines showing the cross-section just upstream from the bend apex. Consequently, water is driven radially outwards to maintain continuity, leading to outward secondary flow. These arguments agree with the explanation put forward by the previous researchers[9,10].

At bankfull stage, the two bends show different flow patterns in the inner half of the channel. At the upstream bend, outward flow has been replaced by helical flow over most of the width, as predicted by Bridge[10]. The point bar has been scoured and reprofiled by the high flow and this, combined with the increased stage at almost constant width, has significantly increased the importance of the cross stream hydrostatic pressure gradient, which is now able to drive bed flow inwards. This is not the case at the downstream bend. Here, outward flow over the point bar persists up to bankfull discharge. The reason for this is that the width increases markedly with stage at the downstream bend, so that both the depth and the hydrostatic pressure gradient over the point bar remain small (Fig. 2*b*). Also, the point bar is more prominent in the downstream bend, so that shelving in the downstream direction is maintained at bankfull flow (Fig. 2*b*). This is not the case at the upstream bend, where high flow scouring produces deepening downstream at the inner bank (Fig. 1*b*).

We conclude that both patterns of flow in the inner half of the channel are possible and do occur in nature, depending on the morphology of the channel cross-section. Of particular importance is the stage-width relationship. Where there is marked widening with stage, outward flow persists to bankfull flow, but where width is almost constant with stage, helical flow expands almost to the inner bank. A quick survey of the Fall River bends revealed about equal numbers of bends falling into each category. As all the bends have the same bankfull discharge, sediment load, and bed and bank materials, there seems to be no obvious reason for the different morphologies, raising the possibility of there being two stable bend sections for a given set of independent controls. Clearly, point bar-flow interaction is a topic deserving further consideration and study.

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