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Flows that form: the hydromorphology of concave-bank bench formation in the Ovens River, Australia

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Abstract Ecological processes associated with in-channel benches have become a key focus of environmental flow studies in Australia. In this paper we present an initial investigation into the relationship between the morphology of mature benches and the flow regime responsible for their maintenance. We define benches as depositional features resulting from the vertical accretion of suspended sediment within a river channel. A two-dimensional hydrodynamic model (River2D) was used to represent the hydrodynamic conditions over a concave-bank bench on the Ovens River, southeast Australia, and deposited material was analysed. For stages higher than the bench surface elevation a large low-velocity and generally reverse-flow eddy is evident over the bench with velocities less than 0.2 m s^{-1} allowing for the deposition of silt and fine sand. Our results indicate that deposition on the bench is greatest during large in-channel flows and a depositional environment is still present at near-bankfull flows. These findings identify the importance of in-channel high-flow events for the maintenance of natural channel morphology.

Key words concave bench; deposition; hydrodynamic; reverse flow; vertical accretion

INTRODUCTION

In-channel benches are an important morphological and ecological component in the meandering rivers of southeast Australia, yet the presence of benches is reduced by flow regulation (Walker & Thoms, 1993). The key aim in this research is to identify the range of flows which maintain in-channel benches through deposition. We have defined a bench as “a bank-attached, planar and narrow, fine grained sediment deposit occurring at elevations between the river bed and the flood plain” (Vietz *et al*., 2004). This definition is an extension of that put forward by Erskine & Livingstone (1999) and by focusing on “fine grained” sediment <0.5 mm (Blott & Pye, 2001) and considering processes of formation we can distinguish benches from bars, terms that are commonly used interchangeably. We describe benches as being predominantly the result of deposition of fine grained suspended-load sediment by vertical accretion, whereas bars are predominantly the result of deposition of coarser bed-load material by lateral accretion. This distinction was mooted by Woodyer *et al*. (1979) and the continuum of form elucidated, with bars often forming the nuclei for benches. It is the process of vertical accretion associated with lower velocities in flow expansion zones that we have observed to form benches and this is the focus of our research.

Six distinct bench types have been identified in the Ovens River, southeast Australia (Vietz *et al.*, 2004). The focus of our research is on concave benches which are similar to those described by Carey (1969), Woodyer *et al.* (1979) and Page & Nanson (1982). Relative to other bench types observed in the Ovens River, concave benches are the most recognisable and consistent in morphology, exhibit the most consistency in bench surface elevation (Vietz *et al.*, 2005) and are not as frequent (1 per 2.5 km), yet they store the greatest volume of fine sediment of all bench types. The key question for this research is: "What components of the flow regime are responsible for concave bench formation?"

The frequency with which bench surfaces are inundated has historically dominated the literature on bench hydrology (Woodyer, 1968; Woodyer *et al.*, 1979; Erskine & Livingstone, 1999; Cohen, 2003). Numerous authors have noted the lack of understanding of the relationship between in-channel morphological features and hydrological factors responsible for their formation (Steiger *et al.*, 2001; Changxing *et al.*, 1999; Thoms & Sheldon, 1996). Bench formation has been associated flows that "just inundate" benches aggrading through "mud drapes" (Thoms & Walker, 1993) to moderate and "catastrophic" sized floods (Erskine & Livingston, 1999; Webb, 2002).

The hydrological factors responsible for concave bench formation require an understanding of hydrodynamics. We have applied two-dimensional (2-D) steady-state hydrodynamic modelling to complement field observation of flow conditions at concave benches. Similar models have been successfully used to model compound channel hydraulics (Vionnet *et al.*, 2004). Previous researchers have investigated bench hydromorphology in three ways: casual observation (Carey, 1969; Hickin, 1979; Page & Nanson, 1982); field velocity measurements at bankfull flows (e.g. Burge, 1997); inference from sediment size analysis (e.g. Changxing *et al.*, 1999) or bench stratigraphy (e.g. Woodyer *et al.*, 1979; Cohen, 2003). As noted by Cohen (2003) the latter approach is not feasible in fine sediment. Page & Nanson, (1982, p.530) observed that for concave benches "the problem of formative hydraulic conditions remains an ongoing research project dependent on the occurrence of particular flow conditions". Hydrodynamic models overcome this problem by allowing the flow environment at concave benches to be analysed over a range of flow magnitudes.

RESEARCH SITE

This research was undertaken on the Ovens River northeast Victoria (Fig. 1) and preliminary results from Site 1: "Big Eddy" bench are presented. The Ovens River is one of the last largely unregulated rivers in the Murray Darling Basin with a relatively intact hydrological and sedimentological regime. The Ovens River at Peechelba has a high suspended sediment load by Australian standards with a mean concentration of 21.5 mg L^{-1} and 90th percentile of 33.6 mg L^{-1} (Cottingham *et al.*, 2001). The lower reaches contain mostly undisturbed vegetation and channel morphology, providing a unique opportunity to investigate natural bench morphology in a lowland stream. This reach of the Ovens River has a highly sinuous channel with numerous anabranches, clay banks and a sandy to fine-gravel bed. The site catchment area is approximately 7000 km^2.

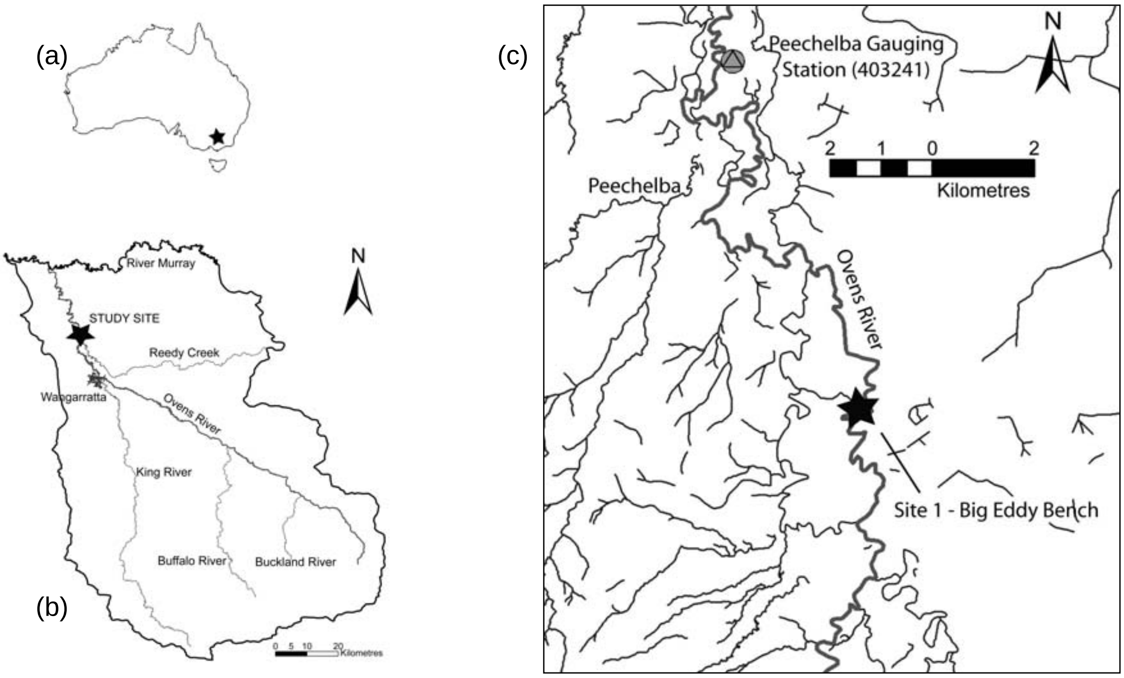

Fig. 1 (a) Site within Australia. (b) Tributaries of the Ovens River catchment. (c) Lower Ovens River showing the location of the detailed study site: "Big Eddy" bench.

METHODS

Site hydrology

Daily discharges are recorded at the Ovens River streamflow gauge at Peechelba, approximately 18 km downstream of the site. These data were modified to reflect the loss of discharge at the site due to a high level anabranch that departs from the Ovens River main channel immediately upstream of the site and returns upstream of the streamflow gauge. We created a rating curve for the anabranch based on three measurements of discharge in the anabranch and interpolation/extrapolation using Manning's equation.

Hydrodynamic modelling

We chose to use the 2-D hydrodynamic model River2D for the purpose of replicating the hydrodynamic conditions at the study site for several reasons:

1. River2D was specifically developed to replicate local-scale hydraulic conditions within a natural channel (Ghanem *et al*., 1994);
2. River2D can simulate flow adjacent to complex structures including large eddies (Waddle *et al*., 2000) and recirculation zones (Schwartz, 2003);
3. River2D has been widely used to predict channel change, e.g. Lacey & Millar (2004) and hydraulic habitat, e.g. Hanrahan *et al*. (2003) and River2D results have been field-verified with reasonable results (Schwartz, 2003; Waddle *et al*., 2000);

4. River2D has a user-friendly graphical interface and excellent output for visualization of hydraulic conditions.

River2D is a finite-element depth-averaged model developed at the University of Alberta. The hydrodynamics of River2D are based on the St Vennant equations for the conservation of mass and momentum along with the Petrov-Galerkin upwinding formula for stability. Three-dimensional hydrodynamic modelling was considered for this task but the additional complexity is not warranted considering the focus here is on the laminar flow environment beyond the flow separation envelope.

Topographic survey requirements for the model are an accurate representation of the surface. We used a Topcon GTS-229 Total Station to identify 1087 points over the 440-m reach, from the bed to flood-plain level (Fig. 2). Greater detail was extracted in the immediate vicinity of the bench and on the concave bank upon which the velocity thread impinges. Key in-channel features such as woody debris and large trees were identified to assist in interpreting the data and determining roughness values.

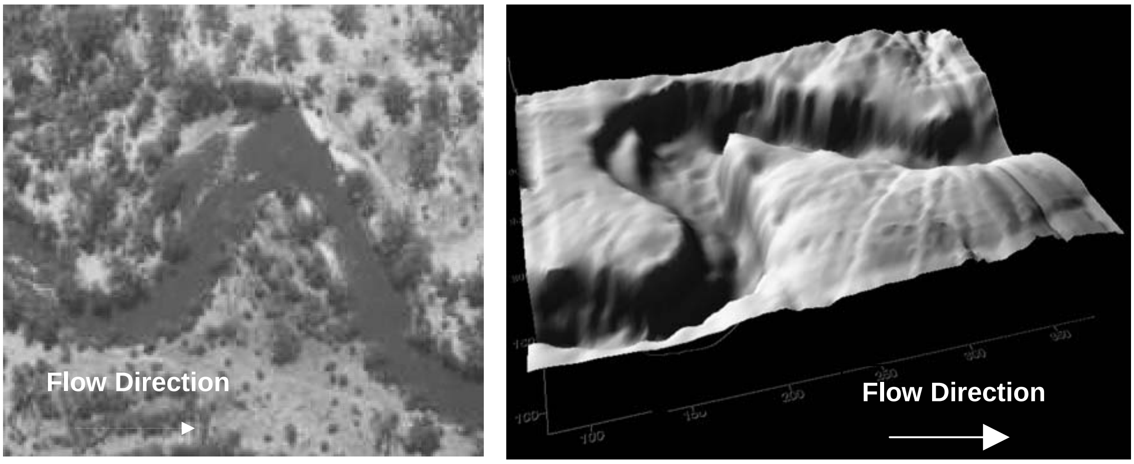

Fig. 2 (a) Site Big Eddy Bench aerial photograph (1989), and (b) 3-D representation of the study site from surveyed points (plotted using Surfer®).

Calibration was achieved by comparison of gauged discharges with water surface levels and surveyed water slopes at three discharges ranging from below the bench surface to near-bankfull. Modifications were made to the key model parameters of surface roughness and eddy viscosity, as well as channel topography, in both cases due to trees. During a near-bankfull flood in February 2005 (peak magnitude 200 $m^3 s^{-1}$) velocity measurements were made from a secured boat, on the receding limb two days after the peak. Readings were taken both within the main flow thread and in the reverse flow over the bench, with the velocity direction manually recorded and the location of readings and the separation envelope surveyed. At each location, velocity readings were recorded at three depths and the depth-averaged velocity was identified through the use of the three-point formula of Fenton (2002). Depth-averaged field velocities over the bench ranged from zero to 0.36 $m s^{-1}$, being greatest on the downstream side of the bench (where the reverse flow enters) and over the bench trough adjacent to the bank attachment of the bench. In the main flow, depth-averaged velocities are not reliable as the maximum reach of the velocimeter was 1.5 m and depths were up to 7.9 m. Surface point velocities of up to 4.3 m s^{-1} were recorded in the main flow thread immediately upstream of the bench.

Sediment accretion collection and analysis

Sediment accretion on the bench surface was measured during floods using artificial turf mats, 30 × 30 cm in dimension, collected following three inundation events. Six mats were placed on the bench on a 2 × 3 grid along the bench surface. Sediment removal and analysis of the samples was undertaken using an approach similar to that described by Steiger *et al.* (2003). Samples were wet sieved and all fines passing a 710-µm sieve analysed using an LS 130 Coulter Counter particle size laser analyser. The resulting sediment fractions (% coarse sand to clay) are reported in Table 1. Organic content was determined by loss-on-ignition with fractions greater than 710 µm containing on average 99.7% organic content.

RESULTS

Representativeness of the hydrodynamic model

Field observations of the large reverse-flow eddy over the bench indicate that the gross form is stable and persistent, and this was well replicated in the model at the highest observed flow (Fig. 3). The location at which the main flow thread impinges on the concave bank and the flow separation envelope were also accurately reproduced. Small vortices within the flow separation envelope were observed in the field but are not persistent. They result from vortex shedding and, as such, are not represented in the model.

Depth averaged velocities over the bench surface were slightly underestimated by the hydrodynamic model. In the deeper sections of the channel, while depth averaged velocity is not entirely reliable (for the reasons given above), the model also slightly underestimates average velocities. Further refinement of boundary conditions should improve this situation but for the purposes of the present discussion the flow environment over the bench is adequately characterized.

Velocity fields over the concave bench

The hydrodynamic model was run through steady-state computations over a range of discharge (Q) scenarios from initial bench inundation to near-bankfull discharge (Fig. 4). The velocity within the vicinity of the bench is consistently within the range 0–0.5 m s^{-1} and only these fields are shown in the shading. Note the outline of the bench at Q = 51 m^3 s^{-1} prior to inundation (with artificial turf mats identified as black squares) and the bench morphology at partial inundation (Q = 71 m^3 s^{-1}) with the ridge (not inundated) and trough (mostly inundated).

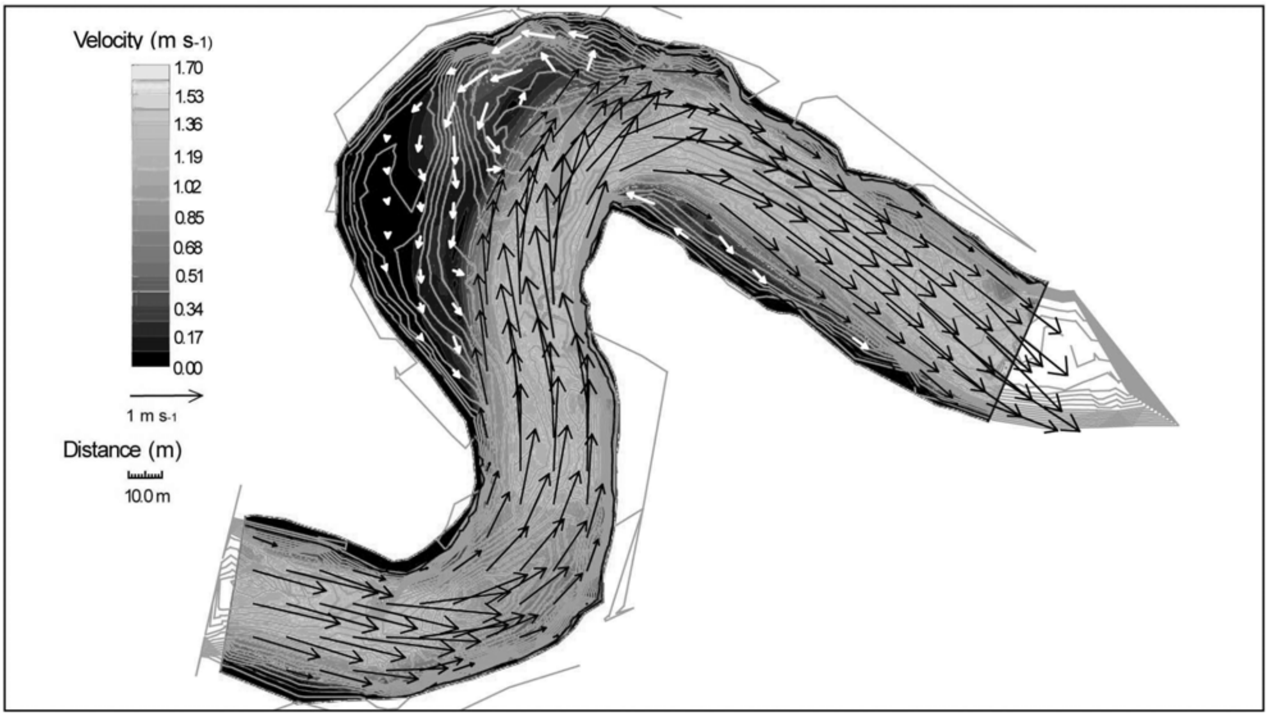

Fig. 3 Velocity vectors and fields for the largest observed flow of 157 m^3 s^{-1} (for colour figures see http://www.sages.unimelb.edu.au/staff/stewardson.html).

Sediment accretion

Sediment accretion mats revealed the ability of the largest flood (200 m^3 s^{-1} peak) to deposit considerable amounts of sediment on the bench surface, with 1.53 kg of sediment on one mat (17 kg m^{-2}). Particle size analysis (averaged across six mats) reveals that the majority of sediment being deposited is in the fine to coarse silt fractions (Table 1).

Table 2 Flood sizes and sediment analysis results (*from Blott & Pye, 2001).

	Floods February	July	August
Peak magnitude (m^3 s^{-1})	200	65	65
Duration over bench (days)	8	3	11
Average sediment mass (kg m^{-2})	13.3	2.2	0.7
Sediment fractions*			
% Clay (<4 µm)	9.3	7.8	5.9
% Fine to medium silt (<16 µm)	34.9	33.7	29.7
% Coarse silt (<63 µm)	39.7	44.3	43.9
% Fine sand (<250 µm)	15.5	13.8	15.5
% Medium sand (<500 µm)	0.6	0.3	3.6
% Coarse sand (>500 µm)	0.0	0.0	1.4

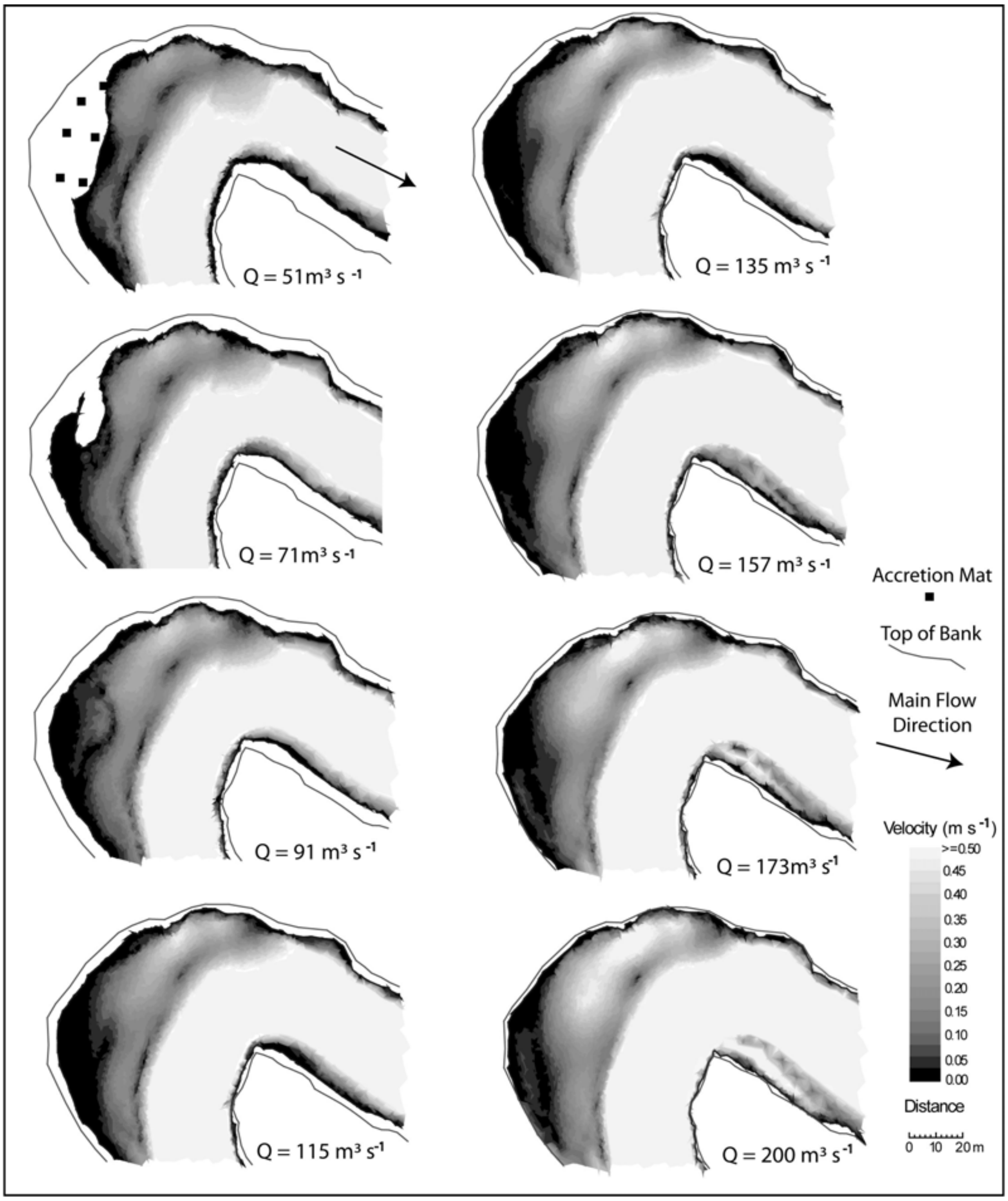

Fig. 4 Modelled flow velocity scenarios over Big Eddy bench for a range of flow magnitudes (*Q*) from the inception of inundation to near-bankfull. Note the high velocity stem flow (mostly light) and adjacent flow separation envelope (thin darker line) beyond which velocity is generally reverse-flow (darker shades).

DISCUSSION

The hydromorphology of bench formation

The concave bench at the Big Eddy site is similar to that described by Carey (1969) where, at an abrupt meander bend (>90°), the main velocity thread impinges on the concave bank immediately upstream of the bend apex. This creates a flow split at the wall, a flow separation boundary upstream due to highly sheared flow (Hickin, 1979) and a large pressure eddy upstream of the apex in the expansion zone.

At the Big Eddy bench the large reverse-flow eddy is evident at the full range of flow stages from bench inundation to bankfull flow (see Fig. 4). While the model is not stable at overbank flows, and none have been observed in the field at this level, the remnant debris of an overbank flow indicates reverse-flow at this level. The flow separation envelope was consistently several metres from the streamside edge of the bench, in contrast to the findings of Hickin (1979, p.200) who found that "the boundary of the bench coincides exactly with the flow-separation envelope". There is in fact a strong reverse flow thread between the edge of the bench and the flow separation envelope, of approximately 0.3 m s^{-1} at near-bankfull flows (see Fig. 4), which would discourage deposition at this boundary. The model shows little movement of the flow separation envelope adjacent to the main flow thread.

Sediment accretion on benches reveals the ability of channels to significantly alter their form through the deposition of suspended sediment. On the Big Eddy bench, one near-bankfull flow deposited more than 10 t of sediment. This supports comments by Woodyer *et al*. (1979) that considerable deposition of suspended load is not confined to overbank zones. The pattern of sedimentation over the bench reveals that the greatest aggradation occurs on the downstream face, in the zone where the reverse flow enters the bench, explaining in part the upstream slope of the bench, as noted by others, e.g. Woodyer *et al*. (1979) and Nanson & Page (1983). This is quite distinct from the downstream slope of the point bar present at the site, and is a critical distinction between these two in-channel features (Vietz *et al*., 2004). The sediment masses also reveal the importance of antecedent conditions on suspended load with greater deposition (2.2 kg m^{-2}) occurring in the July event, after four months with little rain, compared with the August event (0.7 kg m^{-2}) of the same peak but longer duration.

Hydrological components responsible for bench formation

Considering silt and fine sand are the dominant fractions of contemporary accretion, the range of flows "most effective" in aggrading the mature bench would be those responsible for providing the velocity fields from which these fractions are deposited. According to Hjulstrom (1939), the flow velocity at which particles in the fine-sand size fraction will begin to deposit is 0.02 m s^{-1}. Assuming a logarithmic velocity profile, we conservatively accepted a depth-averaged velocity of 0.05 m s^{-1} to provide velocities at the surface of the bench for which deposition of sediment would be expected.

The change in the velocity field over the bench from 51 m^3 s^{-1} to 200 m^3 s^{-1} reveals subtle but interesting trends (Fig. 4). With increasing discharge above inundation there is an increase in velocity, particularly over the downstream edge of the bench and over the bench ridge. Deposition would be expected throughout the entire range of flows at some location on the bench, however velocities greater than 0.05 m s^{-1} are experienced in the earlier stages of inundation and at near-bankfull flows with up to 0.35 m s^{-1}. The highest velocities occur over the bench ridge on the downstream face (the reverse-flow entrance zone) where velocities of up to 0.5 m^3 s^{-1} are experienced during near-bankfull flows, reflected in the sand fraction captured at this location. As discharge increases from 115 to 170 $m^3 s^{-1}$ there is little increase in the velocity over the bench indicating an environment conducive to deposition. At flows greater than 170 $m^3 s^{-1}$ velocities over the bench trough increase. The low velocity environment is reflected in the retention of un-decomposed organic matter overlain by fine sediments on accretion mats following all flood events. This indicates that for concave benches, even bankfull flows are not destructive, nor does the scour of organic matter occur at these flows.

CONCLUSIONS

This initial investigation reveals that concave benches are:

- the result of a reverse-flow environment throughout the range of discharges;
- maintained by the full range of flows between the bench surface and bankfull, particularly flows mid-way between these stages;
- aggraded predominantly by silt and fine-sand through vertical deposition;
- neither destroyed nor scoured by flood flows and retain considerable amounts of organic matter; and
- can account for significant storage of suspended sediment within the channel.

This research is leading to a better understanding of the flows required to maintain in-channel morphology and may ultimately assist in environmental flow recommendations.

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