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Monitoring and modelling flow and suspended sediment transport processes in alluvial cutoffs

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Abstract Sedimentation within cutoffs is controlled by mean and turbulent flow structures that drive suspended sediment transport by advection and diffusion and control particle settling and resuspension processes. The relationship between these flow and sedimentation processes is poorly understood at present due to the difficulty of collecting synchronous instantaneous velocity and sediment concentration data above an undisturbed bed. These relationships are examined using a combined approach involving field monitoring and numerical modelling applied to a site on the River Culm, Devon, UK. Flow and suspended sediment time series were monitored using an array of Acoustic Doppler Velocimeters (ADVs), which provide synchronous instantaneous measurements of three-dimensional (3-D) velocity and sediment concentration at a frequency of 25 Hz. ADV data provide an estimate of the net sediment flux into the cutoff and allow the relationship between vertical turbulent sediment transport and momentum transport events to be examined. Results from a two-dimensional (2-D) finite volume numerical model are also presented and provide further insights into the stage-dependent nature of hydraulics at this site.

Key words alluvial cutoff; ADV; numerical model; suspended sediment

INTRODUCTION

Alluvial cutoffs are typically subject to very high rates of sediment deposition (Lewis & Lewin, 1983) due to their proximity to the river channel and high frequency of inundation (Nicholas & Walling, 1997). Transport of fine sediment into these features is driven by complex flow structures at the interface between the dead water in the cutoff and the flow of the main channel (Nicholas & McLelland, 1999). However, these processes are not well understood at present because little research has been conducted to examine flow and sedimentation within cutoffs, largely due to problems of collecting representative process data in natural rivers. Here we present some results from a study of three-dimensional (3-D) flow hydraulics and suspended sediment transport at a channel-cutoff interface on the River Culm, Devon, UK. Acoustic Doppler velocimeters (ADV) were used to monitor patterns of mean flow, turbulence and suspended sediment concentration simultaneously. Flow data are also compared with results from a two-dimensional (2-D) numerical model which further elucidates the stage-dependent nature of interface hydraulics at this site.

FIELD DATA COLLECTION

Velocity and sediment concentration data were collected at a transect located near the interface between the main channel and a cutoff area at a site on the River Culm, Devon, UK. Data were collected using an array of four ADVs at two separate discharges. A 10-m long, adjustable frame was built to allow easy deployment of the ADVs and eradicate any need for the researcher to enter the water, thus reducing disturbances to the flow and fine sediment. The ADVs were orientated looking into the flow and positioned in a vertical profile separated by gaps of 0.05 m at low discharge and 0.1 m at high discharge. A total of 80 measurements were obtained at 20 vertical profiles at low flow, compared to 64 measurements obtained at 10 vertical profiles at high flow.

The ADV transmits a short acoustic pulse at a frequency of 10 MHz, from a transmitter at the centre of the probe head, into the water column. Air bubbles and small suspended particles reflect acoustic energy back to three receivers focused on a sampling volume of ~0.05 m below the probe head. Velocities can be calculated from the Doppler-shifted phase of the reflected acoustic energy. At each measurement position ADV data were collected for ~4 minutes at a sampling rate of 25 Hz (6000 data points). Data were post-processed using the methods of McLelland & Nicholas (2000).

ADVs provide measurements of 3-D mean velocity and turbulence statistics. They can also be used to obtain simultaneous measurements of suspended sediment concentration since this is related to the intensity of backscatter monitored by the ADV. The probes used here were calibrated by collecting one 250-ml bottle of water from the head of each ADV, using a pump sampling system for each ADV measurement point. Mean suspended sediment concentrations determined for each bottle sample were used to derive a calibration relationship between backscatter intensity and sediment concentration for each probe. Once calibrated in this way the ADV can be used to examine sediment concentration time series and their relationship with turbulent flow structures (cf. Nikora & Goring, 2002).

NUMERICAL SIMULATION

A 2-D finite volume model was used to predict patterns of flow depth and depth-averaged velocity at the field site. The model was implemented using a regular grid, with a resolution of 0.5 m, representing the topography of the field site. The continuity of mass and momentum equations solved by the model can be written as follows:

$$\frac{\partial h}{\partial t}+\frac{\partial q}{\partial x}+\frac{\partial r}{\partial y}=0 \tag{1}$$

$$\frac{\partial q}{\partial t}+\frac{\partial (q^2/h)}{\partial x}+\frac{\partial (qr/h)}{\partial y}+\frac{g}{2}\frac{\partial (h^2)}{\partial x}+gh\frac{\partial z}{\partial x}-\frac{1}{\rho}\frac{\partial (h\tau_{xy})}{\partial y}-\frac{1}{\rho}\frac{\partial (h\tau_{xx})}{\partial x}+\frac{\tau_{bx}}{\rho}=0 \tag{2}$$

$$\frac{\partial r}{\partial t}+\frac{\partial (r^2/h)}{\partial y}+\frac{\partial (qr/h)}{\partial x}+\frac{g}{2}\frac{\partial (h^2)}{\partial y}+gh\frac{\partial z}{\partial y}-\frac{1}{\rho}\frac{\partial (h\tau_{yx})}{\partial x}-\frac{1}{\rho}\frac{\partial (h\tau_{yy})}{\partial y}+\frac{\tau_{by}}{\rho}=0 \tag{3}$$

where h is the flow depth (m), q and r are unit discharge ($m^2\ s^{-1}$) in the x and y directions respectively, t is time (s), z is bed elevation (m), g is acceleration due to gravity, ρ is the fluid density, τ_{xx}, τ_{yy}, τ_{xy} and τ_{yx} are turbulent stresses (calculated using a zero order eddy viscosity model), and τ_{bx} and τ_{yx} are the bed shear stresses (calculated as a quadratic function of velocity). For example, in the x direction:

$$\frac{\tau_{bx}}{\rho}=\frac{g}{(Ch)^2}q\sqrt{q^2+r^2} \tag{4}$$

where C is the Chezy friction coefficient. An optimum uniform value of C within the river channel was determined by comparing model predictions with depth and velocity data collected from 20 cross sections along the study reach.

FLOW HYDRAULICS

ADV data (Figs 1 and 2) and model results (Fig. 3) show broadly consistent changes in flow structures at the channel-cutoff interface as discharge rises. At low discharge (Fig. 1(a)) water enters the cutoff at its upstream end (point B) and returns to the channel where it meets the cutoff bank (point A). At high discharge (Fig. 1(b)) flow into the cutoff is restricted to a 2-m portion of the transect AB. Results shown in Fig. 2 (based on depth-averaged ADV data) illustrate changes in flow direction across the transect in greater detail. At low discharge (Fig. 2(a)) the interface can be divided into three broad regions. Zone I contains water flowing out of the cutoff and from B to A. Zones II and III are characterized by water

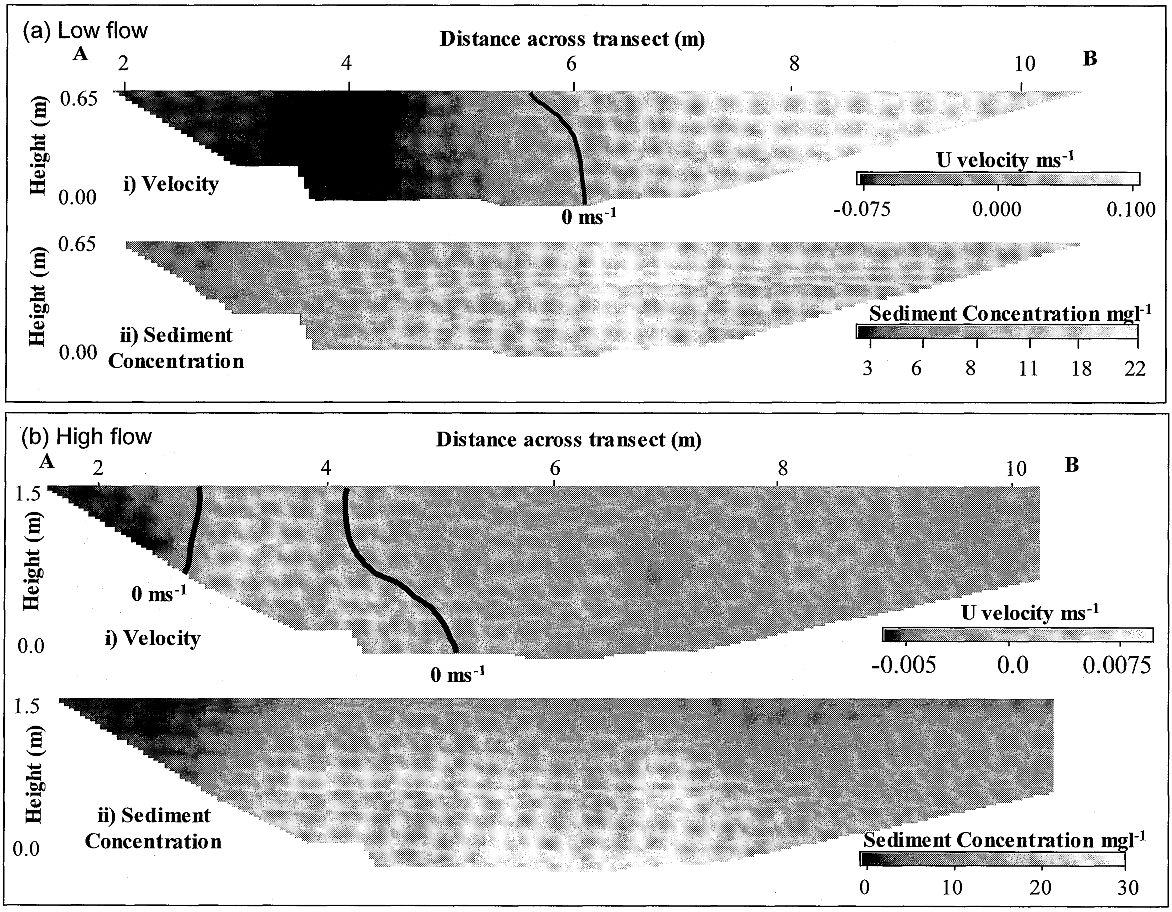

Fig. 1 Mean ADV velocity (perpendicular to measurement transect) and sediment concentration data across the transect A–B for low and high discharge events. Positive U velocity indicates flow into the cutoff.

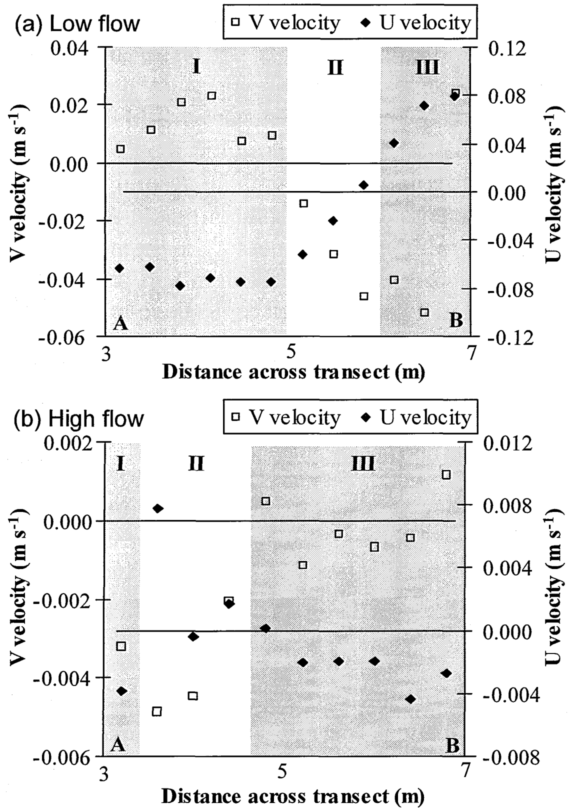

Fig. 2 Depth averaged ADV data obtained along transect AB. Highlighted regions indicate areas characterized by distinct flow structures. Positive U and V velocities indicate flow moving into the cutoff and from B to A, respectively.

moving from A to B, out of the cutoff in zone II and into it in zone III. This pattern of circulation is broadly equivalent to that shown in the model results at low discharge (Fig. 3), the main difference being that the circulation cell is more symmetrical in the model while in the field, flow out of the cutoff occupies a larger part of the channel-cutoff interface. At high discharge (Fig. 2(b)) the interface can again be split into three zones. Zone I represents a small recirculation cell near the bank at A. The fact that this feature is not predicted by the model may be due to the resolution of the model grid. Zone II contains water that is predominately entering the cutoff and flowing from A to B. In zone III, water is leaving the cutoff and moving weakly from A to B. It is also noticeable that velocities are generally an order of magnitude lower in the field at the higher discharge. Both the overall reduction in flow velocity and the circulation patterns observed in zones II and III are reproduced by the numerical model (Fig. 3).

Model results suggest that the significant reduction in velocity and the reversal in the direction of flow circulation at the channel-cutoff interface occur because the main channel flow moves away from the cutoff as discharge rises. At the low discharge, water is clearly flowing directly into the cutoff. In contrast, at bankfull discharge the high velocity core within the channel is displaced approximately 5 m to the right so that it bypasses the cutoff.

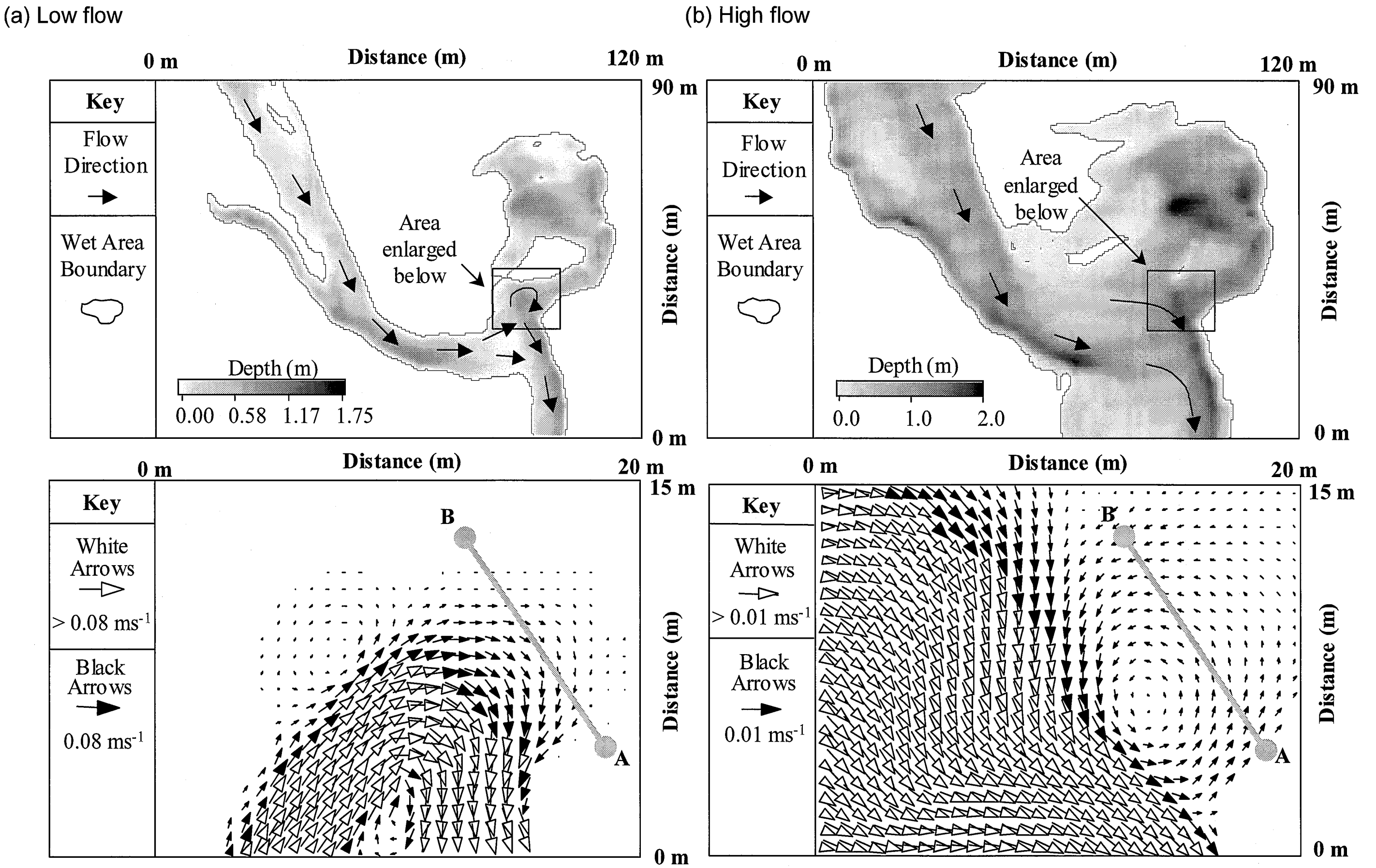

Fig. 3 Modelled flow depth within a 150 m reach of channel (upper diagrams) and velocity vectors at the channel-cutoff interface (lower diagrams).

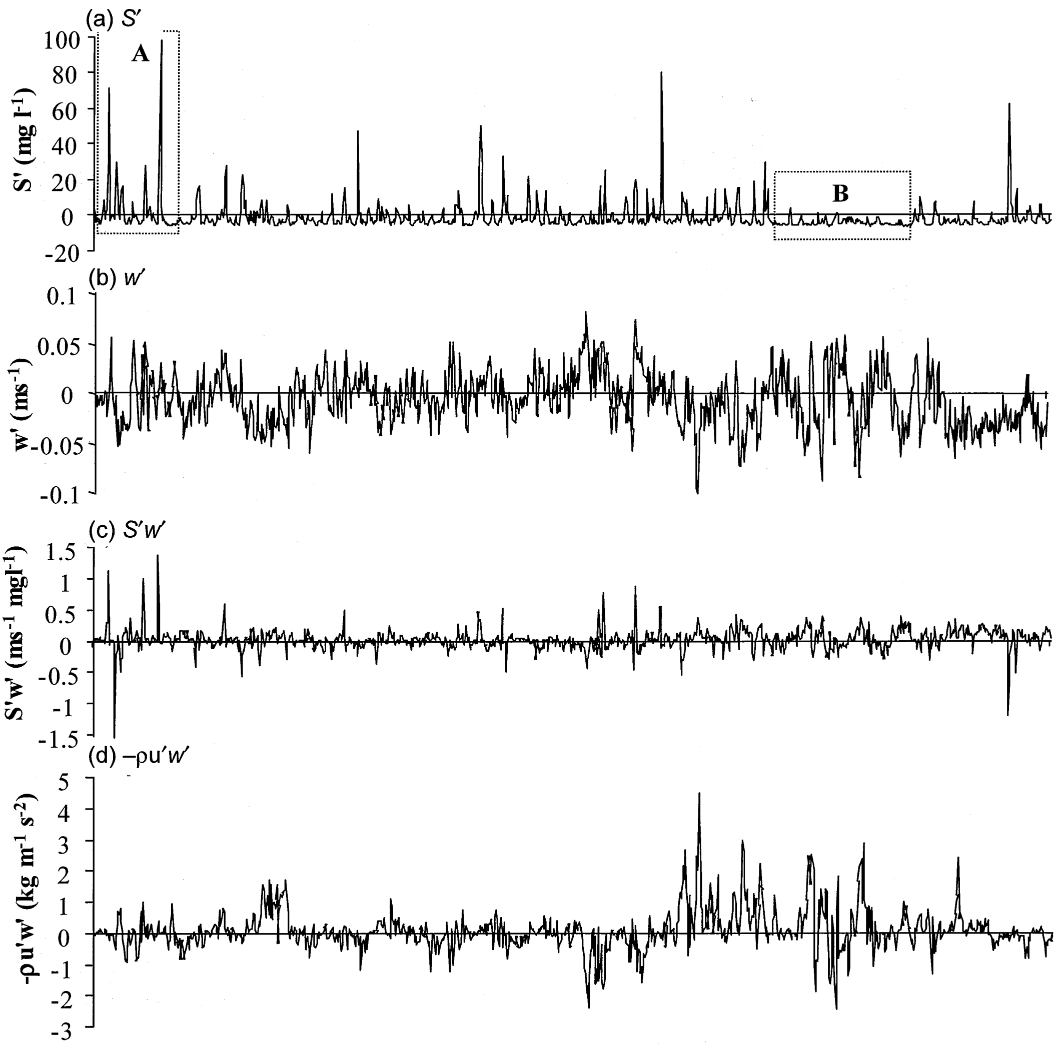

Fig. 4 Forty-second time series from one ADV located 5.5 m along the transect AB and 0.1 m above the bed during the low flow event.

entrance and a recirculation zone forms within this slack water area. The presence of this recirculation zone agrees well with other field studies (Nicholas & McLelland, 1999; Hankin *et al.*, 2001) and laboratory experiments (Kimura & Hosoda, 1997) that have identified such flow structures as common where channels are attached laterally to near-stationary water bodies.

SUSPENDED SEDIMENT TRANSPORT

Mean suspended sediment concentration estimates calculated using the ADV (Fig. 1) show clear systematic trends with peak concentrations occurring near the bed and in the centre of the channel-cutoff interface. Integration of the sediment flux across the interface at low discharge (using sediment concentration and velocity data) indicates that there is net sediment transport into the cutoff which is, presumably, balanced by deposition within this feature. The average deposition rate over the cutoff estimated in this way is in the order of 108 g m^2 day^{-1}, which is consistent with evidence of medium-term sedimentation rates on the River Culm derived from radionuclide studies (e.g. Nicholas & Walling, 1997).

Preliminary analysis of velocity and sediment concentration time series obtained using the ADV illustrate the potential for using this technique to investigate turbulent sediment transport within cutoff environments. Figure 4 shows 40 seconds of a single ADV time series obtained at low discharge at the 5.5 m point of the measurement transect. Upward turbulent sediment transport ($S'w' > 0$) can be linked with two phenomena. First, highly intermittent peaks in sediment concentration (S) that are associated with positive w' events, but which do not appear to be linked to significant Reynolds shear stress ($-\rho u'w'$) production (region A marked on Fig. 4(a) provides a good example of this). Second, periods of lower than average sediment concentration ($S' < 0$) where contributions to upward turbulent sediment transport are due to downward movement ($w' < 0$) of clean water (region B on Fig. 4(a)). These periods are sometimes associated with Reynolds shear stress production during sweep-type events.

SUMMARY

Results have been presented from an investigation of flow and suspended sediment transport at the interface between the main channel and a cutoff on the River Culm, Devon, UK. Comparisons between field data and model results are consistent and suggest that flow structures in such locations are likely to be strongly dependent on stage. At high flow the cutoff is occupied by a recirculation zone similar to that observed in previous field-based and experimental studies. However, differences in flow direction within the main channel prevent this recirculation pattern from forming at low stage. These hydraulic structures have important implications for the transport of fine sediment into and out of the cutoff by advective and diffusive mechanisms.

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