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Modelling and monitoring flow and suspended sediment transport in lowland river flood plain environments

A. P. NICHOLAS
Department of Geography, University of Exeter, Exeter, Devon EX4 4RJ, UK
a.p.nicholas@exeter.ac.uk

Abstract This paper examines the potential for investigating flow and suspended sediment transport mechanisms on lowland flood plains using a combination of three-dimensional numerical modelling and acoustic Doppler velocimetry. Model results show that, contrary to the common perception that suspended sediment transport is controlled predominantly by turbulent mixing processes, horizontal sediment exchanges between the channel and flood plain are largely a product of advection along topographically determined flow lines. Modelled and monitored profiles of time-averaged flow illustrate that vegetative roughness promotes characteristic velocity and turbulent kinetic energy profiles that contrast markedly with the logarithmic "law of the wall". Instantaneous velocity and sediment concentration data obtained at a high sampling frequency confirm that while horizontal sediment transport is dominated by advection, the vertical sediment concentration profile in the lower half of the flow is controlled strongly by the balance between turbulent ejection and sweep events.

Key words acoustic Doppler velocimeter; flood plain; numerical model; suspended sediment

INTRODUCTION

In many lowland river systems a large proportion of the total suspended sediment load is transported during periods of overbank flow. At such times, deposition of sediment on the flood plain surface results in a substantial conveyance loss. For example, recent field investigations suggest that flood plain sediment storage may represent 30–50% of the total suspended load of several UK rivers (Walling *et al.*, 1998). Deriving precise estimates of either sediment loads or conveyance losses is problematic for a number of reasons. First, because flow conditions and sediment concentrations within overbank flows are highly spatially-variable, hence continuous monitoring of stage and sediment concentration at a single main channel location provides only a first-order estimate of the load. Second, because overbank deposition rates are also characterized by spatial variability which reflects the complex relationships between flood plain topography, flow and sedimentation processes. Third, because although theoretical models have been developed with which to simulate these processes, they have yet to be evaluated fully in natural flood plain environments. The latter situation reflects both the complexity of boundary conditions on natural flood plains, and the difficulty of obtaining high quality flow and sediment transport data with which to calibrate and validate models. This paper examines new approaches in modelling and monitoring of flow and suspended sediment transport on flood plains and evaluates the prospects for using these methods to develop an improved understanding of overbank process mechanics.

NUMERICAL MODELLING

Previous attempts to simulate flow and suspended sediment transport and deposition on natural flood plains have been conducted predominantly using two-dimensional depth-averaged models (e.g. Nicholas and Walling, 1997; Middlekoop & Van der Perk, 1998; Stewart *et al.*, 1998). Such approaches are flexible, robust, and provide distributed information quantifying depths, velocities, sediment concentrations and sedimentation rates. However, these models incorporate simplified treatments of flood plain roughness and turbulence, and are unable to represent the mechanics of sediment deposition fully because, being depth-averaged, they do not resolve the vertical profile of flow or sedimentological conditions.

A higher level of process representation can be achieved using three-dimensional Computational Fluid Dynamics (CFD) models, and these have been used recently to simulate flow and sediment transport for a range of in-channel environments (Nicholas & McLelland, 1999; Fang & Wang, 2000). However, such models are not easily applied to natural flood plains since the majority are not capable of predicting the position of the water surface where inundation patterns are complex. Instead this must be specified as a model boundary condition. One way to overcome this problem is to adopt an approach that involves a combination of two-dimensional (2-D) and three-dimensional (3-D) modelling. For example, distributed predictions of inundation extent and water surface elevation derived from a 2-D model can be used to specify boundary conditions in 3-D CFD simulations. The governing equations for flow and sediment transport that are solved when implementing this strategy are summarized below. Further details of the modelling approaches applied here, and the numerical solution techniques involved, can be found in Beffa & Connell (2001), Nicholas (2002), and Nicholas & Mitchell (2003).

Patterns of overbank inundation and unit discharge in two horizontal directions are simulated using a two-dimensional hydraulic model (*hydro2de*) that solves the depth-averaged shallow water form of the Navier-Stokes equations:

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

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

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

where h is the flow depth, q and r are unit discharge in the x and y directions, respectively, t is time, z is bed elevation, g is the acceleration due to gravity, ρ is the fluid density, τ_{xx}, τ_{yy}, τ_{xy} and τ_{yx} are turbulent stresses, determined using a zero order eddy viscosity model, and τ_{bx} and τ_{by} are bed shear stresses, which are calculated as a quadratic function of the velocity and Manning roughness coefficient.

Three-dimensional velocities are modelled by solving the equation for mass continuity and Reynolds-averaged Navier-Stokes equations, which can be written in cartesian form as:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{4}$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j}\left(u_i u_j\right) = \frac{\mu}{\rho}\frac{\partial}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial u_i}\right) - \frac{\delta_{ij}}{\rho}\frac{\partial p}{\partial x_i} - \frac{F_i}{\rho} + \frac{\partial}{\partial x_j}\left(-\overline{u_i' u_j'}\right) \tag{5}$$

where p is pressure, μ and ρ are the viscosity and density of water, u_i is the velocity in the x_i direction, δ_{ij} is the Kronecker delta, F_i denotes external forces (including drag on flood plain vegetation), and the final term on the right-hand side represents the Reynolds stresses resulting from the decomposition of instantaneous velocities into their mean and fluctuating components. The latter are represented using a two-equation $k - \varepsilon$ model.

Three-dimensional patterns of suspended sediment concentration are modelled using the following mass balance relation for particle setting and sediment transport by advection and diffusion (also in cartesian form):

$$\frac{\partial C}{\partial t} + \frac{\partial}{\partial x_i}\left(\left(u_i - w_0\right)C\right) - \frac{\partial}{\partial x_i}\left(\nu_S \frac{\partial C}{\partial x_i}\right) = |u|CE \tag{6}$$

where u_i is the fluid velocity in the x_i direction, $|u|$ is the magnitude of the resultant velocity, w_0 is the particle settling velocity (which is zero in the horizontal), C is the suspended sediment concentration, ν_S is the sediment diffusivity and E is the trapping efficiency of flood plain vegetation, which is a function of local hydraulics and vegetation type (and is zero above the vegetation layer).

These models were applied to simulate flow and suspended sediment transport processes within an 800-m reach of the flood plain of the River Culm, Devon, UK. This was carried out using a high resolution digital elevation model (DEM) with a uniform horizontal cell size of 1.5 m generated by conducting detailed topographic surveys of the flood plain and channel bed. Conditions at the upstream boundaries of the model domain were specified by continuous monitoring of water levels and suspended sediment concentrations.

The numerical models described above incorporate a number of parameters, the values of which must be calibrated. This was accomplished by conducting model runs for a wide range of parameter combinations and comparing predicted variables with field data monitored within the study site during a series of eight flood events over a three-year period. Predicted flow characteristics are most sensitive to the parameterization of surface roughness (in both the 2-D and 3-D models), while predicted sediment concentrations are influenced most strongly by the vegetative trapping efficiency parameter in equation (6). Calibration was carried out using field measurements of flow depth, inundation extent mapped using a DGPS, three-dimensional velocity monitored using an array of acoustic Doppler velocimeters (ADV, see below), and suspended sediment concentration measured using the ADV and optical backscatter sensors (OBS). Coefficients of determination calculated for comparisons between predicted and monitored variables were generally in the range 0.9–0.95 (for flow depth), 0.55–0.65 (for velocity), 0.3–0.45 (for turbulent kinetic energy) and 0.6–0.75

(for suspended sediment concentration). Models were observed to reproduce the spatial trends in the field data, both across the flood plain and vertically throughout the water column (discussed below). However, the field data contain substantial local spatial variability that is not replicated by the models, as reflected in the low values of the coefficient of determination for turbulent kinetic energy and, to a lesser extent, velocity. This apparently random variability in the field data is in fact a product of small-scale flow structures generated by vegetation and flood plain micro-topography that is too small to be represented by the 1.5 m resolution model DEM. This highlights the fact that while the models used here are near physically-based, the representation of flow and sedimentation processes that they provide is not scale-independent.

Figure 1 shows the simulated pattern of suspended sediment dispersion within a part of the study reach for a single grain size class at a discharge corresponding approximately to the peak of the mean annual flood. Sediment concentration declines with distance from the main channel at rates that vary with local flow characteristics. The latter control both the relative importance of advective and diffusive sediment transport mechanisms and rates of sediment deposition. Previous theoretical and flume based research has emphasized the role of sediment diffusion driven by turbulent vortices at the main channel–flood plain interface (James, 1985; Pizzuto, 1987). However, simulation results suggest that suspended sediment transport on natural flood plains is dominated by advection (as illustrated by the sediment plumes along major flow paths). Diffusive mechanisms are less significant except at ponded sites that are separated from the main channel by a well-developed shear layer.

Simulation results also provide insight into the interactions between flood plain surface roughness, vertical profiles of mean and turbulent flow properties and sedimentation processes. For example, both modelled and monitored velocity profiles (Fig. 2) are often characterized by strong shear above the vegetation layer (which typically occupies the lower 10–30% of the water column for the shallow flows considered here) and turbulence intensities which exhibit a peak at approximately $y/h = 0.3 - 0.4$. These trends contrast with those observed for two-dimensional open-channel flows where velocities generally fit the logarithmic "law of the wall" and peak turbulence intensities occur near the bed (Nezu & Nakagawa, 1993). Reduced velocities and turbulence intensities within the vegetation layer are responsible for promoting sediment deposition even where depth–mean flow characteristics exceed theoretical threshold conditions for sedimentation (e.g. Van Rijn, 1993). This observation is consistent with the fact that previous applications of depth-averaged suspended sediment transport models have identified a need to use relatively high values of the critical shear for deposition in order to optimize model performance (Middlekoop & Van der Perk, 1998).

MONITORING FLOW AND SUSPENDED SEDIMENT TRANSPORT

Numerical models provide effective tools for studying the interaction between flow and sediment transport processes and simulating rates and patterns of sedimentation at spatial scales that are difficult to consider using empirical approaches alone. However, models suffer from a number of limitations, most importantly that they provide a

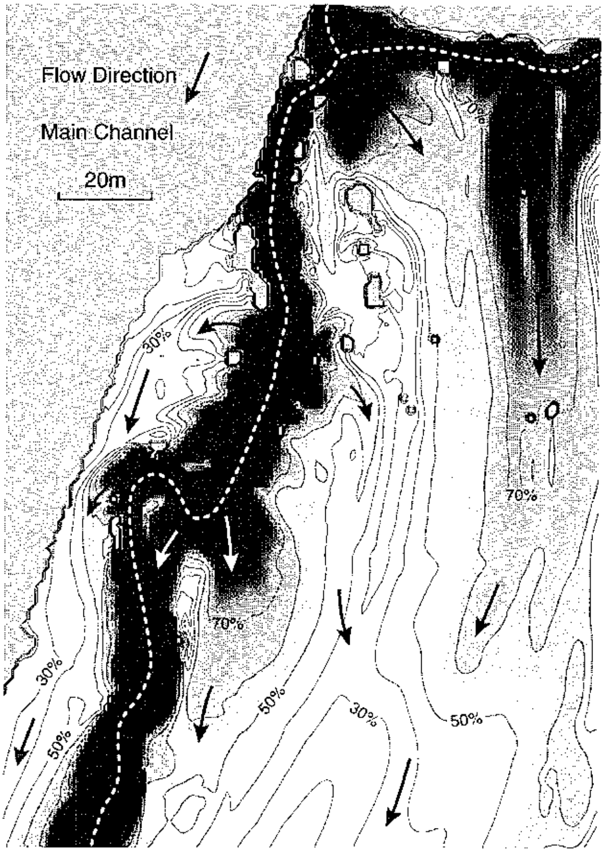

Fig. 1 Simulated pattern of suspended sediment concentration (as a % of that in the main channel) for the 63 μm size fraction at a discharge of 60 $m^3 s^{-1}$.

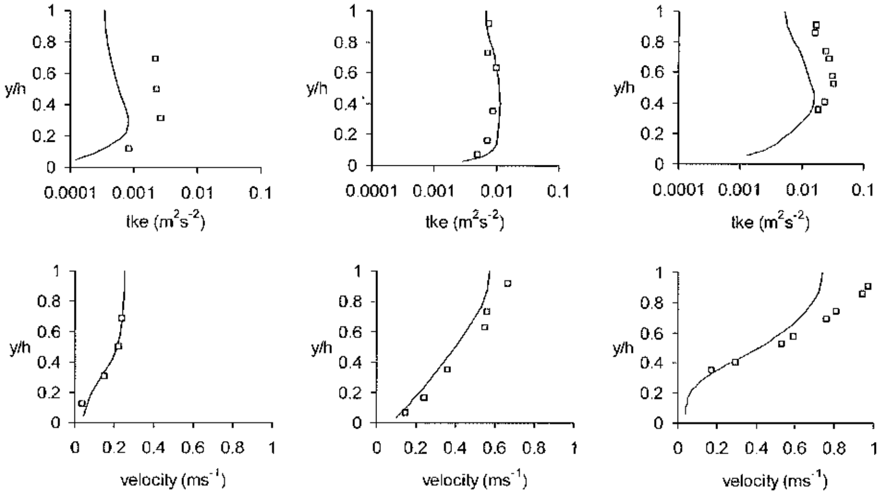

Fig. 2 Modelled (lines) and monitored (symbols) velocity and turbulent kinetic energy profiles at three representative flood plain locations.

simplified representation of physical processes and, even in the case of near physically-based 3-D models, incorporate parameterization schemes that are difficult to calibrate conclusively. Consequently, distributed field measurements of three-dimensional flow velocity and suspended sediment concentration remain invaluable, both to assist model calibration and validation, and to elucidate mechanisms of sediment transport and deposition in the natural environment.

Distributed measurements of flow conditions and suspended sediment concentration were obtained from a variety of locations across the study site using an array of acoustic Doppler velocimeters (ADVs). The ADVs use the Doppler shift principle to measure three-dimensional velocities at frequencies of up to 100 Hz in a small sampling volume located 0.05 m from the probe head. The ADV emits an acoustic pulse at a frequency of 10 MHz from an element at the centre of the probe head. Acoustic energy is reflected by particles suspended in the fluid and the echo from the sampling volume is monitored by three receivers arranged around the transmit element. The phase of the received signal is Doppler-shifted owing to the velocity difference between signal scatters and the probe, hence measurement of the phase shift enables the calculation of three-dimensional velocities (cf. Lohrmann *et al.*, 1994). Although the ADV was designed principally to measure water velocity, the intensity of the acoustic backscatter monitored by the receivers is proportional to the concentration of scatters in the sampling volume, hence there is some prospect for using the ADV to monitor suspended sediment concentrations (Nikora & Goring, 2002). The great advantage of this approach over conventional monitoring techniques, such as OBS, is that since flow and sediment data are obtained from the same sampling volume at the same instant in time the potential exists to investigate turbulent mechanisms of suspended sediment transport.

Calibration of the ADVs was accomplished in the laboratory using suspended sediment samples of known concentration with similar grain size characteristics to the sediment load of the River Culm (Fig. 3). The acoustic backscatter intensity can be derived from the instantaneous measurements of signal amplitude recorded by the ADV for each receiver using the relationship presented by Lohrmann *et al.* (1994). Each ADV must be calibrated individually and separate relationships are required for different instrument configurations (because the variance of ADV velocity measurements is dependent upon the user-specified velocity range).

Figure 4 shows a typical vertical profile of flow characteristics and suspended sediment concentration monitored in shallow sheet flow on the backslope of a levee approximately 15 m from the main channel. Mean velocity and turbulent kinetic energy profiles above the vegetation layer follow the trends identified in the results of the 3-D hydraulic model (i.e. marked shear above the vegetation layer and a peak in turbulence intensity displaced well above the flood plain surface). Suspended sediment concentrations also follow the expected trend, declining towards the water surface. However, sediment is predominantly confined to the lower half of the profile below the peak in the turbulent kinetic energy. Further insight into the relationship between turbulence characteristics and suspended sediment transport can be gained by examining the instantaneous velocity and sediment concentration time series monitored using the ADV. Previous studies have used ADV data to conduct such analysis (e.g. Nikora & Goring, 2002). However, since the calibration relationships shown in

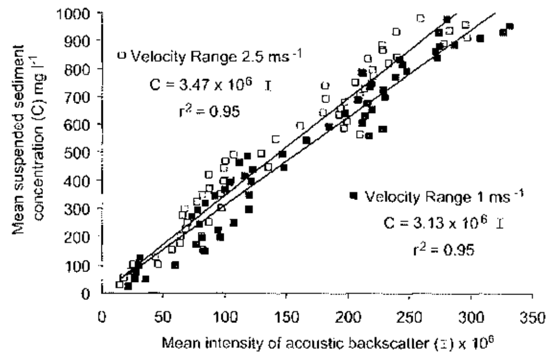

Fig. 3 Calibration relationships (for one ADV at two instrument velocity ranges) between time-averaged acoustic backscatter intensity and suspended sediment concentration.

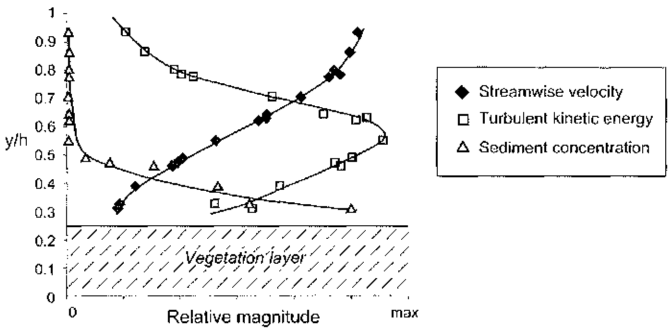

Fig. 4 Typical profile of mean flow velocity, turbulent kinetic energy and suspended sediment concentration monitored using the ADV (lines show best fit profile shapes).

Fig. 3 are for time-averaged variables there is some uncertainty in the calculated instantaneous sediment concentrations.

Figure 5 shows a three-second portion of an ADV time series obtained halfway between the top of the vegetation layer and the mid-point of the profile shown in Fig. 4. Contributions to the $-u'v'$ Reynolds shear stress are predominantly positive (Fig. 5(a)) and are associated with sweep events (fluid that moves downward relative to the mean flow with a faster than average streamwise velocity—i.e. $u' > 0$, $v' < 0$) and ejection events (fluid that moves upward relative to the mean flow with a slower than average streamwise velocity—i.e. $u' < 0$, $v' > 0$). Ejection events are associated with peaks in the instantaneous sediment concentration time series (Fig. 5(b)) that are the result of sediment being brought up from lower in the profile. Sediment concentration data are strongly skewed and are lower than the time-averaged concentration over the majority of the time series. Consequently, downward transport of water characterized by lower than average concentrations during sweep events also contributes to the net upward turbulent sediment flux. These results are consistent with observations made in a variety of estuarine and fluvial environments that have demonstrated the link between fluid ejection events and suspended sediment transport (e.g. Thorne *et al.*, 1996; Nikora & Goring, 2002). Application of quadrant analysis to ADV time series

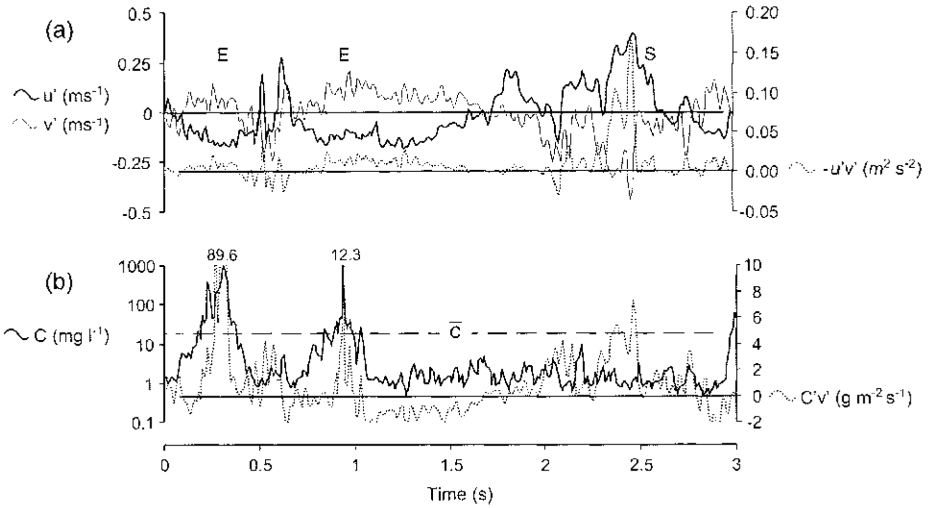

Fig. 5 A three-second portion of an ADV time series obtained at a sampling frequency of 100 Hz. (a) Horizontal (*u'*) and vertical (*v'*) velocity fluctuations and Reynolds shear stress (–*u'v'*). Sweep and ejection events are labelled S and E. (b) Instantaneous sediment concentration (*C*) and vertical turbulent sediment flux (*C'v'*).

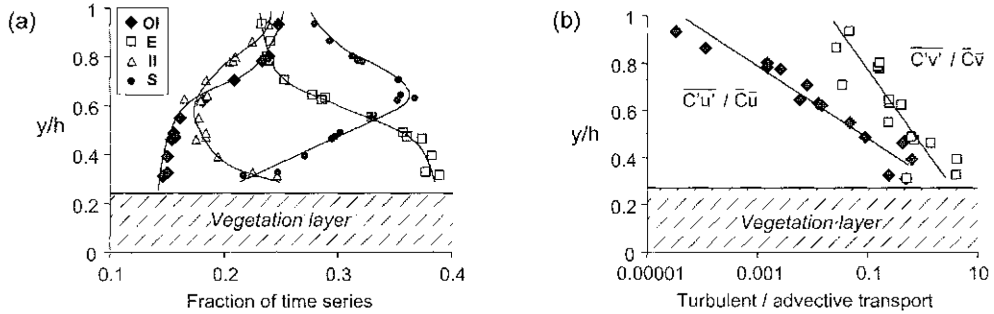

Fig. 6 (a) Proportion of the ADV time series occupied by fluid events in each of four quadrants (OI: Outward Interactions, E: Ejections, II: Inward Interactions, and S: Sweeps). (b) Ratio of turbulent to advective suspended sediment transport in the horizontal (*u*) and vertical (*v*) directions.

monitored throughout the profile shown in Fig. 4 illustrates clear vertical trends in the relative importance of momentum transport events (Fig. 6(a)). Positive contributions to the –*u'v'* Reynolds stress (i.e. sweep and ejection events) dominate throughout the profile. However, a clear transition is evident between the region immediately above the vegetation layer (where ejection events occur 35–40% of the time) and the mid-point of the profile (where ejections become less common and sweep events dominate the time series). This transition corresponds to the peak in the turbulent kinetic energy profile and the point at which sediment concentration approaches zero. The sharp break in the sediment concentration profile undoubtedly reflects the reduced frequency of ejection events and the increasing proportion of the time series occupied by water moving downward relative to the mean flow.

Figure 6(b) shows changes in the ratio of the turbulent to advective suspended sediment fluxes throughout the profile. In both the horizontal (*u*) and vertical (*v*) directions turbulent transport mechanisms are most important immediately above the vegetation layer and contribute a declining proportion of the total sediment flux higher in the profile. Indeed, turbulent fluxes make a negligible contribution to horizontal transport within the top 50% of the profile. Vertical turbulent fluxes contribute >10% of the total load over the majority of the profile and are equal to or greater than advective fluxes in the lower half of the flow. While the relative importance of advective and turbulent transport varies across the flood plain with mean flow velocities, these data are representative of ADV measurements obtained in a variety of locations and are consistent with the results of the 3-D sediment transport model. Both model output and ADV data illustrate that while horizontal sediment transport is dominated by advection, vertical transport, and hence sedimentation processes, are strongly influenced by turbulent mechanisms that exhibit systematic variations in intensity throughout the profile. These results suggest that the ADV may have considerable potential as an instrument for investigating suspended sediment transport and deposition processes in flood plain environments. However, further field and laboratory testing is required to assess the dependence of calibration relationships on sediment grain size characteristics, and to evaluate the errors in calculated sediment concentrations that is a product of noise in the ADV data.

CONCLUSIONS

Preliminary results suggest that three-dimensional models provide a realistic, near physically-based framework for investigating flow and sediment transport processes in natural flood plain environments. Consequently, they offer a partial solution to the problems inherent in monitoring these processes during floods. Despite the prospects for simulating natural flood plains, many modelling issues require further attention. These include calibration of spatially-variable boundary roughness, representation of dynamic aspects of floodwave propagation, choice of turbulence closure and parameterization of sediment–vegetation interactions. The final two are of particular concern in the context of modelling sedimentation processes, and will only be resolved with the aid of an improved quantitative understanding of the mechanics of sediment transport and deposition in field environments in the presence of vegetation. The ADV has significant advantages over other instruments designed to monitor these processes, principally in that it can be used to measure instantaneous three-dimensional velocity and sediment concentration in the same sampling volume at high frequencies.

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