The distribution of fine sediment deposits in compound channel systems

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Abstract

During periods of high flow in compound channel systems, suspended sediment is transferred to flood plain sections by convection and by turbulent interaction between flow regions. This transfer has a significant effect on the distribution of suspended and deposited material. The complex, three-dimensional problem of describing the vertical, transverse and longitudinal distribution of suspended material in a compound channel system is solved by decomposition. Two numerical models are presented which can be used conjunctively to describe the suspended distributions as well as the distribution of deposits on the main channel and flood plain surfaces. One model describes the vertical and transverse distributions over the flood plain and the other describes the vertical and longitudinal distributions along the main channel. These models consider steady, longitudinally uniform flow and do not account for bed load movement or the role of the bed as a source of suspended material. Application of the models is illustrated by a hypothetical example. The models have been used to explain distributions of heavy minerals in ancient fluvial systems and could also be useful for pollution studies.

Introduction

During periods of high flow in a channel with a compound section incorporating a flood plain, a strong interaction takes place between flows over the flood plain and within the main channel. This interaction takes the form of a series of turbulent eddies along the interface between the deep, fast flow within the main channel and the relatively shallow, slow flow over the plain (Sellin, 1964). The interaction transfers longitudinal momentum between the two flow regions, decreasing flow velocity and boundary shear within the channel and increasing them over the flood plain (Wright and Carstens, 1970; Ghosh and Jena, 1971; Myers and Elsawy, 1975; Myers, 1978; Rajaratnam and Ahmadi, 1979; 1981). In addition, there is an exchange of suspended sediment across the interface (James, 1985). Because the concentration is higher within the channel region than over the plain by virtue of the greater flow depth and velocity, the net result of the interaction is a transfer of fine sediment from channel to plain. The transfer of sediment is enhanced if a component of flow normal to the channel direction exists, such as at a bend or where the channel is not parallel to the steepest gradient of the plain. Once transferred to the plain region sediment tends to settle out because of the reduced transport capacity of the flow. The distribution of sediment deposited on the flood plain depends on characteristics of the channel, the plain, the sediment particles and the flow (James, 1984b). The transfer of suspended sediment out of the main channel also affects the distribution of fine sediment deposits in a longitudinal direction.

The numerical models presented in this paper have been developed to enable prediction of the extent and relative distribution of fine sediment deposits, both transversely and longitudinally, through a compound channel system under overbank flow conditions. At present only steady, longitudinally uniform flow is considered and the effects of bed load movement and the bed material as a source of suspended material are not accounted for.

The three-dimensional distribution of suspended sediment concentration in a compound channel system is described by two two-dimensional models. One model describes the transverse and vertical distributions across the plain and the other the longitudinal and vertical distributions within the channel. This paper describes the model decomposition and details of the longitudinal model; details of the transverse model are described elsewhere (James, 1985).

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Theory

The transfer of suspended material through a fluid under the influence of turbulence is analogous to a diffusion process, with material moving from regions of high concentration to regions of low concentration at a rate which is proportional to the concentration gradient. In addition, suspended material will be transferred by convection associated with flow velocity components or the influence of gravity, i.e. settling. The distribution of suspended sediment concentration can therefore be determined by considering a mass balance of sediment under the influence of diffusive and convection transfer components. The general three-dimensional equation describing concentration distribution is:

$$\frac{\partial C}{\partial t} + \sum_{i=1}^{3} u_i \frac{\partial C}{\partial x_i} = \sum_{i=1}^{3} \frac{\partial}{\partial x_i}(\varepsilon_i \frac{\partial C}{\partial x_i}) \qquad (1)$$

in which C is concentration, t is time, x_i are the coordinate directions, u_i are the convection velocity components in the coordinate directions and ε_i are the diffusivities in the coordinate directions. In the system under consideration the longitudinal, vertical and transverse directions are represented by x, y and z respectively (Fig. 1). For sediment particles the convective velocity in the vertical direction is the particle fall velocity, w, assumed to be positive downwards. The longitudinal convective velocity, v, is the velocity of particles in the flow direction. If the channel is not parallel to the direction of the steepest gradient of the plain there will be a component of flow velocity normal to the channel above the plain level, giving rise to a transverse convective velocity, u. The transport of particles by longitudinal diffusion is insignificant compared with longitudinal convection (Sarikaya, 1977) and can be ignored. For steady conditions the concentration will not vary with time and $\frac{\partial C}{\partial t} = 0$.

Under steady flow conditions Equation (1) can therefore be written for the system being considered as:

$$0 = -v\frac{\partial C}{\partial x} + w\frac{\partial C}{\partial y} - u\frac{\partial C}{\partial z} + \frac{\partial}{\partial y}(\varepsilon_y \frac{\partial C}{\partial y}) + \frac{\partial}{\partial z}(\varepsilon_z \frac{\partial C}{\partial z}) \qquad (2)$$

The variations of deposits transverse to a channel and along its length are both determined by the transfer of suspended material from the channel to the plain and both depend on the vertical distribution of suspended material. The distribution of deposits therefore depends on the distribution of suspended material in three dimensions during transport. The scales of the variations of deposits in the transverse and longitudinal dimensions are significantly different, however, with variations being much more gradual longitudinally than transversely. Because of the level of detail required to describe the transverse distribution, a three-dimensional model capable of describing the relatively gradual longitudinal variations of deposits as well would be extremely large and the computational effort required for its solution would be prohibitive. The three-dimensional problem, represented by Equation (2), has therefore been decomposed and solved using two two-dimensional models.

The first model describes the vertical and transverse distribution of suspended sediment concentration above the plain and the deposition of particles on the plain surface. The second model describes the vertical and longitudinal distribution of suspended sediment concentration within the channel subject to deposition on the bed and transfer to the plain. The rates of transfer to the plain depend on transverse concentration gradients which are determined by the first model. The second model uses this output from the first to determine longitudinal concentration variations. The transverse model is applied at intervals determined by accuracy requirements; concentration gradients at intermediate sections are assumed to be proportional to local concentration. Conjunctive use of the two models describes transverse and longitudinal variations of deposits through the channel system. The model decomposition is illustrated in Fig. 1.

The transverse distribution model

If it is assumed that sediment concentration will not vary with longitudinal distance over short distances then $\frac{\partial C}{\partial x} = 0$ can be substituted in Equation (2) to yield

$$0 = w\frac{\partial C}{\partial y} - u\frac{\partial C}{\partial z} + \frac{\partial}{\partial y}(\varepsilon_y \frac{\partial C}{\partial y}) + \frac{\partial}{\partial z}(\varepsilon_z \frac{\partial C}{\partial z}) \qquad (3)$$

The solution of this two-dimensional elliptic partial differential equation describes the distribution of suspended sediment concentration over a closed domain of integration. This domain can be defined as the area above the flood plain bounded by the plain surface, the water surface, a vertical interface between plain and channel flow on one or both sides and a solid vertical boundary on one side if only one interface boundary is used. The relative distribution of plain deposits can be determined from the concentration distribution.

Equation (3) is expressed in finite difference form and solved numerically by the method of Successive Over-Relaxation, using an accelerator which is optimized at each step (Apelt and Isaacs, 1972). The numerical solution is described in detail by James (1985).

The solution of Equation (3) requires values of turbulent diffusivities and particle velocities in both the transverse and vertical directions. These parameters are estimated using theoretical and empirical relationships developed for certain channel geometries by other researchers.

Diffusivities for sediment are related to diffusivities for momentum. The diffusivity for momentum in the vertical direction is estimated using the parabolic distribution derived from

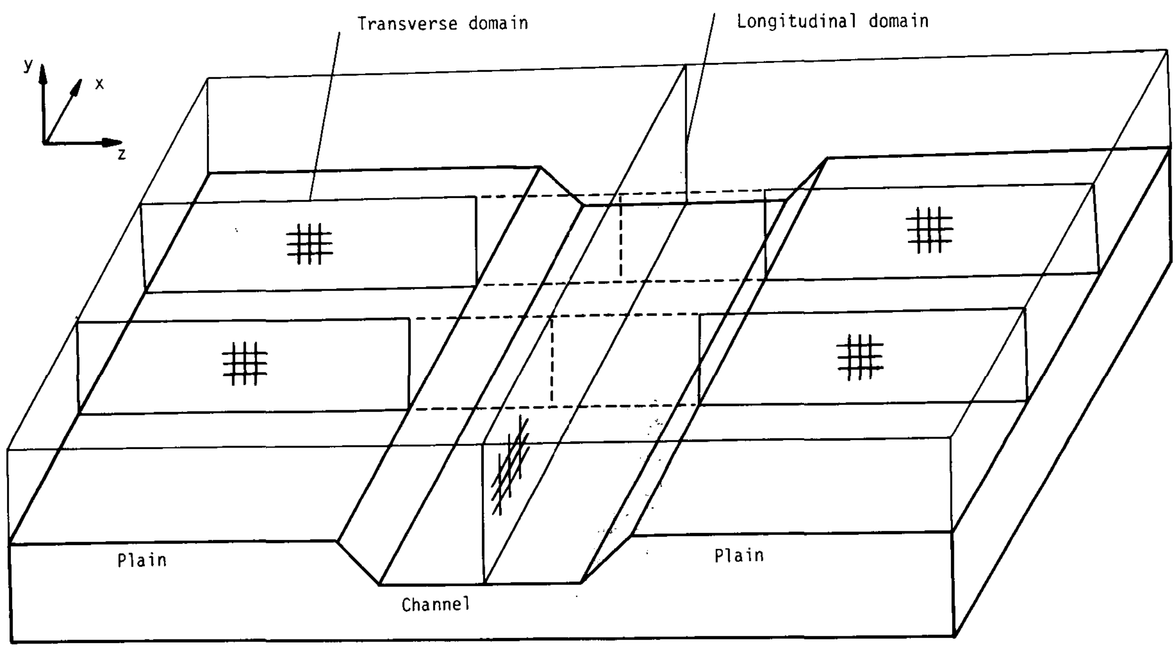


Figure 1
The deposition environment showing model decomposition and the domains of integration.

Prandtl's mixing length theory assuming a linear distribution of shear stress (Graf, 1971). Transverse diffusivity within the interaction zone is estimated using an empirical relationship proposed by Rajaratnam and Ahmadi (1981), who also proposed a distribution of boundary shear used in the estimate of vertical diffusivity. Beyond the interaction zone transverse diffusivity is calculated by a relationship developed from results presented by Lau and Krishnappan (1977). Diffusivities for fine sediment and momentum are assumed to be equivalent in the vertical direction and in the transverse direction beyond the interaction zone. Within the interaction zone, where strong vorticity occurs, the relationship between sediment and momentum diffusivities determined by Singamsetti (1966) is applied.

The vertical particle velocity is assumed to be the terminal fall velocity in quiescent water. The transverse particle velocity is calculated as the component of sediment velocity over the plain normal to the channel direction. Flow velocity components are assumed to be proportional to the square roots of the bed gradients in the appropriate directions and sediment velocities are related to flow velocities according to results presented by Sumer (1974). Convection associated with secondary circulation is assumed to be accounted for in transverse diffusivity. Flow velocities in the channel and over the flood plain are calculated using Manning's equation with wetted perimeters defined by a procedure based on experimental results obtained by Wormleaton *et al.* (1982).

Boundary conditions must be specified for all surfaces defining the integration domain, in terms of either derivatives or concentration values. Channel interface boundaries are defined in terms of concentration values. These are either input or calculated relative to a specified reference concentration according to a theoretical solution of a one-dimensional diffusion – settling equation first proposed by Rouse (1937). No sediment can be transferred across the water surface or the solid vertical boundary and at the plain bed the rate of transfer is defined by the probability that a particle reaching the bed will deposit. This probability can be estimated by using formulations applied in sediment transport models, such as those of Engelund and Fredsoe (1976) or Einstein (1950).

The calculations of the transfer components and boundary conditions are described in detail by James (1984a and 1985).

The transverse distribution model has been verified experimentally by comparing predicted and measured distributions of sediment deposits on different flood plain surfaces in a laboratory channel. The experimental procedure and results are described by James (1984a and 1985).

The longitudinal distribution model

The longitudinal distribution model describes the variation of sediment concentration within the main channel subject to deposition on the bed and transfer to the plain. It is assumed that there is no transverse variation within the channel itself, i.e. sediment is uniformly distributed across the width of the channel.

Equation (2) can be used to describe the distribution of sediment in the vertical and longitudinal directions along a channel reach. This equation can be rearranged slightly as

$$0 = -v\frac{\partial C}{\partial x} + w\frac{\partial C}{\partial y} + \frac{\partial}{\partial y}\left(\varepsilon_y \frac{\partial C}{\partial y}\right) - u\frac{\partial C}{\partial z} + \frac{\partial}{\partial z}\left(\varepsilon_z \frac{\partial C}{\partial z}\right) \qquad (3)$$

The first three terms on the right hand side of this equation are the same as used by Sarikaya (1977) to describe the longitudinal distribution of sediment in a channel with a simple cross section. The last two terms account for the transverse movement of sediment across the interface between deep and shallow regions of a compound section. These two terms can be evaluated by applying the transverse distribution model and may therefore be treated as constants in the formulation of the longitudinal model. Equation (3) is then parabolic in form and can be expressed in terms of finite differences and solved using an explicit method.

Initial conditions are specified as concentration values along a vertical section at the beginning of the reach. In addition to the predetermined components of transfer to the plain, boundary conditions need to be specified at the water surface and the channel bed. These boundary conditions are of the derivative type and require that there can be no transport of suspended material across the water surface and that the rate of transfer to the bed is defined by the probability that a particle reaching the bed will be deposited. These conditions are satisfied by applying appropriate finite difference formulations at all boundary points.

Values for vertical diffusivity, transverse diffusivity through the interaction zone, particle velocities and deposition probability are determined using the same relationships as for the transverse model.

Numerical solution of the longitudinal model

The longitudinal distribution equation (Equation (3) is solved numerically using a finite difference approach. The domain of integration is defined by the water surface, the channel bed and vertical planes at the beginning and end of the reach. This domain is divided into N equal vertical increments and M equal horizontal increments as shown in Figure 2. Finite difference grid

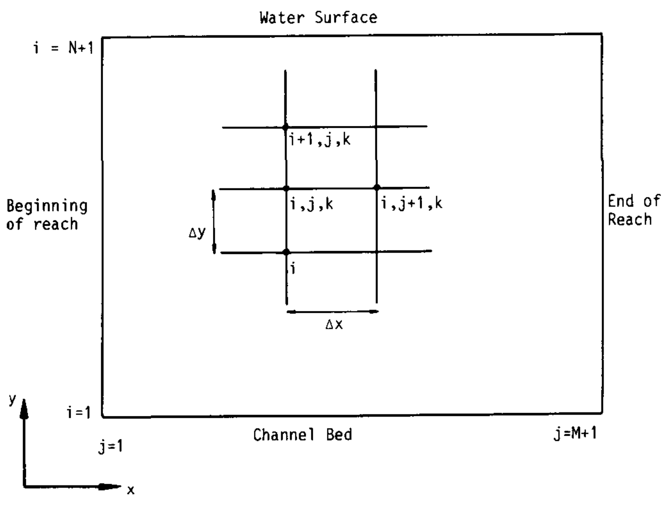


Figure 2
The integration domain and finite difference grid for the longitudinal model.

intersections are numbered vertically from i = 1 on the channel bed to i = N + 1 at the water surface and longitudinally from j = 1 at the beginning of the reach to j = M + 1 at the end of the reach.

A finite difference grid must also be specified in the transverse plane so that the transverse transport components can be specified. It is assumed that sediment concentrations will not vary across the width of the channel and points on both sides of the channel can therefore be represented by the same grid point, as shown in Figure 3.

The finite difference equations can be formulated by con-

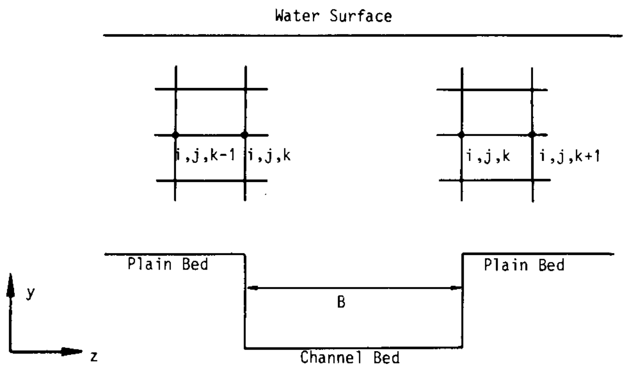


Figure 3
The finite difference grid in the transverse plane as used in the longitudinal model.

sidering the mass balance of suspended material entering and leaving a fluid element while satisfying appropriate boundary conditions. Material transported by diffusion across a boundary is equal to the product of diffusivity and concentration gradient and material transported by convection across a boundary is equal to the product of convective velocity and concentration (James, 1984a, 1985). Interior fluid elements have dimensions of Δy, Δx and $(\Delta z + B)$, where B is the channel width. A typical element is shown in Figures 4 and 5 with the transport components in the x

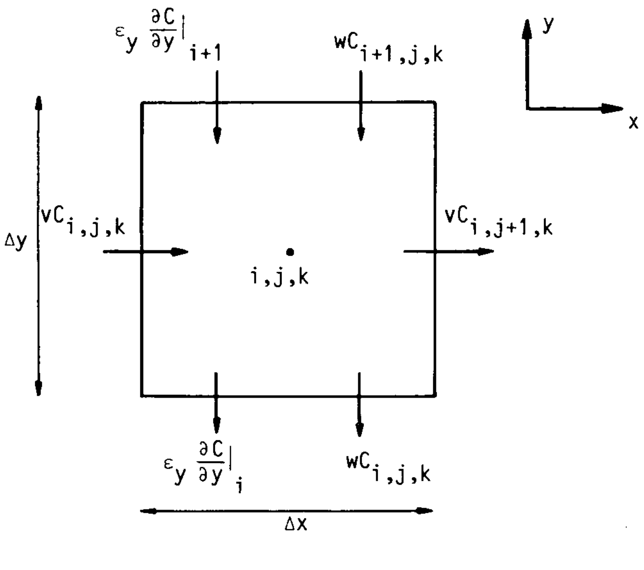


Figure 4
Longitudinal section through a fluid element for interior points showing transport components in the longitudinal (x) and vertical (y) directions.

and y directions and the z direction respectively. For a steady process the net mass entering the element from all directions is zero and therefore:

$$(\varepsilon_y \frac{\partial C}{\partial y}\Big|_{i+1} + wC_{i+1,j,k} - \varepsilon_y \frac{\partial C}{\partial y}\Big|_i - wC_{i,j,k})(\Delta z + B)\Delta x$$
$$+ (vC_{i,j,k} - vC_{i,j+1,k})(\Delta z + B)\Delta y$$
$$+ (\varepsilon_z \frac{\partial C}{\partial z}\Big|_{k+1} + uC_{i,j,k-1} - \varepsilon_z \frac{\partial C}{\partial z}\Big|_k - uC_{i,j,k})\Delta y \Delta x = 0 \qquad (4)$$

The following finite difference approximations are made:

$$\frac{\partial C}{\partial y}\Big|_i \rightarrow \frac{C_{i,j,k} - C_{i-1,j,k}}{\Delta y} \qquad (5)$$

$$\frac{\partial C}{\partial y}\Big|_{i+1} \rightarrow \frac{C_{i+1,j,k} - C_{i,j,k}}{\Delta y} \qquad (6)$$

The terms for concentration gradient in the z direction are evaluated using the transverse distribution model and supplied as input to the longitudinal model. It is therefore not necessary to express these terms in finite difference form.

The diffusivity values between adjacent grid points are calculated as the averages of the point values, i.e.

$$E_y(i) = \frac{\varepsilon_{yi,j,k} + \varepsilon_{yi-1,j,k}}{2} \qquad (7)$$

$$E_y(i+1) = \frac{\varepsilon_{yi+1,j,k} + \varepsilon_{yi,j,k}}{2} \qquad (8)$$

The concentration value $C_{i,j,k-1}$ is expressed in terms of $C_{i,j,k}$ and the input concentration gradient, i.e.

$$C_{i,j,k-1} = C_{i,j,k} - \frac{\partial C}{\partial z}\Big|_k \Delta z \qquad (9)$$

Substituting expression (5) to (9) in Equation (4), dividing by $\Delta x\ \Delta y\ (\Delta z + B)$ and rearranging gives an expression for the unknown $C_{i,j,k}$ in terms of known values, i.e.

$$C_{i,j+1,k} = \frac{\Delta x}{v}\Big\{\Big(\frac{E_y(i+1)}{\Delta y^2} + \frac{w}{\Delta y}\Big) C_{i+1,j,k} + \frac{E_y(i)}{\Delta y^2} C_{i-1,j,k}$$
$$- \Big(\frac{E_y(i+1)}{\Delta y^2} + \frac{E_y(i)}{\Delta y^2} + \frac{w}{\Delta y} - \frac{v}{\Delta x}\Big) C_{i,j,k}$$
$$+ \frac{\varepsilon_z}{(\Delta z + B)} \frac{\partial C}{\partial z}\Big|_{k+1} - \Big(\frac{\varepsilon_z}{(\Delta z + B)} + \frac{u\Delta z}{(\Delta z + B)}\Big) \frac{\partial C}{\partial z}\Big|_k\Big\} \qquad (10)$$

The last two terms in Equation (10) are omitted for all points below the level of the plain surface, where transverse transport obviously does not occur.

The mass balance approach is used to derive finite difference equations which satisfy the relevant boundary conditions for water surface and channel bed points. Fluid elements associated with these points will have dimensions of $\Delta y/2$, Δx and $(\Delta z + B)$.

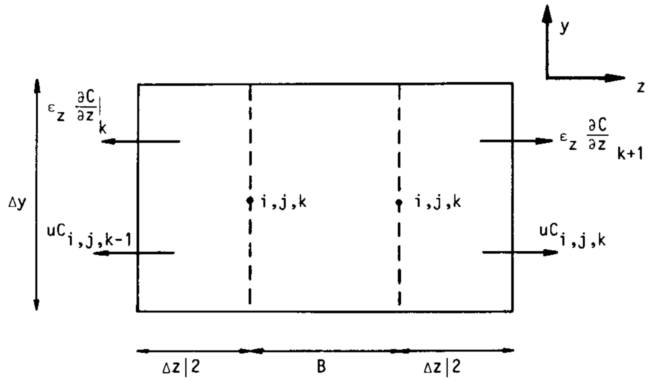


Figure 5
Transverse section through a fluid element for interior points showing transport components in the transverse (z) direction.

At the water surface the diffusion component is zero because vertical diffusivity decreases to zero at the surface and the convective term is also zero because there can be no settling from above the surface. The finite difference equation for concentration at water surface points is:

$$C_{i,j+1,k} = \frac{2\Delta x}{v}\left\{\frac{E_y(i)}{\Delta y^2}C_{i-1,j,k} - \left(\frac{E_y(i)}{\Delta y^2} + \frac{w}{\Delta y} + \frac{v}{2\Delta x}\right)C_{i,j,k} + \frac{\varepsilon_z}{2(\Delta z + B)}\left.\frac{\partial C}{\partial z}\right|_{k+1} - \left(\frac{\varepsilon_z}{2(\Delta z + B)} + \frac{u\Delta z}{2(\Delta z + B)}\right)\left.\frac{\partial C}{\partial z}\right|_{k}\right\} \quad (11)$$

At the channel bed the diffusion component is again zero because diffusivity decreases to zero at the bed. The rate of convective transfer across the bed boundary, i.e. deposition, is determined by the probability of deposition, p. There is no transverse transport at the bed because the channel bed is always below the level of the plain. The finite difference equation for concentration at channel bed points is:

$$C_{i,j+1,k} = \frac{2\Delta x}{v}\left\{\left(\frac{E_y(i+1)}{\Delta y^2} + \frac{w}{\Delta y}\right)C_{i+1,j,k} - \left(\frac{E_y(i+1)}{\Delta y^2} + \frac{pw}{\Delta y} - \frac{v}{2\Delta x}\right)C_{i,j,k}\right\} \quad (12)$$

Equations (10) to (12) enable calculation of the concentration values at all grid points in a vertical section explicitly from known values at the previously calculated section.

Sarikaya (1977) established a criterion for stability and convergence of his explicit solution in terms of Δx and Δy. Sarikaya's diffusion – settling equation differs from Equation (3) only in that it does not include the transverse components which are treated as constants in the formulation of the longitudinal model. The stability and convergence conditions can therefore be expected to be similar for the two equations. Sarikaya's criterion is:

$$\frac{\Delta x}{\Delta y^2} \leq \frac{2Z + T\Delta y}{4Z^2 + 4TZ\Delta y + T^2\Delta y^2} \quad (13)$$

in which $Z = \frac{\varepsilon_{y\max}}{D_c v_{\max}}$ (14)

and $t = \frac{w}{v_{\max}}$

in which D_c is the flow depth in the channel.

This criterion has been found to give a good indication of stability conditions for the longitudinal distribution model.

Application of the models

The models have been applied to a hypothetical channel system to illustrate their use and the effect of transverse transfer on the distribution of deposits.

A single small channel with a trapezoidal cross section has been considered. The channel width varies from 2,4 m at the level of the plain to 1,2 m at its bed, 0,5 m below the plain level. The channel has a gradient of 0,002 and is parallel to the steepest plain gradient for a distance of 100 m and thereafter deviates 2 degrees from this direction for a further 100 m. The surface roughness on the plain and within the channel is represented by 2 mm grains and Manning's n is assumed to be 0,015 for the channel and 0,02 for the plain. The distribution of deposits of 0,3 mm quartz density particles with a fall velocity of 0,035 m/s through this channel system has been simulated for a flow depth of 0,50 m on the plain.

The probability of deposition of particles reaching the bed of the channel or plain is estimated as the complement of the erosion probability defined by Einstein (1950).

For simulation of the distribution of sediment deposits the channel is divided into a number of reaches. The transverse distribution model is applied at the beginning of each reach to determine the distribution of deposits over the plain on either side of the channel and the concentration gradients across the plain-channel interfaces. These concentration gradients are then used in the longitudinal distribution model in determining the variations of sediment concentration and deposition along the reach. The gradients are proportioned to the magnitude of concentration and are adjusted at each calculation step in the longitudinal model as concentrations vary. At the end of the reach the computed concentration profile is used as input to the transverse distribution model for calculations at the beginning of the following reach. The lengths of the reaches are selected according to the degree of accuracy required and considering the rates of variation of the vertical concentration profile.

In this hypothetical example the sediment was introduced to the beginning of the channel with a concentration of 100 units distributed uniformly over the water depth. Units of concentration are arbitrary because the distribution of deposits is required in a relative sense only, but any appropriate units could be used for other cases. The channel was divided into 10 m reaches over the first 60 m because of the initial rapid change in concentration profile, and into 20 m reaches for the remaining 140 m.

The longitudinal variation of the vertical concentration profile within the channel is shown in Figure 6. The variation is rapid initially as the uniform profile adjusts towards an equilibrium consistent with the hydraulic conditions. Thereafter concentration values decrease gradually as sediment is lost to the bed and the plain areas. The variation in average concentration shown in Figure 7 reflects this gradual decrease over the length of the channel. The apparent increase in average concentration near the beginning of the channel is due to the selected vertical grid spacing being large relative to the very steep concentration profile which develops near the bed, exaggerating the local sediment content.

Figure 8 shows the variation of deposits on the channel bed, relative to the deposition at the beginning of the channel. The effect of the adjustment of the vertical concentration profile is again apparent. Deposition increases rapidly initially as the concentration near the bed increases to conform to the equilibrium profile and decreases gradually thereafter. The overbank transfer of sediment constitutes a loss from the channel and therefore affects the longitudinal distribution within the channel. Both Figure 7 and 8 also give results for a simulation in which transfer of sediment to the plain areas was not accounted for. It can be seen that for this example the plain transfer reduces both average concentration and channel bed deposition by about half after 200 m. The effect of plain transfer depends on characteristics of the channel system, the sediment and hydraulic conditions (James, 1984a) and has been verified qualitatively by preliminary laboratory tests. Although the effect does decrease as the channel width increases the model also becomes less accurate because it assumes no transverse variation within the channel, i.e. complete mixing takes place between length increments, which is unrealistic for wide channels.

Figures 9a and 9b show transverse distributions of sediment deposits at 20 m intervals along the channel length. All deposi-

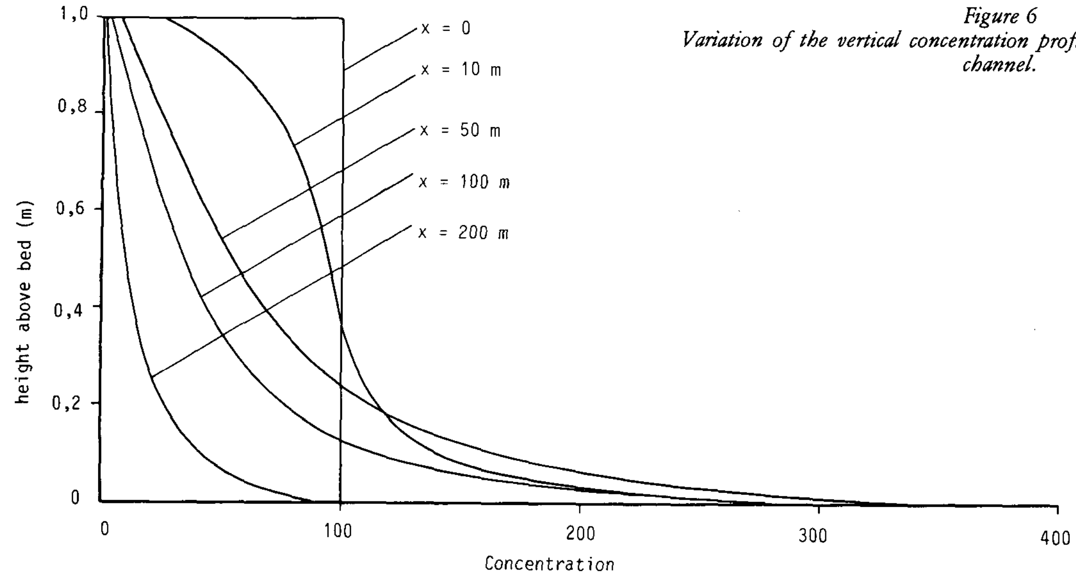


Figure 6
Variation of the vertical concentration profile with distance along the channel.

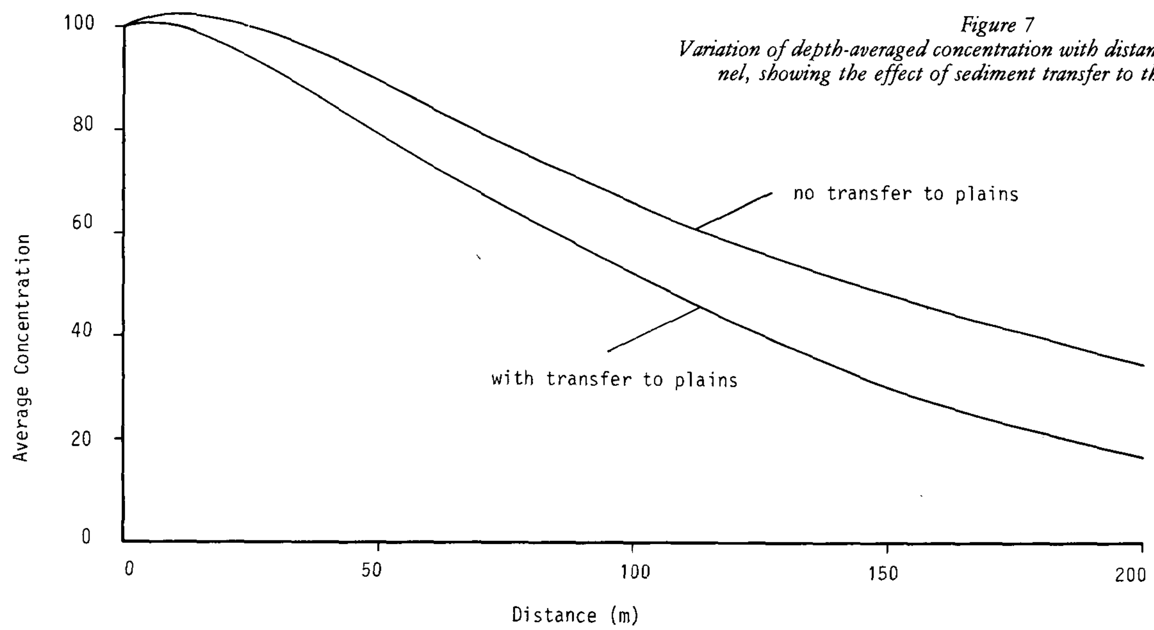


Figure 7
Variation of depth-averaged concentration with distance along the channel, showing the effect of sediment transfer to the plain areas.

tion values are relative to the average deposition within the channel at the beginning of the channel. Deposits within the channel are seen to be greater than on the plains except at the beginning of the channel before adjustment of the vertical concentration profile. Under different conditions, e.g. a steeper gradient, plain deposits could be consistently higher than channel deposits. The plain deposits are symmetrical about the channel over the first 100 m where channel and plain flow are parallel. Over the second 100 m, where the channel direction was specified to deviate from the steepest gradient of the plain, the distribution of deposits is distorted with more sediment on the 'down-stream' side of the channel than on the other. All deposits decrease along the length of the channel once adjustment of the vertical concentration profile has taken place.

Conclusion

The large, complex problem of describing the three-dimensional distribution of suspended sediment concentration in a compound channel can be solved efficiently by decomposition. Two relatively small two-dimensional models, based on the diffusion analogy, have been presented which can be used conjunctively to solve the three-dimensional problem. One model describes the transverse distribution and the other the longitudinal distribution. This concept could also prove useful for simplifying other three-dimensional transport problems where scales of variation are significantly different in different directions.

A hypothetical application of the models illustrates how the distribution pattern of deposits of specific particles through a compound channel can be predicted. Sediments with different size and density characteristics can be considered separately, enabling prediction of the composition of deposits at all points in the system. The hypothetical application also demonstrates the effect of transfer to overbank sections on the longitudinal distribution of suspended sediment within the main channel. In large, irregular, natural systems more sediment will be transferred to flood plains by convection than by diffusion but the diffu-

Figure 8

Variation of deposition on the channel bed with distance downstream, relative to the deposition at the beginning of the channel. The effect of sediment transfer to the plain areas is also shown.

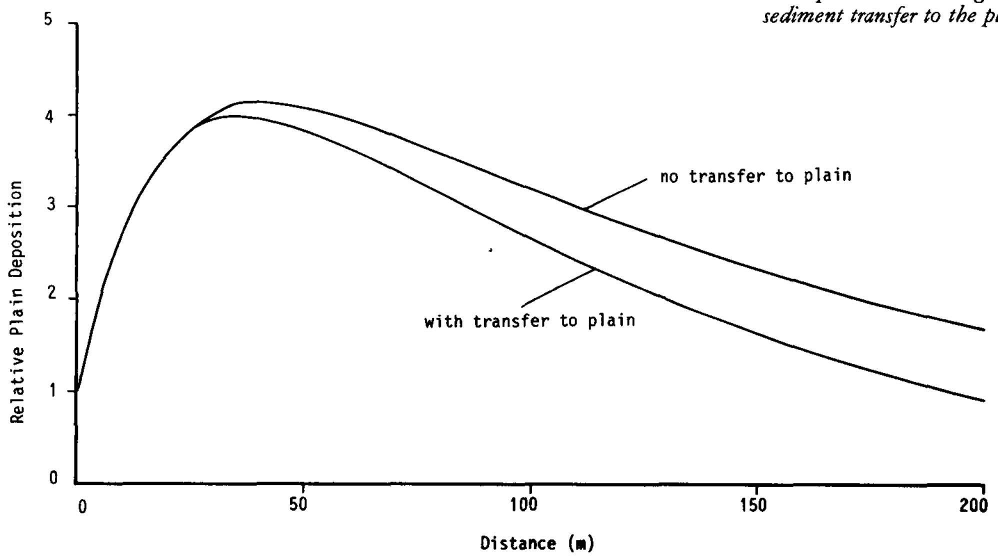
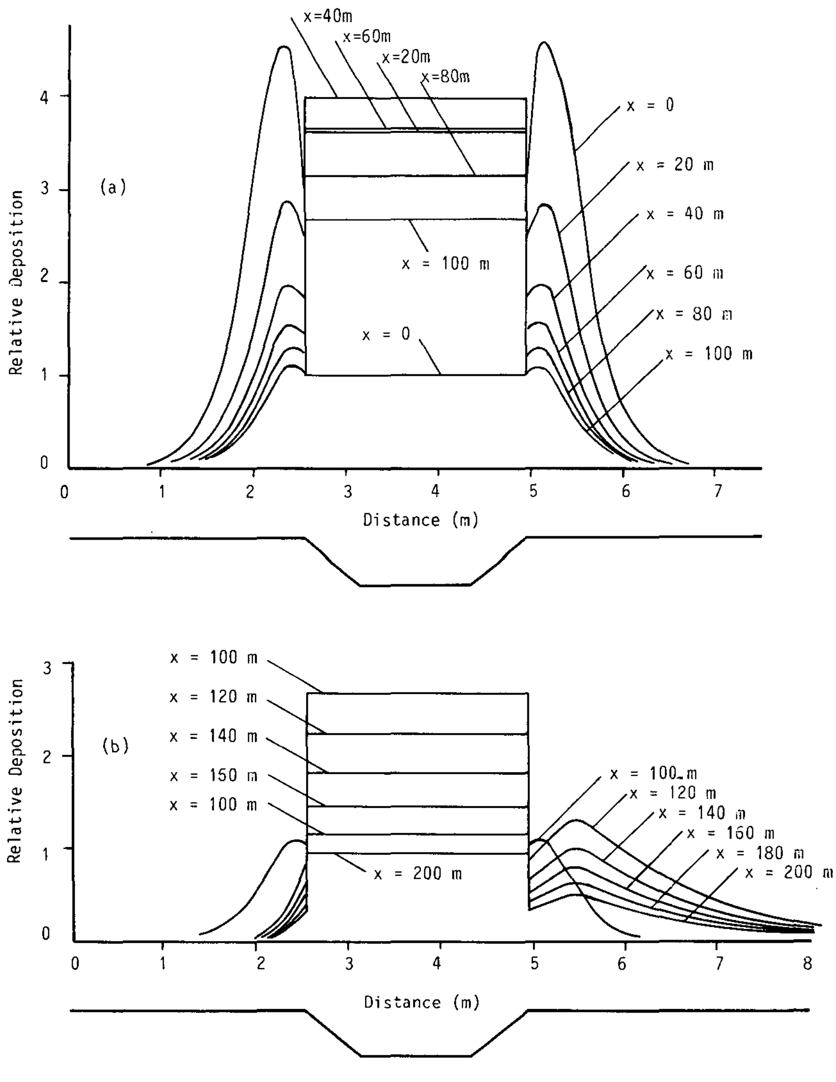


Figure 9

Variation of the transverse distribution of deposition with distance (x) along the channel for the first (a) and second (b) one hundred metre reaches. Deposition is relative to the average channel deposition at x = 0.



sion component has been shown to be significant in certain situations.

The models consider only steady, longitudinally uniform flow. Gradually varied flow could be accounted for by approximating nonuniform profile by consecutive uniform reaches. The models do also not account for bed load movement and the role of the bed as a source of suspended sediment. These limitations impose restrictions on their practical application but additional components could be introduced to describe these processes.

The models are currently being used to explain distribution of heavy minerals in ancient distributary fluvial systems. They could also be useful for determining ultimate distributions of point source particulate pollutants through channel systems under flood conditions.

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References

APELT, C.J. and ISAACS, L.T. (1977) On the estimation of the optimum accelerator for SOR applied to finite element methods. *Computer Methods in Applied Mechanics and Engineering*. 12 383-391.

EINSTEIN, H.A. (1950) The bed-load function for sediment transportation in open channel flows. *Tech. Bull.* No. **1026**, United States Department of Agriculture. Soil Conservation Service, Washington, D.C.

ENGELUND, F. and FREDSOE, J. (1976) A sediment transport model for straight alluvial channels. *Nordic Hydrology* 7 293-306.

GHOSH, S. and JENA, S.B. (1971) Boundary shear distribution in open channel compound. *Proc. Instn. Civ. Engrs.* **49** 417-430.

GRAF, W.H. (1971) *Hydraulics of sediment transport.* McGraw-Hill Book Company.

JAMES, C.S. (1984a) Numerical modelling of gold transport and deposition, Ph.D. Thesis, University of the Witwatersrand, Johannesburg, South Africa.

JAMES, C.S. (1984b) The distribution of fine sediment deposits on flood plains. *Proceedings of the 1984 International Symposium on Urban Hydrology. Hydraulics and Sediment Control*, University of Kentucky, Lexington, Kentucky. 247-254.

JAMES, C.S. (1985) Sediment transfer to overbank sections. *J. Hyd. Res.* **23**(5) 435-452.

LAU, Y.L. and KRISHNAPPEN, B.G. (1977) Transverse dispersion in rectangular channels. *J. Hyd. Div. Amer. Soc. Civ. Eng.* **103**(10) 1173-1189.

MYERS, W.R.C. (1978) Momentum transfer in a compound channel. *J. Hyd. Res.* **16**(2) 139-150.

MYERS, W.R.C. and ELSAWY, E.M. (1975) Boundary shear in channel with flood plain. *J. Hyd. Div. Amer. Soc. Civ. Eng.* **101**(7) 933-946.

RAJARATNAM, N. and AHMADI, R.M. (1979) Interaction between main channel and flood plain flows. *J. Hyd. Div. Amer. Soc. Civ. Eng.* **105**(5) 573-588.

RAJARATNAM, N. and AHMADI, R.M. (1981) Hydraulics of channels with flood plains. *J. Hyd. Res.* **19**(1) 43-60.

ROUSE, H. (1937) Modern conceptions of the mechanics of turbulence. *Trans. Amer. Soc. Civ. Eng.* **102** 463-543.

SARIKAYA, H.Z. (1977). Numerical model for discrete settling. *J. Hyd. Div. Amer. Soc. Civ. Eng.* **103**(8) 865-876.

SELLIN, R.H.J. (1964) A laboratory investigation into the interaction between the flow in the channel of a river and that over its flood plain. *La Houille Blanche* (7) 793-802.

SINGAMSETTI, S.R. (1966) Diffusion of sediment in a submerged jet. *J. Hyd. Div. Amer. Soc. Civ. Eng.* **92**(2) 153-168.

SUMER, B.M. (1974) Mean velocity and longitudinal dispersion of heavy particles in turbulent open-channel flow. *J. Fluid. Mech.* **65**(1) 11-28.

WORMLEATON, P.R., ALLEN, J. and HADJIPANOS, P. (1982) Discharge assessment in compound channel flow. *J. Hyd. Div. Amer. Soc. Civ. Eng.* **108**(9) 975-994.

WRIGHT, R.R. and CARSTENS, M.R. (1970). Linear momentum flux to overbank sections. *J. Hyd. Div. Amer. Soc. Civ. Eng.* **96**(9) 1781-1793.