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A SIMPLE NUMERICAL METHOD TO SIMULATE SPOIL DISPERSAL FROM SURFACE DREDGER DISCHARGES

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ABSTRACT

This report describes a series of analytical models developed to simulate the short term dispersion of dredged spoil disposed of in an estuary or at sea. Spoil from dredging operations is often disposed of by transporting the material to a spoil ground to be discharged from a hopper. Alternatively the material can be discharged directly over the side of a working dredger in an operation known as sidecasting. In the latter case the effectiveness of the method depends on the existence of suitable cross-currents to carry the sediment away from the dredge site before it returns to the bed.

The models predict the 'footprint' of dredged material that may be expected to be found downdrift of its release point as a result of sidecast operations. They were tested against results from field dispersion experiments carried out during 1973 and 1976. Operating dredgers were used for the experiments which took place in the River Plate, Argentina, and the Severn Estuary.

The results showed that in spite of the diversity of tidal conditions and sediment types found on the field experiments, the models were able to simulate the pattern of deposition resulting from the experimental discharges.

Port Authorities incur significant costs as a result of dredging operations, and spoils polluted by industrial wastes impose an often unquantified environmental cost. The conclusions therefore suggest that further investigations should study the mechanisms involved in spoil dispersal leading to the further development of suitable mathematical techniques which can economically be used by Port Authorities, conservators, consultants and the dredging industry.

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1 INTRODUCTION

Recent years have seen a substantial increase in the size and draught of vessels passing through ports. Many ports require a regular programme of dredging to maintain navigable depths in the docks and in the entrance channels. Such maintenance dredging is costly and methods are continually sought to reduce the input of effort into such maintenance.

Part of the solution is clearly to be found in the appropriate design of ports and their access channels. Their design should minimize the hydraulic conditions that favour settlement of suspended material. In existing ports, however, and those where physical factors are contrary, the maintenance of deep water may be an unavoidably heavy burden.

Historically maintenance dredging has been carried out using local experience to determine when and where to dump the dredged spoil. There is increasingly greater pressure to maximize dredging efficiency. In addition, and perhaps more importantly, dredging exercises in channels which pass through industrial areas involve moving sediments which may have significant accumulations of pollutants. These then either become concentrated on the spoil grounds, or thrown into suspension in the mud clouds caused by dredging works. A recent publication[1] has suggested that dumped dredged spoils represent a major input of trace metals to the marine environment. It states that the mass loads could be substantially higher than the total input to the seas around England and Wales from the dumping of industrial wastes and sewerage sludges.

It is clearly of interest then, from an environmental point of view as well as from an engineering standpoint to gain greater insight into the dispersal of material arising from dredging operations. Mathematical models are increasingly recognised as useful tools in any research programme, and in the context of dispersal of dredged spoil, polluted or otherwise, they attempt to answer the two questions regarding where the material goes to and what happens to it on the way. The answer to the first question is governed by the hydrodynamic processes taking place in the area of dispersal. The answer to the latter question is governed by the physical processes of sediments falling to the bed.

This report describes the formulation of simple numerical models that simulate advection and dispersal of spoils. The work is by no means exhaustive but provides a basis for more sophisticated model development. Two cases are presented; the first is the determination of the 'foot print' of material that remains on the bed after a number of hours have elapsed since release. The second is a study of the concentration of the turbidity plume resulting from a release.

1.1 Dredging practice

The main cause of sediments accumulating in docks, harbours and navigable waterways is the natural result of silt laden waters entering areas of relatively still water where the energy level in the flow is insufficient to keep the sediment in suspension. The regular rise and fall of water levels with the tide exacerbate the problem by repeatedly recharging such areas with silt laden water. The sources of the sediment are varied. In many UK estuaries it is indigenous and highly mobile. In other cases sediment can be either fluvial or marine in origin, or a combination of the two. In docking areas general debris and lost cargo may also add to the maintenance dredging load.

When dredged spoil is disposed of at sea (as opposed to being pumped ashore) it is usually by one of two ways. The hopper dumping method is perhaps the most widely used. The spoil is physically transported some distance from the dredged sites in hoppers, to be discharged above a spoil ground, usually in deep water, through doors at the base of the hoppers.

The other method is sidecasting or 'agitation dredging', a process in which the material is dredged and discharged overboard in a single operation. The spoil may be pumped either directly overboard, or through a floating pipeline to a remote discharge point with the intention that the prevailing currents carry the sediments away. The effectiveness of spoil removal with sidecasting is dependent on the rate at which the sediment falls to the bed and the existence of favourable currents. Sidecasting has been found to be particularly effective in shoaled silty material, giving high unit volume savings over that of suction hopper dredging[2].

Which ever method is used, as soon as the material is released into water it becomes diluted in the receiving waters and the concentration of the release decreases with increasing distance from the source. The distribution is affected by the mechanisms of advection, diffusion and settling. The dilution process is dominated by diffusion caused by turbulent eddies. The effect of these is orders of magnitude larger than molecular diffusion.

1.2 Review of previous studies

These complex physical processes, in spite of the obvious importance of the problem have not been extensively investigated in the past. This is probably because of the difficulty of obtaining sound data upon which to base such investigations. Of the earliest attempts to define the mechanism taking place in the falling plume, one is recorded by Koh and Chang[3] and another by Edge and Dysart[4]. Krishnappen[5] summarized the work of the above authors. He suggested that since both methods assumed the spoil to behave in a manner similar to a denser liquid, they suffered a common weakness; that they may only be justified if the particles constituting the spoil are very fine. Krishnappen used laboratory experiments to study the behaviour of particle movements to produce a method for predicting the movement of dredged spoil in which there were discrete solid particles. The experiments involved the use of a water tank containing a homogenous stationary body of water. Different volumes of solid particles were released into the water as slugs, without any initial momentum.

Fig 1 shows schematically what happens when material is bottom dumped. On opening the hopper doors the material accelerates as a result of its excess density, from zero to some maximum value. While the plume descends the leading edge entrains water, grows in size and its rate of descent reduces. On leaving the hopper some of the material leaves the main body of sediment to form an 'injection cloud'. As the plume hits the bed an 'impact cloud' is formed made up partly of dredged material and partly of resuspended bed sediment. The length of fall determines whether the descending plume slows to a point where a terminal velocity equal to the fall velocity of the individual particles is reached. It also influences the quantity of material that breaks away from the plume to become part of a cloud with higher than background concentration of solids (sometimes termed the 'turbidity cloud').

Both the Krishnappen and the Koh-Chang models concentrated their attentions on the falling sediment plume generated by bottom dump methods of disposal. Their models are compared by Johanson and Boehmer[6]. Neither make provisions for the generation of a turbidity cloud by material separating from the plume as it descends or when it impacts on the bottom. Johanson and Boehmer supported this omission by quoting earlier work by Gordon[7,8] which estimated from observed data that the turbidity cloud in the vicinity of the falling plume from a static bottom dump contained less than 1% of the dumped material. Other studies have been carried out,[9,10,11] all concentrate on the dispersal of spoil in the area immediately local to the dump position.

It is clear that there is still much to learn regarding the fall and spread of material from a hopper dump and much more to learn about the mechanism that generates the turbidity cloud especially as sidecast methods aim to generate a turbidity cloud to maximise dispersion.

2 THE MATHEMATICAL MODELS

2.1 General description of physical processes

The main factors influencing the spread and deposition of suspended solids may be said to be the current velocity, diffusion due to turbulent fluctuations and the settling velocity of the sediment.

Current velocity

The movement of particles originating from a surface source is distinct from the motion of particles originating from the bed. In the latter case motion is caused by water flowing over the bed and sediment may be carried at a reduced velocity as in the case of a contact load, or intermittently as the case of a saltation load. From a surface source however, the horizontal velocity of a particle is determined by the bulk movement of the water into which it falls. This motion is known as advection.

Settling velocity

The trajectory of particles comprises the horizontal component of velocity imparted by advection and a vertical component of velocity; the length of time particles remain in suspension is a function of the rate of descent and the depth of water. The vertical component of velocity is partly dependent on the characteristics of the flow, such as turbulence, and partly on on the properties of the sediment itself. The latter can be further divided into properties of the particles such as size, shape and density, and those of the sediment as a whole such as its tendency to flocculate. The settling velocity reflects these properties.

Diffusion

In a current an initially dense cloud of suspended material is advected away from the source at the same rate as the current. Longitudinal diffusion caused by the difference of velocities in the surface and bed waters is orders of magnitude smaller than the effect of advection. Lateral diffusion determines the rate of spread of the cloud, and occurs by reason of the natural turbulence generated within the moving current. Within an estuary, where the scale of turbulent eddies are restricted laterally, the cloud moving with the current may form a long thin ribbon, spreading sideways only very slowly. In open water however, turbulence occurs over a much wider range of scales and the rate of mixing will be dependent on the relative sizes of the cloud and the turbulent eddies.

2.2 General description of the models

The models described in this report attempt to simulate the dispersion of spoil over a wide area. They do not make provision for the mechanisms that give rise to very local dispersal. The models are based upon the equation for the conservation of matter simplified to represent the mean concentration of suspended solids through the depth and deposition on the bed as a function of distance from the source.

The models are steady state analytical models in which a release of material is considered to be either steady and continuous or instantaneous. It is assumed that the velocity of flow is constant and along a line defined as the x axis. The distribution of sediments is therefore symmetrical about the centreline of the plume. Depth is uniform throughout and coefficients to describe longitudinal and lateral diffusion are prescribed.

The zone of interest is subdivided into a number of relatively small cells of dimensions Δx and Δy; the models then determine either the concentration or the deposition at each node of the grid.

2.3 The differential equation

The basic differential equation is:

$$\frac{\partial}{\partial t}(dc) + \frac{\partial}{\partial x}(duc) + \frac{\partial}{\partial y}(dvc) - \frac{\partial}{\partial x}(dD_x \frac{\partial c}{\partial x}) -$$

$$\frac{\partial}{\partial y}(dD_y \frac{\partial c}{\partial y}) + W_s (c - c_e) = 0 \qquad (1)$$

where:

c	=	depth averaged concentration (kg/m^3)
d	=	water depth (m)
x,y	=	co-ordinate directions parallel and normal to the flow (m)
u,v	=	flow velocity in the x and y directions respectively, (m/s)
D_x,D_y	=	Diffusion coefficients in the x and y directions respectively (m^2/s)
W_s	=	particle fall velocity (m/s)
c_e	=	depth averaged background concentration (kg/m^3) ($c > c_e$)
t	=	time(s)

2.3.1 Simplification of equation

For simplicity it has been assumed that the velocity, depth and turbulent diffusion remain constant for the length of the plume. It is also assumed that flow is uni-directional with flow parallel to the x direction. Concentration (c) is defined as the excess over the background, and it is assumed that the material is fully mixed throughout the depth from the point of release. Taking account of these assumptions the basic equation reduces to:

$$\frac{\partial c}{\partial t} + \frac{\partial(uc)}{\partial x} - D_x \frac{\partial^2 c}{\partial x^2} - D_y \frac{\partial^2 c}{\partial y^2} + \frac{W_s}{d}(c - c_e) = 0 \qquad (2)$$

This partial differential equation is the continuity equation for the spread of material from a source. The terms represent the rate of change of concentration with time, the rate of decrease of concentration per unit volume by advection, longitudinal diffusion, lateral diffusion, and loss of material from suspension due to deposition, respectively.

By modification of the methods of Carslaw and Jaeger[12], Equation 2 can be solved for a number of different cases as described below.

2.3.2 Solution for a point release

The equation may be solved for the situation shown in Fig 2 where a slug of material is instantaneously released into a body of water flowing at velocity u. Then the concentration at time t from release is:

$$c(x,y,t) = \frac{Q}{4\pi t d \,(D_x D_y)^{\frac{1}{2}}} \exp\left\{ -\frac{1}{4t}\left[\frac{(x-ut)^2}{D_x} + \frac{y^2}{D_y}\right] - \frac{W_s t}{d} \right\} \qquad (3)$$

where:

Q = mass of substance released (kg)

D_x, D_y = diffusion coefficients in the x and y directions respectively (m^2/s)

boundary conditions are:

$c_{(\infty,t)}$ = background for $t = 0$

$\frac{\partial c}{\partial x} \rightarrow 0$ as $t \rightarrow \infty$

Equation 3 gives a gaussian concentration profile with the centre moving downstream at velocity u

(Fig 3), and with a decay term to represent material falling out of suspension to the bed.

If the release is continuous, at a constant rate q; over the increment of time dt, a quantity of qdt units of material will be released. As t tends towards infinity a steady regime is established and the concentration at position (x,y) is found, by integration of the Equation 3 with time, to be:

$$c(x,y) = \frac{q}{2\pi d\,(D_x D_y)^{\frac{1}{2}}}\, e^{\left[\frac{xu}{2D_x}\right]} K_o \left\{ \frac{R}{2} \left[\frac{u^2 + 4\beta D_x}{D_x} \right]^{\frac{1}{2}} \right\} \quad (4)$$

where:

$$R^2 = \frac{x^2}{D_x} + \frac{y^2}{D_y}$$

$$\beta = \frac{W_s}{d}$$

and K_o is the modified Hankel function of zero order (Appendix).

If q_b is considered to be the quantity of material falling onto a unit area of bed in a unit period of time, then

$$q_b = W_s c$$

where c is derived by solving Equation 4

It may be seen therefore that multiplying the right hand side of Equation 3 and integrating with time, the total deposit on the bed (Q_b) arising from either an instantaneous or steady release of material of mass Q where Q = qdt is:

$$Q_b(x,y) = \frac{QW_s}{2\pi d(D_x D_y)^{\frac{1}{2}}} e^{\left[\frac{xu}{2D_x}\right]} K_o \left\{ \frac{R}{2} \left[\frac{u^2 + 4\beta D_x}{D_x} \right]^{\frac{1}{2}} \right\} \quad (5)$$

2.3.3 Solution for a spread release

It may be considered more realistic to consider that the material is released over an area (Fig 4) where

$$-a \leqslant x \leqslant a, \; -b \leqslant y \leqslant b$$

The concentration at time t after an instantaneous release is determined by integration of Equation 3

$$c(x,y,t) = \frac{Qe^{-\beta t}}{16dab}$$

$$\left[\mathrm{erf}\left\{\sqrt{p_y}(y+b)\right\} - \mathrm{erf}\left\{\sqrt{p_y}(y-b)\right\}\right]$$

$$\left[\mathrm{erf}\left\{\sqrt{p_x}(x+a) - \frac{q}{\sqrt{p_x}}\right\} - \mathrm{erf}\left\{\sqrt{p_x}(x-a) - \frac{q}{\sqrt{p_x}}\right\}\right] \quad (6)$$

where:

$$q = \frac{u}{4D_x}$$

$$p_x = \frac{1}{4D_x t}$$

$$p_y = \frac{1}{4D_y t}$$

Similarly the total deposit on the bed arising from a release of mass Q, whether instantaneous or steady then becomes;

$$Q_b(x,y) = \frac{QW_s}{8\pi dab\,(D_x D_y)^{\frac{1}{2}}} \int_{x'=-a}^{x'=a} \int_{y'=-b}^{y'=b} e^{\left[\frac{(x-x')u}{2D_x}\right]}$$

$$K_o \left\{ \frac{R'}{2} \left[\frac{u^2 - 4\beta D_x}{D_x} \right]^{\frac{1}{2}} \right\} dx'\, dy' \qquad (7)$$

where:

$$R'^2 = \frac{(x - x')^2}{D_x} + \frac{(y - y')^2}{D_y}$$

In the case of a spread release the material is considered to disperse instantaneously uniformly through the entire volume of a receiving sub cell of dimensions 2a and 2b in the x and y directions respectively. The continuity equation is then solved for a similar sized sub-cell centred over each node of the prescribed grid. The integral shown in equation 7 is carried out using a trapezoidal summation across a grid within the sub cell.

2.3.4 Quasi steady state model

In the solutions described above there is a relatively unsophisticated relationship between the rate of spread of the plume caused by lateral diffusion and the value for the lateral diffusion coefficient. This allows for the fact that the diffusion processes in the open ocean can be on a grossly different scale to the processes in a tidal estuary. Much has been written in literature about diffusion of substances in the open ocean and although there is considerable disagreement on how to formulate a suitable law, there is general agreement that the magnitude of the eddy diffusion coefficient increases significantly with size of the area being considered. Brooks[13] discussed the evidence that diffusion from ocean sources should be represented by the equation:

$$D_y = \alpha L^{4/3}$$

where:

L = the width of the plume (m)

α = an empirical constant (0.0005 in SI units)

A further model has been developed that incorporates this so called '4/3 law' for D_y. The model calculates the plume concentrations and deposition rates downstream of a continuous spread source. If the diffusion in the longitudinal direction is neglected then concentration is calculated as follows:-

$$c(x,y) = \frac{c_o e^{\left[\frac{-W_s x}{u\, d}\right]}}{2} \left[\operatorname{erf}\left\{\frac{\frac{b}{2} + y}{(4\alpha t')^{\frac{1}{2}}}\right\} + \operatorname{erf}\left\{\frac{\frac{b}{2} - y}{(4\alpha t')^{\frac{1}{2}}}\right\} \right] \qquad (8)$$

where:

c_o = initial suspended solids concentration (kg/m^3)

b_o = initial plume width (m)

$$t' = \frac{b_o^{\,2}}{24\,\alpha} \left[\left\{ 1 + \frac{8\alpha t}{b_o^{\,2}} \right\}^3 - 1 \right]$$

$$b = b_o \left[1 + \frac{8\alpha t}{b_o^{\,2}} \right]^{3/2}$$

This model is quasi 'steady-state' but has been formulated to take some account of changes in the strength and direction of currents with distance from the source. This is done by prescribing the x,y ordinates of the plume centreline at intervals equivalent to equal increments of time. In this case the trajectory and rate of advance of the plume may be determined by use of float tracking in the field, or of flow models of the area in which the plume moves. This model also allows the suspended sediment at the dredger to be specified in several narrow particle size bands, for each of which a unique settling velocity can be prescribed. Each size is treated separately in the model.

The quasi-steady state model has not yet been applied in the context of dispersal of dredged spoil for lack of adequate data. No further reference is therefore made to it in the paragraphs that follow.

2.4 Model sensitivity

There are two ways in which the most important results from the models may be presented. Firstly the rate at which the plume grows as it moves away from the release point, and secondly the rate at which the deposition increases (or concentration decreases) along the longitudinal axis of the plume. A series of tests were carried out to test the sensitivity of the models to changes of the diffusion coefficients, and settling velocity, and to determine the difference associated with using a point or a spread release. Comparisons were made of the material depositing on the bed from tests using identical conditions but varying one parameter.

2.4.1 Sensitivity to diffusion coefficients

Figs 5 to 9 show families of curves that illustrate the effects of varying the diffusion coefficients D_x and D_y for both a point and a spread release of material. With the exception of Fig 7, the figures represent the total deposit across the width of the plume downstream of the release zone as cumulative percentages in the longitudinal direction.

a) Longitudinal diffusion

Figs 5 and 6 show that the total quantity of deposit across a section normal to the plume centreline is insensitive to the range of values of D_x between 0.003 m^2/s and 30.0 m^2/s. The lateral distribution of sediments is virtually unaffected by changes to the longitudinal diffusion coefficient.

b) Lateral diffusion

In contrast, changes to the lateral diffusion coefficient significantly modify the rate of spreading of the plume downstream of the release zone. Fig 7 shows the sensitivity of the distribution of sediments deposited across a section normal to the centreline of the plume to changes in the lateral diffusion coefficient. The pattern is similar for both a point and a spread release.

The longitudinal distribution is also affected by lateral diffusion . The effect becomes significant for coefficients outside of the range 0.1 to 10.0 m^2/s for a spread release and 1.0 to 10.0 m^2/s for a point release. This is illustrated in Figs 8 and 9 where it can be seen that the lower values for the lateral diffusion coefficient give rise to an overestimate of the total quantity on the bed from a point release, and an underestimate from a spread release. Analysis of the computational method indicates that the result becomes increasingly less accurate for values of D_y less than approximately 0.1 m^2/s.

2.4.2 Sensitivity to grid size

Further to the inaccuracy referred to above, the relationship between the prescribed values for lateral diffusion coefficient and grid width significantly influence the accuracy of the results as described below.

For the case of a point release the variation of the result according to the choice of grid width and lateral diffusion coefficient is shown in Fig 10. A prescribed value of 1.0 m^2/s for the coefficient gave the most consistent results over a wide range of grid widths, lower values require that a small grid width is used.

For the case of a spread release, the solution shows more tolerance to the relationship between diffusion coefficient and grid width. Fig 11 shows that for coefficient values less than 0.1 m^2/s, a small grid width is required.

Similar sensitivity tests were carried out in which the relationship between the lateral dispersion coefficient and grid length was studied. It was found that variations in the grid length do not significantly influence the result.

It is therefore evident that grid dimensions are not significantly modify the results providing the diffusion coefficients remain within the ranges suggested. It is also clear that the influence of the lateral diffusion coefficient on the pattern of deposition downstream of the source is significantly greater than that of the longitudinal diffusion coefficient.

2.4.3 Sensitivity to particle settling velocity

The results of this final sensitivity test are shown in Fig 12. The figure shows, as would be expected, that the rate of deposition of material downstream of the source is increased as the prescribed settling velocity is increased. The results for a point release are not shown, but behave in a similar way.

3 APPLICATION TO PREVIOUS SITE STUDIES

3.1 River Plate

The port of Buenos Aires lies on the south west bank of the River Plate approximately 180 kilometres from the ocean. The port is made accessible from the South Atlantic through many kilometres of dredged navigable channel (Fig 13). During 1973, HR particapted in an extensive study which was carried out to review the existing dredging practices. HR were asked to comment on the hydraulic aspects of loading and disposing of dredged spoil[14]. A radio-active tracer was used to label dredged spoil before disposal and its dispersal was subsequently traced with radiation detection equipment to show the short term movements of the spoil. The dredged material consisted mainly of closely graded non-flocculated particles with a median particle diameter of 0.015 to 0.035 mm (Table), and a fall velocity of about 0.060 mm/s.

Four disposal tests[15] were carried out and two were selected for model application. Dredging Test D4 was used to determine representative values for the lateral and longitudinal diffusion coefficients to be used in the models. Dredging Test D1 was then used to verify the coefficients found from Dredging Test D4. A square grid of size 100 m was used for the calculation, and the material was considered to be released from a spread source.

3.1.1 Dredging Test D4

This experiment took place on 29 November 1973, and simulated a sidecast discharge. The radio-active tracer was injected into the spoil discharge for three minutes during which a slurry containing approximately 171 tonnes of solids was discharged from a height of about 4 m above the water surface. While this material was discharged the dredger travelled about 196 m. For the period of the discharge and the subsequent particle tracking, water velocities varied between 0.2 and 0.4 m/s and water depths between 4.4 and 4.7 m. The flow direction remained virtually constant over the period, crossing the dredged channel at an angle of approximately 45°. On the day following the injection, a bed tracer survey was carried out to determine the distribution of material on the bed.

The models were used to give the deposition on the bed downstream of the release zone. It was found that values of 1.0 m^2/s and 3.0 m^2/s for lateral and longitudinal diffusion coefficients respectively gave the best fit between model results and observations.

Proving in the first instance was carried out by comparing the solution for the distribution of sediment on the bed downstream of release with those observed in the field. The figures shown compare the distribution in the longitudinal and lateral directions as described below. For the River Plate the pattern of tidal variation gave rise to prolonged flood tide phases on the dates of the tests described in this report. It was therefore possible to draw comparisons between model results and observations over a distance of 7 km, equivalent to approximately 6½ hours transit time.

A comparison between the observed and model rates of deposition as a percentage of the total release is made in Fig 14. The figure shows the close agreement between observations and the model results over this distance. The model predicted that between 0.5 and 6.5 km from release, a total of 21% of the material would be deposited, compared with an observed quantity amounting to 21.5%.

Similarly Fig 15 shows a comparison for the lateral distribution of sediments accross the plume at several sections downstream of release. Fig 16 is a contoured chart comparing the observed spatial distribution with the distribution calculated by the model.

It can be deduced from Fig 11 that the solution for a point release would give slightly higher deposition rates for identical prescribed conditions. There is, however, such wide scope for interpreting the data that no conclusion can be drawn regarding the relative merits of considering the release as from a point source or a spread source.

3.1.2 Dredging Test D1

The model was then applied to the Plate dredging Test D1 using the same valves for the coefficients of diffusion and settling velocity already established for the model simulation of Test D4.

This dredging test took place on 23 November 1973, and simulated a side discharge over the hopper overflow weir. The radioactive tracer was injected into the spoil discharge in two doses. The first injection lasted for 4 minutes 15 seconds during which time the dredger travelled 220 m. The second injection lasted for 4 minutes 46 seconds during which time the dredger travelled 370 m. A total of approximately 513 tonnes of solids was discharged from a height of about 2 m above the water surface. Water velocities of 0.2 to 0.25 m/s and depths between 3.8 and 4.0 m persisted for most of the injection and water tracking periods. The flow crossed the dredged channel at an angle of approximately 45°.

The following day the bed tracer survey was carried out to determine the distribution of material on the bed (Fig 17).

The comparison between the observations and the model rates of deposition as a percentage of the total release is shown in Fig 18. The figure shows that the initial rate of deposition was observed to be relatively low, rising to a peak at km 4; it then followed a downward trend as far as km 7. The model results overestimated the initial deposition but the figure shows that there is general agreement between km 3 and km 7. The model predicted that between 0.5 and 6.5 km from release, a total of 28% of the sediment would be deposited compared with the observed quantity of approximately 20%.

The most likely explanation for the difference between model results and observations is that for this test the method of release by the hopper overflow weir resulted in a greater initial dispersion of the slurry on impact with the water surface than was the case with the sidecast discharge of Test D4. If this was true it would give rise to a larger percentage of material being dispersed into the injection cloud than would remain as a body with the falling sediment plume. One might therefore expect the material to be carried in suspension a greater distance before being deposited on the bed.

The photographic plate clearly shows the two types of discharge for dredging Tests D1 and D4. The weir overflow discharge was ejected horizontally from the vessel and fell through a distance of approximately 2 m. As it fell the slurry began to break up before striking the water surface. The lateral pipe discharge used in Test D4 was also ejected horizontally from the vessel.
The spoil fell approximately 4 m, striking the water surface after having attained a vertical velocity of about 9 m/s. The jet appears to remain more or less intact and is seen to hit the water surface as a continuous stream.

Concentration

The models were then used to find the solution for the concentration downstream of the source of material for the case of Test D1. The rate at which material is removed from suspension (ie falls to the bed) is governed by the decay function

$$q_b = e^{\frac{-W_s t}{d}}$$

Fig 19 shows how this function operates for various settling velocities given that the depth is 3.90 m as for Test D1. In the field, concentrations were not measured directly but were deduced from comparisons of the radio-active tracer remaining in suspension downstream of the release zone. The field results showed that between sections at distances of 600 m and 1500 m downstream of the release zone, 27% and 26% respectively of the injected material remained in suspension. This decrease in suspended material implies that the difference is deposited on the bed between the two sections.

The decrease of 1% of suspended material over this distance is smaller than the value of 5% that would be expected using the exponential decay function with a settling velocity of 0.06 mm/s. Fig 18 shows that this zone lies in the initial dip in the observed rate of deposition, whereafter the rate rapidly increases to reach values similar to those predicted by the model. The decay function may therefore be considered to give an acceptable estimate of the rate of change of concentration downstream of the sediment release.

The models, however, are unable to predict the absolute values for concentration. This is because they assume that within the source area all the material goes into suspension, whereas in practice, a large proportion falls directly to the bed as part of the gravity current.

3.2 Severn Estuary

The Severn Estuary is a well mixed saline estuary with a large tidal range, normally between 5.6 m and 11.1 m from neap to spring tides respectively. Tracer experiments were carried out during 1976 to investigate spoil dispersion in the estuary[16]. The material used was dredged from the maintained entrance channel to Cardiff Docks using a trailer suction hopper dredger. It was discharged close to the established spoil ground by pumping the hopper load out over the overflow weirs. The spoil was discharged while the dredger was sailing across the flow direction of the ebbing tide. This method of release most nearly corresponded to the disposal tests already described for the River Plate.

The experiment began on 3 February 1976, 2 hours 20 minutes after high water. The radioactive tracer was injected into the spoil discharge for 2.5 minutes during which time a slurry containing approximately 40 tonnes of solids was discharged from a height of approximately 1 m from the water surface.

In contrast to the material dredged from the River Plate, material from Cardiff docks consisted of a widely graded mixture of silt and sand with a median particle diameter of 0.020 mm (Table). The field test was made at approximately the time of peak ebb velocity of about 1.0 m/s. The release was made at the 'injection bouy' (Fig 20) into 10.3 m of water. The bed survey was made four days later and the distribution of radio-active tracer is shown in figure 20. It is evident that some redistribution of sediments has taken place during the time between the release of the tracer and the bed survey to cause the spoil to spread in both the flood and ebb directions.

For the purpose of the mathematical model it was considered that the range of particle grading was too broad to be satisfactorily represented by the median diameter of 0.020 mm. It was therefore assumed that in view of the high flows the silt fraction (less than 0.060 mm) would be readily dispersed to pass out of the test area and become part of the natural background sediment load. The remaining fraction of sand and coarser material fell between 0.060 and 0.350 mm and constituted only 24% of the dredger load. The median size of this remaining fraction was approximately 0.105 mm, and was assumed to have a particle fall velocity of 7 mm/s[17].

The model was run with the same coefficients for dispersion as were deduced from the River Plate tests. The comparison between observations and model results is shown in Fig 21. It is obvious from figure 21 that in the field test some of the material had been resuspended and redeposited by reversing tidal currents so that after the four days between injection the bed survey a significant quantity of material was found upstream of the injection point. The numerical model, however, is not equipped to simulate what happens to sediments once they have settled on the bed. With this taken into account Fig 21 shows that there was coarse agreement between the model and observations which improves moving away from the near vicinity of the release point. The model calculates that 3 km downstream of release (commensurate with approximately 50 minutes transit time) 19% of material had been deposited on the bed and the rate of deposition had become almost negligible. Observations indicated that at the same position a total of 16.5% of material was found on the bed, also with the deposition rate becoming negligible.

3.3 Discussion

The results described above show the effectiveness of the model in predicting the gross quantity and spread of spoil with very limited data. It is not known how the depths of water varied with distance from the source of release, similarly it is not known how velocity varied with distance, and there is insufficient accurate information regarding the variation of these parameters with time. All of these factors would have influenced the rates of particle settling, and subsequent redistribution by tidal currents in the time between release and bed tracking.

In addition to the unknowns described above, the actual physical behaviour of the material once it leaves the vessel is only described in the models in the simplest of terms, and the models make no distinction between different methods of discharge. As an extreme comparison a sidecast discharge falling 4 m before entering the water column reaches a vertical velocity exceeding 9 m/s. In contrast, the discharge from a hopper enters the water column with a relatively small vertical velocity. The combined effect of all these variables is focused on the prescribed value for particle fall velocity and the similarity between the hindcast deposition rates shown in Figs 14, 18 and 21, and those observed is strongly dependent on a suitable choice of particle fall velocity. This choice may not necessarily reflect the true fall velocity of the material concerned. The fall velocity of 0.06 mm/s used in the simulation for the River Plate dredging tests is commensurate with a particle size of 0.080 mm which is rather closer to the value for D_{10} (Table) than that for D_{50} which might have been considered more appropriate. Similarly the particle fall velocity of 7 mm/s used in the Severn Estuary dredging test is only representative of the sediment fraction after having excluded particles of smaller size than 0.060 mm.

The method is clearly not suitable for the near source region. This is firstly because here the sediment plume tends to fall by gravity in a dense cloud before either spreading to a point where particles begin to behave independently, or hitting the bed to either stick or spread as a mobile near bed layer. Secondly analysis of the behaviour of the mathematical solution shows that it becomes unrealistic very near to the source.

The method is not suitable far away from the source because it is unlikely that either the hydraulic conditions or the bathymetry remain uniform over an extended time or distance.

Taken as a whole it is considered that the models were able to simulate the deposition of sediments that took place downstream of the release zone.

The models were not, however, suitable for simulating the suspended solids downstream of release without further development in this area.

4 CONCLUSIONS AND RECOMMENDATIONS

A series of mathematical models has been produced to simulate the short term dispersal of dredged spoil.

The models were applied to three situations where spoil was discharged into a current by continuous sidecasting through either a discharge pipe or across the hopper overflow weir.

The results of the model studies indicate that they were able to hindcast the spatial distribution of sediments on the bed following release from a surface source.

The scope of the models is limited in that they are unable to adequately simulate suspended solids concentrations downstream of the source. Neither are they able to simulate the distribution on the bed in the near source region. The model's ability to simulate the distribution on the bed in the far field region is restricted by the degree of uniformity of the hydraulic conditions and bathymetry.

Earlier works[3,4,5,6,8] have discussed the mechanisms of hopper drop discharges; the mechanisms involved in dispersal from sidecast discharges are a combination of these and other processes that give rise to the formation and dispersal of the so called 'injection cloud'.

Earlier studies[14,15] have shown that under favourable conditions sidecast disposal methods can significantly improve the efficiency of dredging operations over that of hopper dump methods. This is effected by eliminating the time involved in hauling spoil to a disposal site, even though the disposal efficiency, ie the proportion of sediments effectively removed from the dredging area, may be reduced. This study indicates that the disposal efficiency of sidecasting may itself be improved by adopting methods which result in a higher proportion of spoil being dispersed into the injection cloud to be carried away by the current. Further discussion of such methods is outside the scope of this report but has been identified as an important area of research which has been neglected.

It is recommended that a future research programme should study in detail the physical processes that take place at the points of release of material from both hopper dump and sidecast disposal. The evidence suggests that the two methods of disposal should be considered separately until the process involved are better understood.

It is recommended that the mathematical models be developed to simulate more correctly the complex events taking place when dredged spoil is disposed of in ocean or estuarine waters. Such models should make use of the most recent research such as that described above and take full account of the works referenced in this report.

It is recommended that studies are also carried out into the longer term dispersal of spoil. This would involve studying the stability of the material at spoil grounds as a result of consolidation, and the possible redistribution under wave and tidal action.

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TABLE

DATA FOR SPOIL DISPOSAL EXPERIMENTS

Location	Mode of discharge	Particle size distribution (microns) d_{10}	d_{50}	d_{90}	Water depth at point of discharge (m)	Time of discharge	Max. Water velocity during discharge tide (m/s)
River Plate, (Argentina)	Continuous weir overflow	5	25	50	(3.8m on bank (9.5m* in channel	LW [1] + 1¼h	0.3
	Continuous side-cast				4.4	LW [1] + ½h	0.5
Severn Estuary (Cardiff), UK	Continuous weir discharge	<1	20	120	10.3*	HW + 2¼h	1.0*

Notes: 1 Tides in the River Plate are irregular: end of slack water period is used as LW reference.

* These data were not measured directly but are estimated from other compatible data sources.

APPENDIX The modified Hankel function

The modified Hankel functions are defined as:

$$K_m(z) = \frac{\pi}{2} i^{m+1} H_m^{(1)}(iz)$$

where $H_m^{(1)}$ is the Hankel function of the first kind.

K_m is a solution of the modified Bessels equation:

$$\frac{d^2w}{dz^2} + \frac{1}{z}\frac{dw}{dz} - \left(1 + \frac{m^2}{z^2}\right) w = 0$$

More pertinantly:

$$\tfrac{1}{2} \int_0^\infty \exp\left(-\xi - \frac{z^2}{4\xi}\right) \frac{d\xi}{\xi} = K_o(z); \; R(z^2) > 0$$

For large values of z

$$K_o(z) = \left[\frac{\pi}{2z}\right]^{\frac{1}{2}} e^{-z} \left[1 - \frac{1}{8z} + \frac{9}{128z^2} + 0\left(\frac{1}{z^3}\right)\right]$$

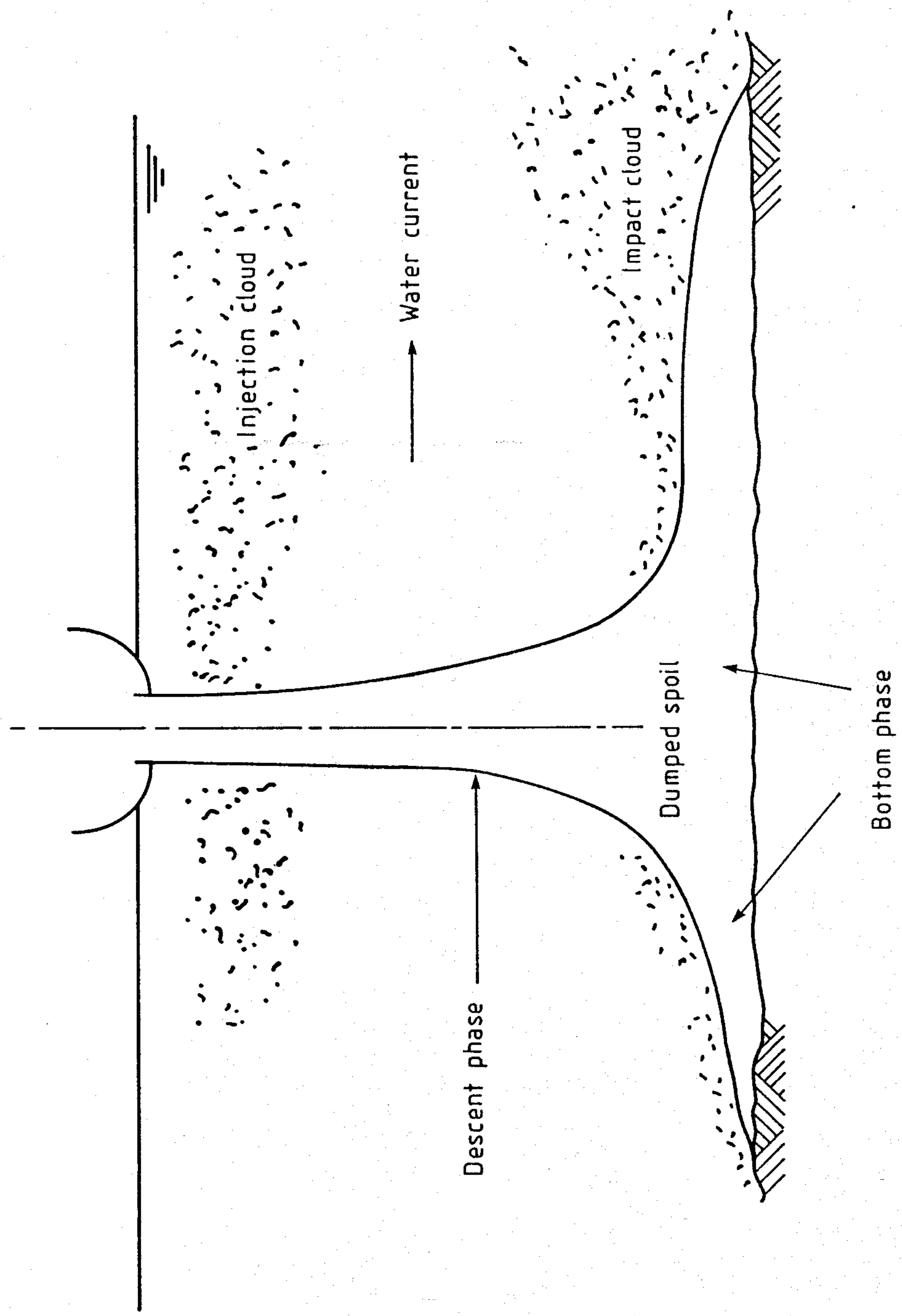


Fig 1 Schematic representation of a hopper dump

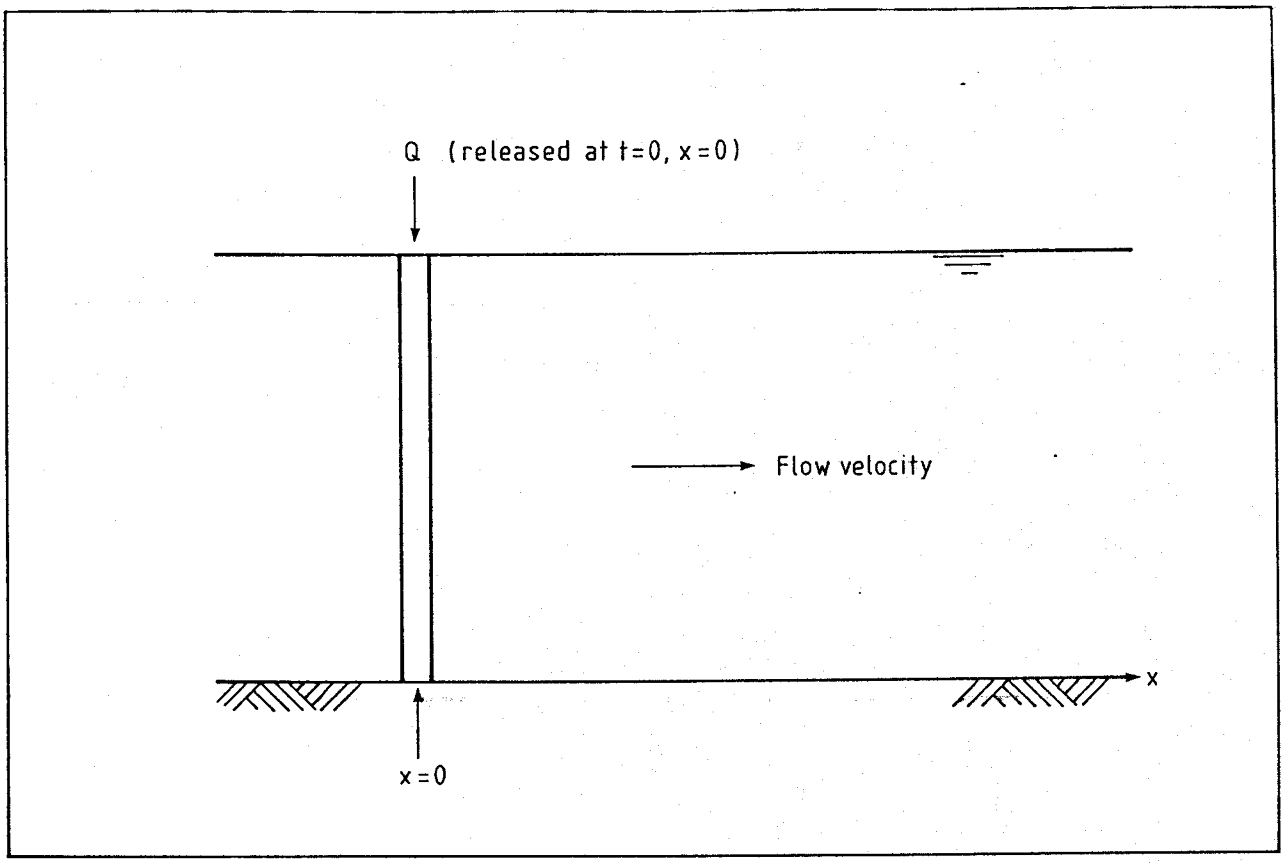


Fig 2 Instantaneous release of a slug of material

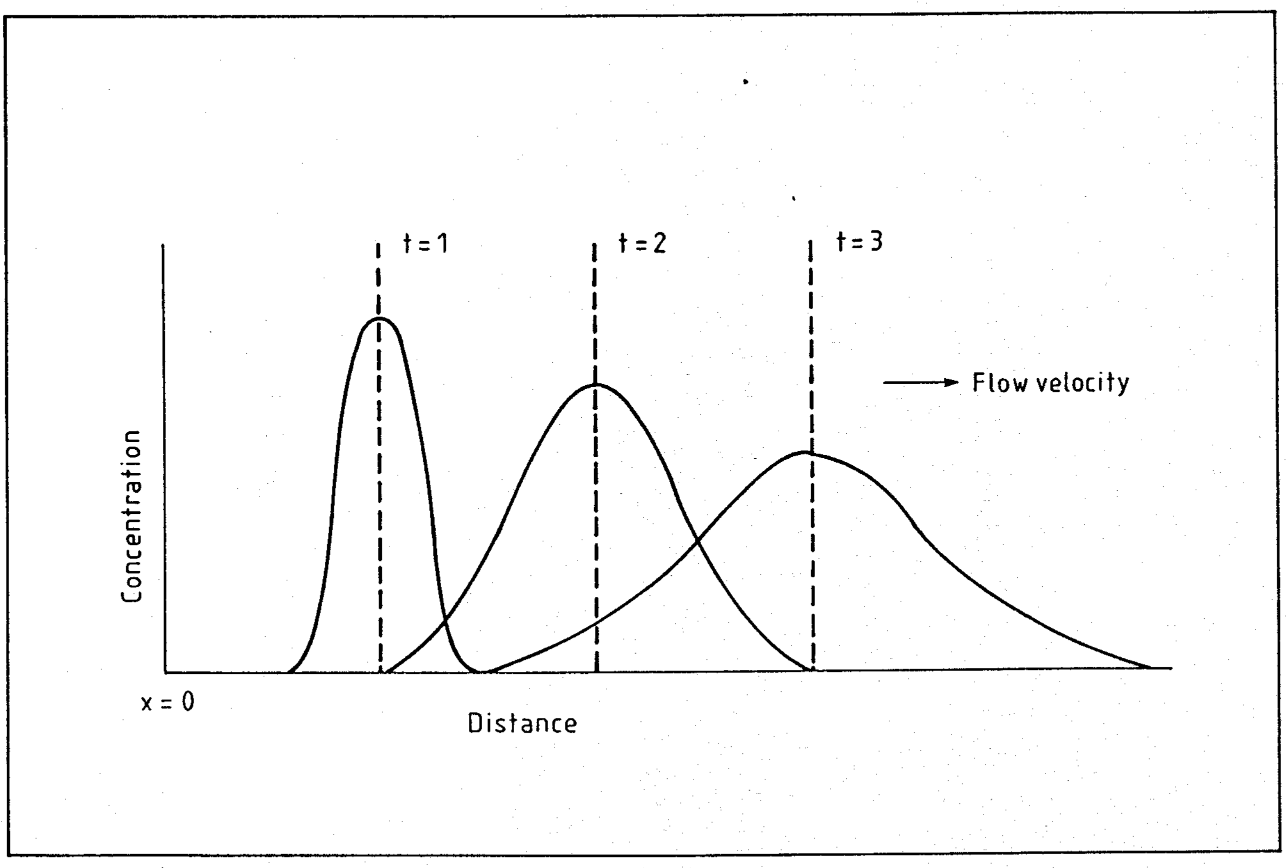


Fig 3 Gaussian concentration profile with centre moving downstream

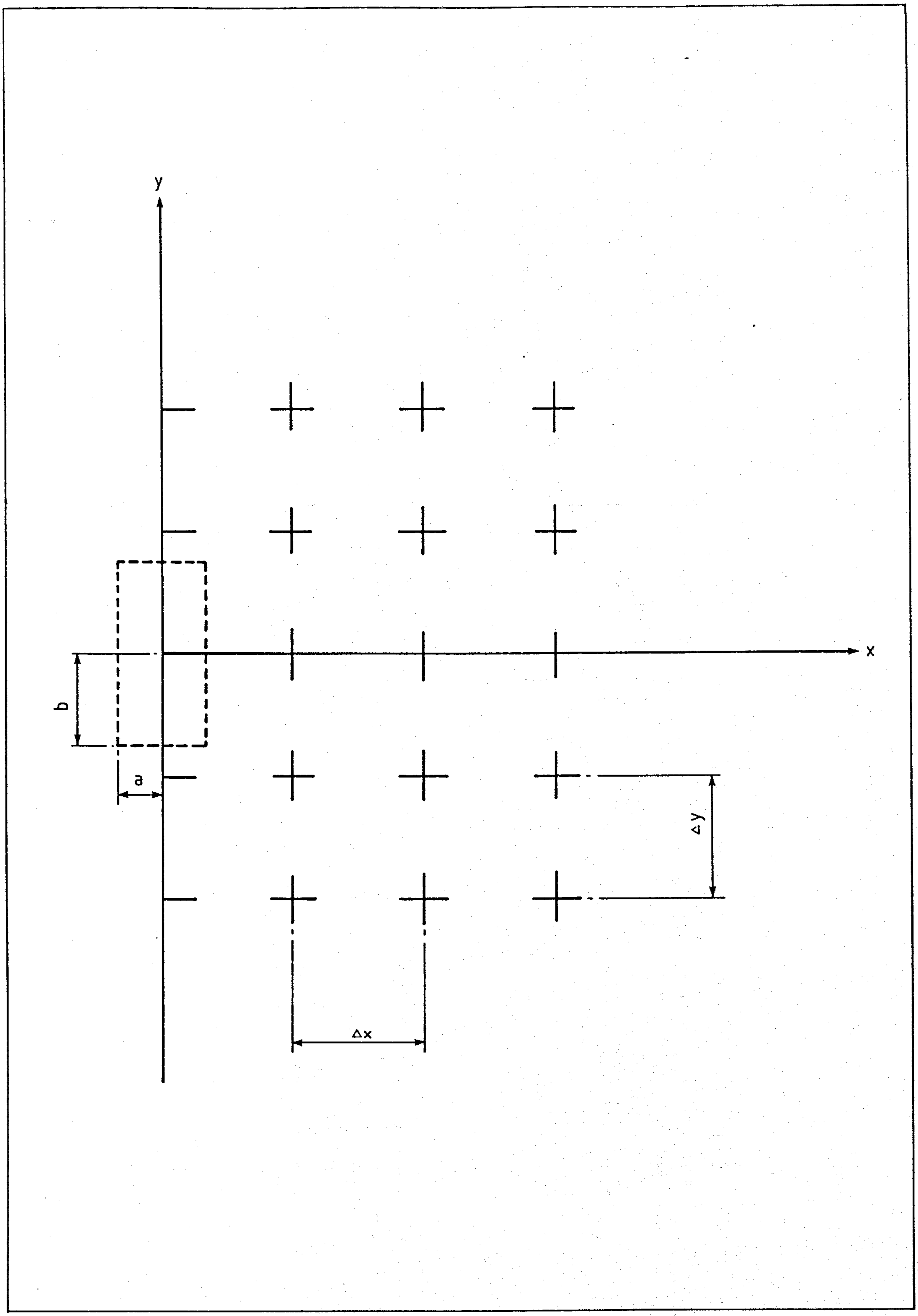


Fig 4 The model grid

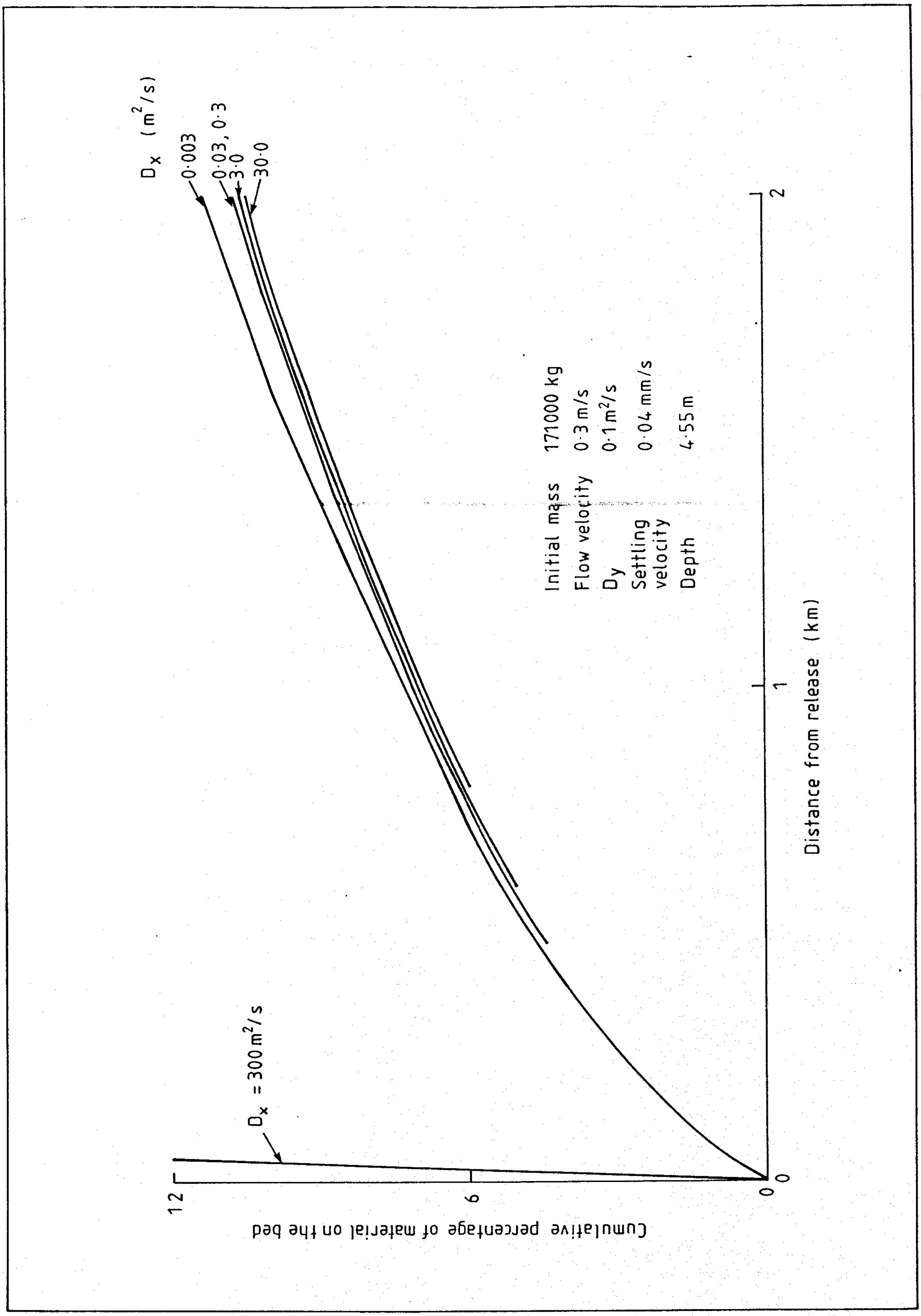


Fig 5 Sensitivity to longitudinal diffusion; point release

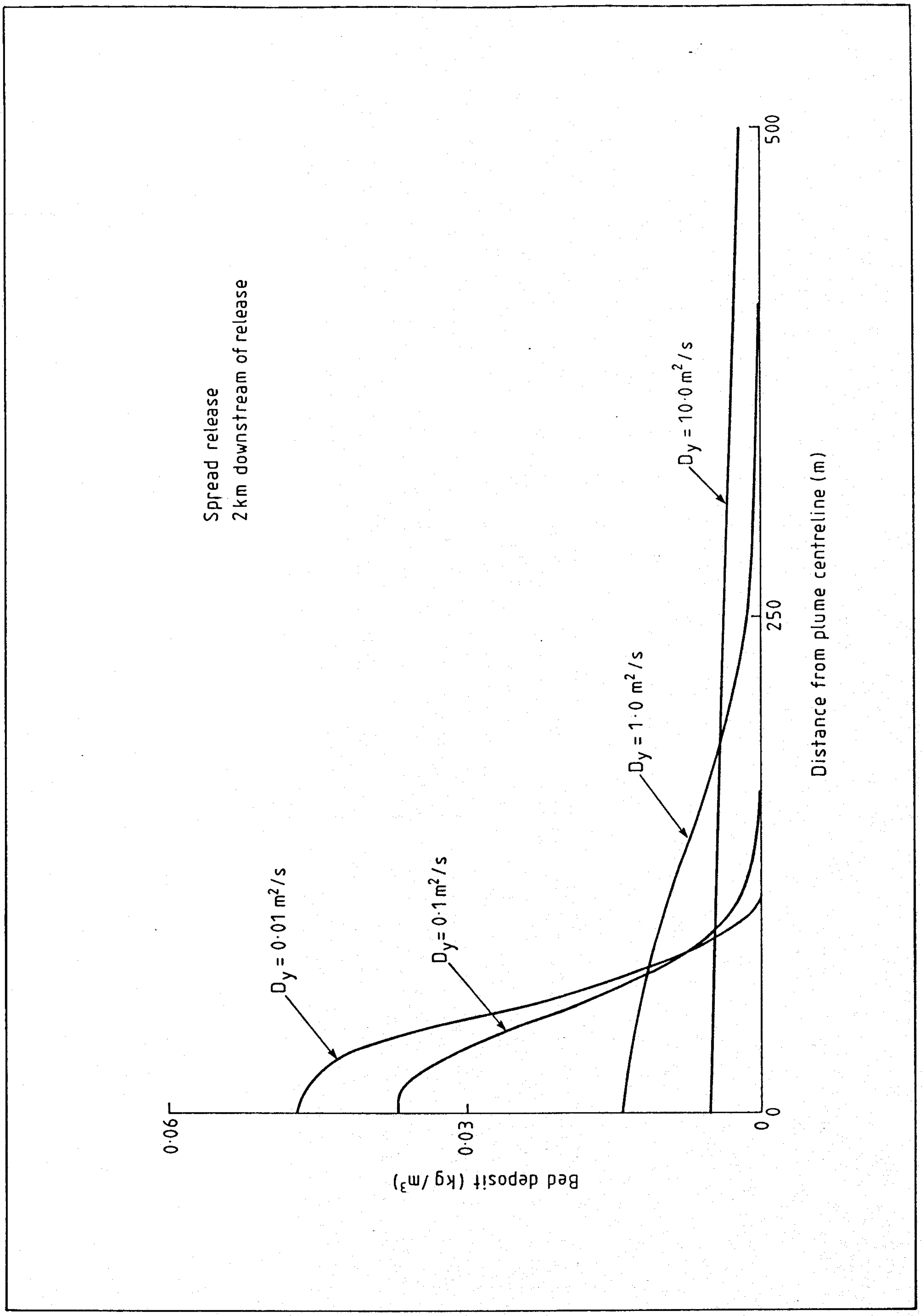


Fig 7 Sensitivity of lateral sediment distribution to lateral diffusion

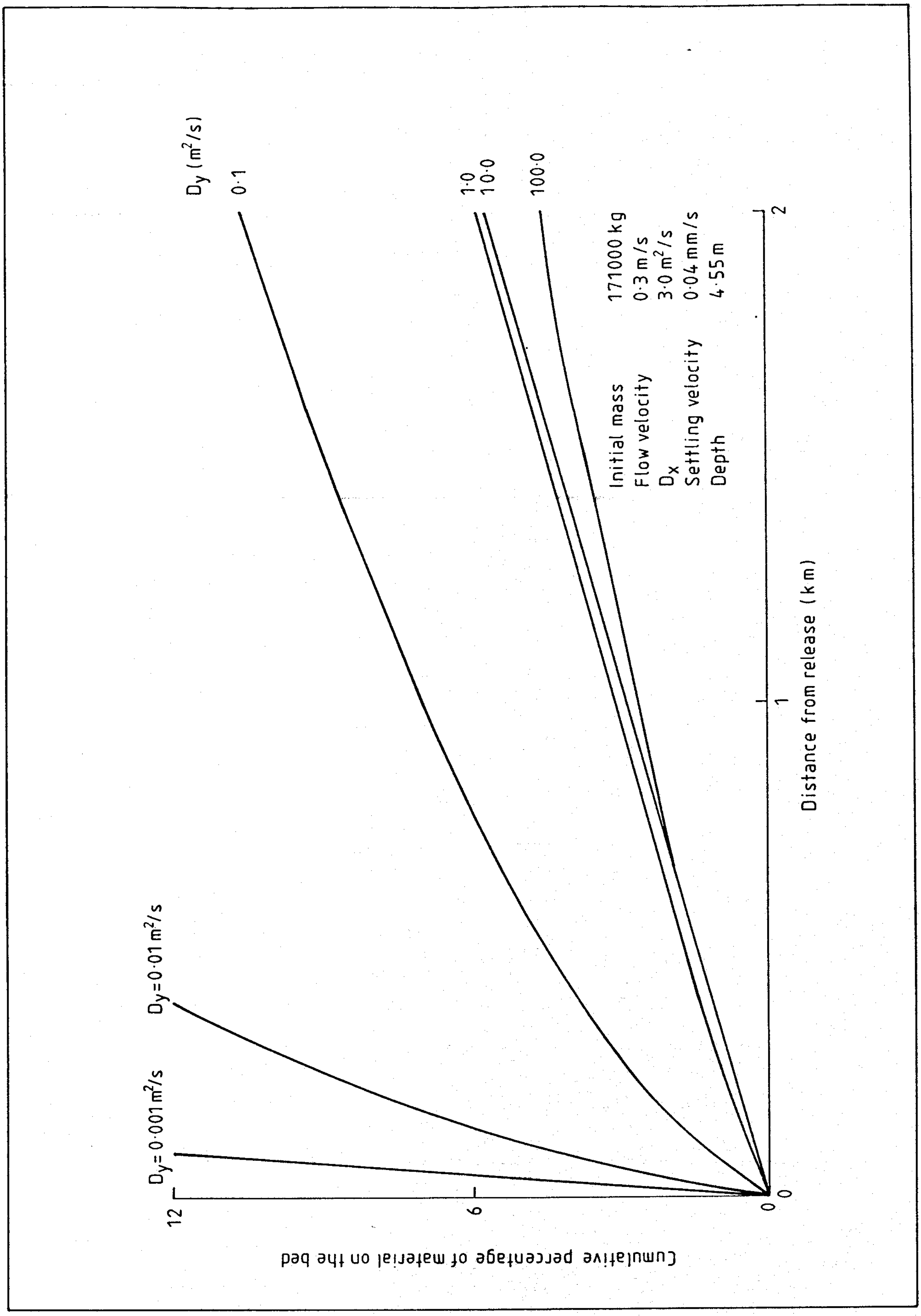


Fig 8 Sensitivity to lateral diffusion; point release

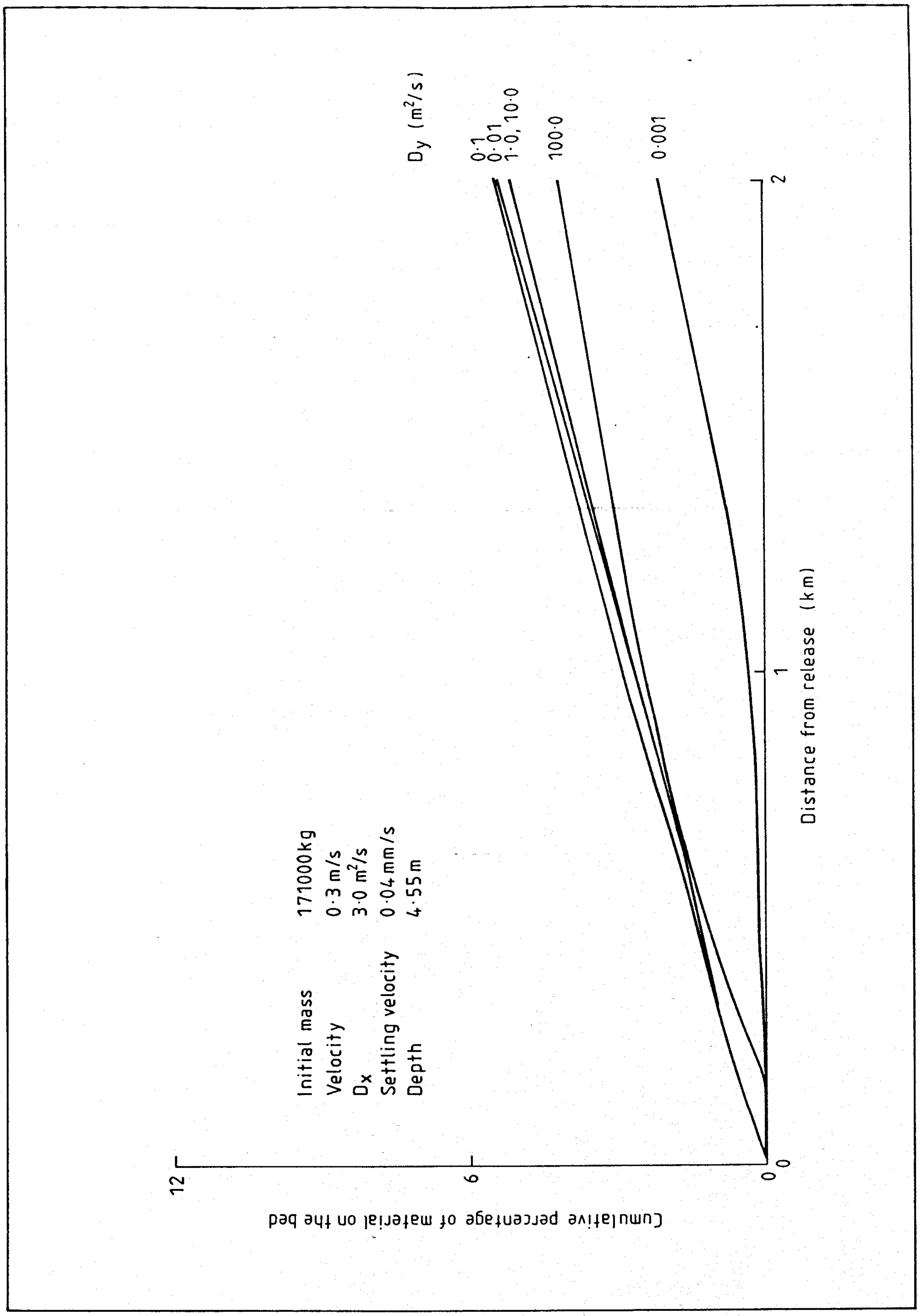


Fig 9 Sensitivity to lateral diffusion ; spread release

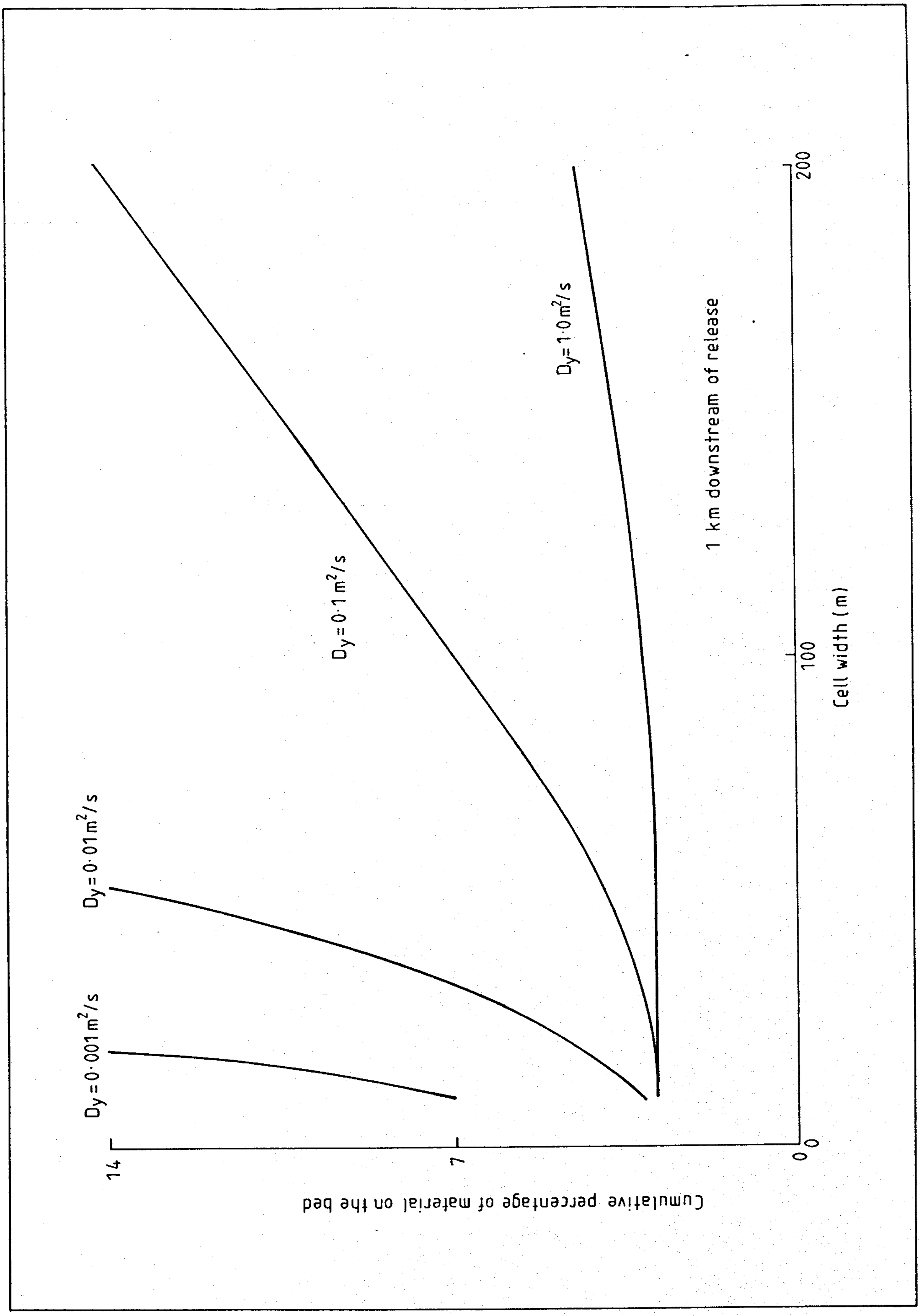


Fig 10 Sensitivity to cell width; point release

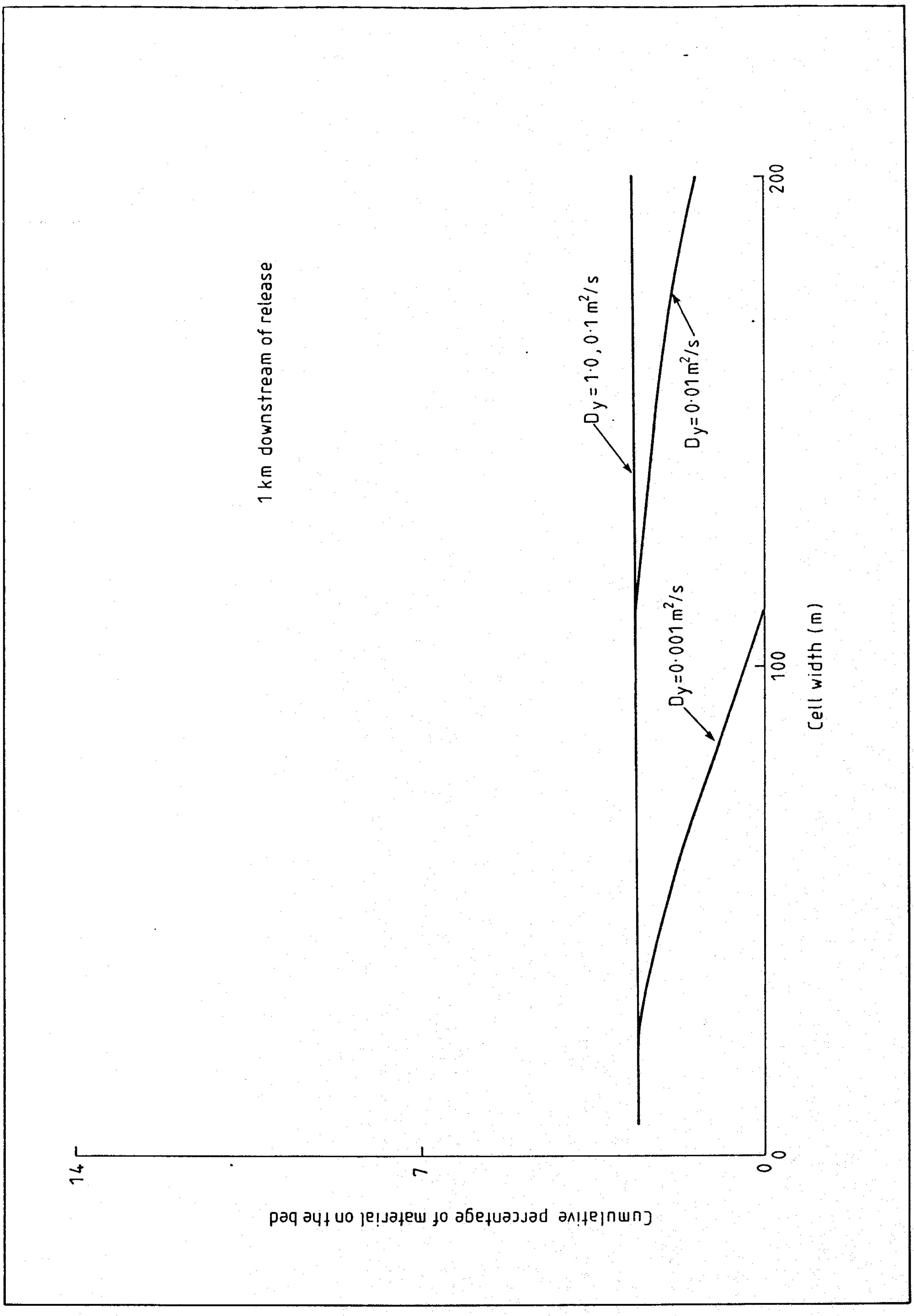


Fig 11 Sensitivity to cell width ; spread release

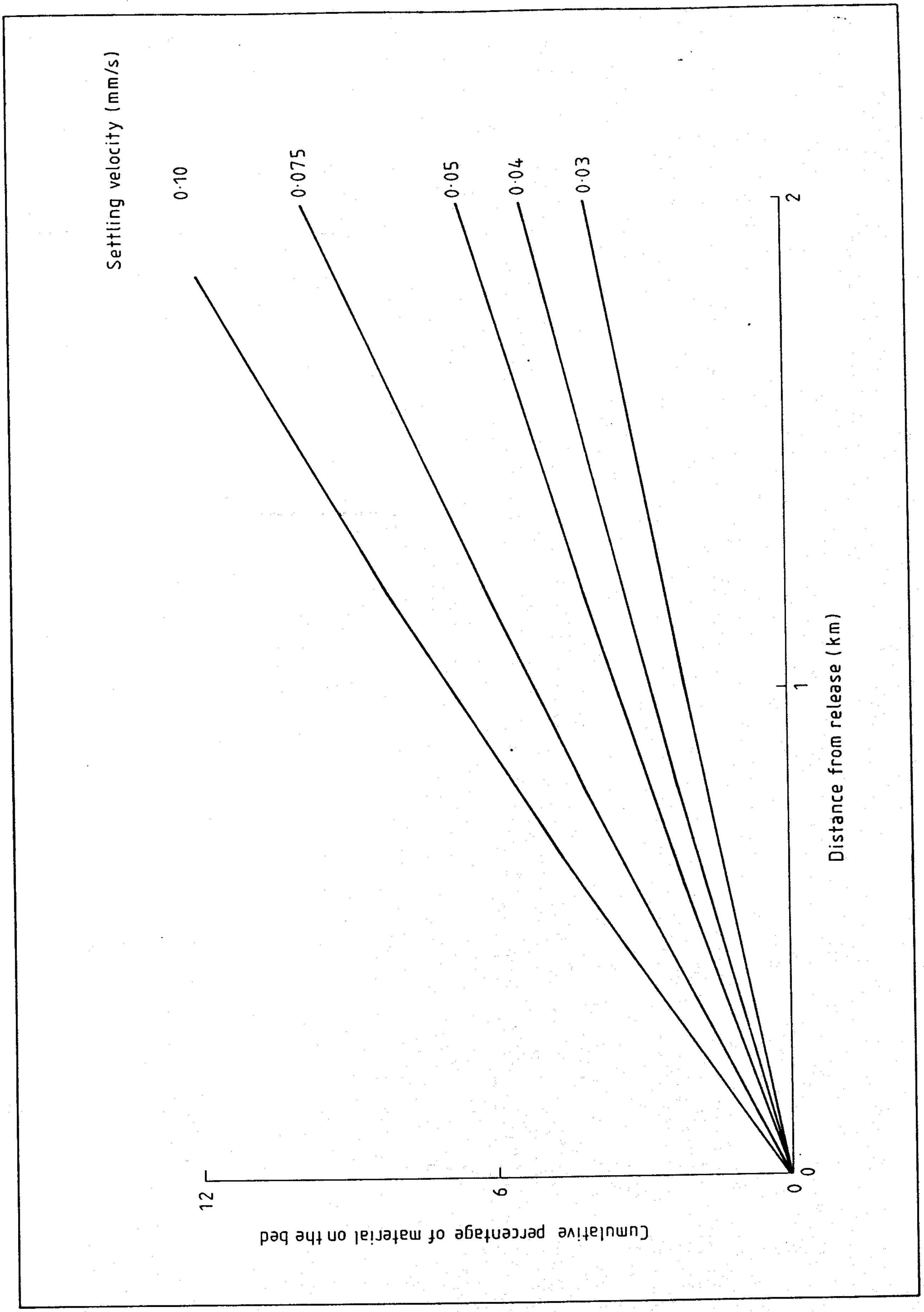


Fig 12 Sensitivity to settling velocity

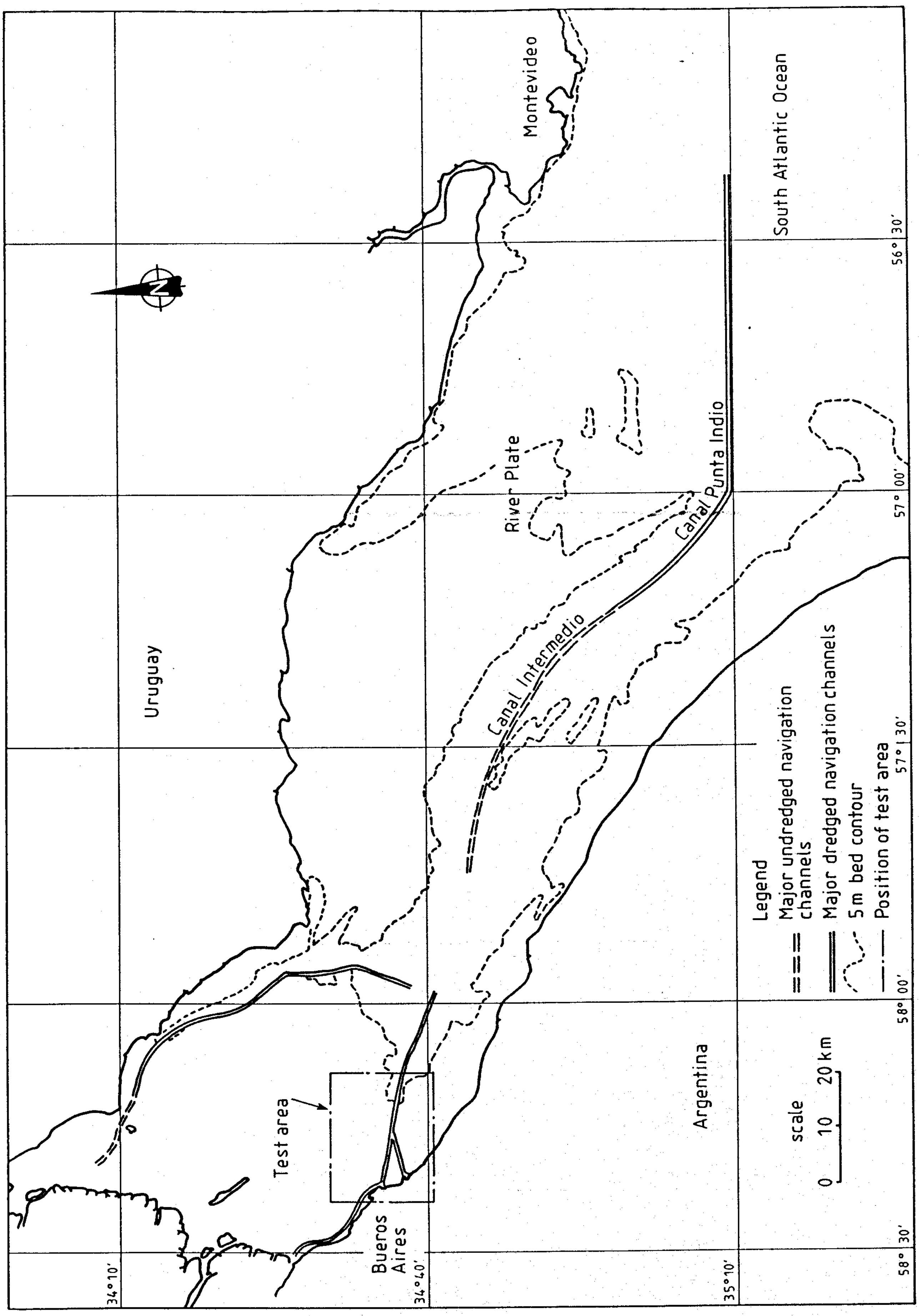


Fig 13 River Plate test site

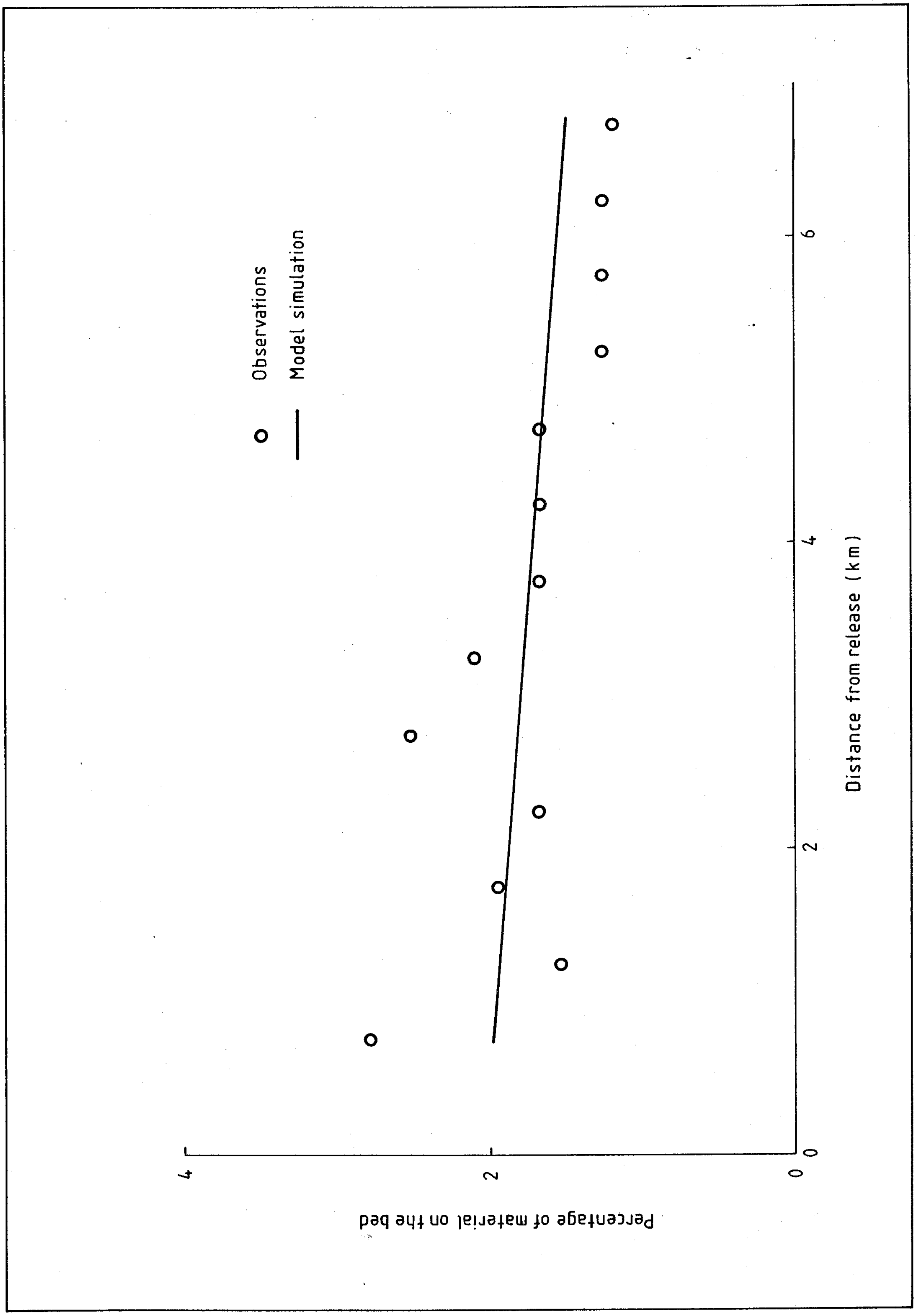


Fig 14   River Plate test D4; longitudinal sediment distribution

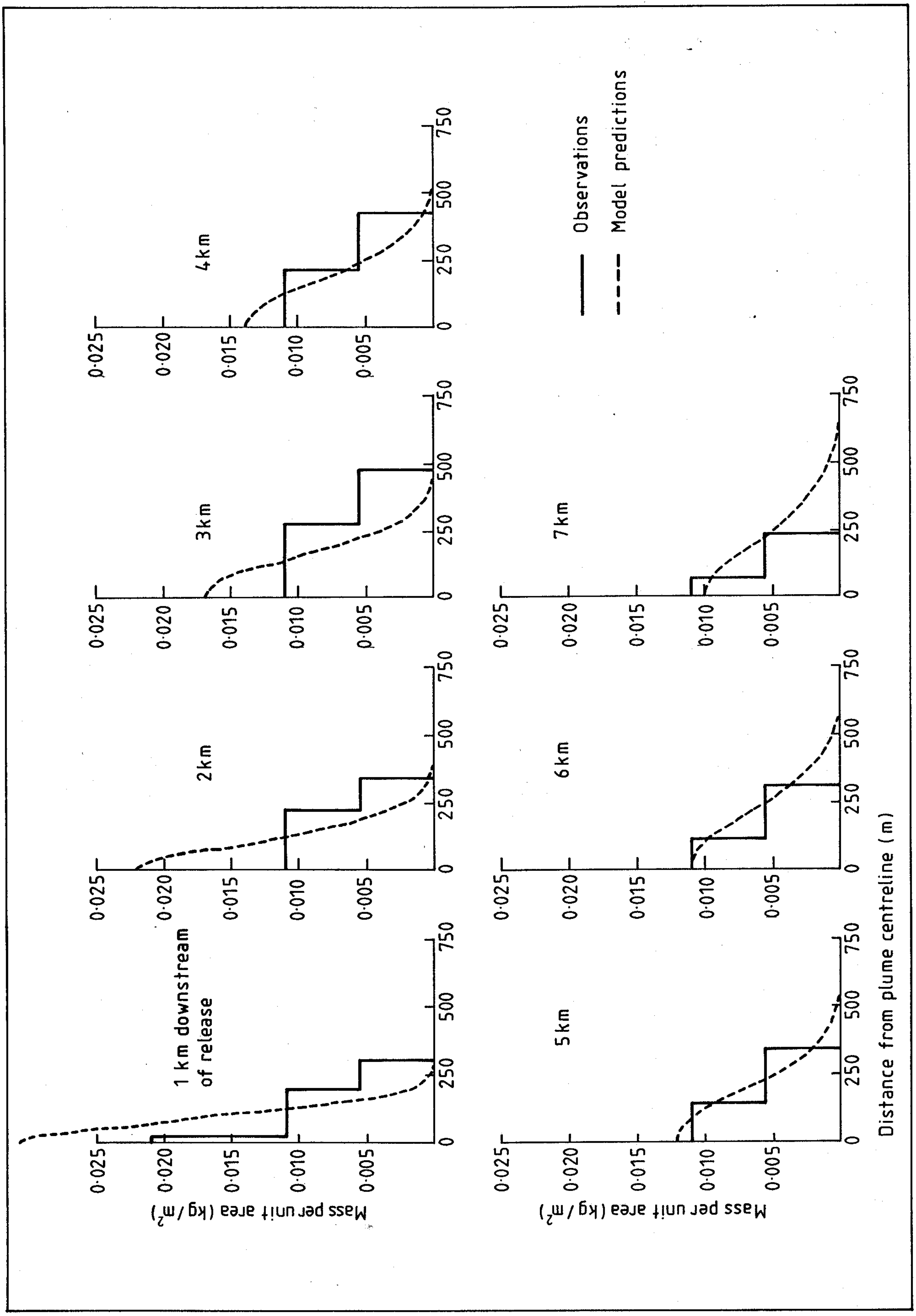


Fig 15 River Plate test D4; lateral sediment distribution

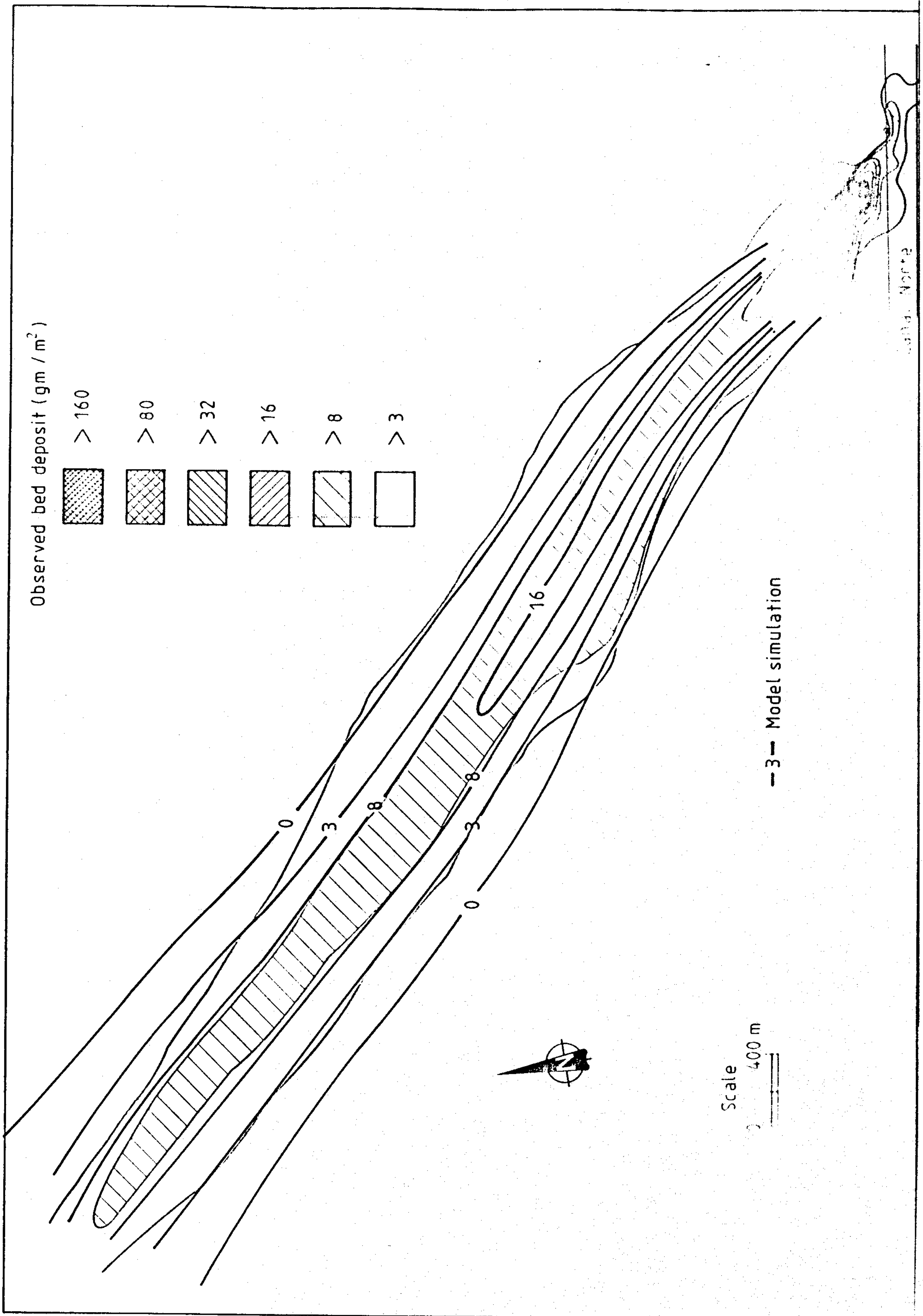


Fig 16 River Plate test D4; bed survey

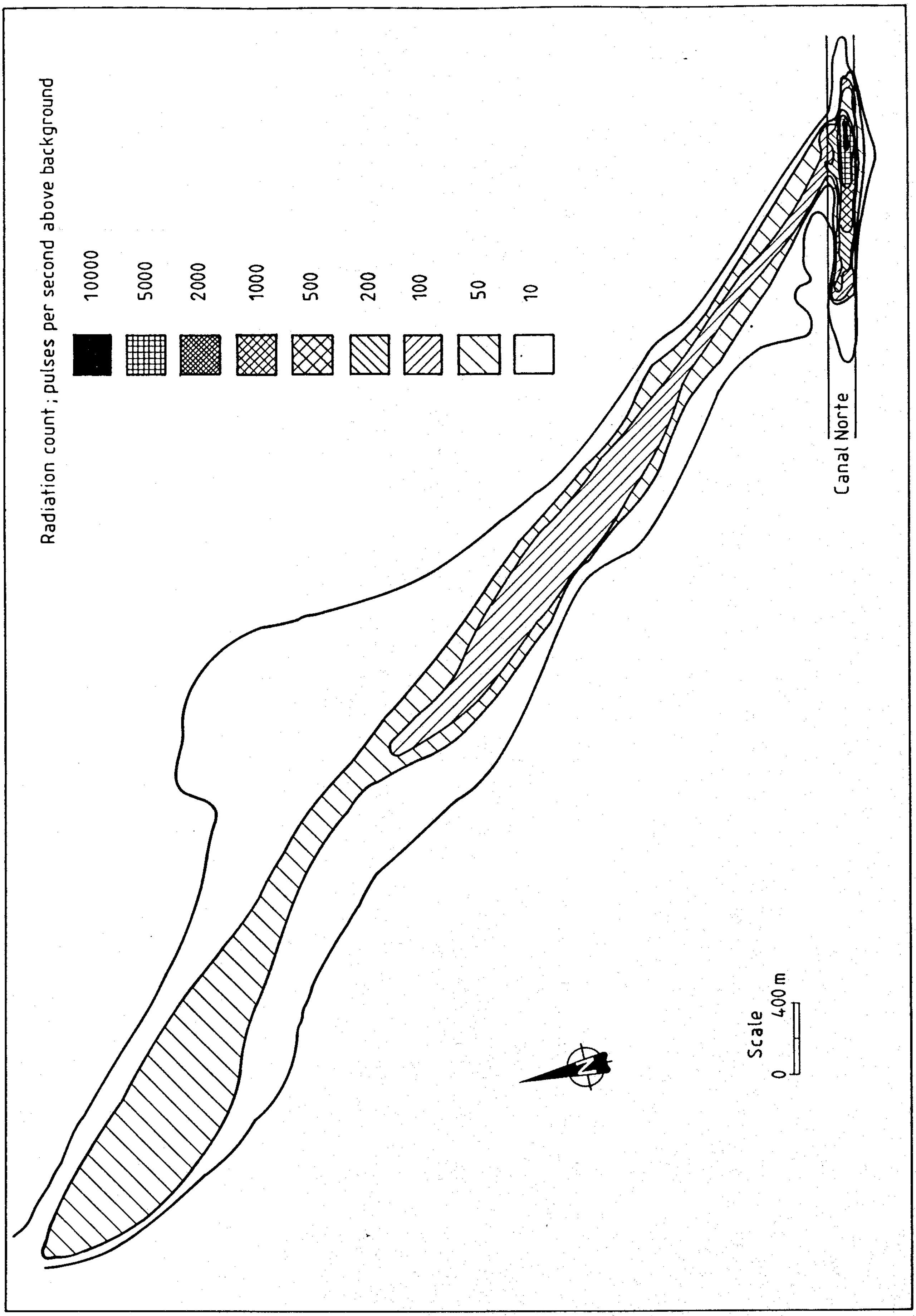


Fig 17 River Plate test D1; bed survey

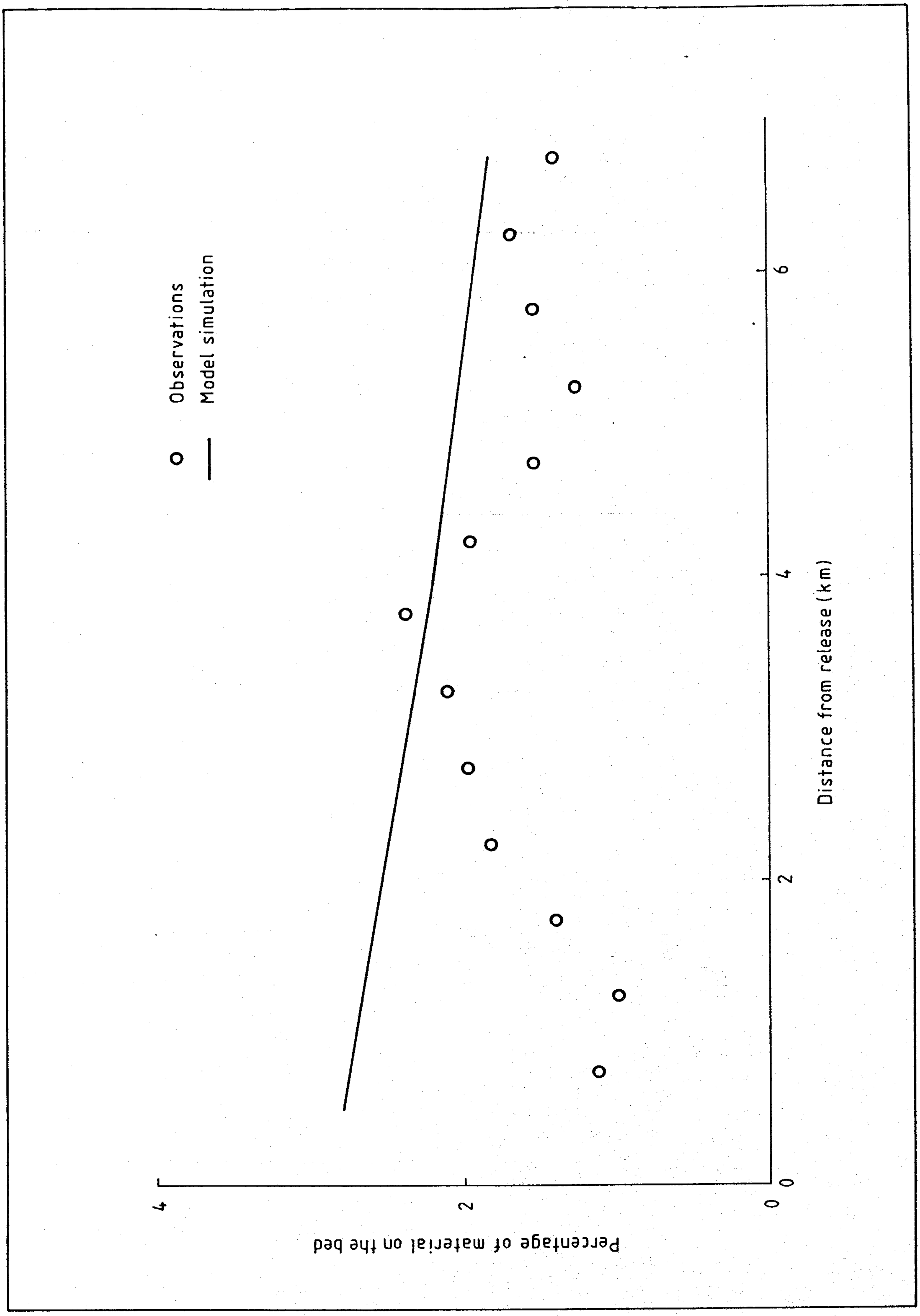


Fig 18 River Plate test D1; longitudinal sediment distribution

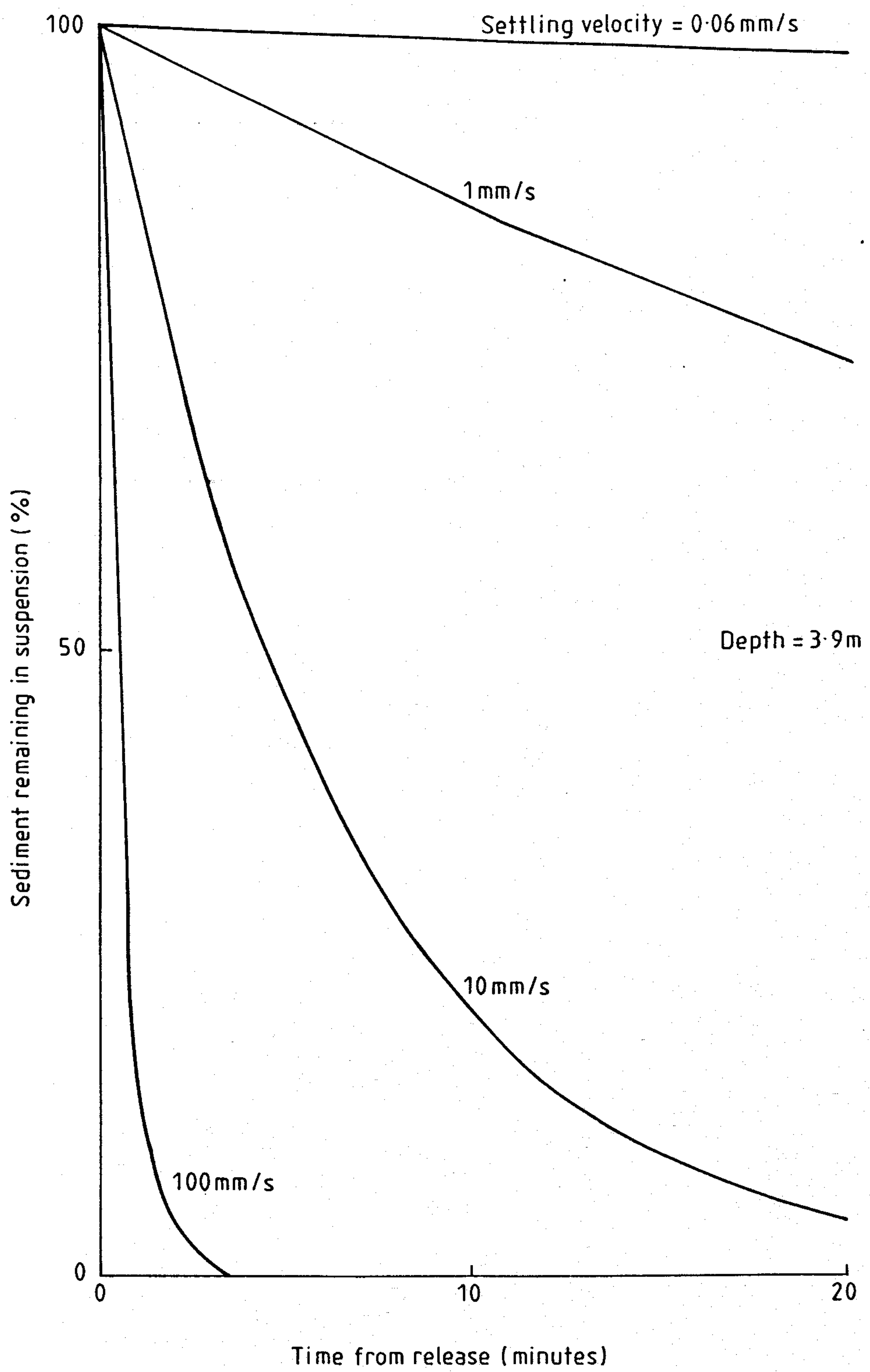


Fig 19 Sensitivity of deposition term to settling velocity

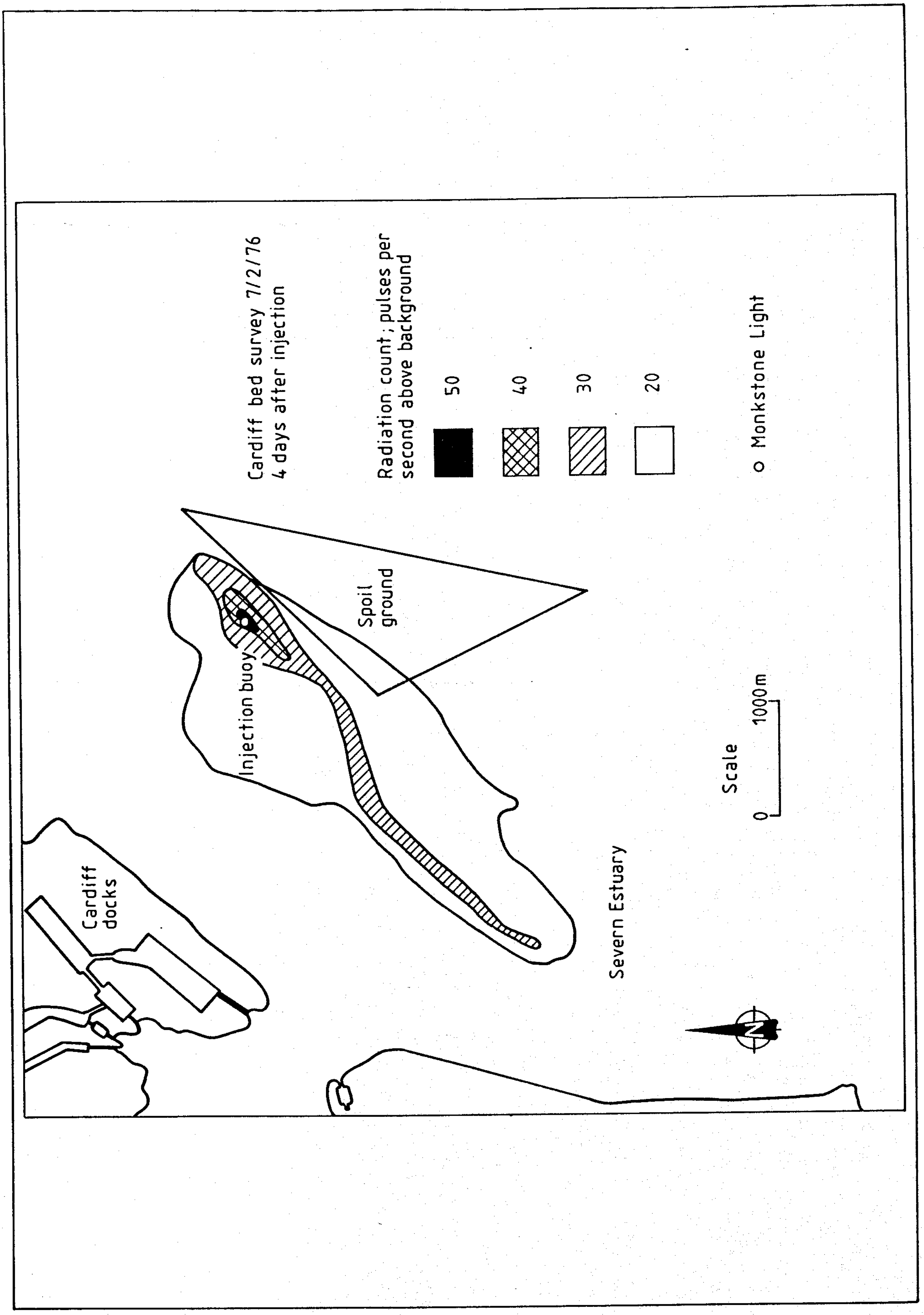
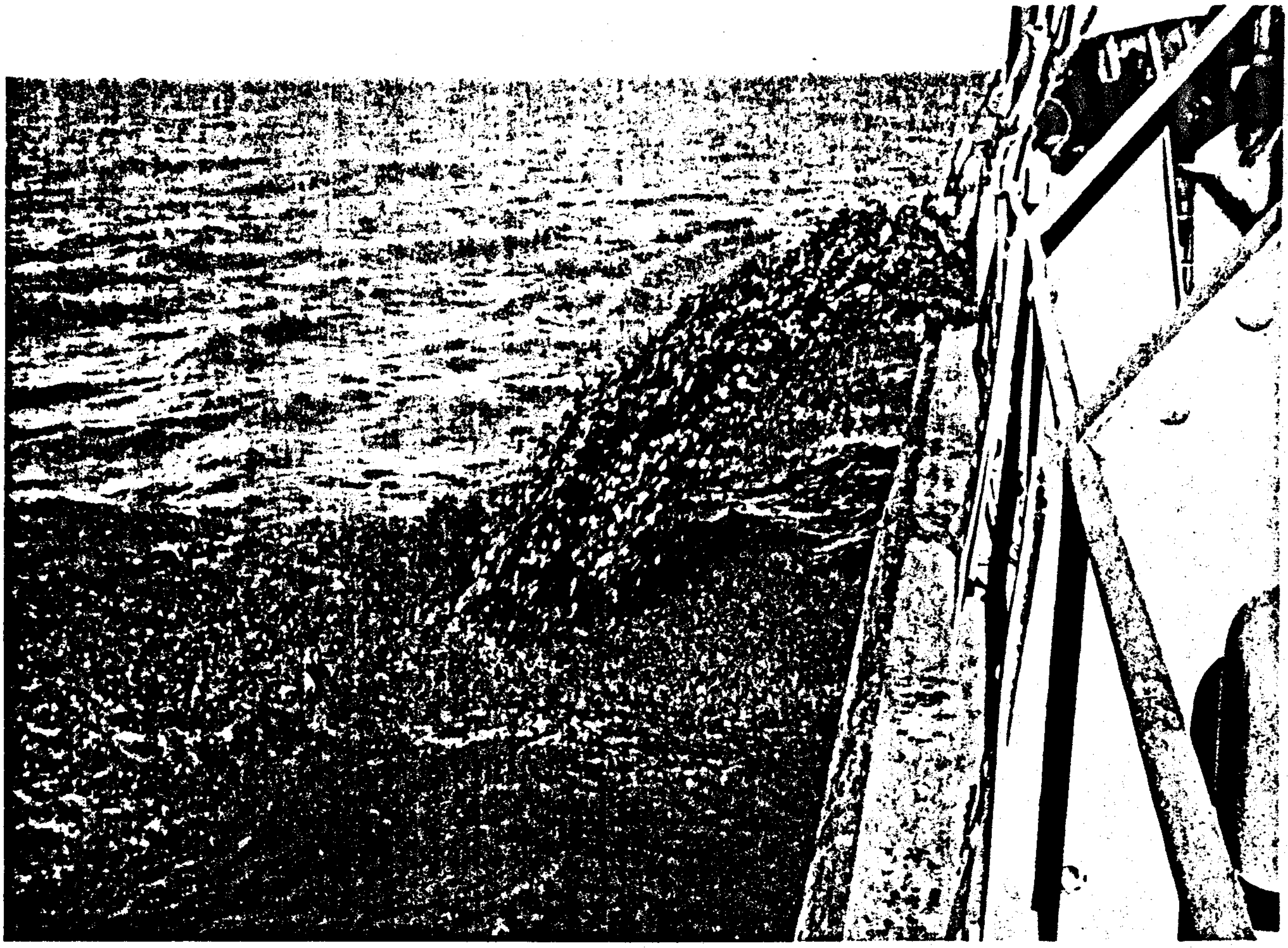
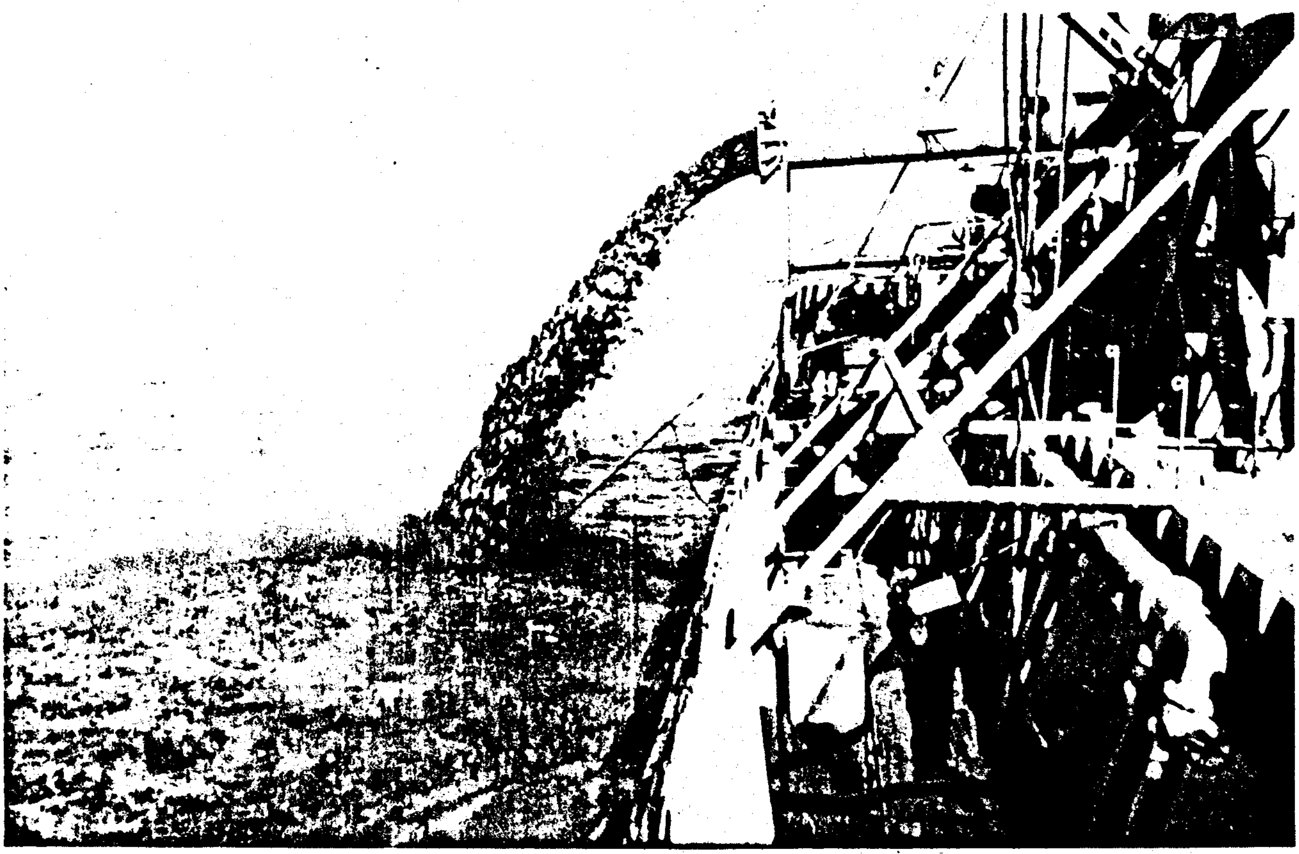


Fig 20 Severn Estuary; bed survey



a. Side discharge over hopper overflow weir



b. Side-casting through shore discharge pipe

PLATE Side discharge of dredged spoil