

The Optimum Location for a Canal Sediment Extractor

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ABSTRACT

A sediment extractor is a device for ejecting sand or gravel from irrigation canals or power channels. It operates on the near bed layer of the canal flow which usually contains a high proportion of the sediment being carried. If an extractor is located immediately downstream from a structure, such as a canal headregulator gate, it will not operate effectively because the high level of turbulence will cause the sediment to be well mixed. Canal bends can also reduce the effectiveness of a sediment extractor because they introduce a swirling motion into the channel flow which causes the high sediment concentrations near the bed to be swept towards the inner bank of the bend. This report sets out methods for determining a suitable location for a sediment extractor so that its performance will not be impaired by structures or bends.

The variation of sediment concentration with height above the channel bed is termed the sediment concentration profile. When the sediment in the flow has settled to an equilibrium state where particle settling is balanced by mixing in the flow, then the profile is an equilibrium sediment concentration profile. The distance from the head of a canal to the point at which an equilibrium profile is established is called the adaption length.

This report describes two methods for predicting the adaption length. The first method uses simplifying assumptions to solve the equation which describes the sediment settling and mixing processes, and the results are used to produce a table for predicting adaption lengths. The second method uses a computational fluid dynamics computer code ('PHOENICS') to simulate the conditions in a channel downstream from a structure without the use of simplifying assumptions. The results of the two methods are compared and little difference between them is found if a 50% increase in adaption length is applied to the simpler method to account for its approximations.

The computational fluid dynamics code was then applied to canal bends. Firstly its predictions were compared with two sets of laboratory data and good agreement was found. The effect of field scale bends on adaption length was then examined and the results are presented in a second predictive table.

SYMBOLS

- C - sediment concentration profile (ppm)
- C_b - sediment concentration at height k_b above the bed (ppm)
- E - ratio of sediment removed to incoming sediment
- Fr - Froude number (= \bar{u}/\sqrt{gh})
- g - gravitational constant = 9.81 (m/s²)
- h - flow depth in the canal (m)
- i - non-dimensional secondary flow intensity in a bend
- k - turbulent energy (m²/s²)
- k_b - height of the bed boundary layer (m)
- k_s - bed roughness height (m)
- L_a - adaption length (m)
- l - length of a settling basin (m)
- R_c - radius of curvature (m)
- u_y - velocity at height y (m/s)
- \bar{u} - mean velocity in the canal (m/s)
- \bar{u}_c - critical mean velocity in the canal (m/s)
- u^* - bed shear velocity (m/s)
- V_s - settling velocity (m/s)

- W - bed width (m)
- w - secondary flow velocity in a channel bend (m/s)
- X_t - sediment transporting capacity of channel flow (ppm)
- x - distance along the channel (m)
- y - height above the bed (m)
- β - ratio of sediment diffusion to momentum diffusion
- ϵ - dissipation rate of turbulent energy (m^2/s^3)
- ϵ_x - sediment diffusion coefficient in the horizontal direction (m^2/s)
- ϵ_y - sediment diffusion coefficient in the vertical direction (m^2/s)
- ϵ_s - sediment diffusion coefficient (m^2/s)
- ϵ_m - momentum diffusion coefficient (m^2/s)
- ν - kinematic viscosity (m^2/s)

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1. INTRODUCTION

This report describes methods for determining the optimum location for a sediment extractor in an irrigation canal. Extractors are used to reduce sediment deposition in canals by extracting sediment from the flow near the canal bed. The maximum benefit is obtained when the extractor is located at a point where the sediment concentrations have adjusted from the mixing introduced by the intake (or canal bends) and have settled to a vertical profile with sediment concentrated near the bed. This location is determined by predicting changes in the vertical sediment concentration profile along a channel.

1.1 Background

Water which is diverted from rivers to irrigation canals often contains high concentrations of bed material sediments. If the sediment load entering a canal exceeds its transporting capacity, then sediment will settle in the canal and reduce its conveyance capacity. The removal of sediment deposits is expensive and a considerable drain on a project's finances. One solution is to install a sediment extractor in the canal headreach, such as a vortex tube sediment extractor. These devices remove water and sediment from the near bed region, which contains the highest sediment concentrations in the flow profile. The extracted flow is passed to an escape channel which usually returns the water and sediment to the river. Extensive research on sediment extractors has been carried out at HR Wallingford by, Sanmuganathan (1976), Lawrence and Sanmuganathan (1981), Atkinson (1987) and Atkinson (1990). The research has been used to produce a design manual, HR Wallingford (1991).

Several factors affect the performance of a sediment extractor, including extractor location and canal layout. At the head of a canal, the headworks structures generate turbulence and recirculation causing the transported sediment to be mixed within the flow. Further downstream the turbulence decays and the sediment begins to settle. The sediment becomes less well mixed, until eventually a balance between sediment settling and mixing is established. The variation of sediment concentration with height above the canal bed is then termed the equilibrium sediment concentration profile. In this report the distance from the head of the canal to this point of equilibrium is referred to as the adaption length.

If a sediment extractor is located too close to the headworks, where sediment is well mixed, the trapping efficiency will be reduced. On the other hand locating the extractor too far away from the headworks increases the distance over which sediment deposition will occur. A further consideration is canal bends which can distort an equilibrium sediment concentration profile and so impair the trapping efficiency of an extractor. The location of a sediment extractor, therefore, needs to be optimised. It should be set at the point where the sediment concentrations have just completed adaption, that is at a distance from the canal intake equal to the adaption length. It is the purpose of this report to present methods for predicting adaption length.

If the flow is uniform and quiescent (i.e. without turbulence) then the adaption length can be taken as the distance required for a sediment particle to settle from the water surface down to the bed. This distance is $\bar{u}h/V_s$, where V_s is settling velocity, \bar{u} is the mean velocity and h the flow depth.

However, the flow in a real canal will not be quiescent because turbulence is generated at the headworks, at the channel boundaries, and by bends. Ahmad (1962) refers to a design where an extractor was placed at $10 \bar{u}_c h/V_s$, where \bar{u}_c is the critical velocity. This is equivalent to the quiescent settling adaption length multiplied by $10/Fr$, where Fr is Froude number. The reason for Ahmad's use of critical velocity is not clear.

A more rational approach is to simulate the sediment settling and mixing processes to obtain a prediction for adaption length. In this report we consider first the simpler case of adaption from mixing at an intake in a straight channel (Chapters 2,3 and 4). The effect of bends is then considered in Chapter 5.

The report describes two methods that can be applied to a straight channel. The first method, which is presented in Chapter 2, uses simplifying assumptions to obtain an analytical solution to the turbulent diffusion equation for sediment. The second method, which is described in Chapter 3, uses a computational fluid dynamics computer code to calculate the flow velocities and sediment concentrations in a canal headreach. In the latter method fewer assumptions are made to simplify the conditions being simulated, so, for example, the turbulence and recirculation introduced by a gate at the entrance to canal is included in the simulation. This more accurate method is compared with the predictions of the simpler method in Chapter 4.

The method using a computational fluid dynamics code was then used to predict the effects of canal bends on adaption lengths.

It is important to note that, as sediments of different sizes settle at different rates, the adaption length is different for each sediment size fraction entering a canal. Adaption length also varies with the discharge in the channel, which will not be constant. Consequently, the adaption length should be regarded as only an approximate measure for the ideal distance between an intake and a sediment extractor, and should be used to guide a decision that will be influenced by other factors such as the need to dispose of the extracted sediment.

2. ADAPTION IN A STRAIGHT
CANAL: ANALYTICAL SOLUTION

The adaption length in a straight channel can be predicted by solving the differential equation which describes the effects of sediment settling due to gravity and sediment mixing due to turbulence, termed the turbulent diffusion equation. The basic equation is given in Dobbins (1944) :

$$U_y \frac{\partial C}{\partial x} = \epsilon_y \frac{\partial^2 C}{\partial y^2} + (V_s + \frac{\partial \epsilon_y}{\partial y}) \frac{\partial C}{\partial y} + \epsilon_x \frac{\partial^2 C}{\partial x^2} \quad (1)$$

Where y = height above the bed (m)

U_y = flow velocity at height y above the bed (m/s)

C = sediment concentration at height y above the bed (ppm)

x = distance along the channel (m)

ϵ_x = sediment diffusion coefficient in the x direction (m^2/s)

ϵ_y = sediment diffusion coefficient in the y direction (m^2/s)

V_s = settling velocity (m/s)

In Equation 1 it is assumed that the concentrations and velocities are uniform across the width, and that the flow is steady. It can also be assumed that sediment diffusion in the x direction is negligible, and can therefore be ignored (Dobbins, 1944). The expression for ϵ_y given by Lane and Kalinske (1942) can be used:

$$\epsilon_y = h u^* / 15$$

Where h = flow depth (m)

u^* = shear velocity (m/s)

By assuming this constant expression for ϵ_y we have further simplified Equation 1. This has introduced some inaccuracy, in particular we have assumed that only the shear velocity (u^*) is affecting turbulence and so the increased turbulence near the intake gate is ignored. If we also assume that the velocity profile is uniform (ie $u_y = \bar{u}$), then Equation 1 becomes:

$$\bar{u} \frac{\partial C}{\partial x} = \epsilon_y \frac{\partial^2 C}{\partial y^2} + V_s \frac{\partial C}{\partial y} \quad (2)$$

Equation 2 can be solved analytically. Its boundary conditions can now be considered. At the free surface sediment is prevented from crossing the boundary, hence:

$$\epsilon_y \frac{\partial C}{\partial y} + V_s C = 0 \quad \text{at } y=h$$

We assume that at the bed boundary the entrainment of sediment is not affected by suspended sediment concentrations in the flow above a bed boundary layer, and that the top of the bed boundary layer is fixed at a height of k_b . We take $k_b = 0.05h$. However the predictions of Equation 2 are not greatly affected by

the value chosen for k_b (Kerssens et al, 1979). These assumptions imply that the entrainment rate is related only to bed shear and sediment size. The shear velocity u^* is assumed to be constant in the canal headreach and so the entrainment rate is also assumed to be constant. Its value can be derived by determining the entrainment rate required to produce a sediment load equal to the sediment transporting capacity when an equilibrium concentration profile has developed.

A description of an analytical method used to solve Equation 2 is given in Dobbins (1944). A similar method, also using Fourier analysis, has been applied here.

The conditions which were taken to obtain values for adaption length were high sediment concentrations at input to the canal headreach adapting to the sediment transporting capacity, X_t . Uniform concentrations were assumed at the head of the canal. The value of X_t is chosen before the solution is made, and the value of entrainment rate calculated from it. The adaption length itself is taken as the distance from the head of the canal to the point at which the excess concentration falls below 5% of the original excess concentration. The calculations were performed with an original sediment load of twice transporting capacity and also five times transporting capacity. The resulting adaption lengths differed by only a few percent.

Because the solution assumes a uniform velocity profile and does not account for flow disturbances and mixing introduced by the intake gate, it is likely that the method will under-estimate the adaption length. To account for this the predicted values of adaption length were increased by 50%, following recommendations by UPIRI (1975).

Table 1, which is copied from the HR design manual for sediment extractors, was computed using the method described above. It gives predicted adaption lengths as a function of discharge per unit width, sediment diameter and channel Froude number. The Engelund (1966) alluvial friction relationship was used to derive the shear velocity for the calculation of ϵ_y . The discharge, Froude Number and bed material sediment sizes were taken as the input to Engelund's relationship. Bed sediment sizes were estimated from the size in transport. The adaption length is given for only a single sediment size fraction, the median sediment grain size entering the canal. Adaption length increases as the discharge and Froude number increases, but decreases as the sediment entering the canal becomes coarser.

3. ADAPTION IN A STRAIGHT CHANNEL: PHOENICS SIMULATIONS

The method described in the previous section makes several simplifying assumptions in order to obtain an analytical solution to the sediment diffusion equation. In particular it assumes a constant sediment diffusion coefficient along the canal reach. Thus there is an uncertainty in its predictions of adaption length. In order to assess the errors which the simplifying assumptions have introduced it is necessary to model turbulence more realistically. A numerical model is required which can solve the flow velocities, turbulence levels and sediment concentrations at a large number of discrete points. For this purpose a commercially developed flow solver, or computational fluid dynamics (CFD) code, was used. It is the PHOENICS code (Malin and Proumen, 1989). The PHOENICS software package simulates fluid flow, turbulence, heat transfer and combustion. It has been successfully used in previous studies of sediment

control processes (Atkinson, 1989). The calculations are made on a grid of computational cells which can be one, two or three dimensional. In this case the grid is two-dimensional. PHOENICS uses an iterative technique to obtain a final solution: an initial guess is improved upon by successive sweeps through the grid of computational cells until the calculations reach an acceptable degree of accuracy (the criteria for convergence are chosen by the user). For each simulation the user is required to specify the size, number and layout of the cells, the fluid properties, the phenomena to be simulated, the boundary conditions, the number of sweeps and other variables.

The PHOENICS package allows a user to introduce his own coding to enable solutions to problems which are not covered by the standard code. The facility has been used in this study to simulate sediment settling. Sediment is simulated using the PHOENICS coding for concentrations, in the same way as dye in the water would be simulated. However, the effect of the settling velocity is imposed on the solution by specifying a sink of material from each cell equal to the product of sediment concentration, settling velocity and fluid density. This sink is partly offset by a source of material equal to the sink from the cell immediately above. This method of solution was tested by comparing the resulting simulations with analytical solutions.

Some of the more important features of the application of PHOENICS to the flow in a canal headreach are outlined in the following three sections.

3.1 Boundary conditions

The free surface of the canal flow is represented by a frictionless horizontal boundary, and the free surface

slope by a pressure gradient (which results in a slight, but insignificant distortion in the flow geometry). The local drawdown of the water surface immediately downstream of the canal headworks is not taken into account.

The canal bed boundary is represented by a rough wall logarithmic law (specified by a roughness height, Launder & Spalding, 1974). The bed boundary condition for sediment concentrations is described in the same way as for the analytical solution of Chapter 2: a constant entrainment rate is assumed and its value related to the sediment transporting capacity when an equilibrium concentration profile has developed. Although sediment can be deposited at the bed in the simulations, time varying effects are not included and so bed level changes due to deposition or scour are not simulated.

At the upstream boundary, drowned flow through a vertical lift gate was modelled (Figure 1). A uniform velocity and concentration profile was introduced at this boundary, and allowed to develop downstream. For each of the flow conditions studied, two gate openings were set: one narrow enough to generate a large recirculation, and the other large enough to reduce the recirculation to only about 20% of the depth.

The simulations were all two-dimensional. It was assumed that the influence canal banks on the flow was negligible and thus that the conditions being modelled were uniform across the canal.

3.2 Modelling of Turbulence

There are two main sources of turbulence: the mixing and recirculation generated by the sluice gate, and the bed friction. The first source (the sluice gate)

is dominant in the region immediately downstream of the gate, and causes sediment in the flow to be well mixed. This turbulence, however, decays after a relatively short distance, after which the second source (bed friction) becomes more important. It is the bed friction which determines the final flow conditions and hence the transporting capacity of the channel. In order to model both sources accurately, a two-equation, energy-dissipation turbulence model (or k- ϵ model) was used. The model is based on the assumption that the turbulence can be described by the turbulent kinetic energy and the dissipation rate of turbulent energy. A full description of the k- ϵ model can be found in Part II of the report by the ASCE Task Committee on Turbulence Models in Hydraulic Computations (ASCE, 1988). Rodi (1984) gives verifications of the model for conditions specific to rivers.

3.3 Sediment diffusivity

A ratio, β , of the sediment diffusion coefficient (ϵ_s) to the momentum diffusion coefficient (ϵ_m) can be used to describe the difference in the diffusion of a discrete sediment particle and the diffusion of a fluid 'particle' (van Rijn, 1984). It would be natural to assume that β ($=\epsilon_s/\epsilon_m$) is equal to unity. However, research has shown that in rivers and canals, β is greater than 1.0 because the centrifugal forces on the sediment particles are greater than those on the water particles (van Rijn, 1984, and Gosh, 1986). A value of β was required for use in the PHOENICS simulations of a canal headreach. It was derived by determining the value of β which produced the most accurate predictions of ϵ_s when PHOENICS predictions were compared with the results of a study by Coleman (1970). A value of $\beta = 2$ was found to give the best

agreement with measured data (see Figure 2) and this value for β has been used for the simulations.

3.4 Setting up the simulations

Adaption length was defined as the distance required for an excess sediment load entering the canal to be reduced to 5% of its initial value. The same definition was used in Chapter 2.

Initial PHOENICS simulations indicated that the more important parameters effecting the adaption length were flow depth, mean velocity and settling velocity. The bed roughness, despite having a significant effect on the value of the sediment transporting capacity, was found to have a second order effect on the predicted adaption length. Two sets of flow conditions were chosen and relatively large Froude numbers were chosen for both cases. The gate opening was set to 20% and 60% of the flow depth for each set of flow conditions. Input values for the PHOENICS simulation are shown below for all four cases.

		Case 1	Case 2	Case 3	Case 4
Depth	(m)	1.0	1.0	2.0	2.0
Mean velocity	(m/s)	1.0	1.0	2.0	2.0
Roughness height	(m)	0.1	0.1	0.1	0.1
Gate opening	(m)	0.2	0.6	0.4	1.2
Shear velocity	(m/s)	0.11	0.11	0.10	0.10

Simulations were carried out for thirteen sediment grain sizes, using sediment settling velocities determined by the Gibbs et al (1971) formula with a sediment specific gravity of 2.65 and a water temperature of 20°C. An adaption length was calculated for each grain size. The grain sizes and settling velocities used are shown below.

Settling velocity (cm/s)	Sediment grain size (mm)
0.6	0.087
1.0	0.116
2.0	0.179
3.0	0.236
4.0	0.292
5.0	0.349
6.0	0.405
7.0	0.463
8.0	0.522
9.0	0.582
10.0	0.644
11.0	0.707
12.0	0.772

The adaption lengths predicted by PHOENICS are shown in Table 2 and Figures 3 and 4. The results can be summarised as follows:

- (i) As the settling velocity increases, the adaption length decreases in an exponential manner.
- (ii) The adaption length is roughly proportional to the discharge per unit width.
- (iii) The effect of turbulence generated at the headworks is insignificant for fine sediments,

which have a long adaption length.

- (iv) For coarse sediments, the increase in turbulence due to recirculation results in a significant increase in the adaption length, approximately equal to ten times the flow depth.

The effect of the gate opening on sediment concentrations in the canal reach downstream is shown in Figures 5 to 8 (these figures are taken from plots produced by the PHOENICS package, and show velocity vectors and sediment concentration profiles for cases 3 and 4 when the settling velocity is 11 cm/s. The vertical scale has been stretched to improve clarity). The first, smaller gate opening of 0.4 m, (Figures 5 and 6), produces a relatively fast flow near the bed. This causes a strong recirculation within the first 20 m, and turbulence levels in this region are correspondingly high. The second, larger gate opening of 1.2 m, (Figures 7 and 8), has slower flow near the bed. The recirculation is then restricted to a very small region of the flow and turbulence levels are not as high. The plots of sediment concentration, Figures 6 and 8, show that the concentration profile takes longer to adapt to an equilibrium value when the gate opening is reduced: this is expected because a reduction in the opening causes an increase in the turbulence levels and mixing immediately downstream of the gate.

4. ADAPTION IN A STRAIGHT CHANNEL: COMPARING METHODS

Figures 3 and 4, which show adaption lengths predicted by PHOENICS, also show the predictions made by solving the turbulent diffusion equation. These predicted adaption lengths are tabulated in Table 2 (PHOENICS

predictions) and in Table 3 (predictions from the diffusion equation). The following observations can be made by comparing both sets of predictions:

- (i) agreement is best when the recirculation predicted by PHOENICS is weakest (corresponding to a large gate opening), and is worst when the recirculation is strongest (corresponding to a narrow gate opening).
- (ii) for very fine sediments the PHOENICS predictions are approximately 20% smaller than the predictions by the diffusion equation.
- (iii) agreement deteriorates as the sediment becomes more coarse and recirculation increases. For the finer sediment this discrepancy lies between 10 m (case 1) and 20 m (case 3).

Despite the differences described above, overall agreement is good. This indicates that the 50% increase in adaption length, which was used in Chapter 2 to account for errors introduced by the simplifying assumptions, is a suitable value. The predictions using PHOENICS confirm that the method described in Chapter 2 is valid for a straight channel.

For the sake of comparison, Figures 3 and 4 also show adaption lengths calculated: (i) by assuming quiescent settling, and (ii) from Vetter's design equation for settling basins (Vetter, 1940):

$$E = 1 - e^{-\left(\frac{V_s}{\bar{u}}\right) \frac{l}{h}} \quad (3)$$

where E = sediment removal efficiency
l = settling basin length (m)
h = flow depth (m)
 \bar{u} = mean velocity in basin (m)

Equation 3 would normally be used to assess the efficiency of a settling basin, and an assumption that the basin's sediment transporting capacity is negligible is implied in the equation. The equation is applied here by assuming that the removal efficiency describes the removal of sediment concentrations which exceed the sediment concentrations at transporting capacity. With this assumption the Vetter equation compares well with PHOENICS predictions for the whole range of settling velocities under the conditions tested. It appears that this adaptation of Vetter's equation provides a simple method for obtaining a reasonable estimate for the adaption length in a straight canal.

The predictions using PHOENICS can also be compared with Ahmad's criterion for siting a sediment extractor. His recommendations for each of the four cases are given in Table 4. Ahmad's criterion appears to overestimate the adaption length by about one order of magnitude, and so is not suitable for design purposes.

5. EFFECTS OF CANAL BENDS

When water flows from a straight reach of an open channel into a channel bend, the variation in velocity with height above the channel bed causes a variation in centrifugal forces. This induces a swirling or 'secondary' flow, which then decays if there is a straight channel section following the bend. The rate of decay depends on the magnitude of the transverse circulation in the bend (which in turn will depend on the flow conditions and the channel geometry).

Secondary currents produced by a bend distort sediment concentration profiles which are approaching their equilibrium state, thereby introducing additional mixing. Sediment near the bed is swept towards the inside of the bend where it is then raised towards the surface, while on the outside of the bend the relatively clear surface water is carried down towards the bed. An equilibrium sediment profile can therefore only be established once the recirculation has decayed sufficiently.

In order to predict the effect of bends on sediment concentrations and hence on adaption length, three-dimensional PHOENICS simulations were used in the same manner as for straight channels. The specification of the bed boundary condition for sediment concentrations was also modified; the lateral variation in bed shear means that a constant entrainment rate at the bed cannot be assumed. Instead, a bed boundary condition which produced no net sediment deposition or scour was specified. This ensured that the total sediment load in the channel was constant through the bend, which is realistic for canal bends.

Before simulations of sediment concentrations at canal bends of field scale were attempted, the application of PHOENICS to predict secondary flow in bends was validated using simulations of two sets of laboratory measurements.

5.1 Validation of PHOENICS simulations

PHOENICS simulations were compared with laboratory data, collected in a flume comprising of a 180° bend. The data is reported in de Vriend (1981). The flume was 1.70 m wide, consisting of a straight inflow

section (6 m long), a 180° bend (radius of curvature of the axis 4.25 m) and a straight outflow section (6m long), the layout is shown in Figure 9. Two experiments, one with a rough flat bed and one with a smooth flat bed, were made in order to show the influence of bottom roughness. In both experiments the discharge was 0.19 m³/s and the flow depth 0.17 m (although backwater effects resulted in some variation of the flow depth, particularly in the rough bed case).

Comparisons with PHOENICS simulations were made for both the rough and smooth bed cases. The variable compared with data was the secondary flow intensity, i , defined by de Vriend as:

$$i = \frac{1}{2} \int_0^h \frac{|w|}{\bar{u} h} dy \quad (4)$$

where $|w|$ = the modulus of w , the secondary component of the flow velocity

The comparisons between PHOENICS and the laboratory data are shown in Figures 10 and 11. Agreement is good for both the rough and smooth bed cases. Typical discrepancies between predicted and observed secondary flow intensities were about 17% for the rough bed case and only about 7% for the smooth bed case. This result indicates that PHOENICS simulations of the effect of a canal bend on suspended sediment concentrations are realistic.

5.2 The effect of bends on the adaption length

A large number of parameters affect the behaviour of sediment concentrations at channel bends. They include:

- mean channel depth
- channel width
- radius of curvature of bend
- angle of bend
- mean flow velocity
- channel roughness
- sediment sizes in the bed material and in transport

In addition to these parameters the depth varies across the channel section in canal bends with alluvial beds. Some simplification of the problem is required to enable the results of PHOENICS simulations to be presented in a tabular form. This approach is justified because the increase in adaption length caused by even a relatively sharp bend was found to be small compared to the overall adaption length. The following simplifying assumptions have been made:

- (i) The channel has a rectangular cross section with a constant depth throughout the bend.
- (ii) Bank roughness effects are not significant.
- (iii) The sediment concentration profile in the flow approaching the bend is the equilibrium sediment concentration profile.
- (iv) Roughness can be described by the worst case condition of $\bar{u}/u^* = 20$, which is a high value for alluvial channels (smaller values of \bar{u}/u^*

were found to produce smaller adaption lengths).

- (v) The sediment size in transport is that which produces a 50% trapping efficiency when 15% of the flow is extracted. Higher trapping efficiencies (larger sediment sizes) caused shorter adaption lengths. Again this may be considered a worst case as sediment extractors would not normally be used if their predicted trapping efficiency was significantly less than 50%. This simplification, together with that of (iv) above, causes a factor of safety in predicted adaption length which can be as high as 2.

These assumptions enabled the problem to be reduced to a set of PHOENICS simulations which assessed the effect of three variables: the ratio of canal width to depth (W/h), the bend angle, and the ratio of radius of curvature to width (R_c/W). The adaption length for the bend was defined as the distance from the end of the bend to the point at which an equilibrium sediment profile was re-established. The criterion for a re-established profile was that a sediment extractor would achieve the same trapping efficiency as it would achieve if it were sited upstream of the bend. The PHOENICS predictions indicated that there was still a substantial lateral variation in sediment concentrations when this criterion was satisfied.

Adaption lengths were made non-dimensional by dividing them by flow depth. The predicted non-dimensional adaption lengths are shown in Table 5, they indicate that:

- (i) The adaption length depends on the ratios W/h and R_c/W and the angle of the bend.

- (ii) Increasing the value of the ratio W/h decreases the non-dimensional adaption length.
- (iii) Increasing the value of the ratio R_c/W decreases the non-dimensional adaption length.
- (iv) The absolute values for these adaption lengths are small when compared to the adaption length in a straight canal with a typical value for suspended sediment size of about 0.116 mm or a settling velocity of 1 cm/s. In case 1 of Chapter 3 the adaption length for a 1 cm/s settling velocity was 279 m (Table 2), while the largest adaption length listed in Table 5 is 80m, that is 80 times flow depth. This represents a very sharp canal bend with a very narrow cross section. The equivalent values for case 3 of Chapter 3 are 1126 m and 160 m respectively. Table 5 also shows predictions of 'minimum trapping efficiency'. This efficiency is defined as the trapping efficiency which is obtained if an extractor is sited where the sediment concentration profile is most distorted. Table 5 can therefore be used to assess both the degree to which a canal bend will reduce a proposed sediment extractor's trapping efficiency and the increase in adaption length which it is likely cause.

6. PROCEDURE FOR SITING A SEDIMENT EXTRACTOR

The work presented in this report can be used to determine the siting of a sediment extractor. In summary, the procedure is as follows:

- (i) Determine the depth, mean velocity, and median sediment size in transport in the canal

headreach for typical operating conditions. Use these to calculate Froude number and discharge per meter width.

- (ii) Determine the adaption length for a straight channel using Table 1. Remember that this is only a representative value, there is likely to be a range of sediment sizes in transport in the canal headreach and each size will have its own adaption length. Adaption lengths will also vary with the canal discharge.
- (iii) If there is a canal structure producing high levels of turbulence (such as a syphon or a cross regulator) in the canal headreach, and the structure is closer to the intake than the adaption length, then the adaption length should be measured downstream from the structure.
- (iv) If there is a canal bend closer to the intake than the adaption length, then use Table 5 to estimate its adaption length. If the minimum trapping efficiency in Table 5 is greater than about 48%, then the adaption length need not be adjusted. However the extractor should not be sited on the bend or closer to the bend than the adaption length derived from Table 5.
- (v) If the minimum trapping efficiency in Table 5 is less than 48% then compute the total adaption length as the sum of: the length given in Table 1, the bend's length, and the length derived from Table 5.
- (vi) Do not locate the extractor closer to the intake (or turbulence generating structure) than the total adaption length. However if other

considerations are overriding, such as limited options for sediment disposal, then guidance on the penalty of poor siting is required. If the predicted trapping efficiency is 50% then it will be reduced by approximately 10% if the extractor is sited at half the adaption length in a straight canal. The penalty of siting an extractor on or near a bend can be derived from Table 5.

- (vii) Locating the extractor further from the intake than is necessary will cause a higher water level at the intake. This is due to the relatively higher canal slope which will form upstream from the point of sediment extraction.

7. CONCLUSIONS

The main conclusions drawn from this study are:

(1) When a sediment extractor is used to eject sediment from an irrigation canal it must be located sufficiently far from the headworks, otherwise the turbulence and mixing introduced by the canal headworks structures will reduce the trapping efficiency of the device. The ideal location for an extractor is where the sediment concentrations have just adapted to an equilibrium state. The distance from the headworks to this point is termed the adaption length.

(2) Adaption lengths can be computed from an analytical solution to the turbulent diffusion equation (Equation 1), provided that some simplifying assumptions are made. Simulations using a computational fluid dynamics code have shown that this

approach provides acceptable predictions of adaption length in straight channels when a 50% increase on adaption length is applied to account for the errors introduced by the simplifying assumptions. Table 1 gives the predictions produced by the analytical solution to the turbulent diffusion equation, and is recommended for specifying the approximate location for a canal sediment extractor in a straight canal.

(3) The increase in adaption length due to a canal bend has been investigated using simulations carried out with the computational fluid dynamics package. The results are summarised in Table 5.

(4) Both Table 1 and Table 5 are contained in the HR design manual for sediment extractors (HR Wallingford, 1991). Detailed advice on how these Tables can be used to determine adaption lengths, and on how to treat other aspects of siting sediment extractors is given in the design manual. A procedure is also given in Chapter 6 above.

8. ACKNOWLEDGEMENTS

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TABLES

Table 1 : Adaption lengths predicted by the turbulent diffusion equation

PREDICTED ADAPTION LENGTHS		(In meters)													
Discharge per m width (m ² /s)	Froude Number	D50 sediment sizes (In suspension) (mm) :													
		0.07	0.08	0.09	0.10	0.11	0.12	0.13	0.15	0.17	0.20	0.25	0.30	0.35	0.40
0.4	Fr=0.1	303	216	160	121	99	83	71	55	46	31	22	17	13	11
	Fr=0.2	344	258	200	160	130	109	92	68	53	39	26	20	14	12
	Fr=0.3	354	267	208	167	137	115	97	73	57	42	28	21	17	14
	Fr=0.4	360	272	213	171	141	118	101	76	60	44	30	22	17	14
0.6	Fr=0.1	478	351	266	205	163	131	109	83	68	47	33	25	20	17
	Fr=0.2	522	393	306	244	200	167	141	106	83	61	41	30	24	21
	Fr=0.3	536	405	316	254	209	175	149	112	88	65	44	32	25	21
	Fr=0.4	544	412	323	260	214	180	153	116	91	67	46	34	27	22
0.8	Fr=0.1	653	482	369	289	232	189	157	113	91	72	44	34	27	23
	Fr=0.2	701	528	412	330	270	226	191	143	112	83	56	41	32	27
	Fr=0.3	718	544	426	342	281	236	200	151	119	88	59	44	35	28
	Fr=0.4	729	553	434	350	288	242	206	156	123	91	62	46	36	30
1.0	Fr=0.1	828	614	471	372	300	247	206	149	115	89	56	43	34	29
	Fr=0.2	881	665	519	416	341	285	242	182	142	105	71	52	41	34
	Fr=0.3	902	683	535	431	354	297	253	191	150	111	75	56	44	36
	Fr=0.4	915	695	545	440	362	304	259	196	155	115	78	58	46	37
1.2	Fr=0.1	1003	747	575	454	368	304	255	186	143	106	67	52	41	35
	Fr=0.2	1062	802	626	502	412	344	293	220	173	127	86	63	50	41
	Fr=0.3	1086	823	645	519	428	358	305	230	181	134	91	68	53	44
	Fr=0.4	1102	837	657	530	437	367	313	237	187	139	94	70	55	45
1.5	Fr=0.1	1266	946	731	580	470	389	327	242	186	135	85	65	52	44
	Fr=0.2	1334	1008	788	632	519	435	369	278	218	161	109	81	63	52
	Fr=0.3	1363	1034	811	653	538	451	385	291	229	170	115	85	67	55
	Fr=0.4	1383	1051	826	666	550	462	394	299	236	175	119	88	70	57
2.0	Fr=0.1	1707	1278	991	789	643	533	450	333	259	189	128	88	70	59
	Fr=0.2	1791	1354	1059	851	699	586	498	376	295	218	147	109	86	71
	Fr=0.3	1828	1387	1089	878	723	607	518	392	309	229	155	115	91	75
	Fr=0.4	1853	1409	1108	895	739	621	531	402	318	236	161	119	94	77
2.5	Fr=0.1	2150	1613	1251	998	815	678	573	426	331	242	162	126	89	74
	Fr=0.2	2249	1703	1333	1071	881	738	628	474	373	276	187	138	109	90
	Fr=0.3	2294	1742	1368	1104	910	764	652	494	390	289	196	146	115	95
	Fr=0.4	2325	1770	1392	1125	929	782	668	507	400	298	203	151	119	98
3.0	Fr=0.1	2596	1950	1515	1209	988	823	697	520	405	296	199	149	109	90
	Fr=0.2	2708	2051	1607	1293	1064	891	759	573	451	334	226	168	132	109
	Fr=0.3	2762	2099	1649	1331	1098	922	787	596	471	350	237	176	139	115
	Fr=0.4	2798	2131	1678	1356	1121	943	806	612	483	360	245	182	144	118
4.0	Fr=0.1	3489	2626	2044	1635	1338	1115	946	708	554	406	273	203	163	125
	Fr=0.2	3631	2753	2158	1738	1432	1201	1023	773	609	451	306	227	179	147
	Fr=0.3	3702	2816	2214	1787	1475	1240	1059	803	634	471	321	238	188	155
	Fr=0.4	3748	2857	2251	1821	1506	1268	1084	823	651	485	330	246	194	160
5.0	Fr=0.1	4387	3306	2577	2064	1690	1411	1197	897	703	518	347	258	205	173
	Fr=0.2	4558	3458	2713	2186	1801	1512	1290	975	768	570	387	287	227	186
	Fr=0.3	4645	3535	2781	2247	1856	1561	1333	1011	799	594	405	301	238	195
	Fr=0.4	4702	3586	2827	2288	1893	1595	1364	1037	820	611	416	310	245	202
6.0	Fr=0.1	5289	3989	3112	2494	2045	1709	1451	1088	853	629	424	313	248	207
	Fr=0.2	5489	4166	3270	2636	2173	1824	1557	1178	928	689	468	348	274	226
	Fr=0.3	5591	4258	3352	2709	2238	1883	1609	1221	965	718	489	364	287	236
	Fr=0.4	5659	4318	3405	2757	2282	1923	1646	1251	991	738	503	375	296	244
8.0	Fr=0.1	7100	5361	4187	3361	2759	2307	1961	1475	1157	854	577	427	337	279
	Fr=0.2	7358	5590	4390	3542	2921	2454	2094	1586	1252	930	632	470	371	305
	Fr=0.3	7490	5708	4497	3638	3007	2532	2165	1644	1300	968	659	491	388	319
	Fr=0.4	7696	6788	4868	3701	3064	2584	2218	1684	1334	995	679	506	399	329
10.0	Fr=0.1	8928	6741	5270	4233	3477	2910	2476	1864	1464	1082	731	543	428	353
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	Fr=0.3	9397	7165	5648	4571	3781	3185	2724	2070	1638	1220	831	619	489	403
	Fr=0.4	9554	7285	5737	4650	3852	3249	2783	2119	1680	1254	856	638	504	415

Table 2. Adaption lengths predicted by PHOENICS.

Settling velocity (cm/s)	Adaption length (m)			
	Case 1	Case 2	Case 3	Case 4
0.6	478	479	1922	1920
1.0	279	281	1126	1122
2.0	131	135	538	534
3.0	82	86	348	336
4.0	57	63	257	241
5.0	43	50	198	184
6.0	34	42	162	146
7.0	28	37	142	121
8.0	24	34	125	104
9.0	21	31	113	92
10.0	19	29	104	82
11.0	17	27	96	75
12.0	15	25	91	69

Table 3. Adaption lengths predicted by solving the turbulent diffusion equation (for comparison with PHOENICS predictions)

Settling velocity (cm/s)	Adaption length (m)	
	cases 1 & 2	cases 3 & 4
0.6	622	2486
1.0	348	1393
2.0	148	596
3.0	89	359
4.0	61	249
5.0	46	188
6.0	36	150
7.0	30	125
8.0	25	107
9.0	22	94
10.0	19	83
11.0	17	76
12.0	16	69

Table 4. Adaption lengths predicted from Ahmad's (1962) method

Settling velocity (cm/s)	Adaption length (m)	
	cases 1 & 2	cases 3 & 4
0.6	5225	14749
1.0	3135	8850
2.0	1567	4425
3.0	1045	2949
4.0	784	2212
5.0	627	1770
6.0	522	1475
7.0	448	1264
8.0	392	1106
9.0	348	983
10.0	313	885
11.0	285	805
12.0	261	737

Table 5. Adaption lengths for bends

(Minimum trapping efficiencies are also given in brackets below the adaption lengths)

Angle of bend	Ratio R_c/W	Adaption length/depth (minimum trapping efficiency, %)		
		W/h = 5	W/h = 10	W/h = 20
45	3	75 (33)	56 (42)	50 (46)
45	10	60 (34)	46 (45)	33 (49)
45	30	55 (40)	33 (48)	- (50)
90	3	80 (25)	51 (34)	41 (44)
90	10	65 (26)	39 (42)	30 (49)
90	30	53 (37)	38 (47)	- (50)

FIGURES

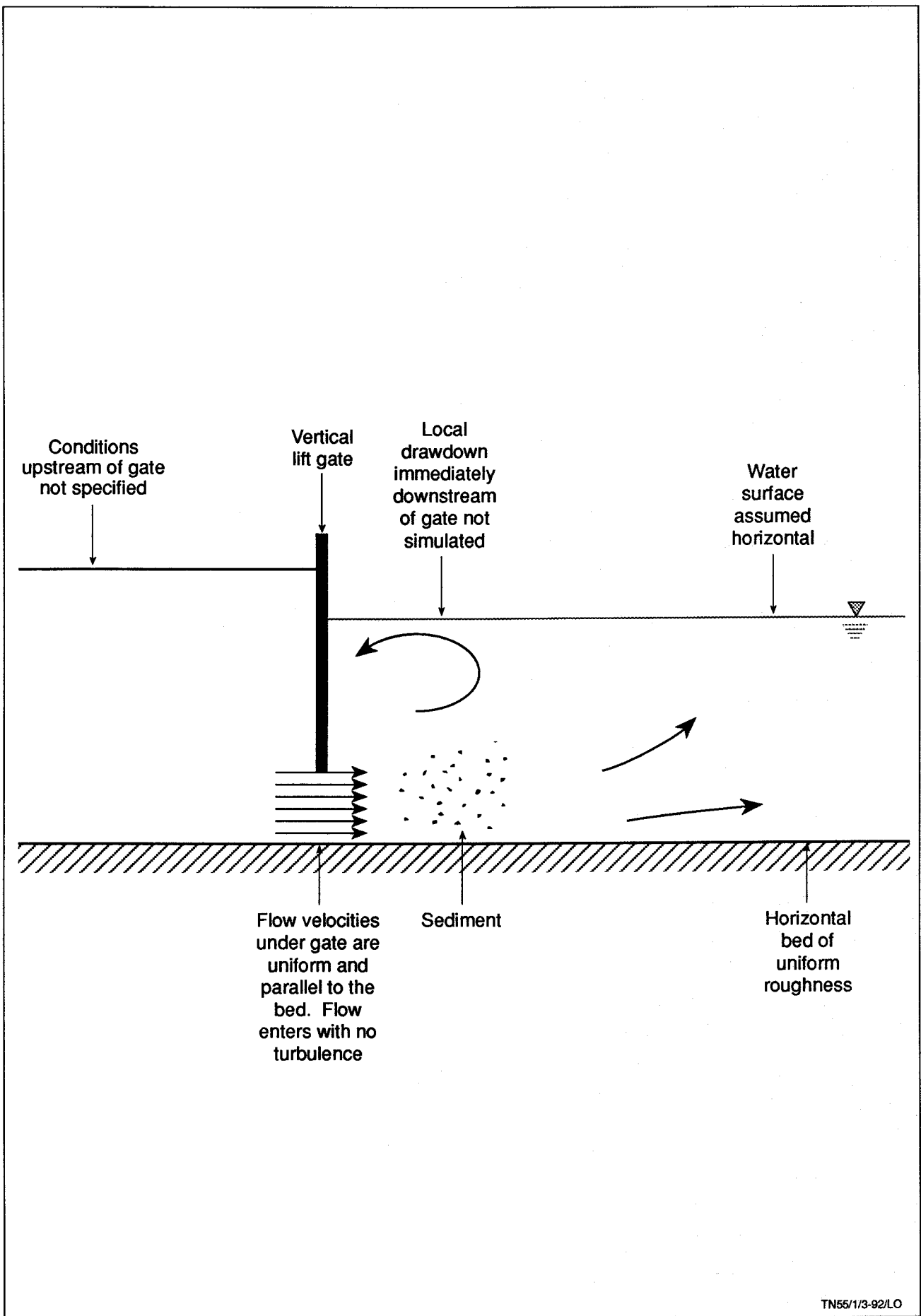
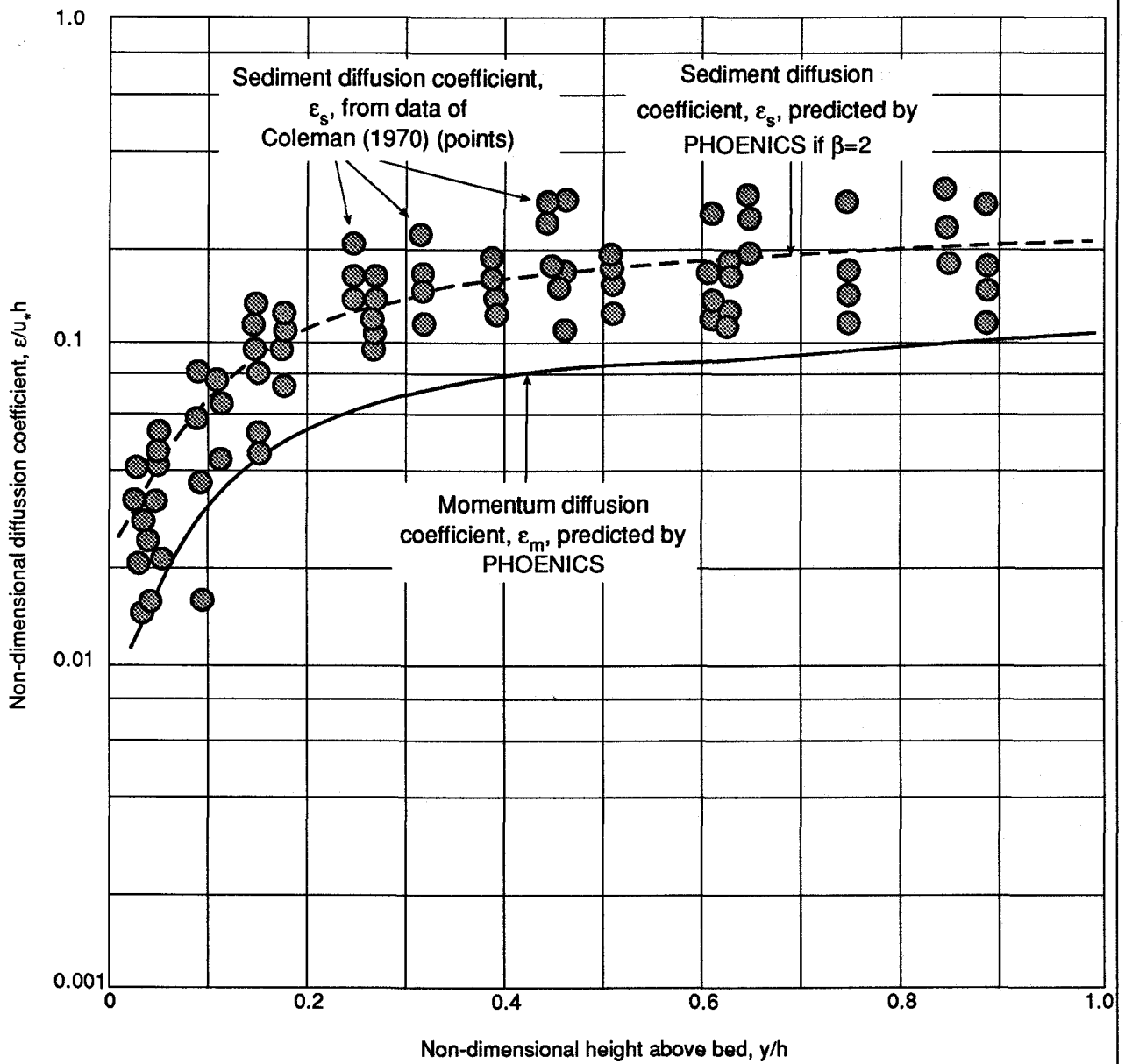
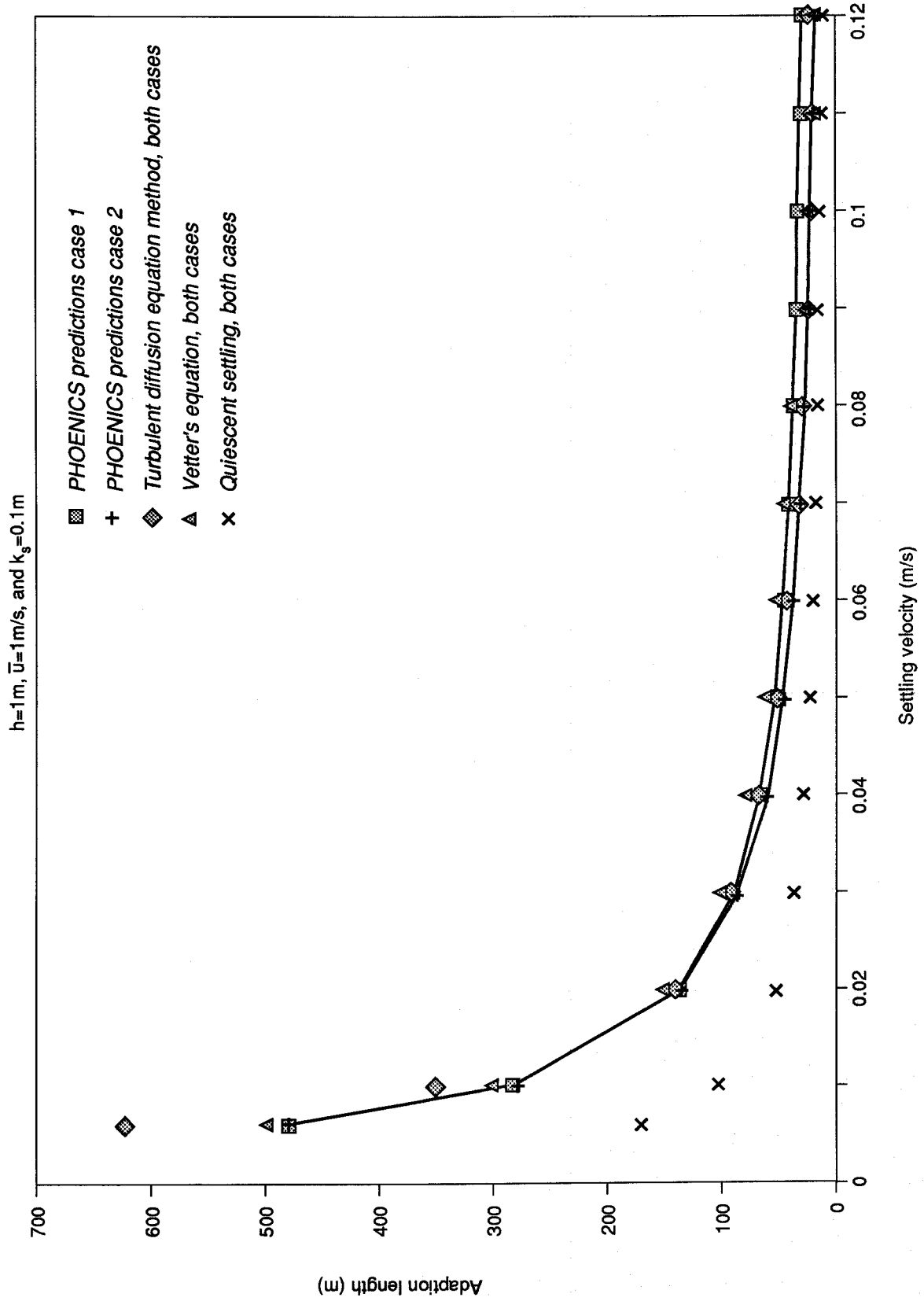


Fig 1 Representation of an intake gate in the PHOENICS simulations



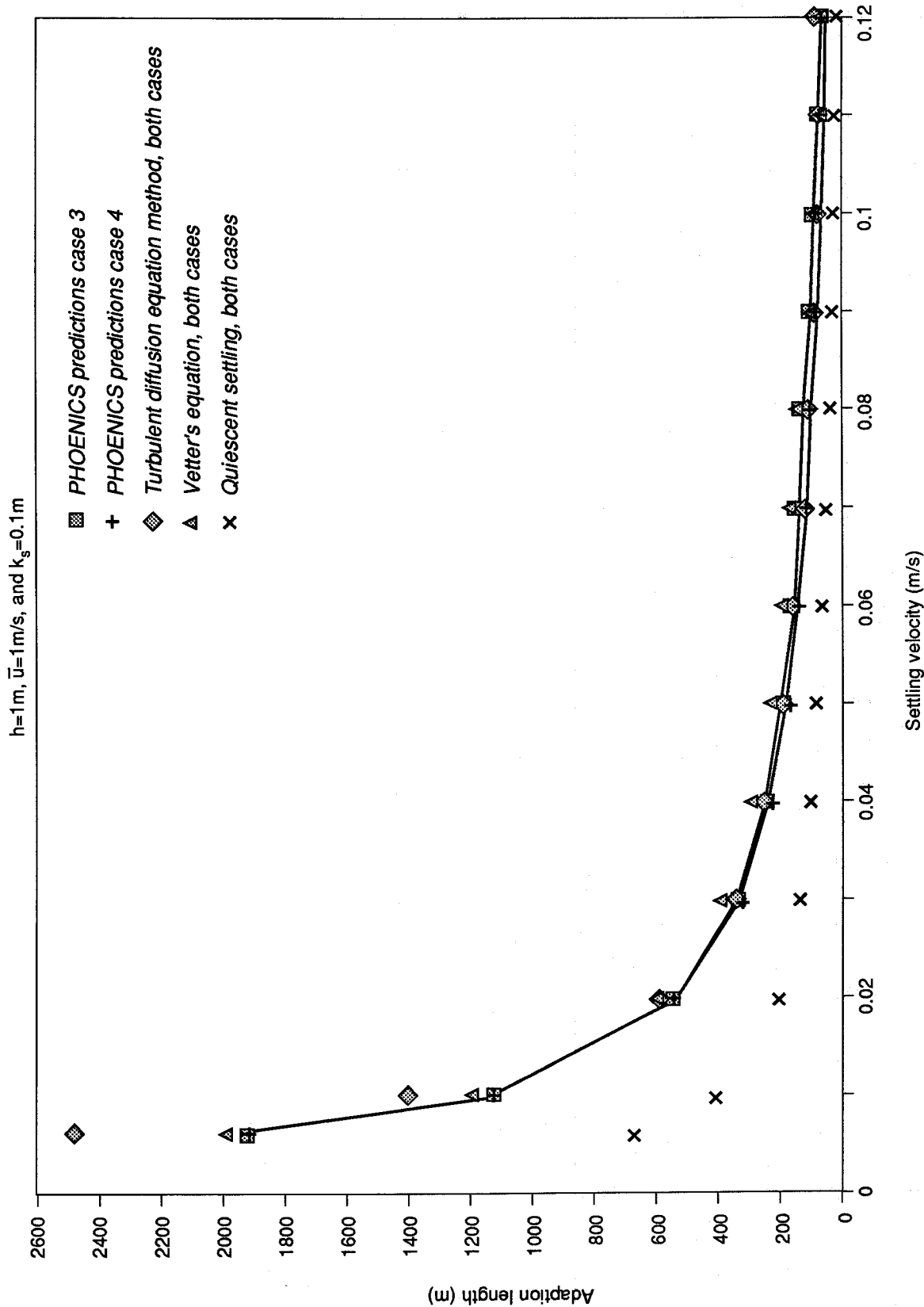
TN55/2/10-91/LO

Fig 2 Comparison between measured and predicted values of the sediment diffusion coefficient



TN55/3/3-92/LO

Fig 3 Predicted adaption lengths for cases 1 and 2



TN55/4/3-92/LO

Fig 4 Predicted adaption lengths for cases 3 and 4

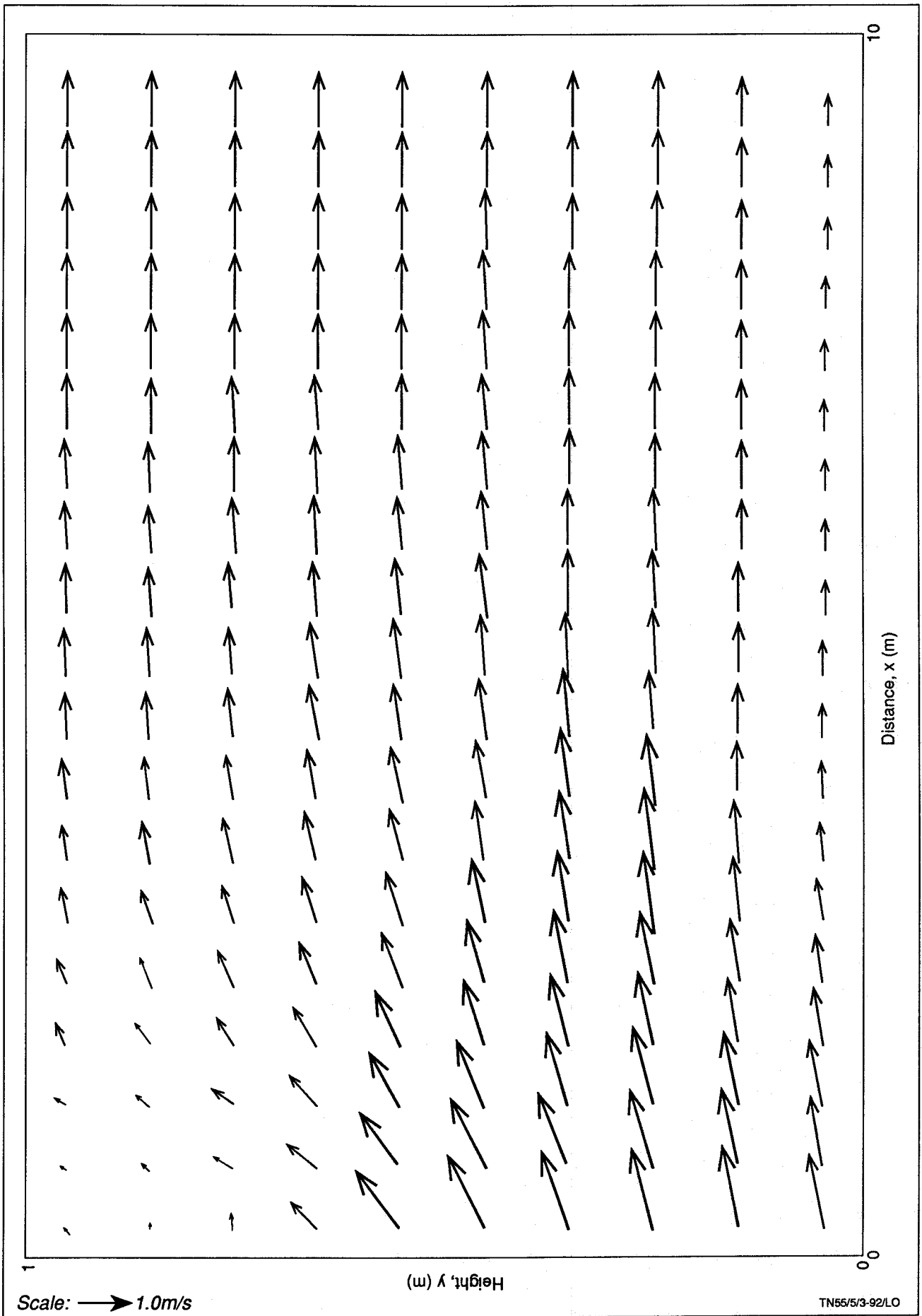


Fig 5 Predicted velocity vectors for case 1

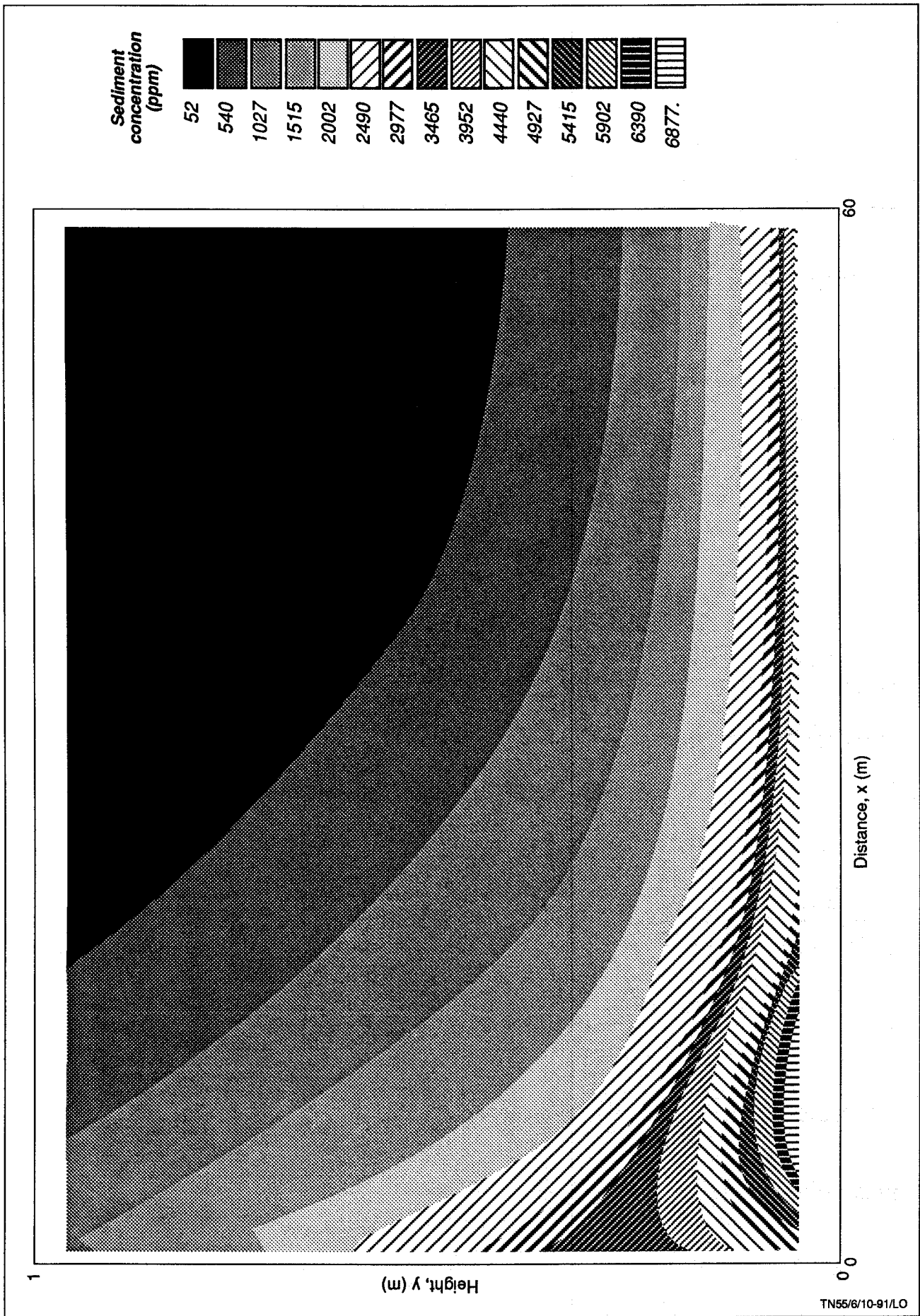


Fig 6 Predicted sediment concentration profile for case 1 (settling velocity is 11cm/s)

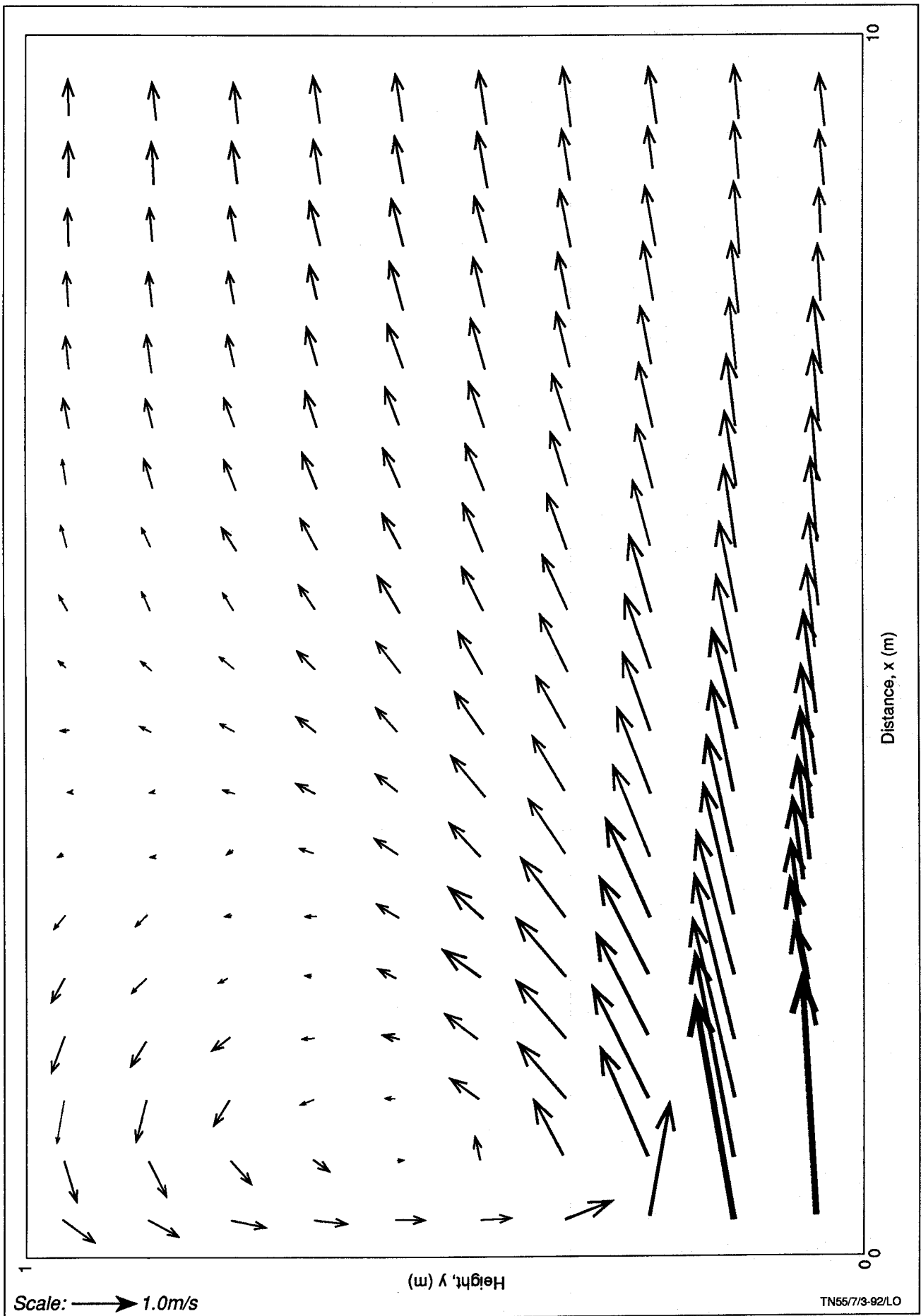


Fig 7 Predicted velocity vectors for case 2

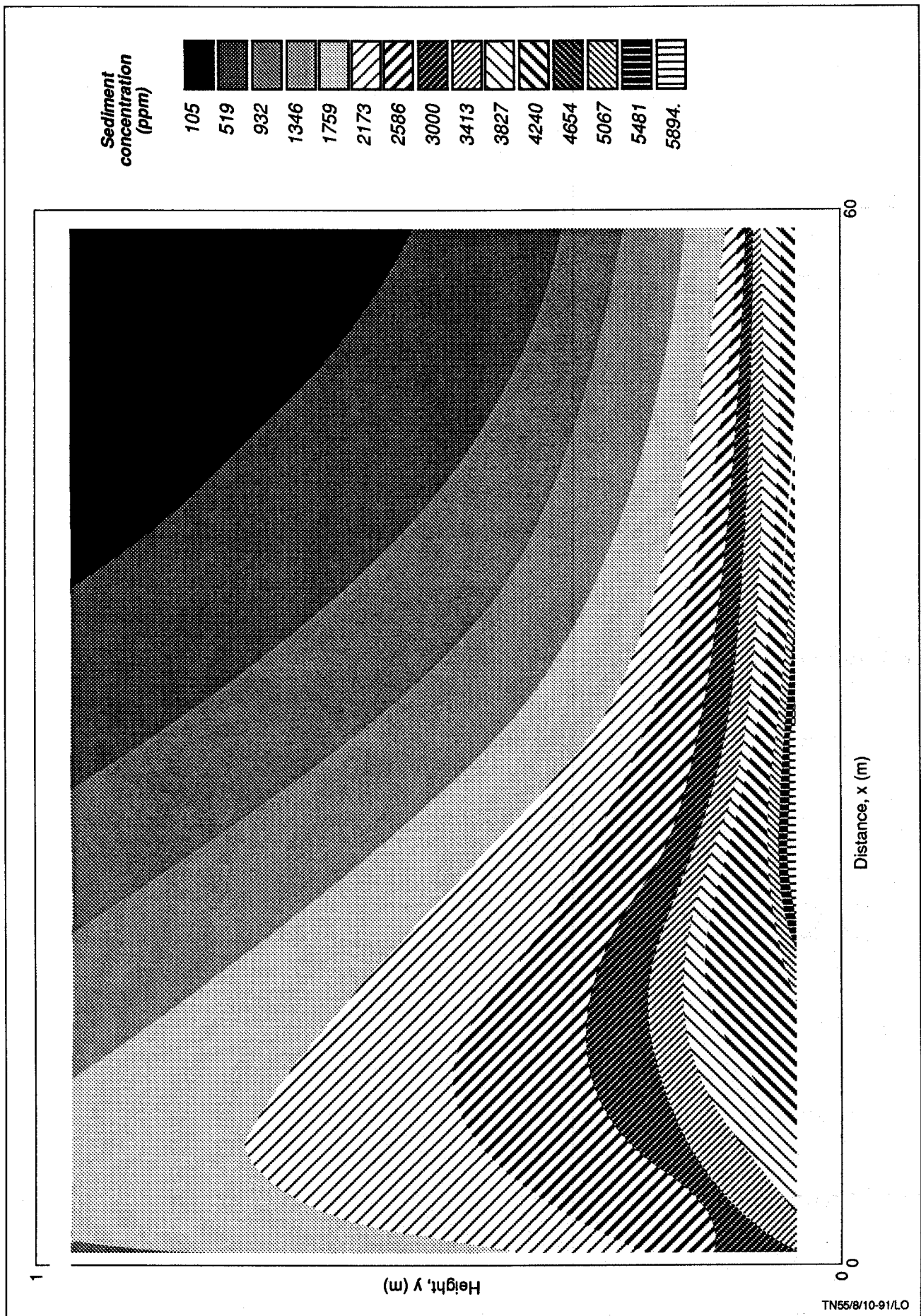


Fig 8 Predicted sediment concentration profile for case 2 (settling velocity is 11cm/s)

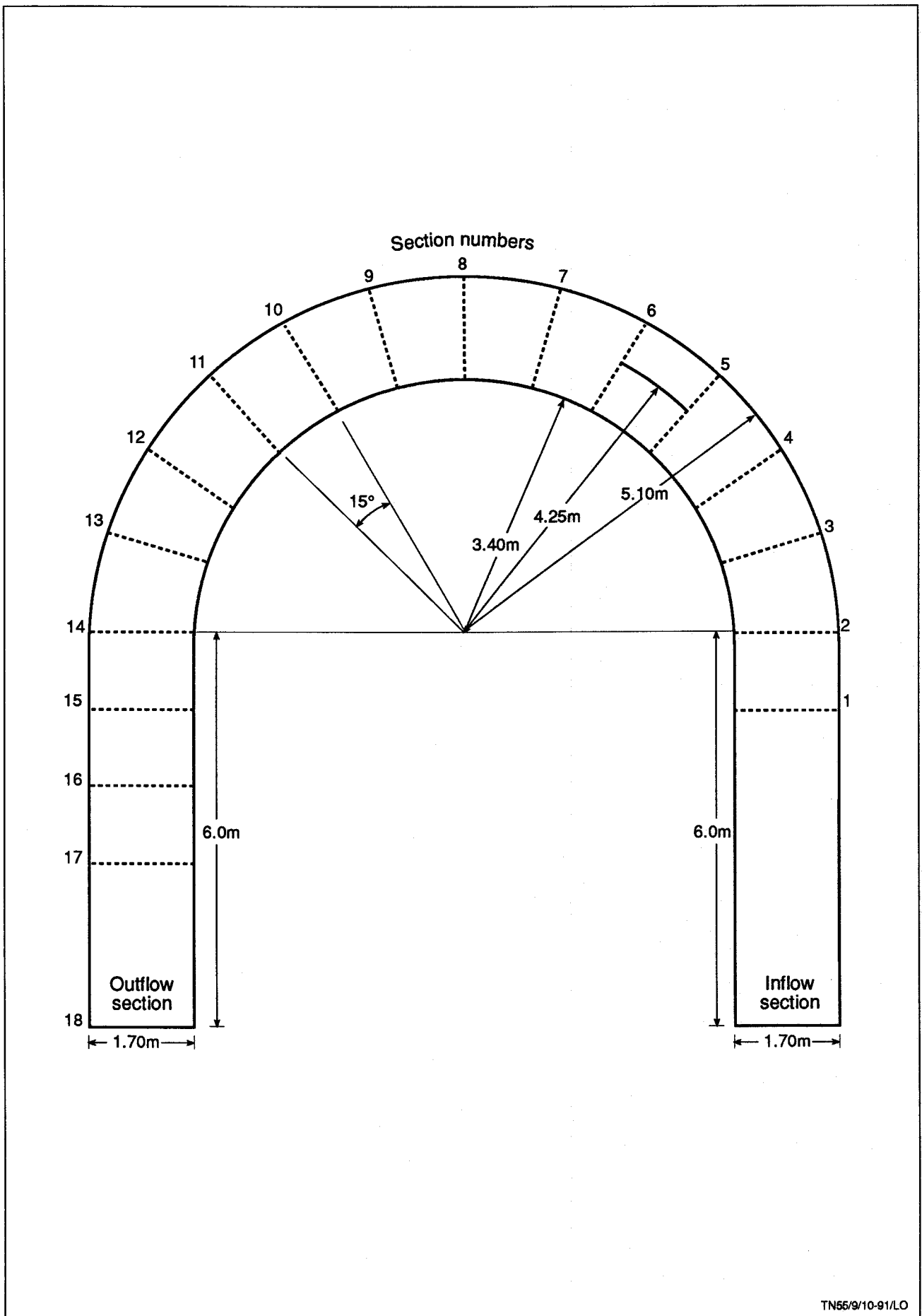


Fig 9 Dimensions of the laboratory flume (de Vriend, 1981)

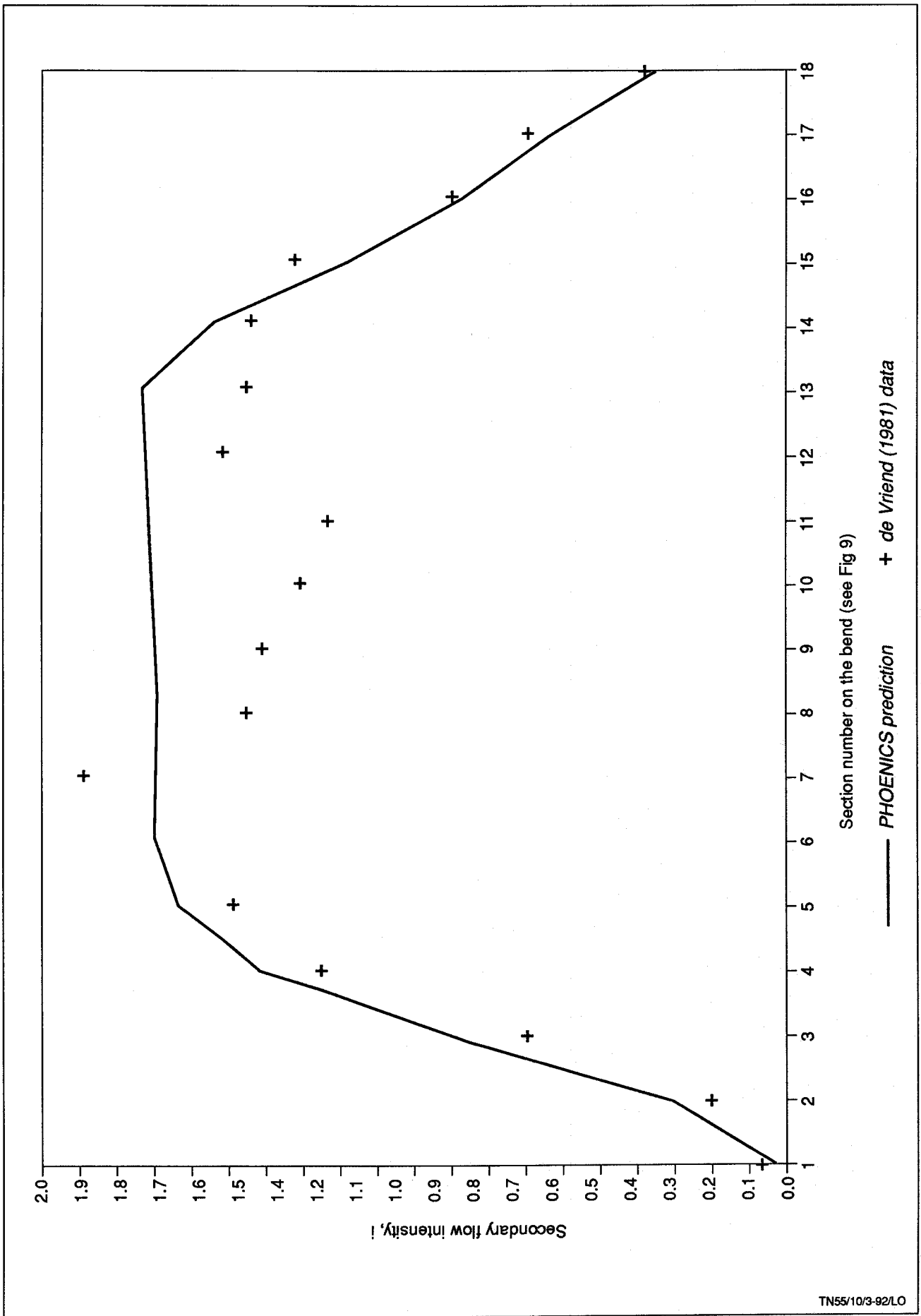


Fig 10 Comparison between measurements and PHOENICS for rough bed cases

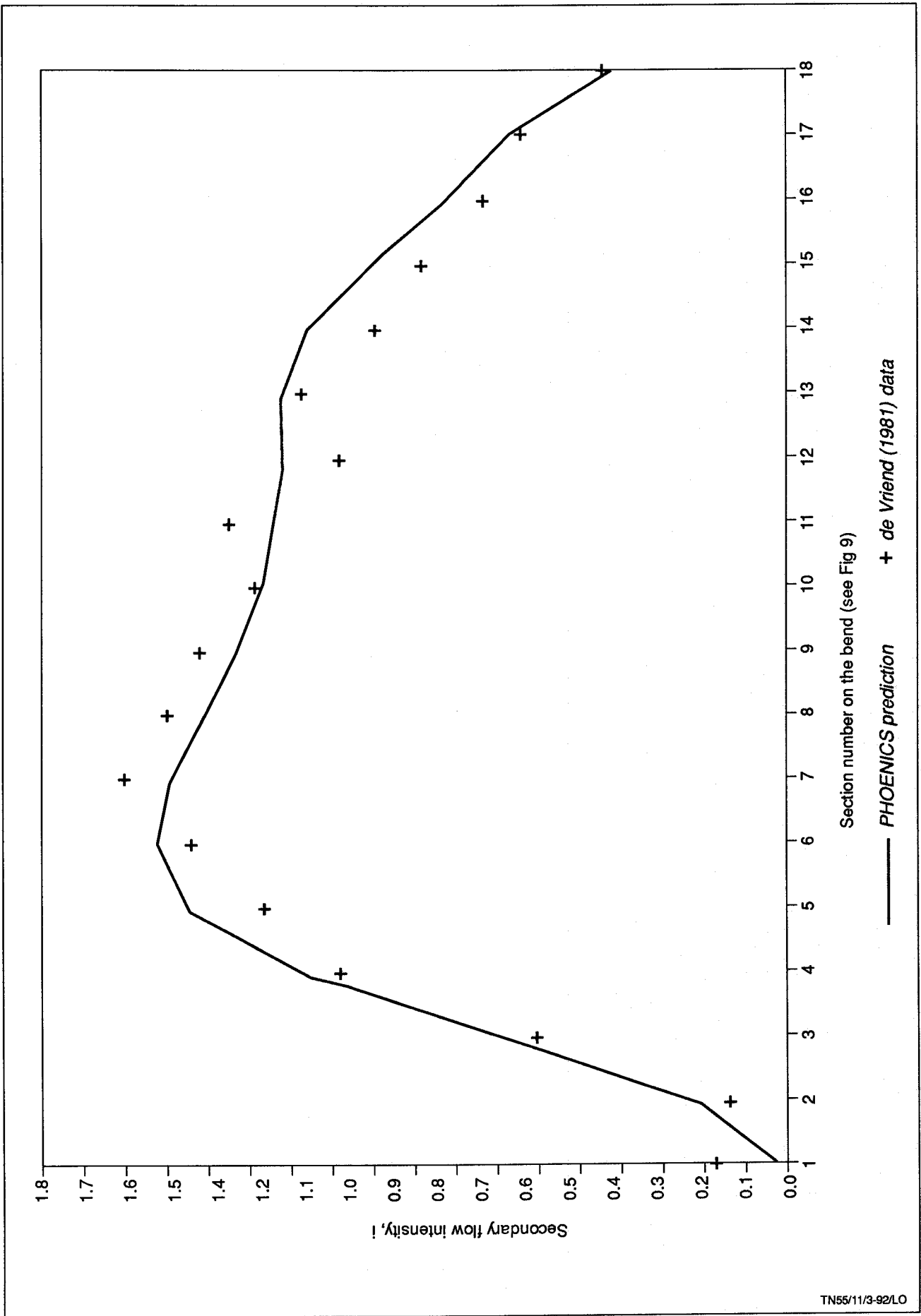


Fig 11 Comparison between measurements and PHOENICS for smooth bed case

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