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Environment Canada
Water Science and Technology Directorate

Direction générale des sciences et de la technologie, eau
Environnement Canada

Backscatter measurements of suspended sediment concentration and size in an estuary

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NWRI Contribution # 93-24

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BACKSCATTER MEASUREMENTS OF SUSPENDED SEDIMENT CONCENTRATION AND SIZE IN AN ESTUARY

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ABSTRACT

Concern for the transport and fate of chemical contaminants in estuaries is the impetus behind recent interest in more effective methods of measuring suspended sediment concentrations than the traditional grab or pumped water sample methods. Backscatterance measurements of particle concentrations offer much promise as a reliable and rapid response method and even the potential in certain cases for remote sensing of concentration. Such new methods would be particularly advantageous in estuaries of the type studied in this work that present difficult sampling problems due to their large horizontal scales and dynamic nature.

A method of obtaining profiles of suspended sediment concentration and particle size spectra from a combination of a direct grab sample of suspended sediment concentration, profiles of optical and acoustical backscattering and a vertical transport model for suspended sediments is outlined and applied to observations in the vicinity of the turbidity maximum of the St. Lawrence estuary. Inferred particle size spectra ranged from 8 to 100 μm with sizes from SILT 16 to 32 μm being ~~predominant:~~ Size estimates were not directly confirmed but rather shown to reduce the scatter between water sample concentration and backscatter response; especially in the case of acoustical backscatter. The apparent invariance of the particle size spectrum over a tidal cycle permitted the use of acoustic backscatter data alone to compute profiles of suspended sediment concentration. For the first time the net suspended sediment flux has been calculated over a tidal cycle and across the 15 km breadth of the estuary. The limitations of the approach presented here and the direction for future research are discussed.

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MANAGEMENT PERSPECTIVE

This work is the first report on a joint study of the upper St. Lawrence estuary undertaken with the Maurice Lamontagne Institute (MLI) in June 1991. While the intention of this study was to provide the necessary observational data with which to drive and test a three-dimensional hydrodynamic model under development by MLI modellers the observations collected by the National Water Research Institute component have in this report been used to explore the question of deducing particle size spectra and suspended sediment concentrations from backscatter observations. The backscatter approach has the great advantage over more traditional methods such as water sample determinations in that it is rapid, in situ and offers in some cases the capability of remote sensing. This novel method, its limitations and its application for the first time to the cross-sectionally and tidal net sediment flux of the St. Lawrence estuary are detailed in the paper. Work continues on the development of the three-dimensional model at MIL.

INTRODUCTION

Interest in the concentration and flux of suspended material in estuaries is broadly based. Recent public concern for possible contamination of estuaries has drawn attention to the need to know the spectra of particle sizes as well as their concentration in order to better understand adsorption-desorption processes. In estuaries such as the upper estuary of the St. Lawrence River of interest here measurement of suspended sediment concentration and particle size spectra presents a formidable sampling problem owing to their large horizontal scales, complex bathymetry and vigorous tidal currents.

As part of a broader program to develop and test a three-dimensional model of the flow, salinity and suspended sediment distribution of the St. Lawrence estuary validating data consisting of individual profiles of current, backscatterance, salinity and temperature were observed concurrently at a number of locations. The purpose of the present paper is to investigate the feasibility of deducing the suspended sediment concentration and particle size spectra and thereby the tidally averaged flux of sediment across the estuary based on direct water sample observations and optical and acoustical backscatter analysis.

Inferences on sediment concentration drawn from backscatter information depends on a knowledge of the size distribution of the scatters present. In general, the size information at a given site is unknown and is a complex function of time and depth. This is due to the interaction of upward turbulent sediment flux and size dependent gravitational settling. As far as is known there have been no direct in situ measurements of profiles of particle size of the finer size range generally found in estuaries. Although too limited in range to be considered as a remote sensing tool, perhaps the most successful method for simultaneously measuring particle size and therefore concentration in situ is by optical diffraction (Agrawal and Pottsmith, 1989). Multifrequency acoustical methods while offering greater range than optical methods have so far been used for the large non cohesive particle sizes associated with beach processes (Hay and Sheng, 1992).

Single frequency acoustic backscatter measurements of suspended sediment in the ocean have been made over the last decade in combination with other information on particle size or concentration. A good example of the importance of particle size information for the acoustical backscatterance determination of sand particle concentrations in an estuary is provided by Thorne *et al.* (1993) who obtained spectra in the laboratory. In a refinement of the single frequency technique for remote sensing of sediment concentration profiles, Libicki *et al.* (1989) proposed that size variations over a range of depths due to differential particle settling could be accounted for in a turbulent boundary layer from a knowledge of the friction velocity, steady state boundary layer theory and an assumption of the particle classes likely to be present. They demonstrated that even at relatively low concentrations which ought to have a limited range of particle sizes concentration estimates could be up to 33% in error. Lynch *et al.* (1991) have applied the boundary layer model and assumed particle size distributions to examine the response of backscattered acoustics and an optical transmissometer on the continental rise. As well, from a comparison of optical and acoustical signals from the same parcel of water they have qualitatively classified the particle distributions into fine or large for a number of episodes over their experimental period. The mathematical basis for interfering particle size from either optical extinction or acoustic backscatter in a steady turbulent boundary layer has been described by Lynch and Agrawal (1991). A non-negative least squares method was applied to acoustic backscatter data from a field experiment and one size class inferred. They noted that inferences from acoustics is biased to larger size classes whereas optics favour the smaller ones. This suggests that both optical and acoustical data should be combined in the inversion method. The purpose of this paper is to develop a method for determining particle size spectra from both optical and acoustical data and to extend the applicability of the method from the case of the steady turbulent boundary layer to the more general stratified water column typical of partially mixed estuaries. Furthermore, the deduced particle size spectrum is employed to correct the optical and acoustical responses for size effects in order to improve the estimation of the concentration of suspended material over the water column.

In an application section of this paper the technique developed is used to estimate the flux of suspended sediment over a tidal cycle in the St. Lawrence estuary.

Backscatter Inversion Theory Based on a Vertical Transport Model of Suspended Sediments

Under the assumption that vertical transport processes dominate over horizontal transport processes, the conservation equation of mass for particles of size class n is

$$\frac{\partial C_n}{\partial t} = W_n \frac{\partial C_n}{\partial z} + \frac{\partial}{\partial z}\left(K_z \frac{\partial C_n}{\partial z}\right) \tag{1}$$

where C_n is concentration of size n which varies over the vertical coordinate z and with time t. The settling velocity, W_n, of a particular size class is governed by the standard Stokes law fall velocity for spherical particles of radius, a_n, and by the density of quartz

$$W_n (\mathrm{cm/s}) = 2.068 \times 10^{-4}\, a_n^2 \,(a_n \text{ in } \mu\mathrm{m})$$

(Lynch *et al.*, 1991).

The vertical eddy diffusivity, K_z, recommended by Fischer *et al.* (1979) for estuaries is

$$K_z = \kappa u_* z(h-z)/h(1+3.33\,\mathrm{Ri})^{-1.5}$$

where κ is the von Kármán constant, 0.4, u_* is the friction velocity taken here as the greater of the surface and bottom boundary layer values. The surface friction velocity is related to the wind speed in the conventional manner while the bottom friction velocity is a linear function of measured flow at the bottom (Hamblin, 1989). The water depth is h and the Richardson number, Ri, is a function of the measured flow field and density structure as in Hamblin (1989).

Boundary conditions at the surface, $z = h$, are no flux:

$$W_n C_n + K_z \frac{\partial C_n}{\partial z} = 0$$

and at the bottom ($z = 0$) in the case of temporally decreasing concentration or free settling

$$K_z \frac{\partial C_n}{\partial z} = 0$$

erosion or temporally increasing concentration,

$$W_n C_n + K_z \frac{\partial C_n}{\partial z} = -e$$

and equilibrium or steady conditions,

$$W_n C_n + K_z \frac{\partial C_n}{\partial z} = 0 .$$

The initial conditions which are not known, in general, are assumed to be the equilibrium profile which in the case of a constant Richardson number, $\overline{Ri} = \frac{1}{h} \int_0^h Ri dz$, has the analytical solution (Teeter, 1986) in terms of a known concentration at a reference height z_r.

$$C_n(z) = C_n(z_r) \left[\frac{(h-z) z_r}{z(h-z_r)} \right]^{z^*}$$

where $z^* = \frac{W_n}{\kappa u_*} (1 + 3.33 \overline{Ri})^{1.5}$.

Numerical solutions to (1) are similar to the above analytical expression in that they are relative to a reference concentration, $C_n(z_r)$. In the following, a normalized C_n, C_n', is used such that $C_n'(z_r) = 1$.

Teeter (1986) has shown by numerical solution of the above vertical transport equation that the stratification of suspended material, $\Delta C/\overline{C}$, where ΔC is the difference between bottom and surface concentrations and $\overline{C}$ is the vertically averaged concentration is equal to 1.5 times the Peclet number, $Wh/\overline{K}_z$ for the case of equilibrium profiles. For the purposes of estimation of the theoretical distributions of C_n initial profiles of concentration are examined for their stratification and Peclet numbers and classified into erosional, equilibrium or depositional (see Table 1). In the case of erosional or depositional conditions, solutions of equation (1) are obtained by explicit integration in time as described in Hamblin (1989) over a time period determined by the time taken for the profile to reach the observed stratification number at the average settling velocity.

Conner and DeVisser (1992) found that the relation between optical backscattering intensity, I_{0n}, and particle size is in accordance with Mie scattering theory, $I_{0n} \alpha C_n/a_n$, in terms of undetermined coefficients, d_0 and f_0,

$$I_0 = d_0 \sum_n C_n/a_n + f_0$$

or in terms of the normalized solutions of equation (1), size fraction, $fr_{n,ref}$, and reference concentration, C_{ref},

$$I_0 = d_0 \sum_n C_{ref} C_n' \, fr_{n,ref}/an + f_0 \qquad \textbf{(2)}$$

Acoustic backscatter instruments such as the 1.2 MHz profiler used in this experiment operated generally within the Rayleigh scattering region ($2\pi a_n/\lambda << 1$), where λ is the acoustic wave length). For particle sizes typical for the St. Lawrence estuary ($a_n < 60$ μm) this criterion is easily satisfied. In this case, the backscattering intensity, I_{An}, is related to the particle size and volume concentration (Lynch *et al.*, 1991)

$$I_{An} = d_A C_n a_n^3 + f_A$$

and the total response,

$$I_A = d_A \sum_n C_n a_n^3 + f_A \quad \text{or}$$

$$I_A = d_A \sum_n C_{ref} C'_n fr_{n,ref} a_n^3 + f_A \qquad (3)$$

The coefficients d_A and d_0 incorporate the effects of the instrumentment responses, particle density and minerology. Consequently, they must be determined from field experiments.

The reference concentration is the grab or seston sample taken at the reference height of 50 cm above the bottom. The inverse problem for the determination of the unknown size fractions, $fr_{n,ref}$, and constants d_o, f_o, d_A and f_A which are represented by the vector, S, may be expressed in matrix form by

$$G_{2m+1,n}\, S_n = \sigma_{2m+1} \qquad (4)$$

where m refers to the various depths where optical and acoustic measurements are made up to M levels. If ℓ size fractions are assumed in the particle size spectrum, then in terms of the non dimensional concentration, $C'_n(z)$,

$G_{m,n} = C'_n(z_m)/a_n$ for m = odd $1,2M-1$; $n = 1,\ell$
$G_{m,n} = C'_n(z_m)a_n^3$ for m = even $2,2M$; $n = 1,\ell$
$G_{m,n} = 1$ for $m = 2M+1$; $n = 1,\ell$
$G_{m,n} = I_{0m}/C_{ref}$ for m = odd $1,2M-1$; $n = \ell+1$
$G_{m,n} = 1/C_{ref}$ for m = odd $1,2M-1$; $n = \ell+2$
$G_{m,n} = I_{Am}/C_{ref}$ for m = even $2,2M$; $n = \ell+3$
$G_{m,n} = 1/C_{ref}$ for m = even $2,2M$; $n = \ell+4$

The right hand side, σ_{2M+1}, is zero except at $m = 2M+1$ where it is unity. The solution of the inverse problem as expressed by equation (4) is over determined if $2M+1$ exceeds $\ell + 4$.

Once the size spectrum at the reference depth, $fr_{n,ref}$ has been determined from equation (4) it may be evaluated at any other depth from the numerical solutions, $C'_n(z)$ and

$$fr_n(z) = fr_{n,ref}\, C_n'(z) / \sum_n fr_{n,ref}\, C_n'(z)$$

In practice, the acoustic backscattered response, I_{Am}, must be corrected for geometric spreading and for attenuation both by the water and by the suspended material. In the sonar equation (Urick, 1948), the spreading is taken as 20 $\log_{10}(r)$ where r is the acoustic range and the attenuation is αr. The water absorption coefficient, α, appropriate to the acoustic frequency used is 0.474 db/m (Lohrmann and Humphrey, 1991).

The corrections to the backscattered acoustic intensity due to scatterers in the water and viscous losses are accounted for according to the particle size and concentration dependent expressions given in Libicki *et al.* (1989). Equation (4) was solved iteratively starting from the assumption of no viscous and scattering losses. For the relatively low concentration of suspended material experienced it was found that one iterative step was sufficiently accurate.

Lynch and Agrawal (1991) have examined in detail two inversion techniques for the solution of equations similar to equation (4), standard least squares and non-negative least squares, but did not consider the effects of combining acoustic and optical data in a single inversion. The latter technique, adopted here, constrains the particle size fractions to positive values which is not the case with the standard least squares method in the presence of noise. The solution algorithm chosen in this study minimizes the sum of squares of equation (4) for particle size fractions in the range 0 to 1 according to the Levenburg-Marquardt strategy for selecting new iterates (IMSL, 1987). As Lynch and Agrawal (1991) pointed out, a drawback of the non-negative least squares method is that there is no theory for estimation of the error in the particle size inversions. A crude check on the accuracy of the inversion is possible by summation of the size fractions and comparison of this sum to unity.

Since the coefficients, $d_{A,0}$ and $f_{A,0}$ are assumed to be invariant from profile to profile, more confidence can be obtained from equation (4) by including additional profiles. If n profiles are considered in (4) there are $n(2M+1)$ equations but only $n\ell+4$ unknowns.

It is noteworthy that equation (4) is a linear least squares problem in the unknown size fractions. It would be more natural to pose the problem in terms of the logarithm of concentration as the standard deviation of sediment concentration was found to be proportional to the concentration (heteroscedastic). Despite various attempts convergence of the nonlinear, non-negative least squares problem could not be obtained, hence, the linear problem is presented here.

OBSERVATIONS

A series of 12 profiles were observed in the St. Lawrence River estuary from June 6 to 12, 1991 either at anchor or adrift. At these locations in the vicinity of the turbidity maximum (Figure 1), suspended sediment concentrations were measured at approximately 0.5 m above the bottom by the collection of a 1 L grab sample and on board filtration through a preweighed filter. At usually 11 evenly spaced levels in total depths ranging from 10 to 19 m, currents were sampled by an acoustic current meter of ES&S manufacture, optical backscatterance readings were taken with a D&A instruments sensor (Downing and Associates, 1985), and temperatures and conductivities were recorded by standard sensors along with the other profile data. Concurrently, profiles of three components of current and acoustic backscatter intensities from each of four downwardly directed beams were logged for later merging with the directly measured profile data by an Acoustic Doppler Current Profiler (ADCP) of 1.2 MHz frequency. The acoustic intensity of each beam resolved at 1 m depth intervals represented an average of 60 samples or pings. A typical dwell consisted of at least three such averages. The ADCP of RDI manufacture was mounted at the surface on the side of the research vessel. While the bottle sampler and optical backscatter sensor were mounted on the same hydrographic line at a separation less than one meter apart and thus sampled approximately similar volumes, the volume sampled by the four diverging acoustic beams is much larger especially close to the bottom. This could result in poorer correspondence between the acoustic and grab sample data than for the optical data. At each profile location surface wind speeds were noted. Further details of the sampling stations are presented in Table 1.

RESULTS

A scatter diagram of optical backscatter output voltages (counts) at the grab sample depths versus the suspended sediment concentration (seston) of the grab samples indicates a reasonable correspondence in Figure 2. The optical backscatterance output represents an average of about 50 readings over a 100 s period of the dwell of the profiler. A plot of the optical backscatter averages against their standard deviations revealed that the standard deviation is directly proportional to the average concentration. By taking the logarithm the standard deviation becomes independent of the sample value. For this reason, logarithmic scales were chosen for this and all scatter plots to follow. As pointed out earlier, unfortunately convergence could not be obtained for the logarithmic form of equation (4). In recognition of possible sampling errors in the grab sample determinations of concentration the maximum likelihood regression line is shown rather than standard linear regression. Similarly, in Figure 3, the acoustic backscatter intensity corrected for beam spreading and water absorption corresponds more poorly to measured sediment concentration than the optical backscatter measurements. All dwell depths for the set of 12 stations are lumped together in the scatter diagram of Figure 4. Station 8, located in the river zone well upstream of the turbidity maximum has the lowest overall response. Figures 2 to 4 serve as a basis of comparison and evaluation of the corrections to be made below in backscatterance response for particle size according to the theory outlined earlier.

When the data shown in Figure 4 are assembled in a set of equations of the form of equation (4) there are 214 equations for 76 unknowns assuming six size fractions per profile. Unfortunately, in this study there was no independent method of choosing the possible range of particle sizes. Krank (1979) found that in the turbidity maximum the most frequent particle size ranged over 10 to 20 μm in bottom sediments while Hamblin (1989) determined an average particle size of 15 μm for suspended sediments downstream from the study area based on sediment settling rates deduced from a match of model results to field observations. On the basis of these studies it was assumed that particles ought to span the range from 4 to 100 μm and that the size classes would be distributed in the usual power-of-two size increments. The upper point is chosen as 100 μm rather than 128 μm as the inversion proved to be nonconvergent over this broader dynamic range of particle sizes. This finding is in agreement with the analysis of Lynch and Agrawal (1991) who showed for solely acoustic response in a turbulent boundary layer that the condition number of the matrix, G, in equation (4) is a function of the dynamic range of particle sizes and depths. Iterations were initialized by the assumption of equal size fractions in each class summing to unity, the constants of proportionality, $d_{A,O}$ of unity and its intercepts, $f_{A,O}$, zero. There were no bounds placed on these last four parameters.

The results of the inversion of equation (4) for particle size spectra at the grab sample or reference depths are presented in Figure 5. It is evident that in all cases the fractions sum closely to unity which is an encouraging indication of the accuracy of the inversion. Most spectra are unimodal with a peak at either 16 or 32 μm. Stations 4 and 8 suggest a bimodal distribution and that at 4 possibly particles larger than 100 μm are present. The remarkable similarity of spectra at stations 9 to 12, all observed on June 12, will be exploited to infer sediment transport in a later section. Unfortunately, there were no independent measurements of particle size spectra with which the results of Figure 5 may be compared. Instead, the spectrum is evaluated indirectly by its application to the estimation of sediment concentration.

Equation (2) may be rearranged to yield the concentration, C(z), based on optical backscatterance

$$C(z) \quad = \quad C_{ref}\sum_n C_n^{\prime}(z)\,fr_n \quad = \quad \frac{(I_0(z) \;-\; f_0)\,\Sigma C_n^{\prime}(z)\,fr_n}{d_0\sum_n C_n^{\prime}(z)\,fr_n/a_n} \qquad (5)$$

or from equation (3) for acoustical backscattering,

$$C(z) \quad = \quad \frac{(I_A(z) \;-\; f_A)\;\sum_n C_n^{\prime}(z)\,fr_n}{d_A\;\Sigma C_n^{\prime}(z)\,fr_n a_n^3} \qquad (6)$$

After correction for size distributions according to equation (5) the near bottom optical backscattering measurements compare more favourably with the concentration from seston samples in Figure 6 than do the uncorrected measurements in Figure 2. The improvement is more marked in the case of the acoustic measurements shown in Figure 7. In this case the correlation coefficient (R) increases from the uncorrected value of 0.89 in Figure 3 to 0.98 in the case of the size corrected backscatter response thereby bringing the acoustical estimation of concentration in line with the optical determination. The optically and acoustically inferred concentrations from equations (5) and (6) are compared in Figure 8 at all sample depths. It is evident that taking into account the size spectra increases R from 0.92 to 0.97 and that the maximum likelihood regression line of the corrected estimate has a slope of 1.056 ± 0.026 and an intercept indistinguishable from zero.

Application to Tidally Averaged Sediment Flux

Past studies have shown that suspended sediment dynamics greatly affect contaminant fluxes in the St. Lawrence estuary. The large width of the estuary containing various flow and mixing regimes prevents estimating fluxes reliably from single stations. In this section, the concepts developed above are applied to estimating for the first time the cross-sectionally and tidally averaged transport and sediment flux.

Measurements of acoustically determined flow and backscattering profiles (ADCP) were carried out over a semi-diurnal tidal cycle on June 12, 1991 in the region between the dashed lines shown in Figure 1. This area was chosen as it is one of the few navigable passages within the maximum turbidity zone. Four complete transects each comprised of about 210 individual profiles over a distance of about 15 km and one partial transect of 69 profiles covered the 10.2 hr sampling period. The ship's position was measured by means of an autonomous global positioning system (GPS) and shipboard gyro compass. A typical speed-made-good of the vessel was 3 m/s as determined by differencing GPS derived position estimates and from bottom tracked velocities from the acoustic profiler. It was decided to use the GPS ship velocities for correction of the current profile data for ship motion despite the potential for errors in GPS velocities of up to 0.2 m/s (Georgiadou and Doucet, 1990). Although the estuary was sufficiently shallow to obtain strong bottom echoes at all profiles the bottom tracked velocities did not compare favourably in shallow water. Also, Stronach and Hodgins (1990) found that in a tidal estuary motion of the bottom sediments at high flow speeds invalidated the fixed seabed assumption for calculating absolute velocities acoustically.

At the beginning and end of most transects profiles of optical backscatter, temperature and salinity were measured. The analyses of these data sets along with the accompanying acoustic data indicated at stations 9 to 12 almost identical particle spectra in Figure 5. On this basis it was assumed that this distribution held for the entire experimental period. Suspended sediment concentration estimates were computed from equation (6) and the size spectra of stations 9 to 12 at 1 m depth intervals over the water column. Components of vertically integrated sediment flux were compiled by summing the flux components at each 1 m depth interval over the water column. Next, the vertically integrated flux data were sorted in time and position so that at each of the 210 points across the estuary a time series of either 4 or 5 points over the tidal cycle resulted. At each point the mean and semi-diurnal constituents of the sediment flux and the transport were calculated by a least squares best fit to the time series. This method of tide removal is a simplified version of one of the approaches outlined by Foreman and Freeland (1991).

The tidally averaged sediment flux at a point along the St. Lawrence estuary is presented in Figure 9. The somewhat irregular track in the northwestern position is caused by averaging of the individual tracks which diverged more in the highly energetic northwestern portion of the study area. The associated mean transport given in Figure 10 also indicates a net upstream flux. Not shown are the major axes of the tidal ellipses of transport and sediment flux which indicate semi-diurnal tidal amplitudes about four times larger than the mean quantities. The total tidally averaged sediment flux and transport over the width of the estuary was calculated according to the line integral, $\int U_n ds$, where U_n is the component of transport or flux normal to the line segment, ds, and was taken as zero at the two land boundaries.

The total net transport was 31,600 m^3/s and sediment flux 2135 kg/s, both in the upstream direction. While not surprising in view of the preponderance of upstream vectors in Figures 9 and 10, the transport does not compare favourably with daily average discharge estimated from June 12, 1991 from river discharge measurements of 11,000 m^3/s (R. Couture, Environment Quebec, pers. comm.). Over the experimental period the observed winds averaging 8 m/s in an upstream direction could result in an upstream transport of 4×10^4 m^3/s based on elementary hydrodynamic and considerations in a channel of 15 km in breadth. If this is the case, then the value of the computed flux is not unreasonable.

DISCUSSION AND CONCLUSION

A method for combining field observations of direct suspended matter concentration, optical and acoustic backscatter responses and a vertical sediment transport model for a shallow estuary has been developed for obtaining profiles of sediment concentration and particle size spectra over the water column. Since the acoustical data were obtained remotely, consideration has been given for the correction of acoustical data for sediment attenuation. The application of this method to the region of the turbidity maximum of the St. Lawrence estuary demonstrated the importance of knowledge of the particle size spectrum in the interpretation of backscattering measurements, particularly for the far field acoustical data considered here.

Unfortunately, independent size spectra were not available to evaluate the inferred spectra. The results of the study indicate somewhat larger sizes than those obtained by laboratory analysis of dispersed bottom samples in the region of the turbidity maximum. This suggests that suspended particles in the estuary may be aggregated into flocs. However, there is possible ambiguity in the interpretation of size as acoustically determined size may differ from optical size which in turn may not be the same as laboratory determinations. Size spectra have been evaluated indirectly by showing that accounting for size in the backscattered response reduces the statistical scatter between grab sample concentrations and those inferred from backscatterance.

Application of the acoustic profiler to the computation of the tidally averaged sediment flux across the estuary was only possible because the four profiles taken during the tidal cycle suggested that the assumption of an invariant size spectrum was reasonable. If the particle spectrum changed over the tidal cycle or across the transect then continuous profiles of optical backscattering and density structure would have been required in addition to the acoustic information. This fortuitous circumstance permitted the calculation of the tidally averaged net sediment flux and transport across the estuary. These results suggested that many such experiments would have to be performed to average out the influence of the wind driven circulation.

Perhaps a more profitable approach would be to use the measured sediment and velocity profiles to verify a three-dimensional model of the wind and tidal circulation which, in turn, is coupled to a sediment transport model. This work is in progress and hopefully will be reported shortly. Such a three-dimensional model may overcome some of the limitations of the approach outlined here namely the neglect of horizontal gradients in equation (1) and some of the uncertainties on the initial conditions of the sediment transport model.

In future studies of sediment concentration and flux in estuaries, it is recommended that sediment concentrations be measured directly from grab samples as frequently as possible. Even optical backscatter sensors must be calibrated in situ to obtain accuracy (Maa *et al.*, 1992). Gibbs and Wolanski (1992) have found size dependent errors of up to 100% in concentration determinations of estuarine sediments using optical backscatter measurements. Size spectra of the grab samples, as well as any independent in situ measurements, would be highly desirable if technically feasible. A method of measuring the optical backscatterance and stratification concurrently with backscatterance acoustics is necessary. A vertically cycling towed instrument package of the type described by Fratantoni and John (1991) would serve this purpose well. Better positional and ships velocity data than is currently available from autonomous GPS navigation systems is highly recommended. Improved knowledge on the specification turbulent mixing from readily measured quantities in estuaries is strongly advised. Further work on inversion algorithms suitable for size analysis from backscatterance data is warranted. In particular, the error analysis of non-negative least squares is in need of attention and the extension of this method to the nonlinear problem involving the logarithm of concentration would likely be an improvement.

ACKNOWLEDGEMENTS

I am grateful to Captain M. Head and the crew of the CSS *Advent* who provided ship support for the experiment and J. Diaz and J. Valdmanis who assisted in the design and operation of the field instrumentation. I thank C. He for his helpful comments on the manuscript and F. Chiocchio for the preparation of the seston filters.

REFERENCES

Agrawal, Y.C. and Pottsmith, H.C. 1989. Autonomous, long-term in-situ particle sizing using a new laser diffraction instrument. Oceans '89 Proceedings, pp. 1575-1580.

Conner, C.S. and DeVisser, A.M. 1992. A laboratory investigation of particle size effects on an optical backscatterance sensor. Mar. Geol. 108: 151-159.

Downing and Associates. 1985. Model OBS-2 Optical Backscatterance Suspended Solids Monitor, Operations Manual. Downing and Associates, Washington, D.C.

Fischer, H.B., List, E.J., Koh, R.C.Y., Imberger, J. and Brooks, N.H. 1979. Mixing in inland and coastal waters. Academic, San Diego, California.

Foreman, M.G.G. and Freeland, H.J. 1991. A comparison of techniques for tide removal from ship-mounted acoustic doppler measurements along the southwest coast of Vancouver Island. J. Geophys. Res. 96: 17,007-17,021.

Fratantoni, D.M. and Johns, W.E. 1991. Development and initial application of a deep-towed ADCP/CTD package for oceanic bottom boundary layer studies. Proc. Oceans '91, Ocean Engrg. Soc. of IEEE 2: 985-991.

Georgiadou, Y. and Doucet, K.D. 1990. The issue of selective availability. GPS World. September/October, pp. 53-56.

Gibbs, R.J. and Wolanski, E. 1992. The effect of flocs on optical backscattering measurements of suspended material concentration. Marine Ecology 107: 289-291.

Hamblin, P.F. 1989. Observations and model of sediment transport near the turbidity maximum of the Upper St. Lawrence estuary. J. Geophys. Res. 94: 14,419-14,428.

Hay, A.E. and Sheng, J. 1992. Vertical profiles of suspended sand concentration and size from multi frequency acoustic backscatter. J. Geophys. Res. 97: 15661-15678.

IMSL. 1987. User's Manual: Fortran Subroutines for Mathematical Applications. Vol. 3, p. 876.

Krank, K. 1979. Dynamics and distribution of suspended particulate matter in the St. Lawrence estuary. Nat. Can. 106: 163-173.

Libicki, C., Bedford, K.W. and Lynch, J.F. 1989. The interpretation and evaluation of a 3-MHz acoustic backscatter device for measuring benthic boundary layer sediment dynamics. J. Acoust. Soc. Am. 85: 1501-1511.

Lohrmann, A. and Humphrey, C. 1991. Field tests and calibration of an ADCP for dredged material plume measurements. MTS '91 Proceedings, New Orleans, LA.

Lynch, J.F. and Agrawal, Y.C. 1991. A model for inverting vertical profiles of scattering to obtain particle size spectra in boundary layers. Mar. Geol. 99: 387-401.

Lynch, J.F., Gross, F.F., Brumley, B.H. and Tilyo, R.A. 1991. Sediment concentration profiling in Hebble using a 1-MHz acoustic backscatter system. Mar. Geol. 99: 361-385.

Maa, J.P.Y., Ku, J. and Victor, M. 1992. Notes on the performance of an optical backscatter sensor for cohesive sediments. Mar. Geol. 104: 215-218.

Stronach, J.A. and Hodgins, D.O. 1990. Scintillometer-acoustic doppler current profiler intercomparison using Fraser River measurements. Unpublished report, Seaconsult, Marine Research Ltd., Vancouver, B.C., Canada.

Teeter, A. 1986. Vertical transport in fine-grained and newly deposited sediment. In: Estuarine Cohesive Sediment Dynamics, A.J. Mehta (Ed.), pp. 170-191. Springer-Verlag, New York.

Thorne, P.D., Hardcastle, P.J. and Soulsby, R.L. 1993. Analysis of acoustic measurements of suspended sediment. J. Geophys. Res. 98: 899-910.

Urick, R.J. 1948. The absorption of sound in suspension of irregular particles. J. Acoust. Soc. Am. 20: 283-289.

TABLE 1: Additional profile data

Station	Date	Time (UCT)	Depth (m)	Stratification	Peclet No.	Class
1	June 6	17:50-18:09	17	1.6	0.8	Depositional
2	June 8	17:16-17:36	19	1.7	1.3	Depositional
3	June 8	19:03-19:23	18.5	0.6	1.6	Depositional
4	June 9	15:23-15:36	11	0.7	0.8	Depositional
5	June 10	12:44-12:54	14.3	1.1	0.4	Erosional
6	June 10	16:19-16:25	12.0	0.06	1.0	Depositional
7	June 10	19:12-19:18	13.2	0.4	1.0	Depositional
8	June 11	19:33-19:47	13.0	0.01	1.4	Depositional
9	June 12	13:08-13:15	13.1	1.7	1.6	Depositional
10	June 12	18:05-18:11	10.5	0.2	1.1	Depositional
11	June 12	20:52-21:00	15	0.3	0.5	Depositional
12	June 12	22:51-23:00	16.5	0.5	0.6	Depositional

LIST OF FIGURES

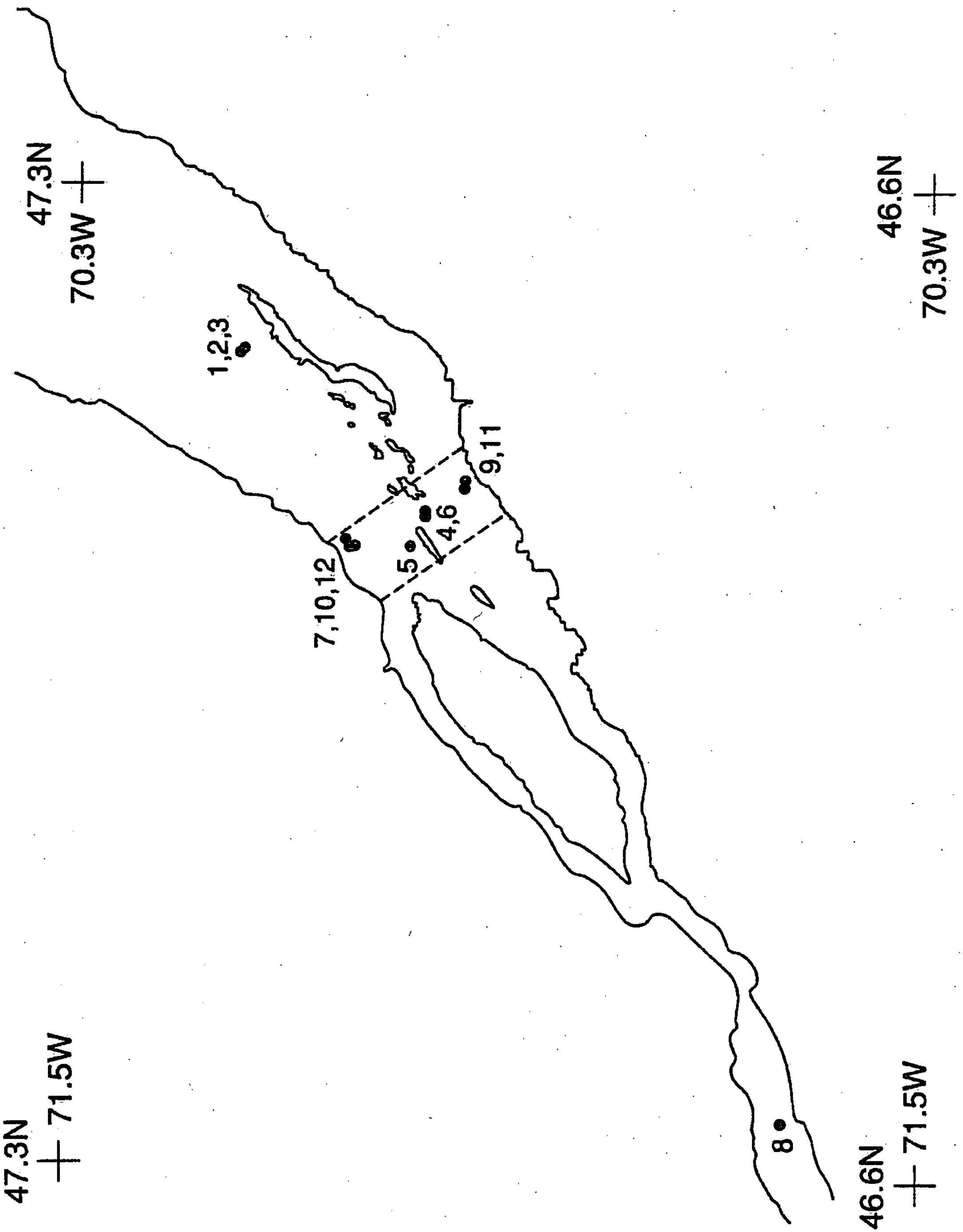

Figure 1

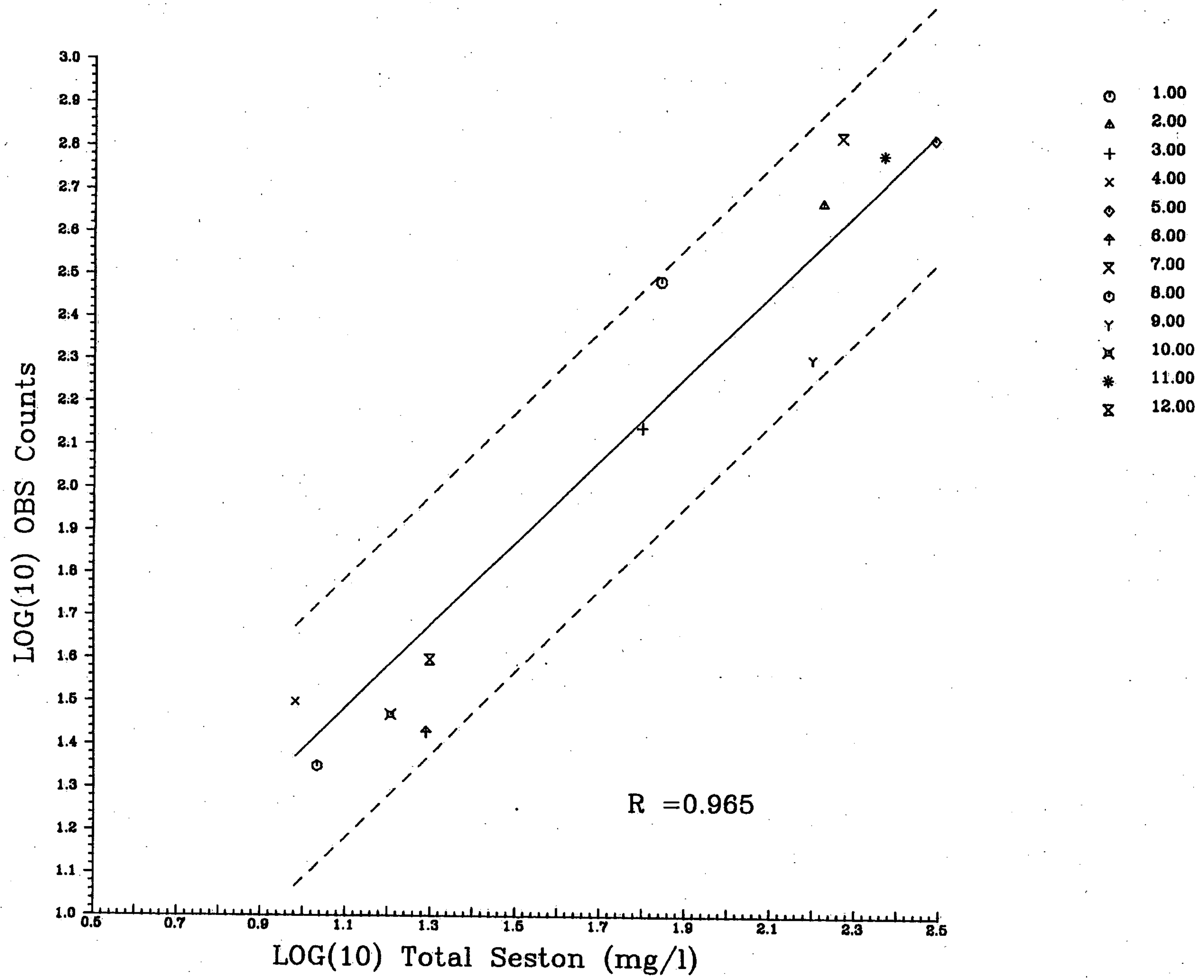
3.0
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
LOG(10) OBS Counts
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
2.1
2.3
2.5
LOG(10) Total Seston (mg/l)
R =0.965
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
10.00
11.00
12.00

Figure 2

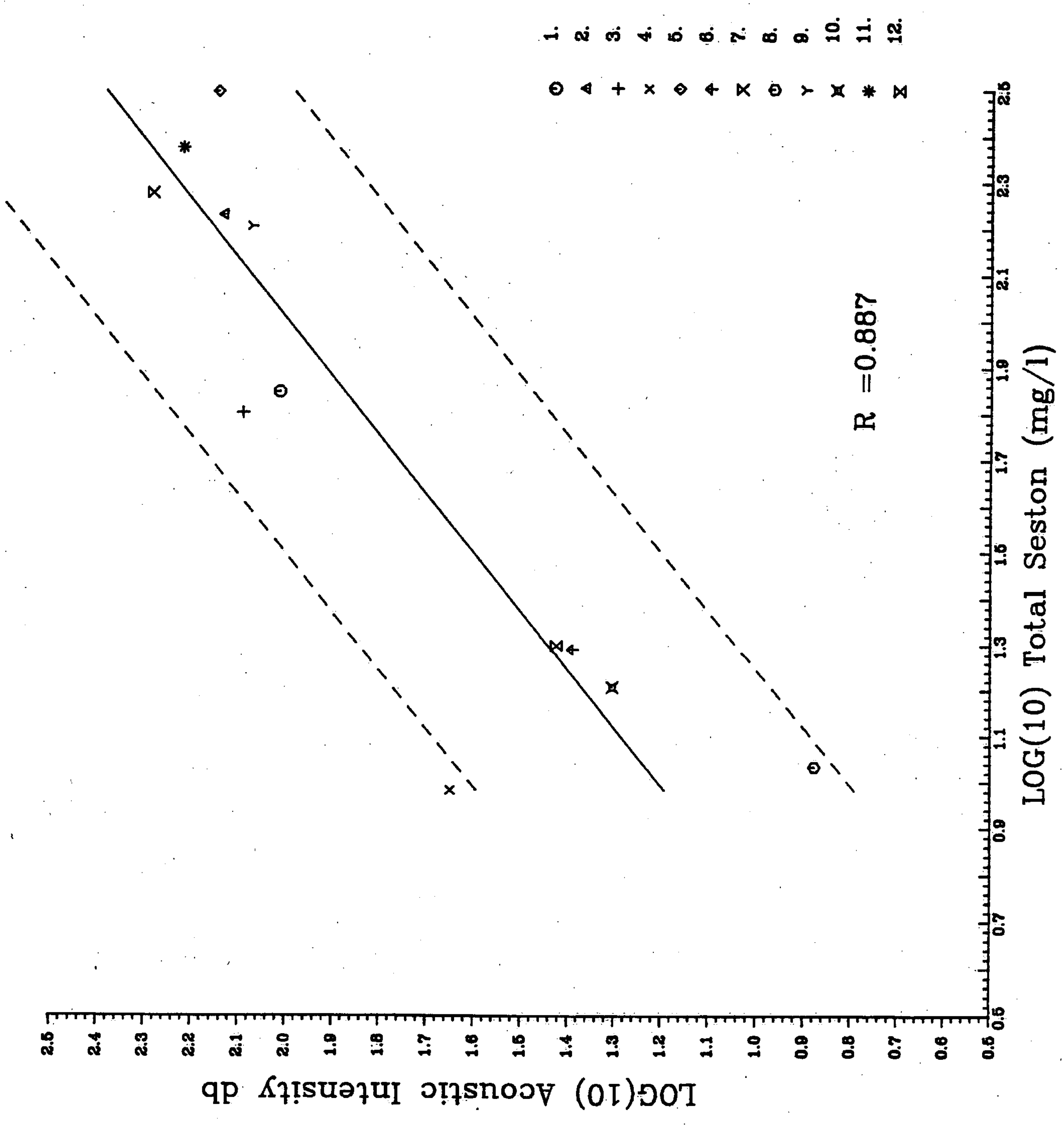
LOG(10) Acoustic Intensity db
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2.1
2.2
2.3
2.4
2.5
LOG(10) Total Seston (mg/l)
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
2.1
2.3
2.5
R =0.887
1.
2.
3.
4.
5.
6.
7.
8.
9.
10.
11.
12.

Figure 3

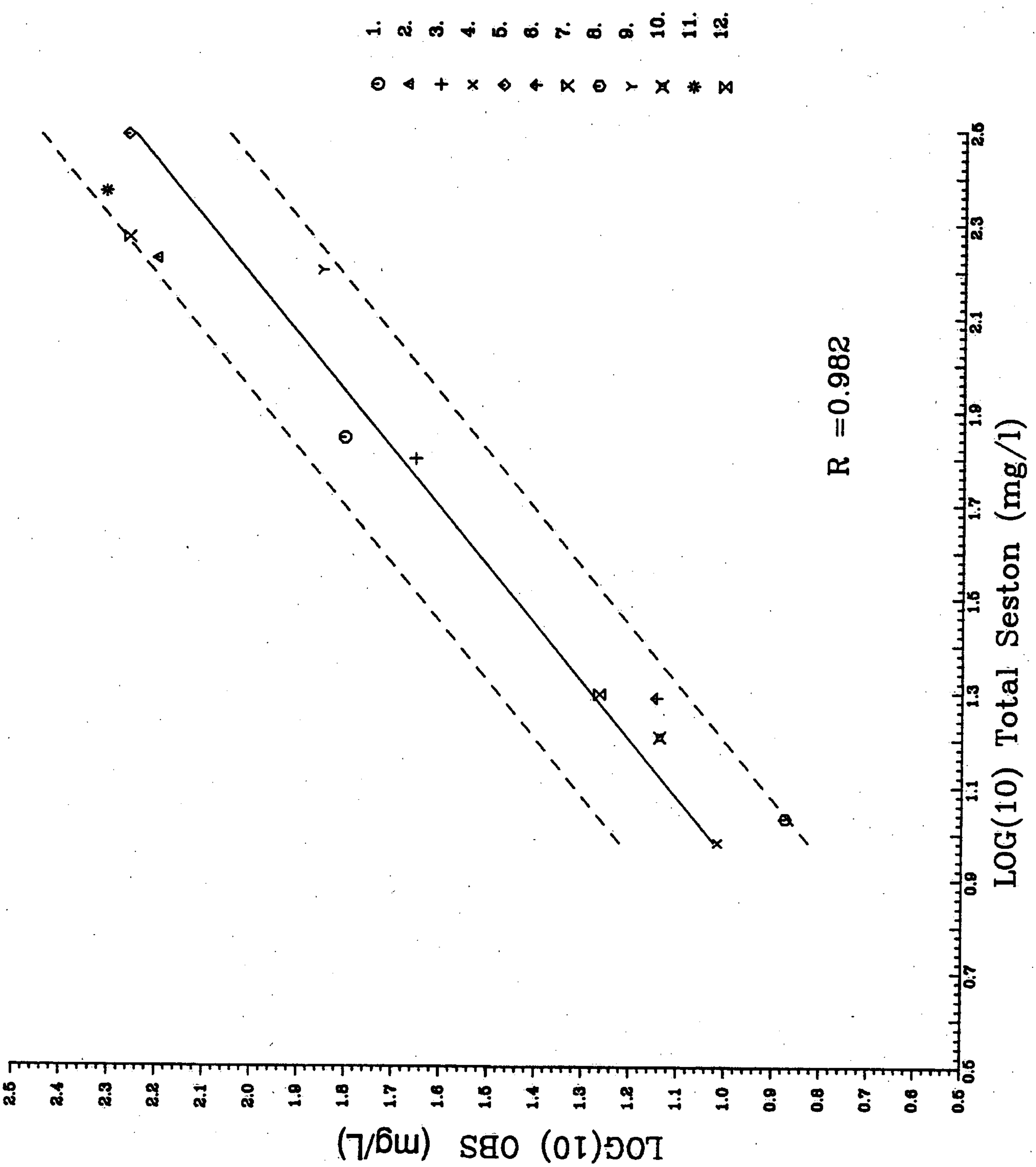
LOG(10) OBS (mg/L)
LOG(10) Total Seston (mg/l)
R =0.982
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2.1
2.2
2.3
2.4
2.5
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
2.1
2.3
2.5
1.
2.
3.
4.
5.
6.
7.
8.
9.
10.
11.
12.

Figure 6

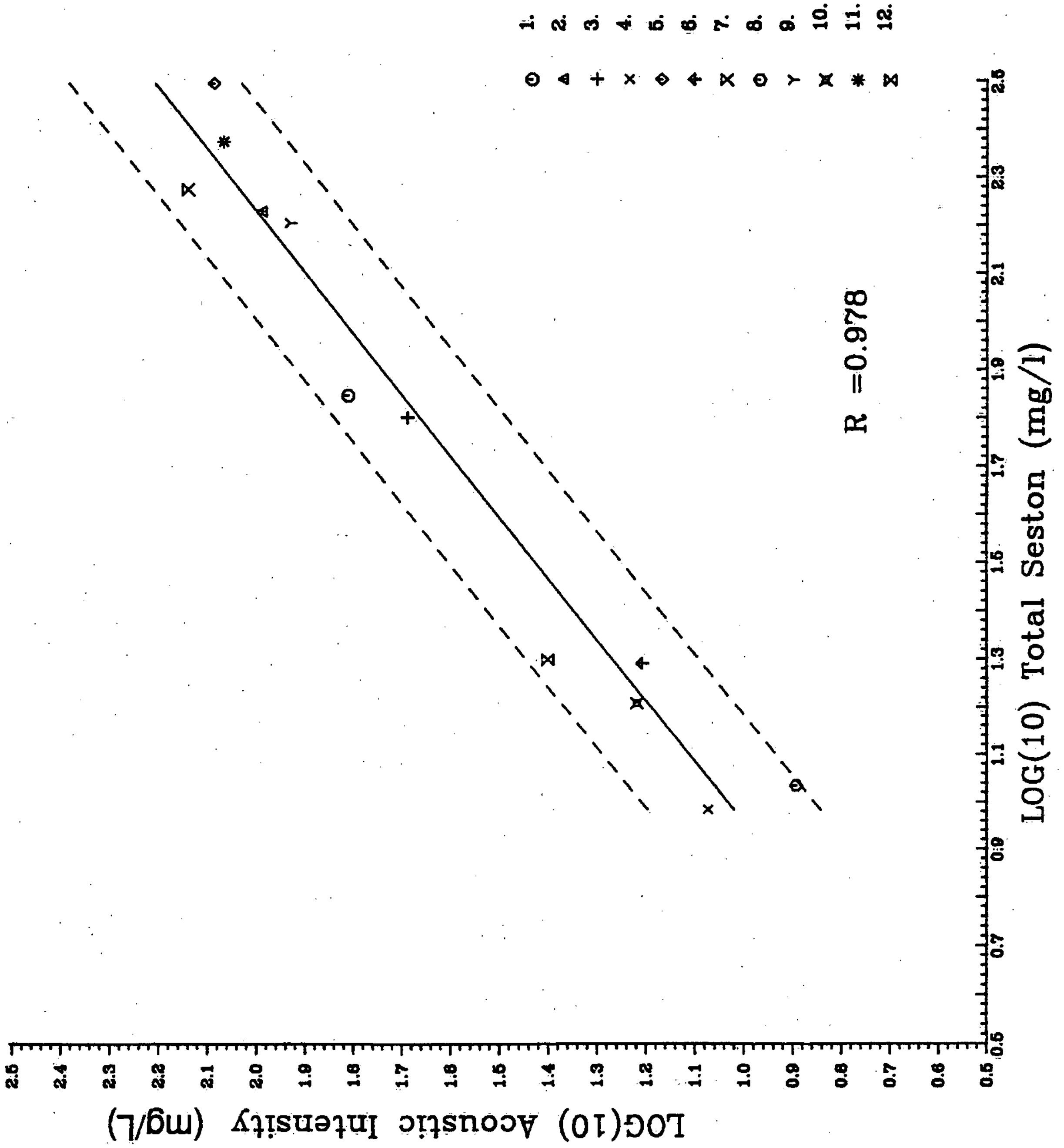
LOG(10) Acoustic Intensity (mg/L)
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2.1
2.2
2.3
2.4
2.5
LOG(10) Total Seston (mg/l)
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
2.1
2.3
2.5
R =0.978
1.
2.
3.
4.
5.
6.
7.
8.
9.
10.
11.
12.

Figure 7

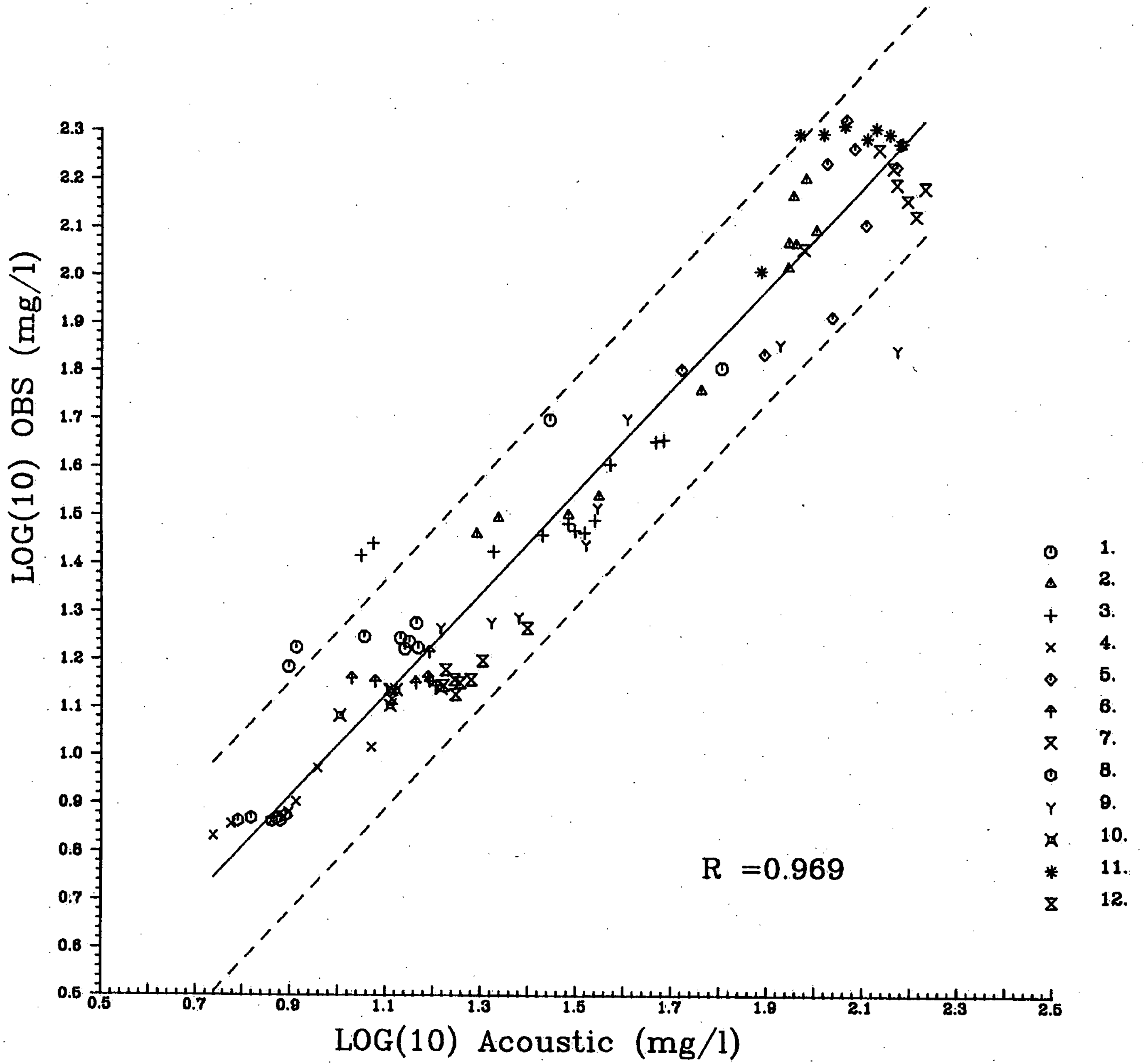
LOG(10) OBS (mg/l)
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
2.1
2.3
2.5
LOG(10) Acoustic (mg/l)
R =0.969
1.
2.
3.
4.
5.
6.
7.
8.
9.
10.
11.
12.

Figure 8

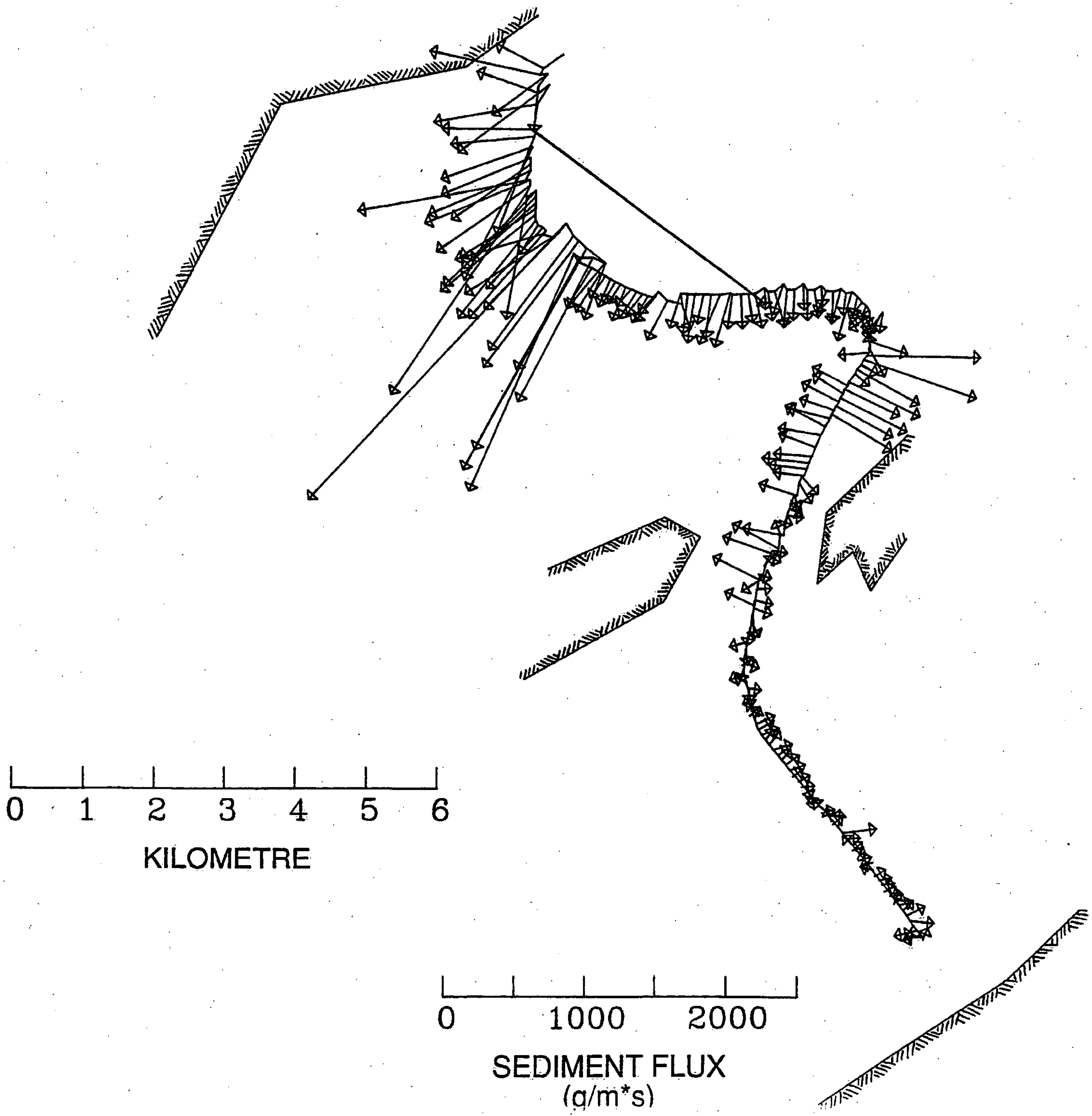

Figure 9

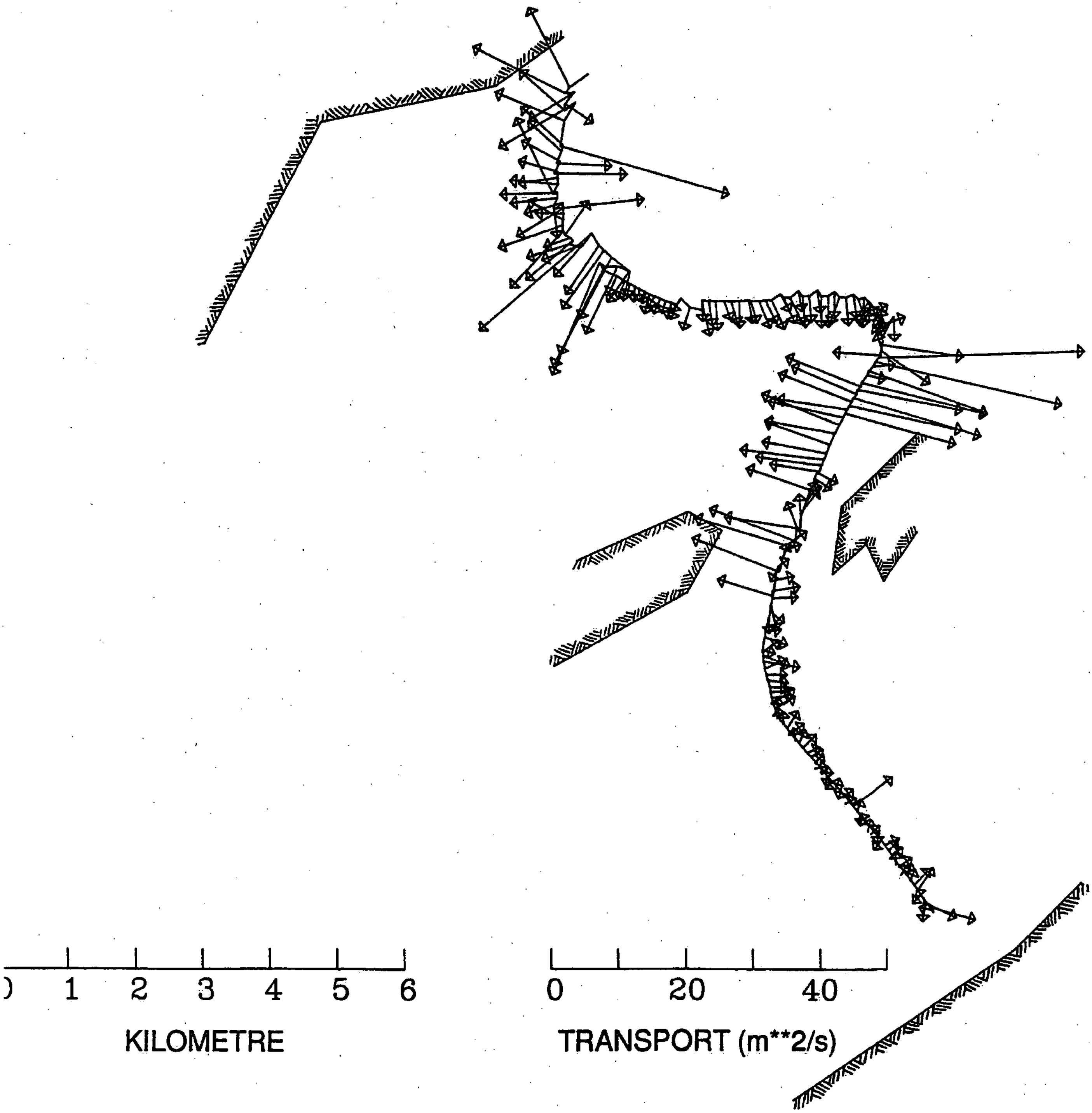

Figure 10

Environment Canada Environnement Canada

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