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MIXING CHARACTERISTICS OF THE ATHABASCA RIVER USING CONSERVATIVE ions

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NWRI Contribution No. 94-152

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MANAGEMENT PERSPECTIVE

In order to be able to accurately model the transport and fate of pollutants using water quality models it is necessary to establish the mixing or dispersion characteristics of the river system being studied under different flow conditions. This is particularly important for the 2 dimensional modelling work being carried out at NWRI to examine the discharge of contaminants from the Tar Sands plants near Ft. McMurray into the Athabasca River. Tracer dye studies are normally used to determine the mixing characteristics but require large field crews and on-site analytical facilities. The method described in this report utilizes naturally occurring water quality parameters to evaluate mixing characteristics downstream from the confluence of two streams. Sampling can be carried out with minimal field equipment and personnel. Results obtained using this method compare well with previous studies using the standard dye tracer method.

ABSTRACT

In many rivers complete sectional mixing is not achieved for long distances from the initial release point of a pollutant. This is the case for the Athabasca River downstream of Ft. McMurray where the release of contaminants from the Tar Sands refinery operations. A two dimensional toxic chemical model is being developed at NWRI to examine the transport and fate of these contaminants. Because of the complex nature of the mixing processes, field tests are required to supply mixing data for the model for a wide range of flow conditions. In order to supplement the few tracer dye studies which have been performed, the mixing of natural water quality parameters at the confluence of the Athabasca and Clearwater Rivers has been used to simulate a steady-state tracer test. The diffusion and dispersion values obtained from this study are compared with earlier dye tracer studies as well as a similar natural water quality tributary mixing study performed 18 years earlier.

INTRODUCTION

Most river water quality models are one-dimensional in nature where complete mixing of pollutants across the river sections is assumed. However, in many rivers complete sectional mixing is not achieved for long distances from the initial release point of the pollutant. This is the case for the Athabasca River downstream of Ft. McMurray where the release of contaminants from the Tar Sands refinery operations near Ft. McMurray is being studied (Brownlee 1990, Booty et al. 1991, Bourbonniere 1992). A two-dimensional toxic chemical model is being developed as part of this project. Because of the complex nature of mixing processes, field tests are required to evaluate the mixing characteristics of the river reaches. These tests usually involve the use of tracers. A number of tracer dye studies have been performed on the Athabasca River downstream of Ft. McMurray (Beltaos 1978, Beltaos, 1979, Van Der Vinne 1993). Information on the hydraulic and mixing characteristics need to be repeated over a wide range of flow conditions and ice/no ice conditions to fully characterize the river reaches. However, tracer dye experiments are quite expensive and are not normally performed very often. In order to supplement the available tracer dye studies, the mixing of natural water quality parameters of a river and its tributaries can be used. At the confluence of two streams, one stream acts as a source of water quality parameters whose concentrations are significantly different from the concentrations of the second stream. Downstream of the confluence the mixing of the two flows produces the equivalent of a steady state tracer test. The feasibility of this approach has been examined previously (Lipsett and Beltaos 1978) for the confluence of the Athabasca River with the Clearwater River at Ft. McMurray. The measured concentration distributions were found to agree well with those predicted by an analytical model of transverse mixing in a prismatic channel. In this study the confluence of the Athabasca and Clearwater Rivers is again used to determine mixing characteristics of the reaches downstream of the confluence under different flow regimes.

THEORY and METHODOLOGY

A representation of the mixing process downstream of the confluence of a tributary and mainstream is shown in Figure 1. In this example the conservative water quality parameter, Cl^- for example, is C_T in the tributary and C_M in the mainstream. Here it is assumed that $C_T > C_M$. It is also assumed that the concentration of any tracer parameter upstream of the confluence is uniform and independent of time. Downstream of the confluence three regions exist. In region 1 near the tributary the concentration is constant and equal to C_T. Moving downstream the width of this region decreases due to transverse mixing and eventually this width is reduced to zero and beyond this point the right bank concentration is less than C_T. The second region is found along the left bank where the concentration is equal to C_M. This region also decreases in width downstream until it reaches zero. Beyond this point the concentration on the left bank is greater than C_M. The third region is the mixing zone where the width is zero at the confluence and increases in the downstream direction, eventually becoming equal to the full width of the river. Eventually, at a point far downstream, a uniform concentration distribution is established across the river.

The principle of conservation of mass of a neutral tracer results in the equation

$$\frac{\partial C}{\partial t} + u(y,z)\frac{\partial C}{\partial x} = \frac{\partial}{\partial x}\left(\varepsilon_x \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(\varepsilon_y \frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(\varepsilon_z \frac{\partial c}{\partial z}\right) \qquad (1)$$

where C is the concentration and ε_x, ε_y, and ε_z are the turbulent diffusivities in the coordinate directions. In order to simplify equation 1 a number of assumptions can be made. As most river channels have widths much greater than average depth, vertical mixing is accomplished within a relatively short distance of the source (50-100 river depths). Beyond this distance reasonably accurate concentration predictions can be made in terms of the depth averaged concentration. Integration of equation 1 in the vertical direction gives a simpler equation describing the depth-averaged concentration, C_d, where the suffix d is used to denote a depth average. Another assumption that can be made is that longitudinal diffusion is negligible as compared to longitudinal dispersion and setting $\partial C/\partial t = 0$ (steady-state mixing), it can be shown that

$$hu_d \frac{\partial C_d}{\partial x} = \frac{\partial}{\partial y}(h\, \epsilon_{yd} \frac{\partial C_d}{\partial y}) \qquad (2)$$

Equation 2 shows that the vertical coordinate, z, has been suppressed and the important mechanisms of mixing are longitudinal convection (lefthand side) and transverse diffusion (righthand side). In the 2-D model being used, the stream tube coordinate transform concept developed by Yotsukura and Cobb (1972) is used. In this approach the river cross section is divided into a number of vertical strips called "stream tubes", such that the discharge within each stream tube is the same. The streamtube transformation permits an analytical solution of equation 2.

Letting q denote the discharge between the left bank, y=0, and any vertical at y, then

$$q = \int_0^y hu_d \, dy = q(y) \qquad (3)$$

where u_d is the depth averaged velocity. A one to one relationship exists between y and q and the transverse coordinate may be represented by q equally as well as y. Using equation 3, the governing equation (equation 2) becomes

$$\frac{\partial C_d}{\partial x} = \frac{\partial}{\partial q}(h^2\, u_d\, \epsilon_{yd} \frac{\partial C_d}{\partial q}) \qquad (4)$$

Yotsukura and Cobb (1972) showed that the variation of the quantity $h^2\, u_d\, \epsilon_{yd}$ with q had very little effect on the solution of equation 4. Consequently it may be assumed that $h^2\, u_d\, \epsilon_{yd}$ is a constant and equal to its average value, that is

$$h^2\, u_d\, \epsilon_{yd} = \overline{h^2\, u_d\, \epsilon_{yd}} = D_y \qquad (5)$$

where the overbar denotes average with respect to q. The simplified two-dimensional convection-diffusion equation describing the distribution of a conservative chemical under steady state conditions can be written in the form

$$\frac{\partial C_d}{\partial x} = D_y \frac{\partial^2 C_d}{\partial q^2} \tag{6}$$

in which x = longitudinal distance below the source, q = cumulative partial discharge measured from a reference bank, C_d is the depth averaged concentration of the chemical at a point (x,q), u = depth-averaged local velocity of flow in the x direction, and D_y = diffusion factor. The diffusion factor is assumed to be constant at a cross-section and is given by

$$D_y = \overline{(m_x e_y uhsup2)} = \frac{1}{Q} \int_0^Q (m_x e_y uh^2)\, dq \tag{7}$$

in which the overbar indicates the average value of the product term, h represents the local depth of water at a lateral distance,y, (the latter being measured from the reference bank), e_y = transverse dispersion coefficient, Q = discharge in the river just below the source, and m_x is a metric coefficient (scaling factor) to correct for differences between longitudinal distances along curved coordinate surfaces and those measured along the x-axis.

The values of D_y can be estimated from the variances of c(x,q) versus q distributions, as outlined by Beltaos (1978) and Yotsukura and Cobb (1972). The program Mixandat by Gowda (1980) has been used in this study to calculate D_y from the relationship with the variance, σ^2_q, of c(x,q) versus q distributions. Both D_y and e_y can be related to bulk flow parameters of the channel. Following Beltaos (1978), an expression for D_y can be written in the form

$$D_y = \psi\, e_y \bar{u}\, \bar{h}^2 \tag{8}$$

in which $\bar{h}$ and $\bar{u}$ denote the cross-sectional mean values of depth and velocity, respectively, and ψ denotes a shape-velocity factor which is used to account for the deviations of local depths and velocities from the cross-sectional mean values. The shape-velocity factor can be evaluated from the relationships presented by Beltaos (1979). A review of the literature indicates that e_y can be expressed as a function of the bulk flow parameters of a channel (Holley et al. 1972,Lau and Krishnappan 1977). Holley et al.(1972) expressed e_y as a function of the average values of depth and velocity of flow by the following expression:

$$e_y = \alpha_2 h u \tag{9}$$

where h and u represent mean depth and mean velocity and α_2 is a nondimensional transverse dispersion coefficient. Lau and Krishnappan (1977) related e_y to the width and velocity of flow. The expression for e_y, developed from a dimensional analysis, is given by:

$$e_y = \beta_e b u \tag{10}$$

where β_e is a nondimensional coefficient. The values of β_e were found to vary from 2.78 x 10^{-4} to 15.17 x 10^{-4} in rectangular flumes.

FIELD DATA

The Clearwater River is a major tributary of the Athabasca River with the confluence at the town of Ft. McMurray. Figure 2 shows the area of study along with the locations of the transects used for sampling. Data required for each transect are 1) longitudinal distance from confluence 2) flow rates 3) depth averaged velocities 4) cross sectional geometry and water temperature. The transects were divided into 10 stream tubes. The number of stream tubes chosen was based on practical rather than theoretical considerations to allow all of the field sampling at each site to be performed within a

reasonable period of time. At each of the centroids of the stream tubes the following measurements are necessary:

1) distance y from the reference bank

2) depth at y

3) depth averaged velocity at y (optional)

4) concentration of tracer ion at y

Further river data required are:

1) flow rate of the Athabasca river upstream of the confluence

2) concentration of the tracer ion in the Athabasca River upstream of the confluence

3) flow rate of the Clearwater River upstream of the confluence

4) concentration of the tracer ion in the Clearwater River upstream of the confluence

In 1993 two separate sampling programs were carried out during the periods of May 22-31 and Aug. 26 - Sept. 7. At each transect a depth profile was carried out using an echo sounder. Water samples were collected upstream of the confluence for both rivers and at the midpoint of each streamtube for analysis of 1) Ca^{2+} 2) Cl^- 3) SiO_2 4) SO_4^{2-} 5) Mg^{2+} 6) K^+ and 7) Na^+. Flow data were obtained for the sampling periods from the WSC gauges located on the Clearwater River near Draper, Athabasca River below Ft. McMurray. Additional flow data were obtained for the Steepbank, Beaver, Muskeg and Mackay rivers which are tributaries to the Athabasca River below the confluence of the Athabasca and Clearwater. Water samples were also collected from these tributaries and were analyzed for the above parameters to examine their possible influences on the mixing of the Clearwater and Athabasca rivers. During the two periods of study, the flows from the smaller tributaries represented less than 1% of the total flow and consequently were not considered to be significant factors. The contribution of groundwater to the Athabasca River along the reach being studied is also a potential source of the tracer ions being considered. As there are no WSC flow gauges on the river downstream of transect 1 it is not possible to accurately determine the groundwater contribution to the study reach. Schwartz, F.W. (1979) carried out a hydrogeological investigation of the Muskeg River Basin. However, no determination was made as to the direct groundwater

contribution to the Athabasca River in that area.

May 1993 Field Data

Examination of the water quality parameter data revealed that of the seven potential tracers, Na^+ and Cl^- were the best to use for the study as the concentrations were significantly different between the Clearwater and Athabasca rivers (Clearwater River: $[Na^+]$ = 19.8 mg/L, $[Cl^-]$ = 27.8 mg/L]; Athabasca River: $[Na^+]$ = 6.65 mg/L, $[Cl^-]$ = 1.6 mg/L) and show the most distinct mixing patterns, as shown in Figure 3 for data collected at transect 1. It can be seen that the other tracers do not exhibit the expected mixing pattern shown in Figure 1.

The hydraulic data measured for transects 1-6 are shown in Figures 4-9 respectively. The concentration profiles for Na^+ and Cl^- for the transects are shown in Figures 10 and 11 respectively. During the sampling period the flows in the Athabasca River at the gauging station below Ft. McMurray ranged from 923 to 652 m^3/s while the Clearwater River flows ranged from 116 to 95 m^3/s.

September 1993 Field Data

Again Na^+ and Cl^- were found to be the best tracer ions. The hydraulic data measured for transects 1-6 are shown in Figures 12-17 respectively. The concentration profiles for Na^+ and Cl^- are shown in Figures 18 and 19 respectively. The Clearwater River $[Na^+]$ = 18.1 mg/L and the $[Cl^-]$ = 23.6 mg/L. During this sampling period the flows in the Athabasca River ranged from 793 to 816 m^3/s while the Clearwater River flows ranged from 116 to 130 m^3/s. It can be seen that the cross sections at transects are significantly different at the two sampling dates as the river bed is composed of sand which is modified during different flow conditions.

RESULTS

A series of Fortran programs originally developed by T.P.H. Gowda (1980) are used to analyze the field data. First the program MIXANDAT is used to perform the

following computations using the field data as input:

1) Average depth and velocity at each transect

2) Simulation of velocity distributions at cross-sections where velocity data are missing

3) Determine the shape-velocity factor for each transect

4) Mass fluxes of tracer at each transect

5) Variance of cross-sectional distributions of tracer

MIXANDAT regresses the variances against different parameters to determine the dimensionless transverse dispersion coefficient β. The program chooses the regression of least error and equates the slope of the linear regression with an expression from which B can be determined. The value of β is used as input to the program MIXCALBN which calculates the dispersion parameter for each reach. The value of β is adjusted to calibrate the predicted tracer spread with the observed concentration distributions. β is at least weakly reach dependent as it represents the rate of spread of the tracer which is dependent on the hydraulic and geometric properties of each river reach.

The results of the calibration of β for Na^+ and Cl^- for the May 1993 study are shown in Figures 20 and 21 respectively. The results of the calibration of β for Na^+ and Cl^- for the September 1993 study are shown in Figures 22 and 23 respectively. Comparing the results for Na^+ for the two sampling periods is can be seen that the value of β ranges from .00065 at transect 1 to 0.0008 at transect 6 for May, 1993 while the value of β is constant at 0.00042 for all 6 transects in September 1993. The variation in the May β values is likely due to the fact that the flows were dropping during the sampling period whereas they were relatively constant during the September study. The higher β values for May are due to the fact that the flows were higher during this period than they were in September. Comparing the results for Cl^- it can be seen that there is a wider range (.0006 - .0009) during May than during September when the values were all about 0.0004, which is again probably due to the varying flows during the May study period. Also, as for Na^+, the values of β are higher during the higher flow period.

Using equations 9 and 10 the values of D_y and e_y can be determined. The values are shown in Table 1.

DISCUSSION

The diffusion and dispersion values from this study are next compared with other transverse mixing studies on this segment of the Athabasca River. In 1974 two dye tracer studies (one in open water and one under an ice cover) were carried out downstream of Ft. McMurray between Suncor and Ft. MacKay (Beltaos 1978). In August of 1976 Lipsett and Beltaos (1978) used natural water quality parameters to examine the mixing characteristics of the Athabasca River at the confluence with the Clearwater River. More recently Van Der Vinne (1993) tracer dye studies were carried out from Ft. McMurray to the Ells River during ice cover. In Table 2 the averaged results of the current study are presented along with the results of the previous studies. Comparing the results of this study with those of Lipsett and Beltaos,1978 it can be seen that the transverse mixing terms are much higher for the earlier study. The flow of the Athabasca River at the gauging station below Ft. McMurray was 1947 m^3/sec during the 1978 study whereas it averaged 792 m^3/sec in May and 805 m^3/sec in June of this study. The earlier study also only considered mixing in a reach only 2400 m downstream of the confluence whereas the current study examined mixing to transect 6 which is 124,800 m downstream of the confluence. The geometric cross sections of the river have also changed since the earlier study as they did between the May and September studies, due to the fact that the river bed is composed of loose sand. The under ice cover studies consistently show much lower mixing conditions than the open water studies. Consequently, for modelling exercises, it would be best to carry out mixing studies for the flow conditions and river geometry that exist at the time. Otherwise, previous mixing data would have to be used and adjusted for the new conditions.

ACKNOWLEDGEMENTS

The work reported herein is part of the continuing Athabasca River study to examine the fate of discharges from the Tar Sands plants near Ft. McMurray. The field data were collected by E. Walker, G. MacInnis, S. Smith, and R. Bourbonniere. Mr Bruce Barnetson, Environmental Monitoring and Systems, Monitoring Operations Branch, Calgary provided the flow data, courtesy of the Water Survey of Canada. The National

Laboratory for Environmental Testing, Ecosystems Sciences and Evaluation, Burlington carried out the water quality analyses.

REFERENCES

Beltaos, S. 1978. Transverse Mixing in Natural Streams, Report No. SWE-78/01, Transportation and Surface Water Engineering Division, Alberta Research Council, 99 pp.

Beltaos, S. 1979. Transverse Mixing in Natural Streams, Canadian Journal of Civil Engineering, 6(4), pp. 575-591.

Booty, W.G., Wong, I.W.S., Kay, D.F. and Lam, D.C.L. 1991. Athabasca River Toxic Chemical Model: Preliminary Results. NWRI Contribution 91-150.

Brownlee, B.G. Editor 1990 Athabasca River Project 1989/90 Progress Report, NWRI Contribution #90-76

Bourbonniere, R.A. Editor 1992. Athabasca River Project 1990/91 Progress Report, NWRI Contribution No. 92-163.

Gowda, T.P.H. 1980. Stream Tube Model for Water Quality Prediction in Mixing Zones of Shallow Rivers. Water Resources Paper No. 14, Water Resources Branch, Ontario Ministry of the Environment. 142 pp.

Holley, E.R., Siemons, J., and Abraham, G. 1972. Some Aspects of Analyzing Transverse Diffusion in Rivers, Journal of Hydraulic Research, 10(1), pp.27-57.

Lau, Y.L., and Krishnappan, B.G. 1977. Transverse Dispersion in Rectangular Channels, Journal of the Hydraulics Division, ASCE, 103(HY10), pp. 1173-1189.

Lipsett, A.W. and Beltaos, S. 1978. Tributary Mixing Characteristics Using Water Quality Parameters. Transportation and Surface Water Engineering Division, Alberta Research Council, Report No. SWE-78/04, 41 pp.

Schwartz, F.W. 1979. Intermin Report on a Hygrogeological Investigation of the Muskeg River Basin, Alberta, Alberta Oil Sands Environmental Research Program, Project JG 1.1.

Van Der Vinne, G. 1993. Winter Low Flow Tracer Dye Studies, Athabasca River, Athabasca to Bitumount, February and March, 1992 Part II: Mixing Characteristics, Northern River basins Study Project Report No. 14, 50 pp.

Yotsukura, N. and Cobb, E.D. 1972. Transverse Diffusion of Solutes in Natural Streams.

U.S. Geological Survey Professional Paper 582-C, U.S. Gov't Printing Office, Washington, D.C. 19 pp.

Table 1 Summary of transverse mixing coefficients

Sodium (May) Transect	β	D_y (m^5/s^2)	e_y (m^2/s)
1	0.00065	3.873	0.2531
2	0.00060	2.060	0.1544
3	0.00060	1.680	0.2356
4	0.00070	2.397	0.1732
5	0.00060	1.582	0.2264
6	0.00080	2.902	0.2922
Chloride (May) Transect	**β**	**D_y (m^5/s^2)**	**e_y (m^2/s)**
1	0.00060	3.164	0.2198
2	0.00070	2.165	0.1710
3	0.00060	1.488	0.2217
4	0.00060	1.842	0.1406
5	0.00060	1.425	0.2148
6	0.00090	2.883	0.3089
Sodium (Sept.) Transect	**β**	**D_y (m^5/s^2)**	**e_y (m^2/s)**
1	0.00042	2.019	0.1469
2	0.00042	1.865	0.1885
3	0.00042	0.988	0.1903
4	0.00042	1.155	0.1229
5	0.00042	0.914	0.1439
6	0.00042	1.165	0.1423
Chloride (Sept.) Transect	**β**	**D_y (m^5/s^2)**	**e_y (m^2/s)**
1	0.00039	1.875	0.1364
2	0.00039	1.731	0.1750
3	0.00039	0.917	0.1767
4	0.00039	1.072	0.1141
5	0.00039	0.848	0.1336
6	0.00040	1.104	0.1355

Table 2 Comparison of mixing parameter values for the Athabasca River downstream of Ft. McMurray

Study	Diffusion Factor (m^5/s^2)	Transverse Mixing Coefficient (m^2/s)	Dimensionless Diffusion Factor β
Below Ft. McMurray (Beltaos,1978)			
Open water	1.26	0.093	0.00077
Ice cover	0.0474	0.041	0.00021
Below Ft. McMurray (Lipsett & Beltaos,1978)			
Open water	5.22	0.541	0.00148
Ft. McMurray to Ells River (Van Der Verre, 1993)			
Ice cover	0.0160	0.0082	0.00032
Below Ft. McMurray (this study)			
Open water (May)	2.289	0.2177	0.00066
Open water Sept.)	1.305	0.1505	0.00041

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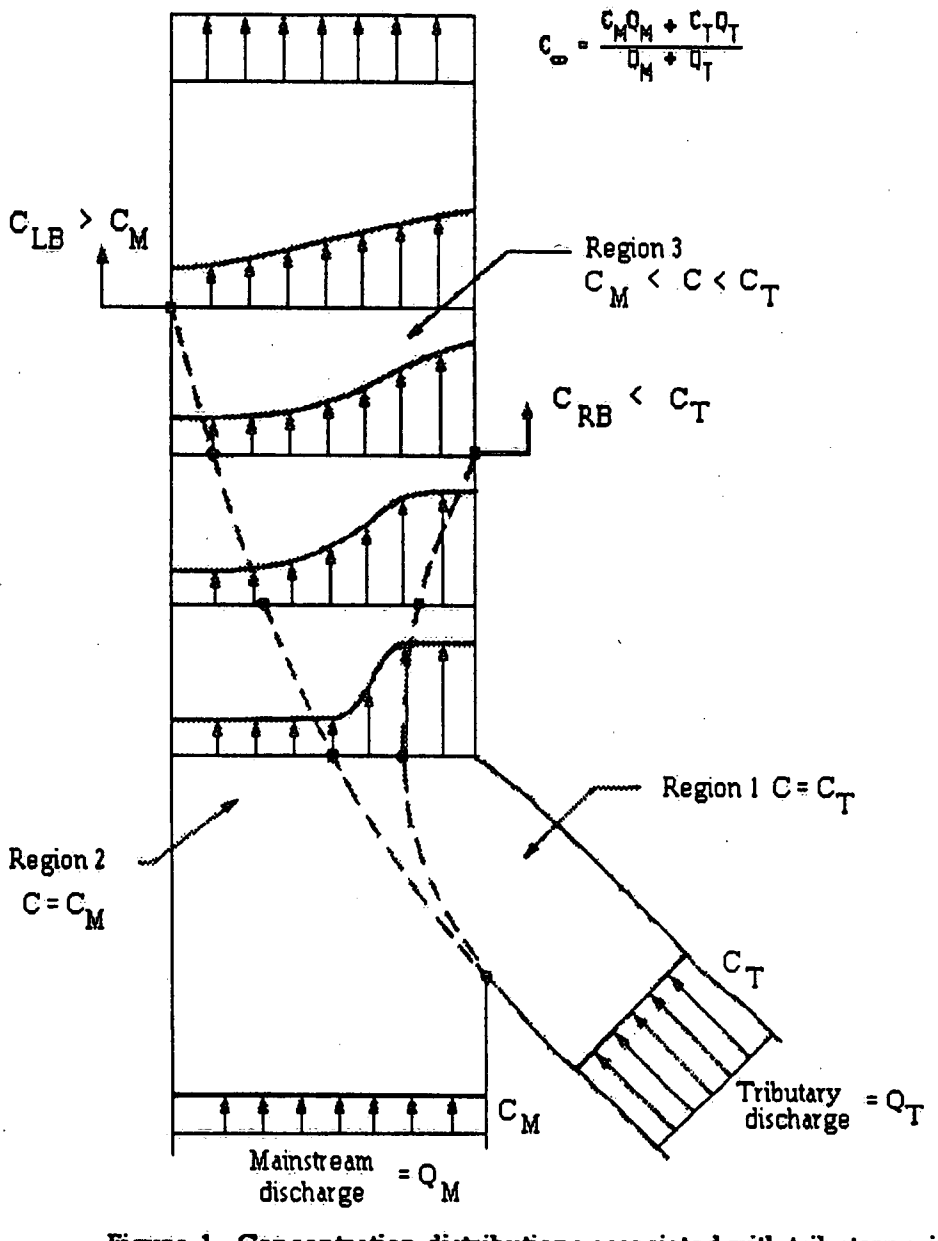

Figure 1. Concentration distributions associated with tributary mixing (modified from Lipsett and Beltaos, 1978)

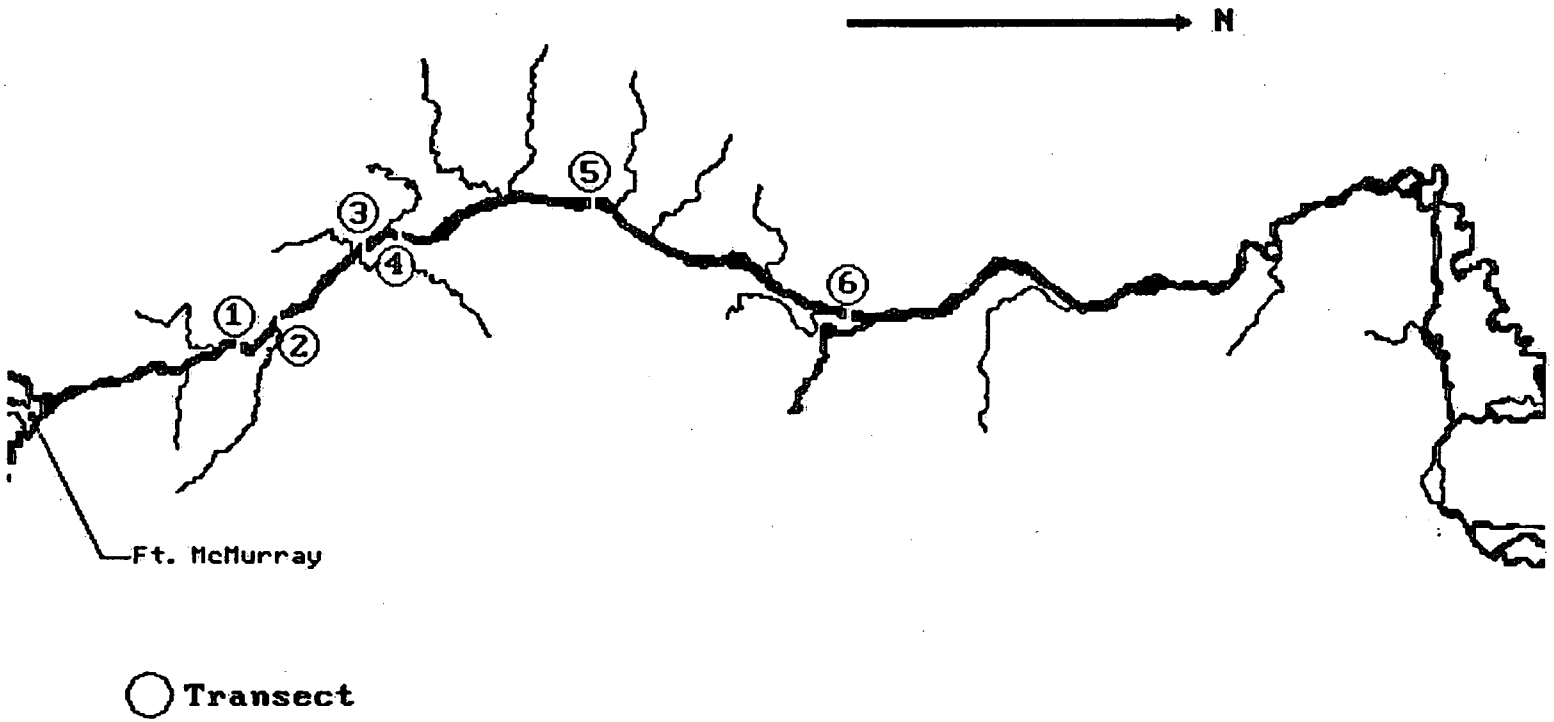

Figure 2. Location of transects downstream of Ft. McMurray

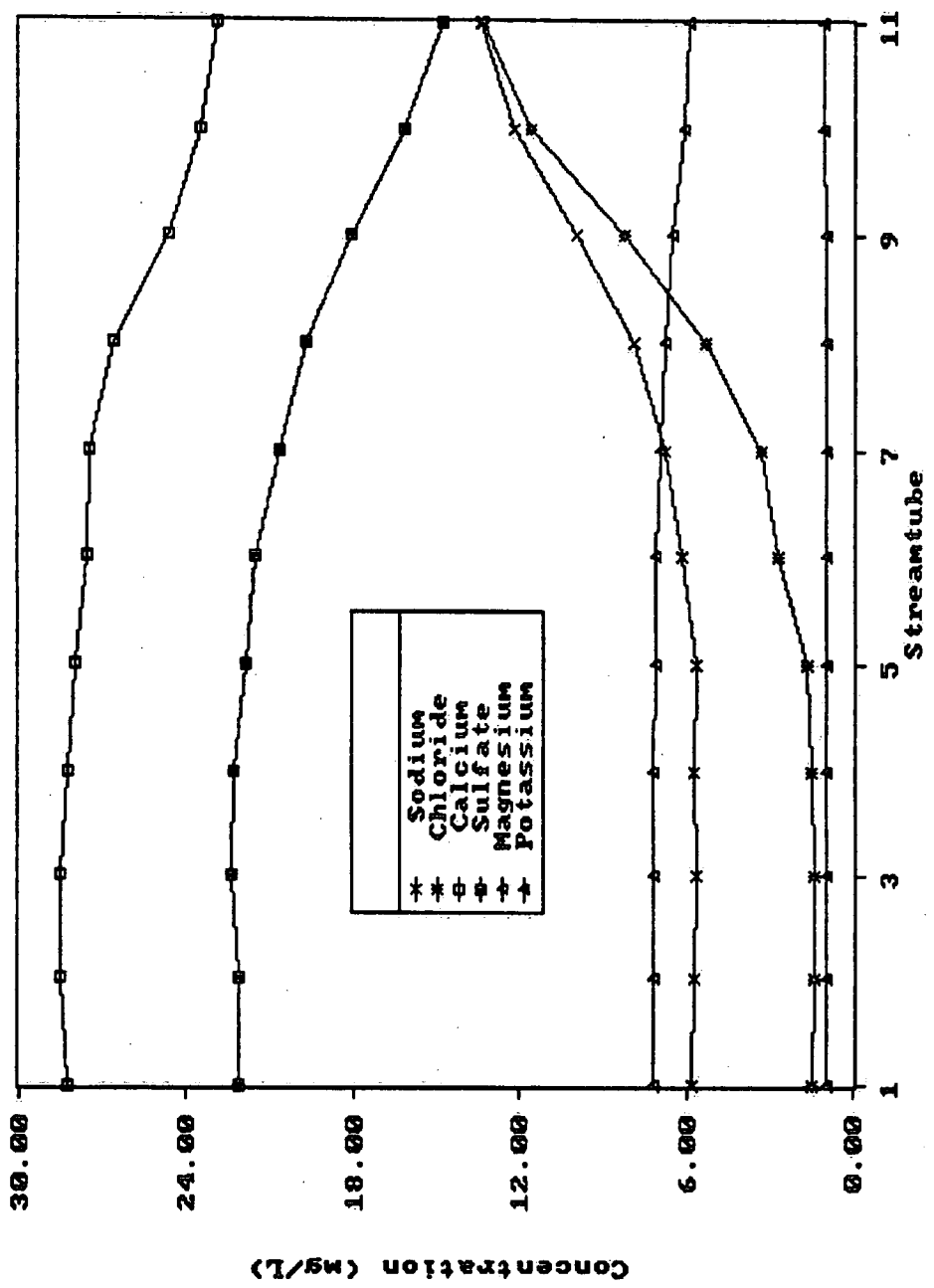

Figure 3. Transect 1 mixing patterns for water quality ions

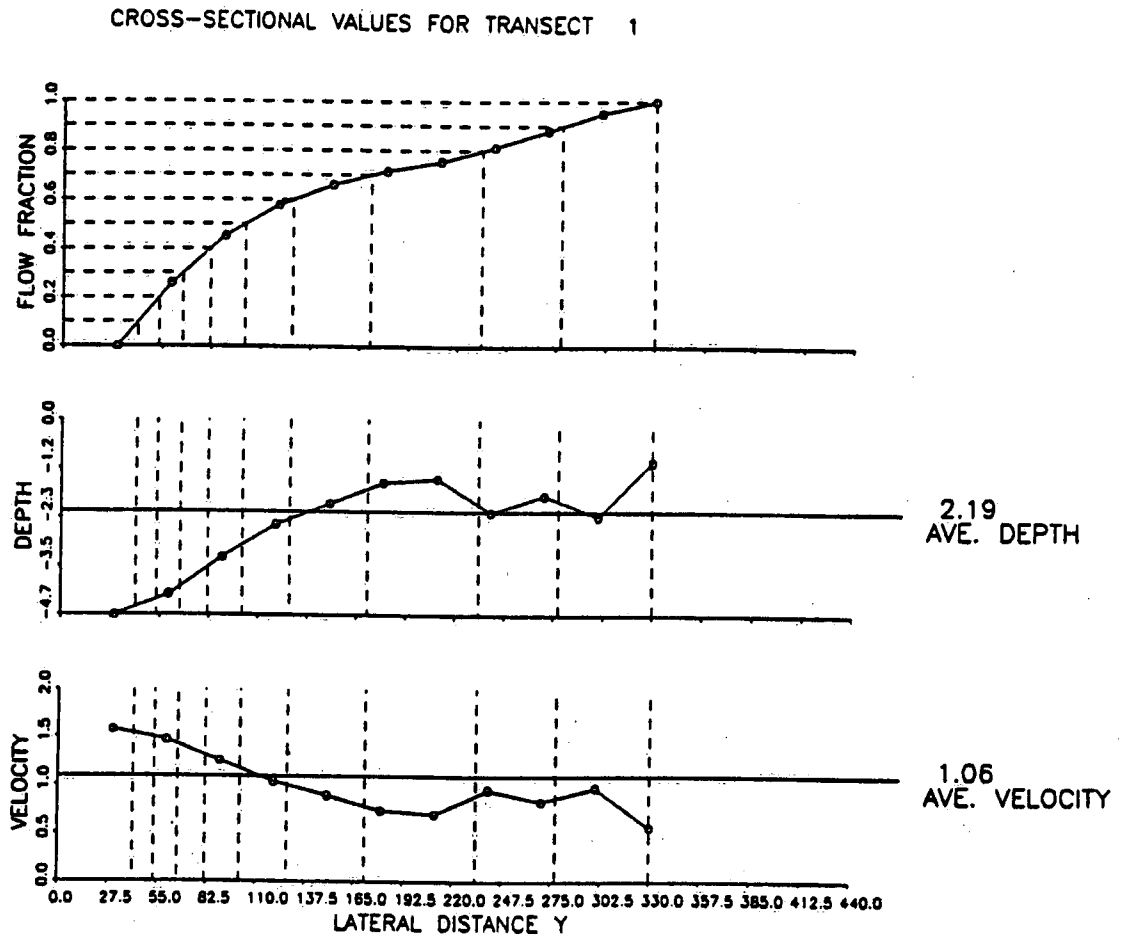

Figure 4. May 1993 hydraulic data measured at transect 1

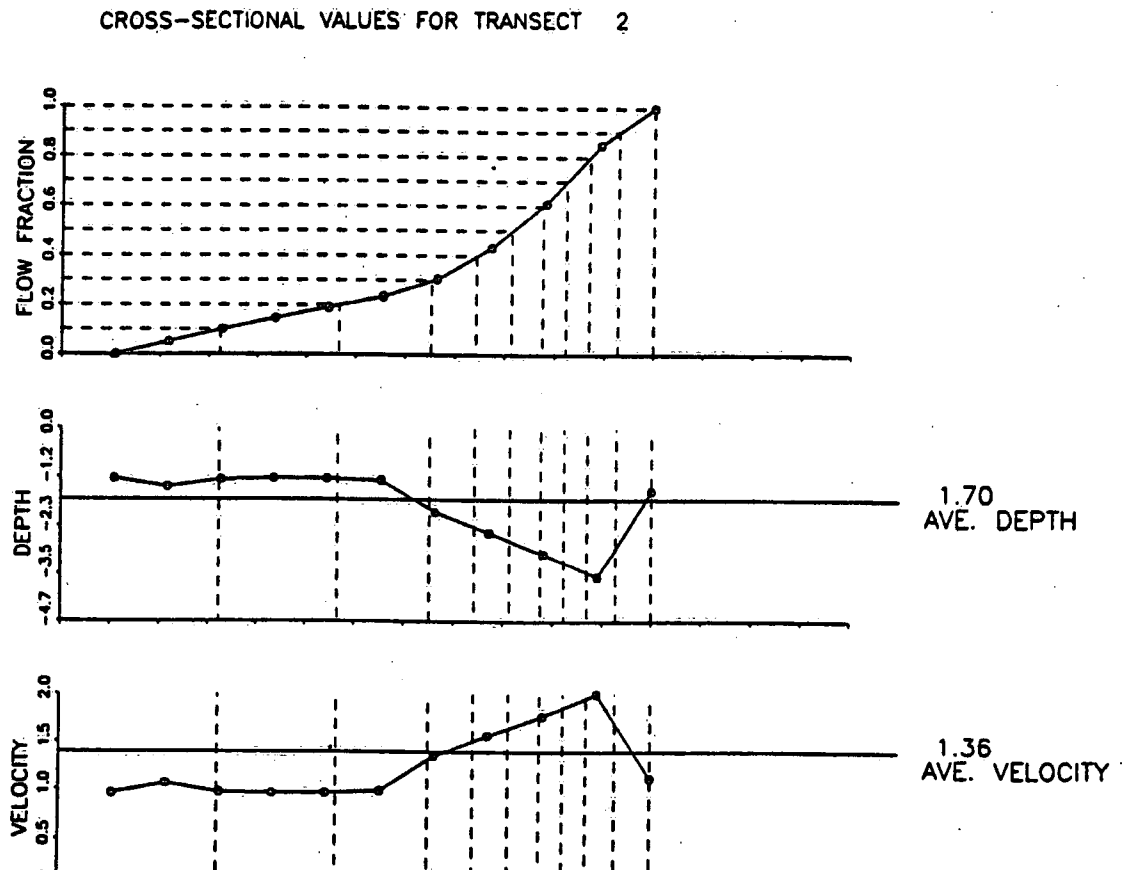

Figure 5. May 1993 hydraulic data measured at transect 2

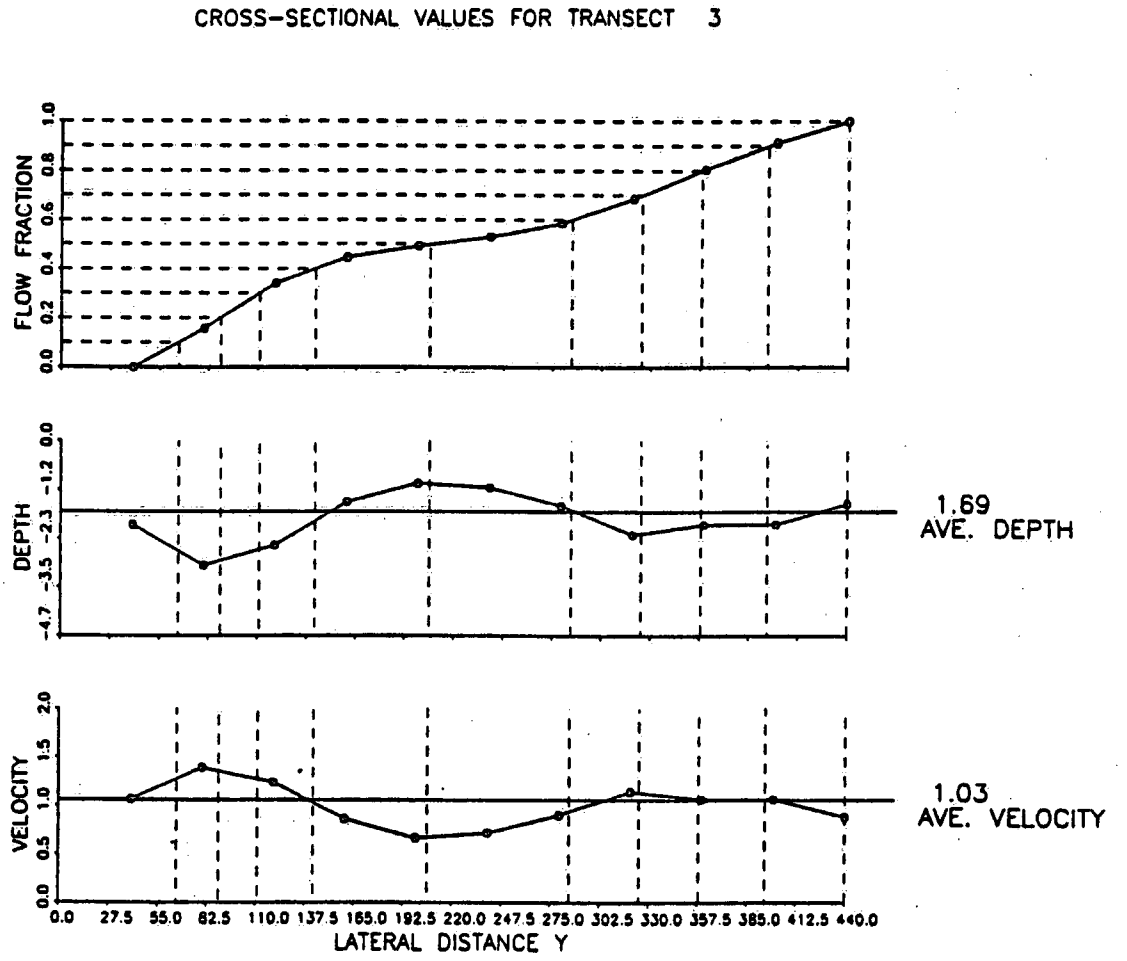

Figure 6. May 1993 hydraulic data measured at transect 3

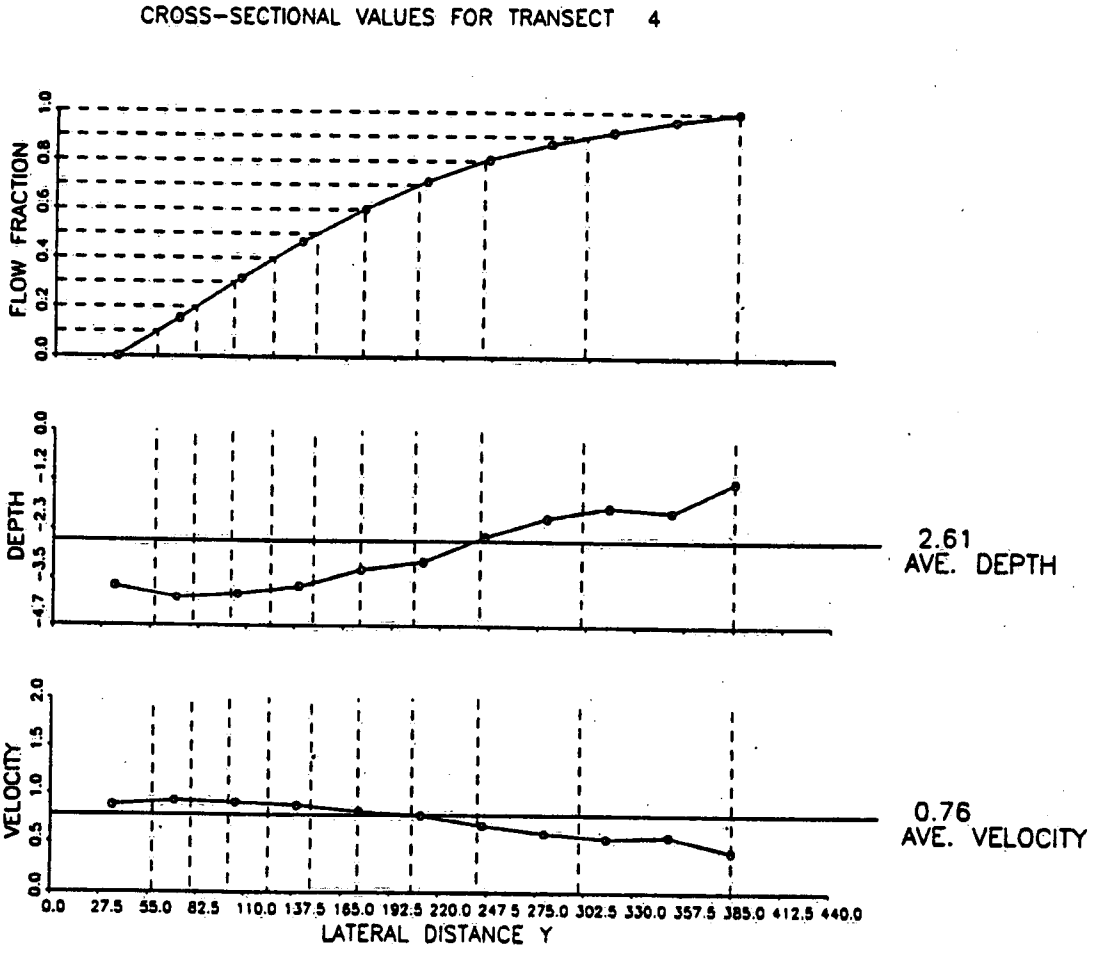

Figure 7. May 1993 hydraulic data measured at transect 4

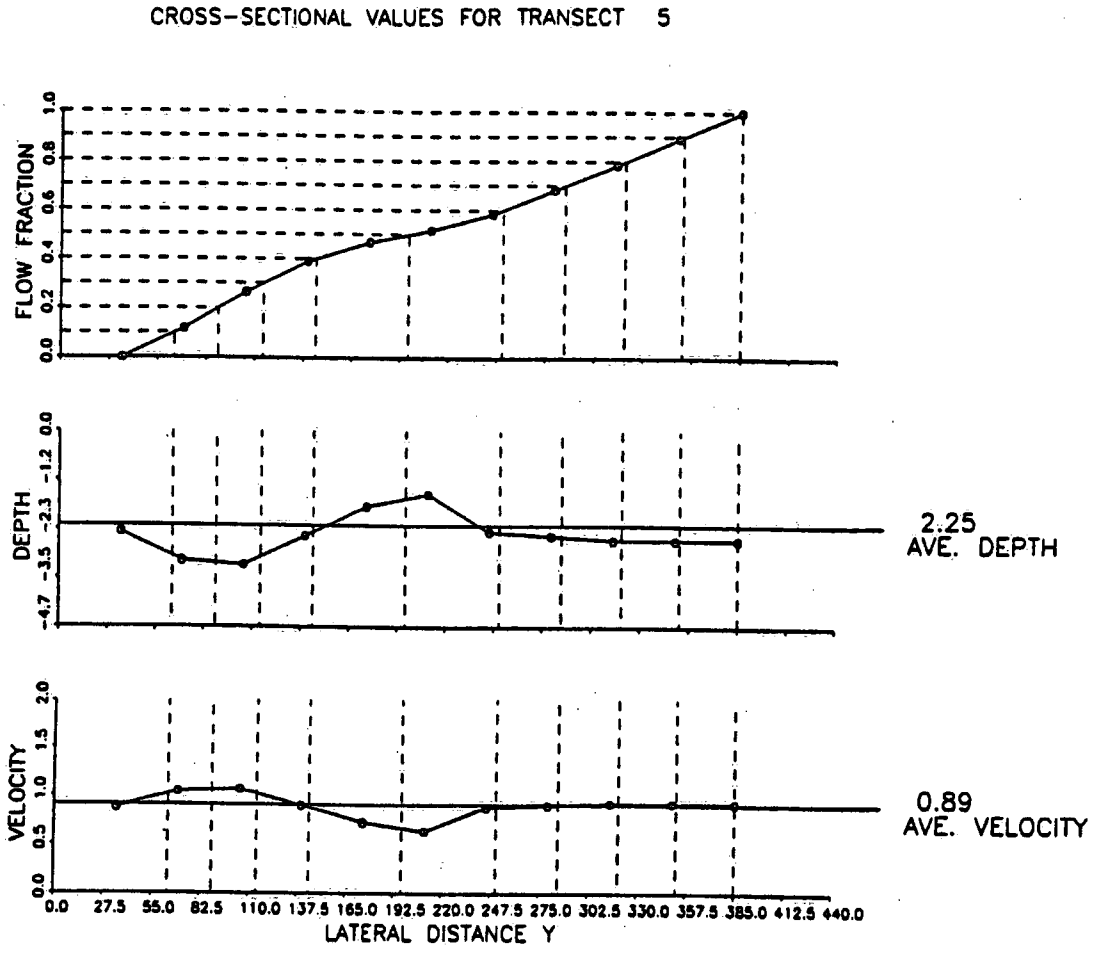

Figure 8. May 1993 hydraulic data measured at transect 5

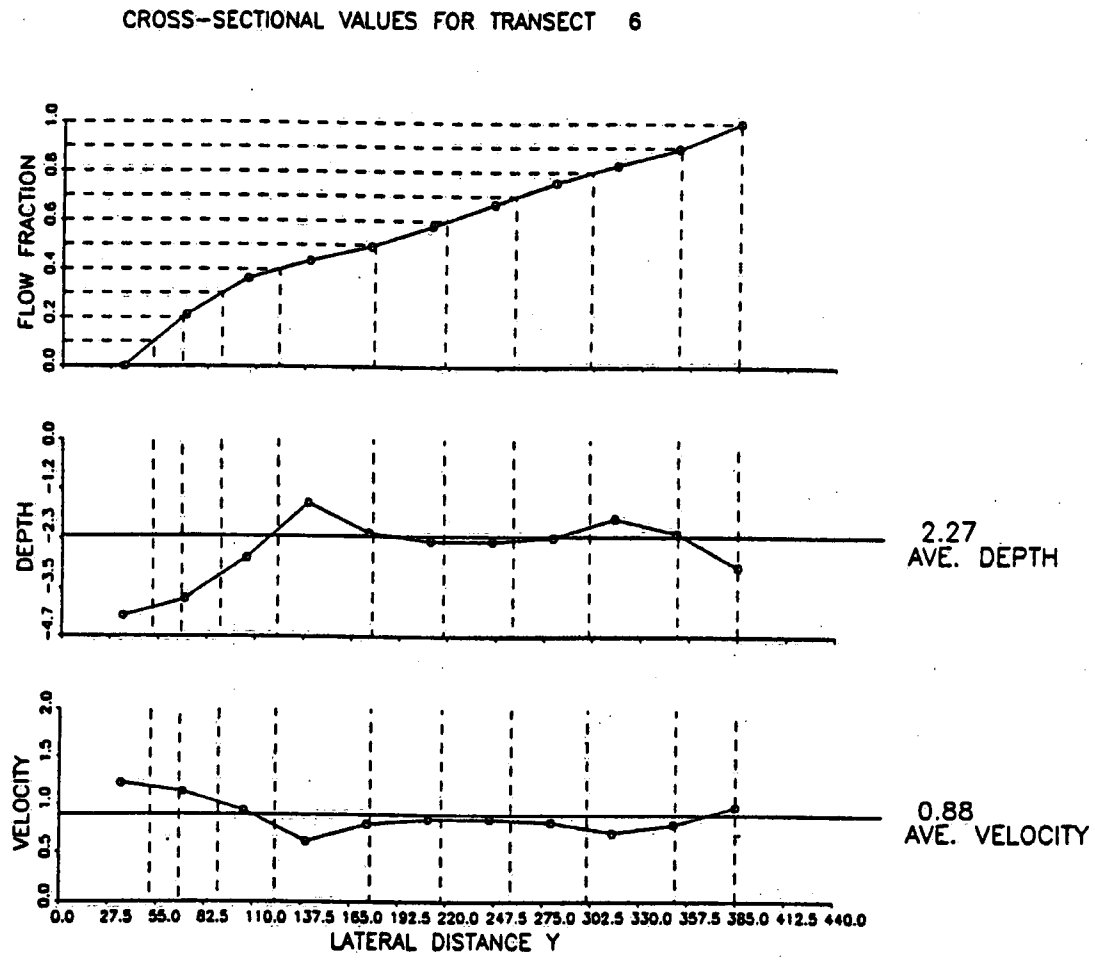

Figure 9. May 1993 hydraulic data measured at transect 6

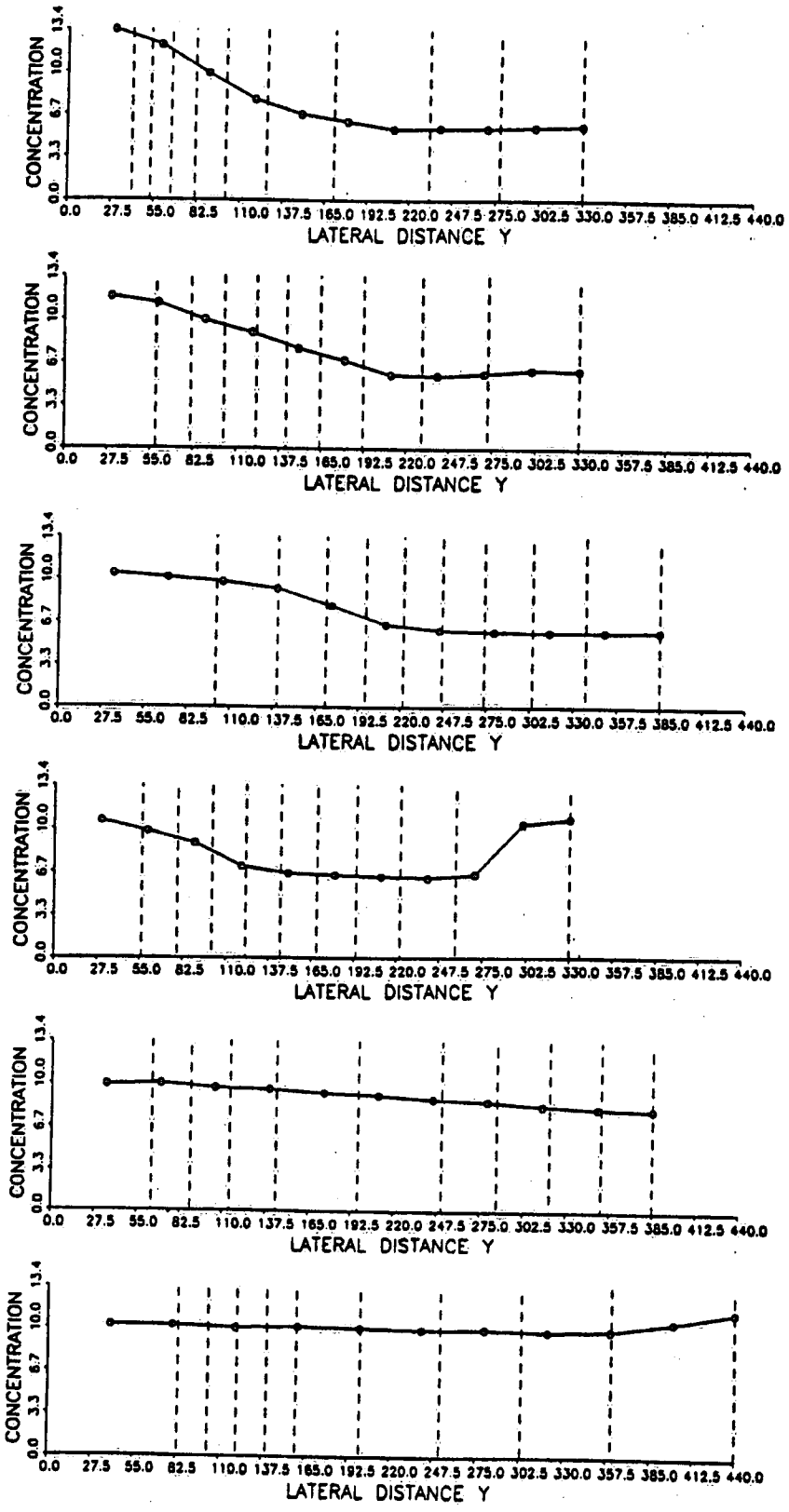

Figure 10. May 1993 Na^+ concentration profiles

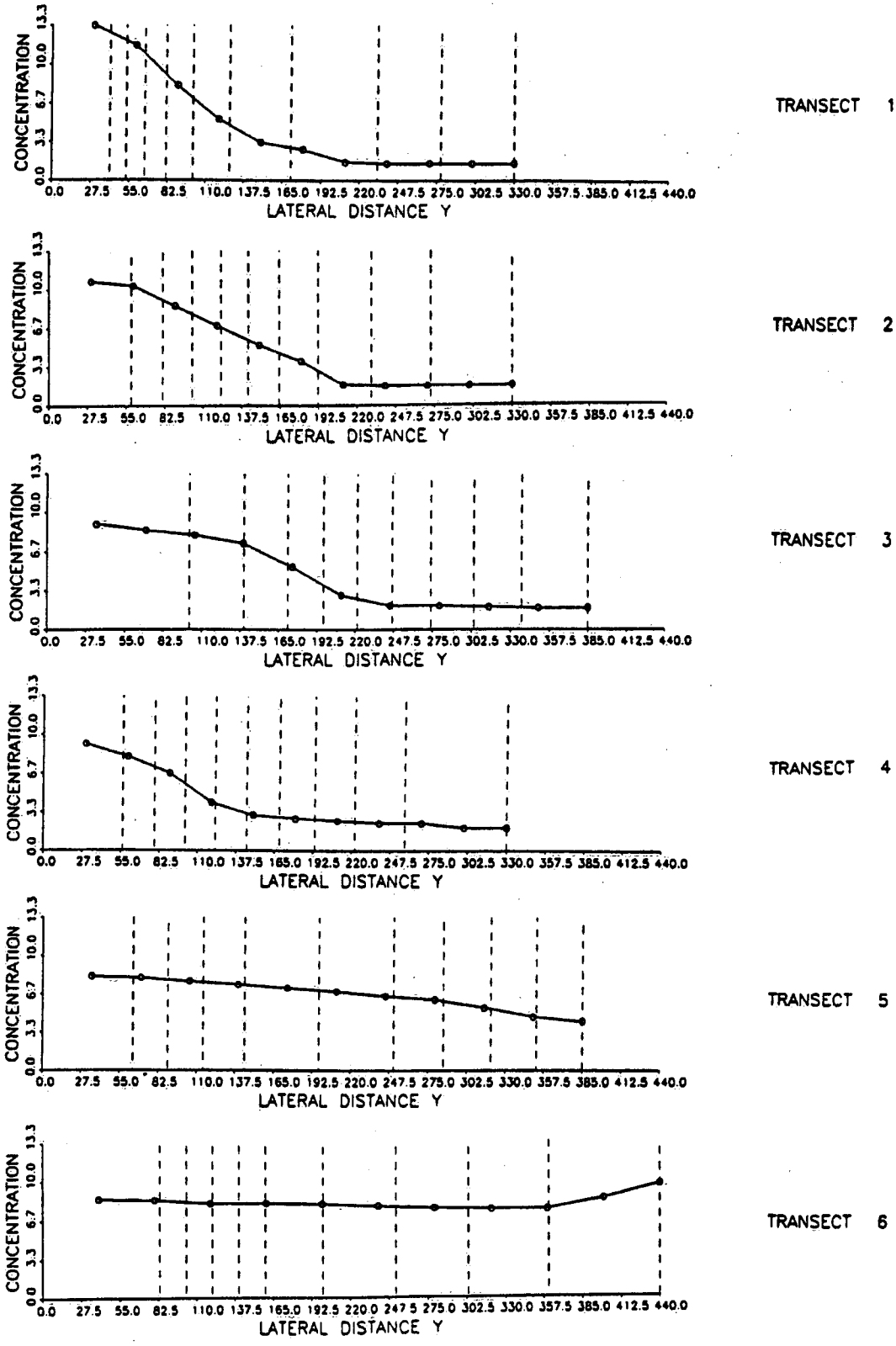

Figure 11. May 1993 Cl^- concentration profiles

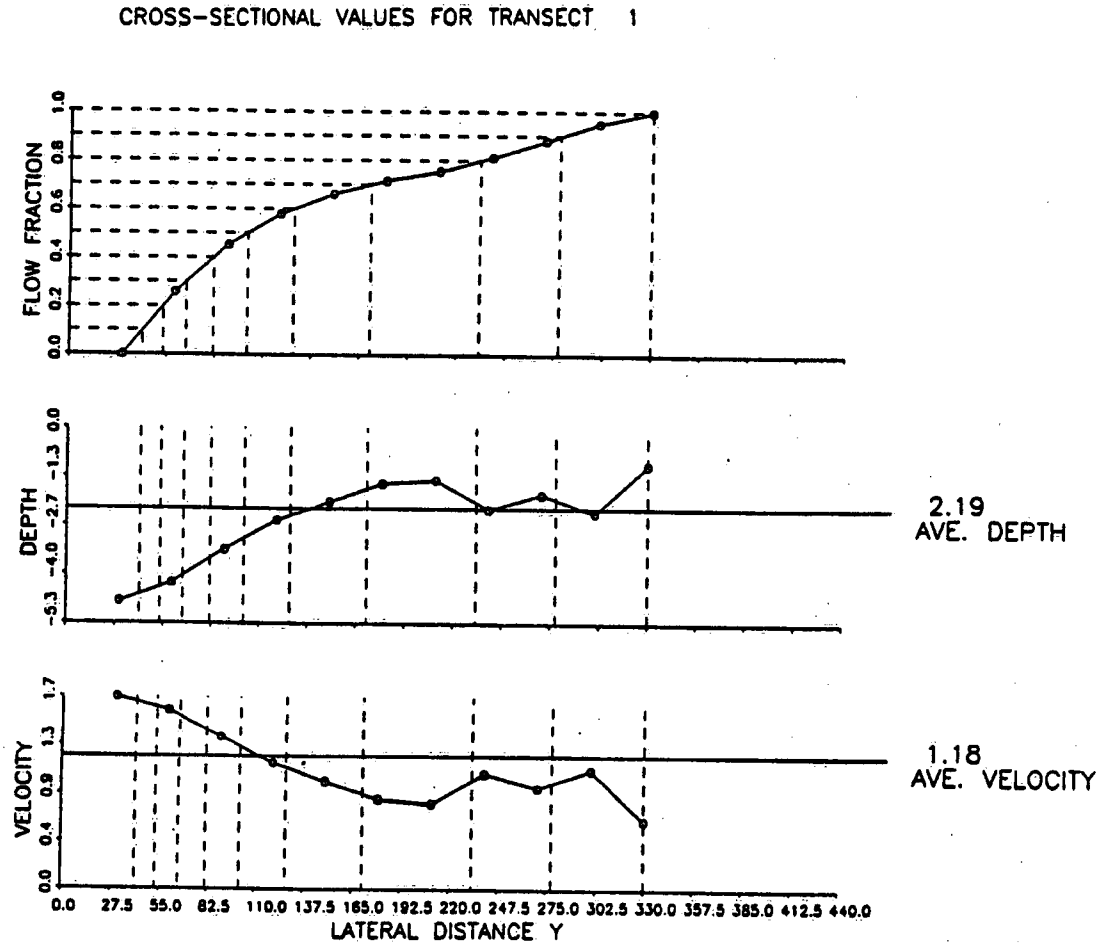

Figure 12. Sept. 1993 hydraulic data measured at transect 1

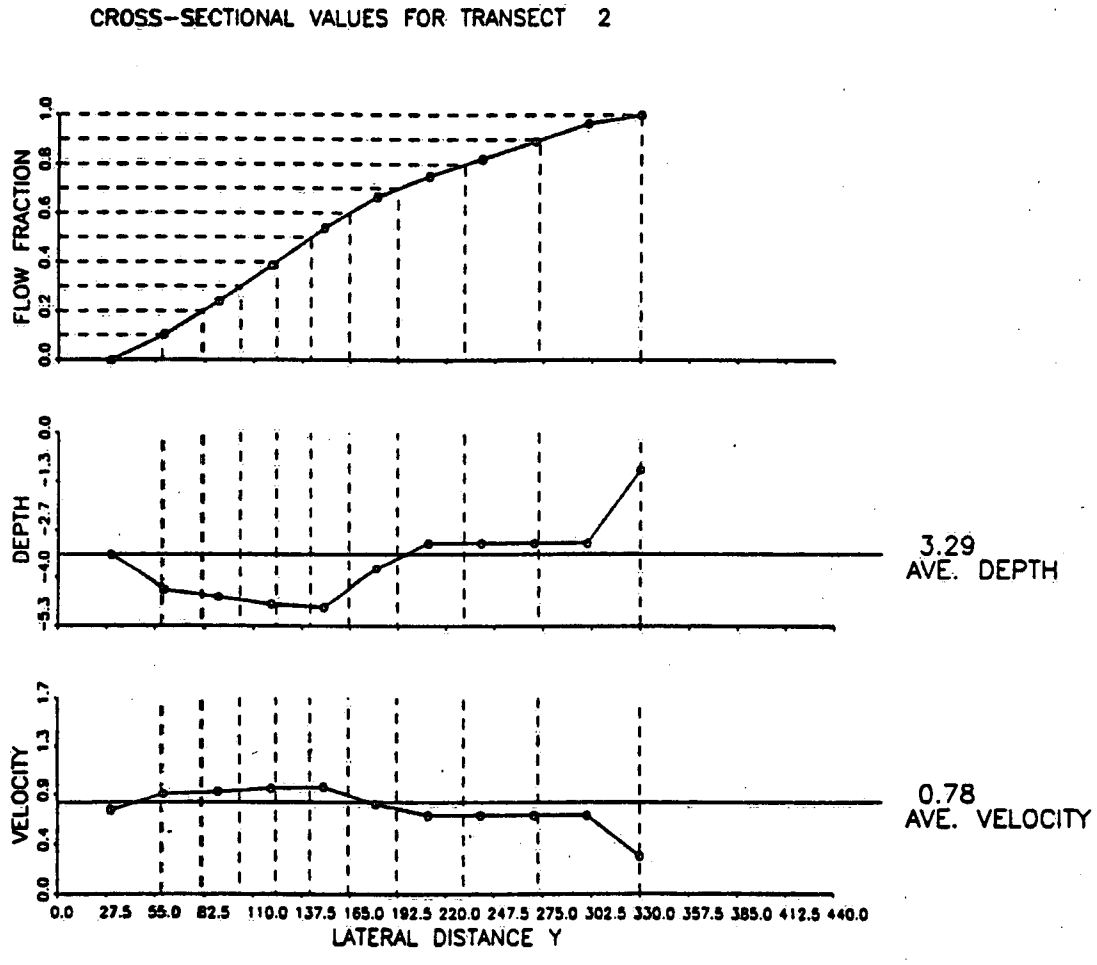

Figure 13. Sept. 1993 hydraulic data measured at transect 2

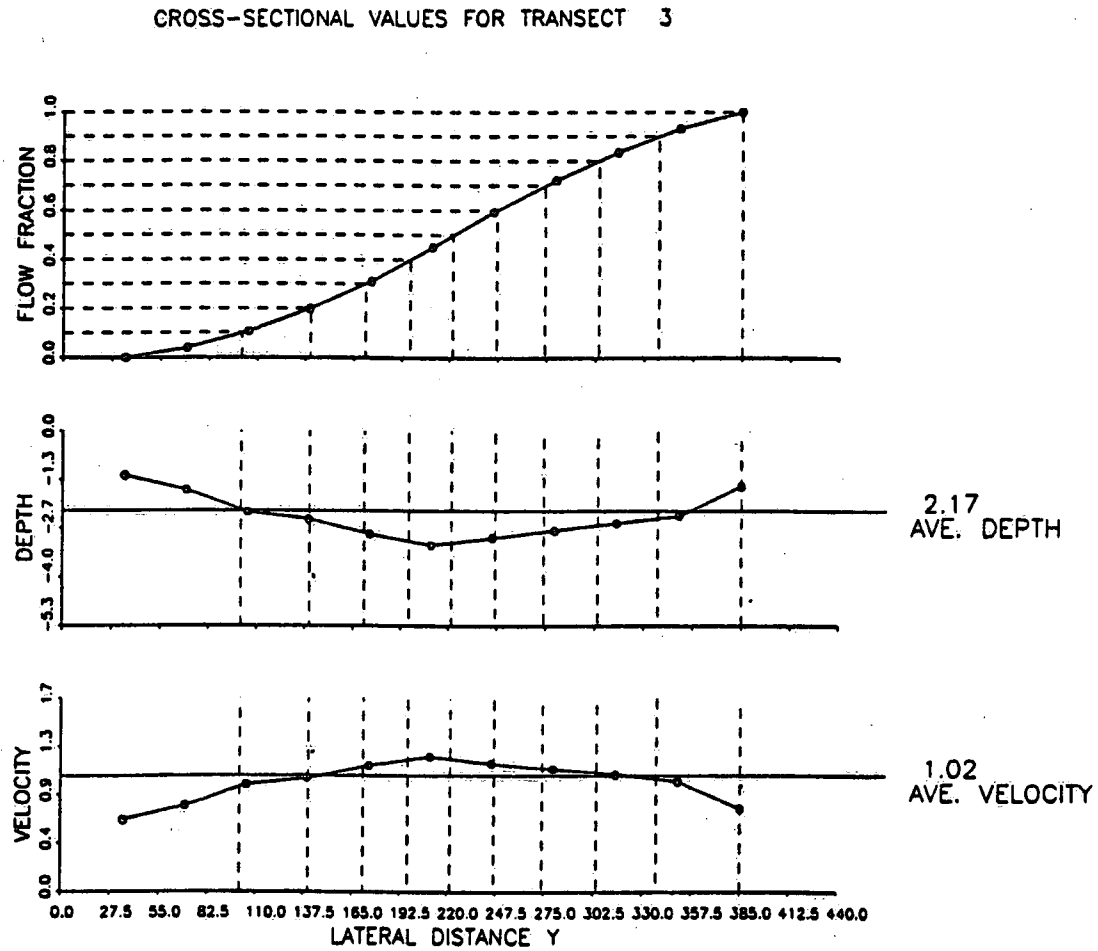

Figure 14. Sept. 1993 hydraulic data measured at transect 3

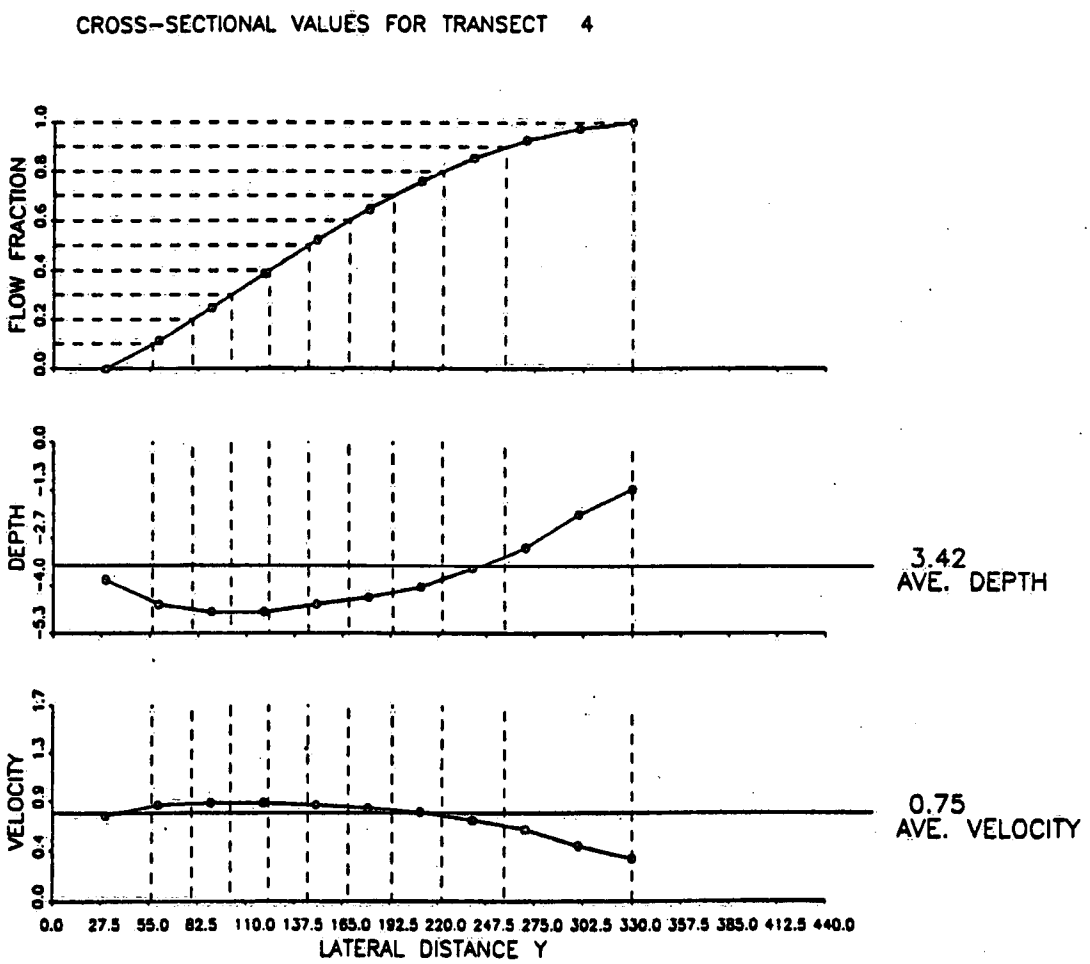

Figure 15. Sept. 1993 hydraulic data measured at transect 4

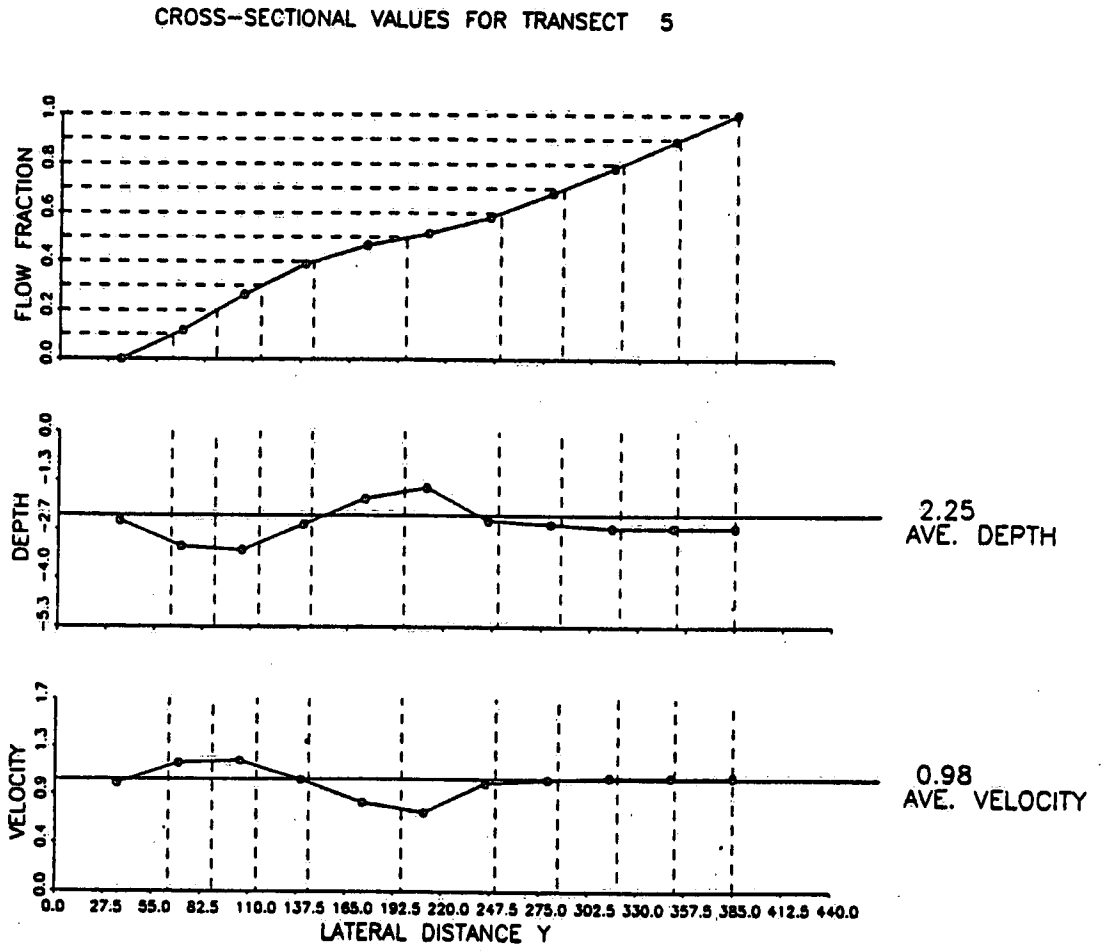

Figure 16. Sept. 1993 hydraulic data measured at transect 5

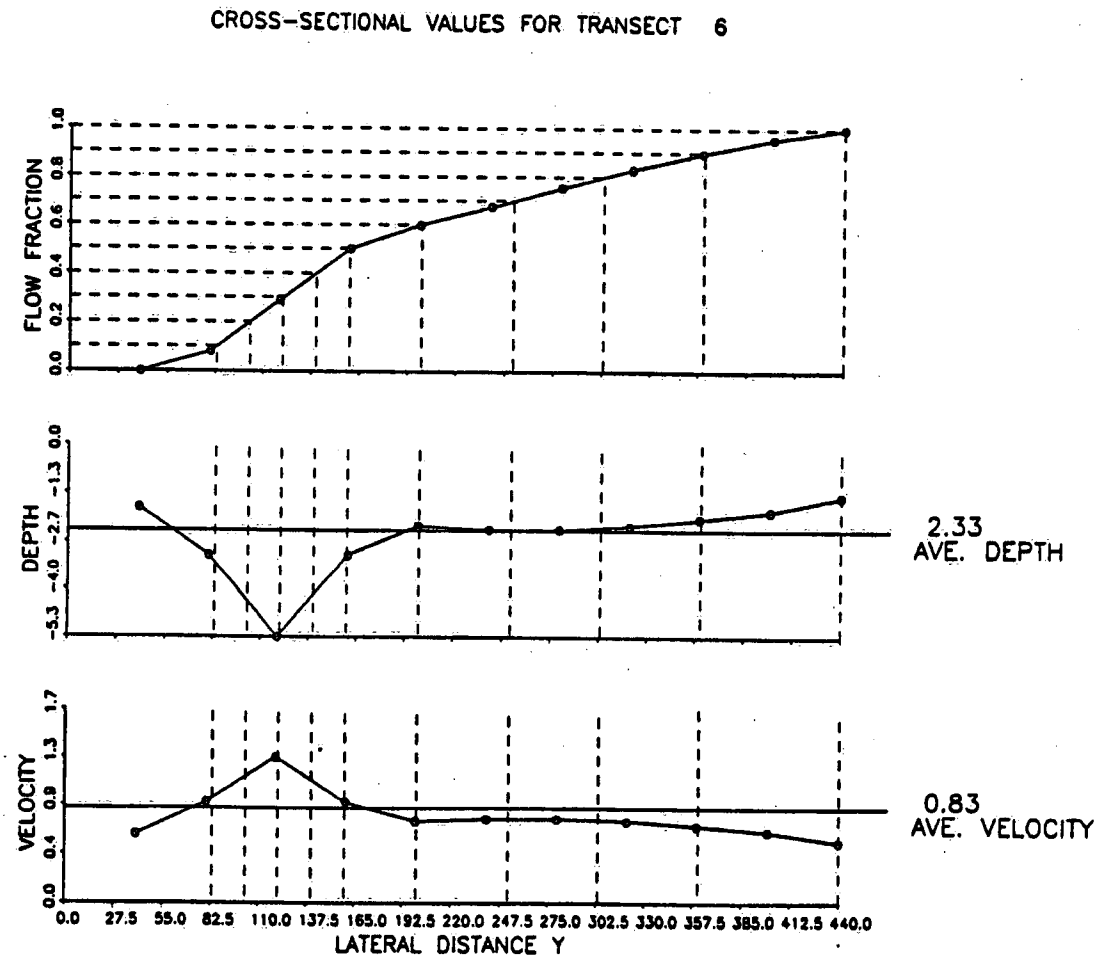

Figure 17. Sept. 1993 hydraulic data measured at transect 6

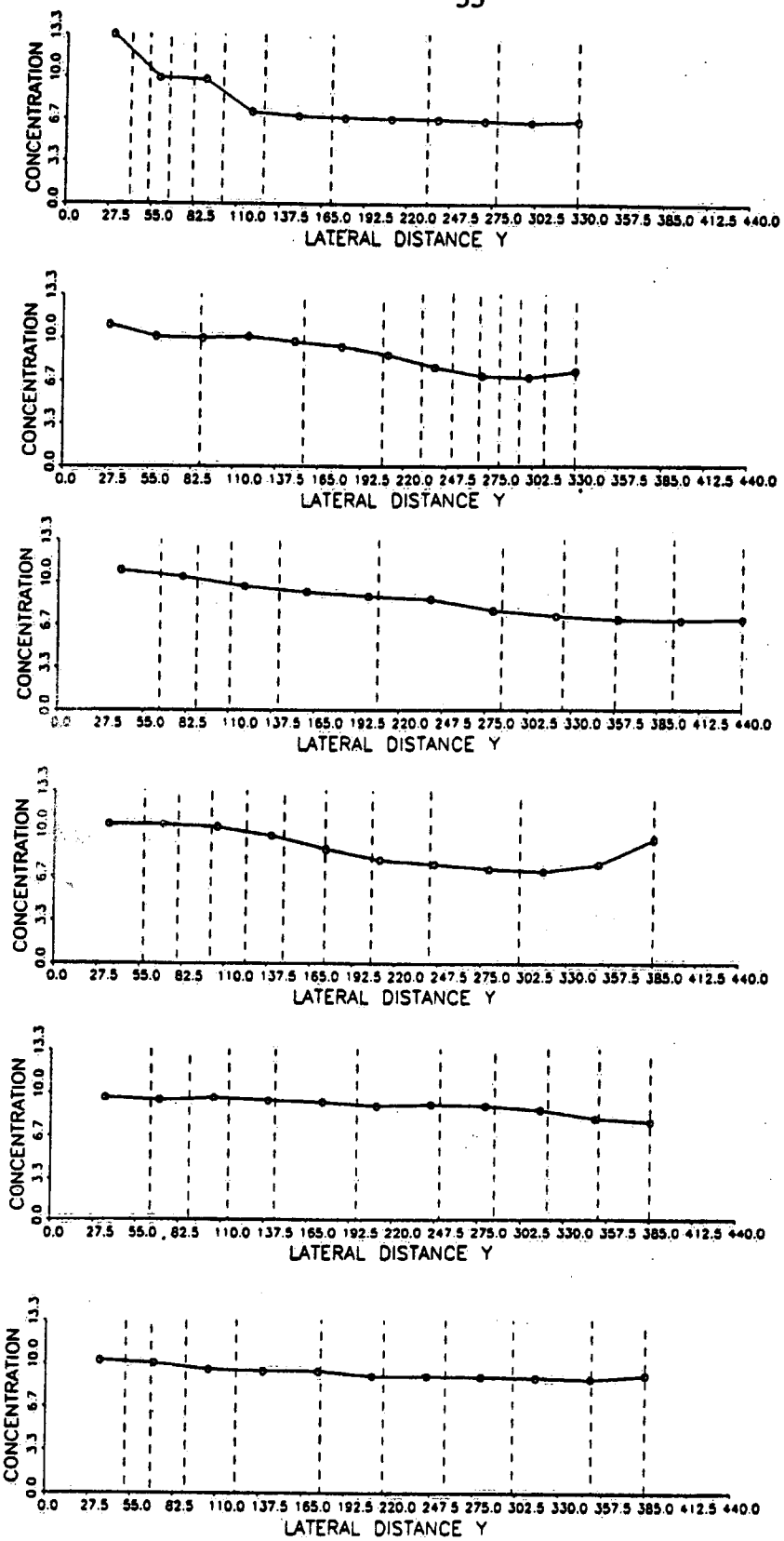

Figure 18. Sept. 1993 Na^+ concentration profiles

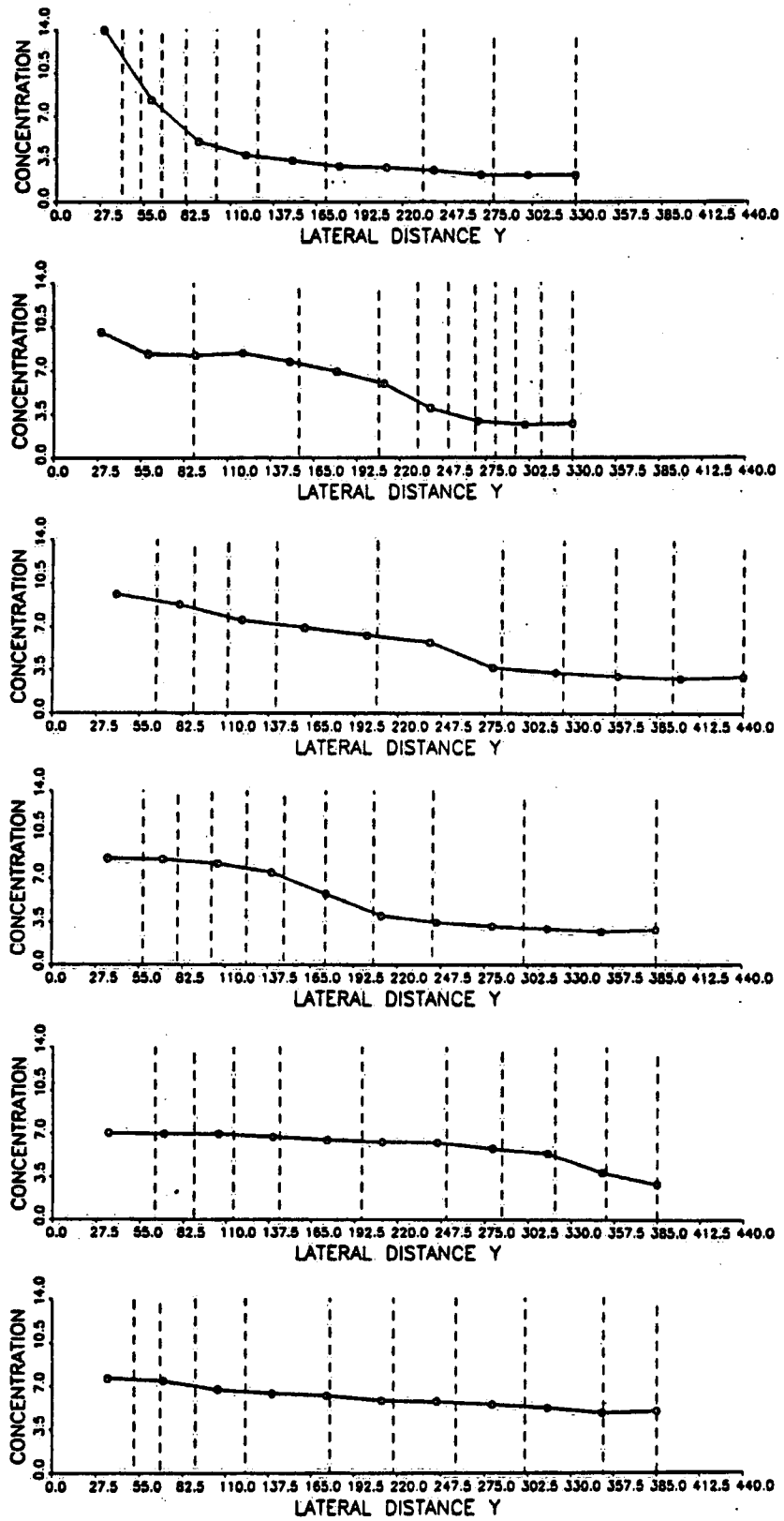

Figure 19. Sept. 1993 Cl^- concentration profiles

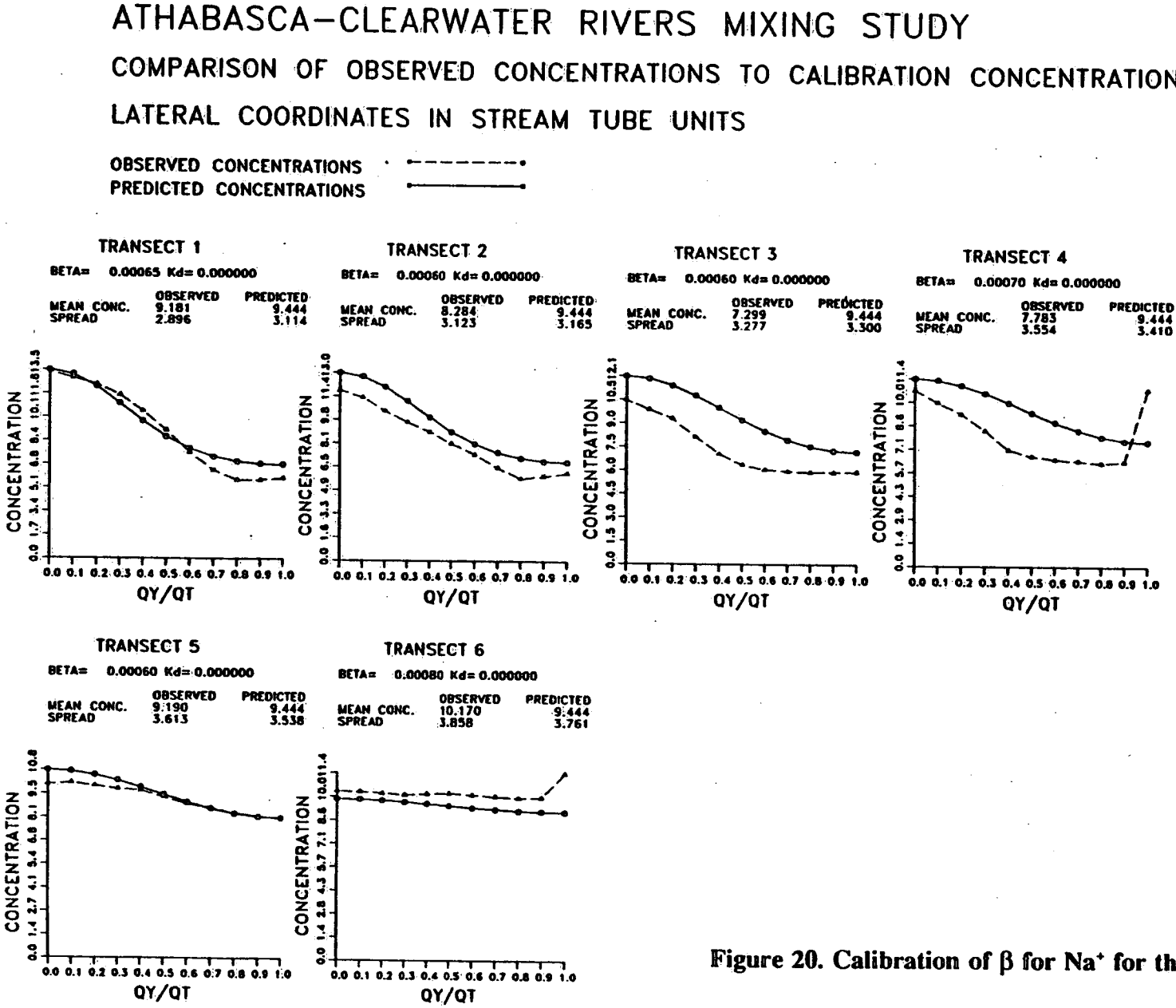

Figure 20. Calibration of β for Na^+ for the May 1993 study

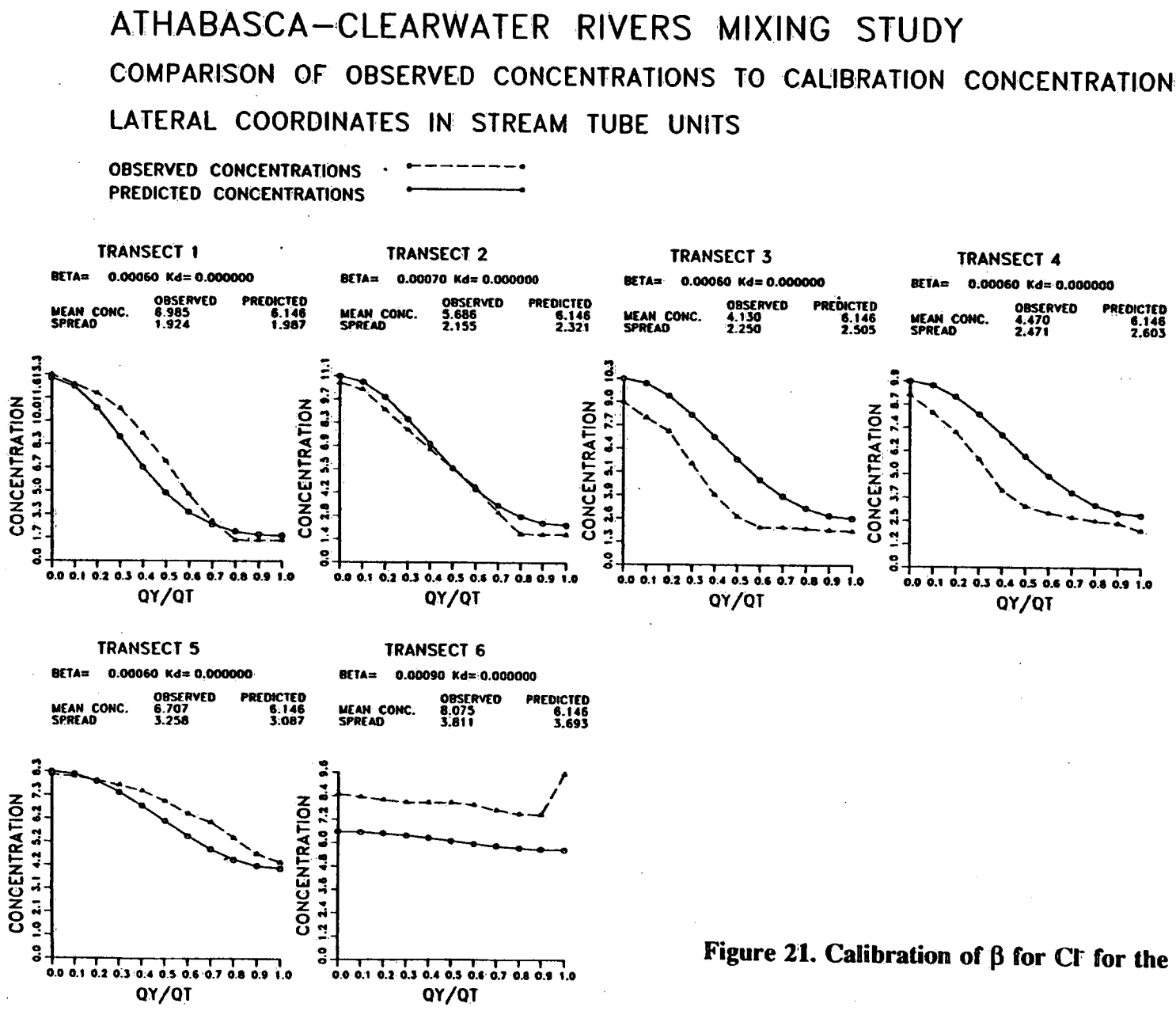

Figure 21. Calibration of β for Cl⁻ for the May 1993 study

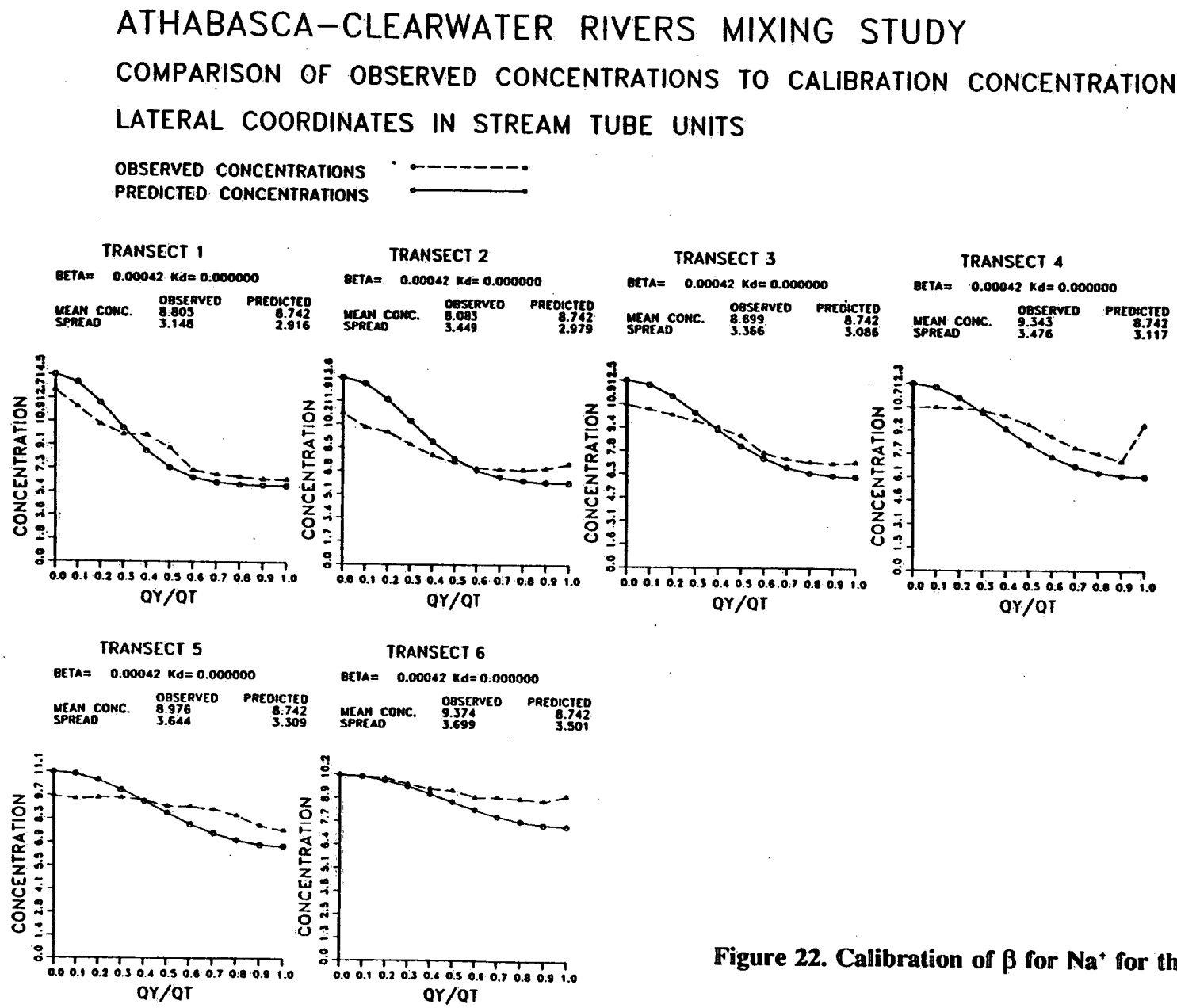

Figure 22. Calibration of β for Na^+ for the Sept. 1993 study

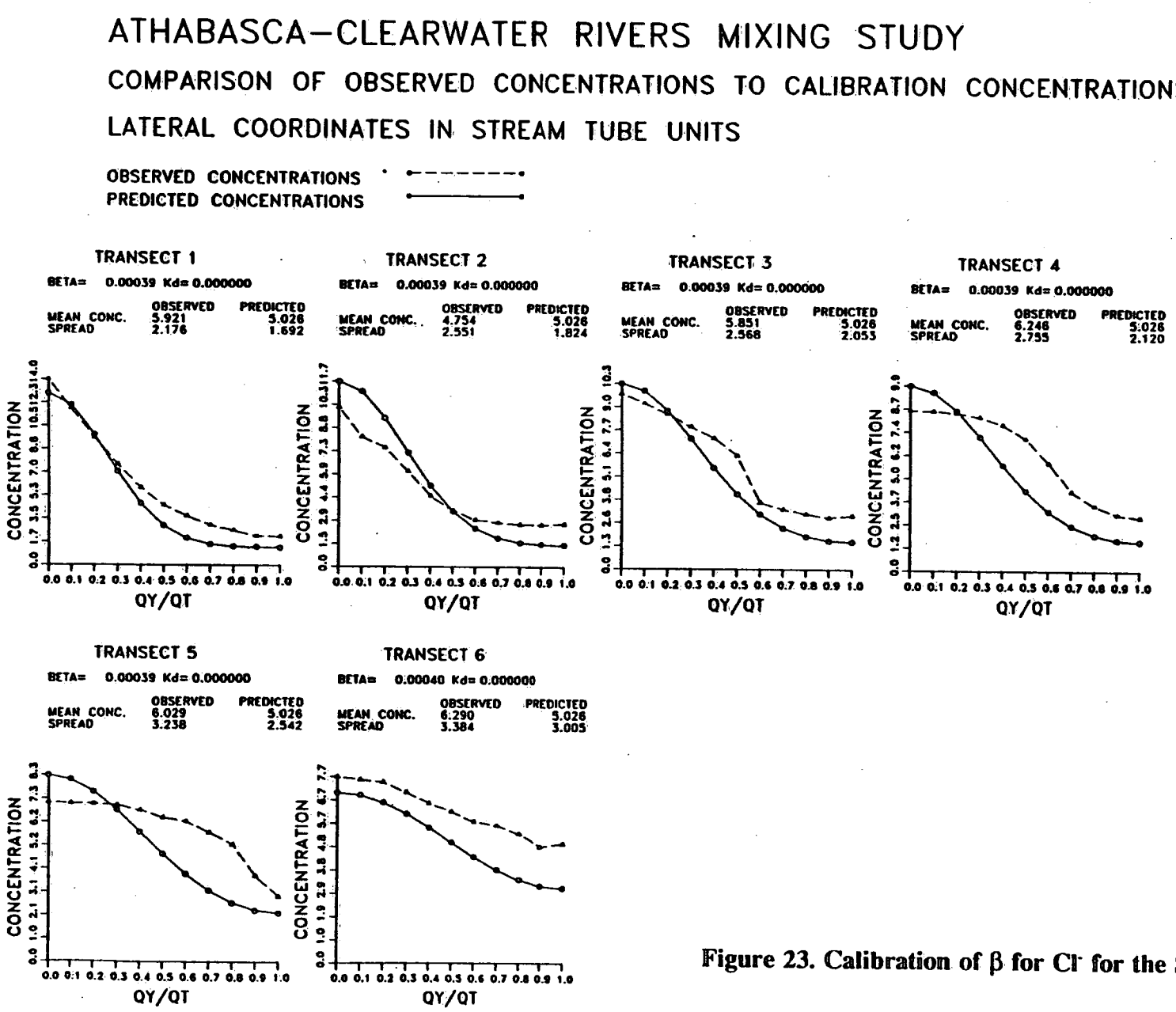

Figure 23. Calibration of β for Cl⁻ for the Sept. 1993 study

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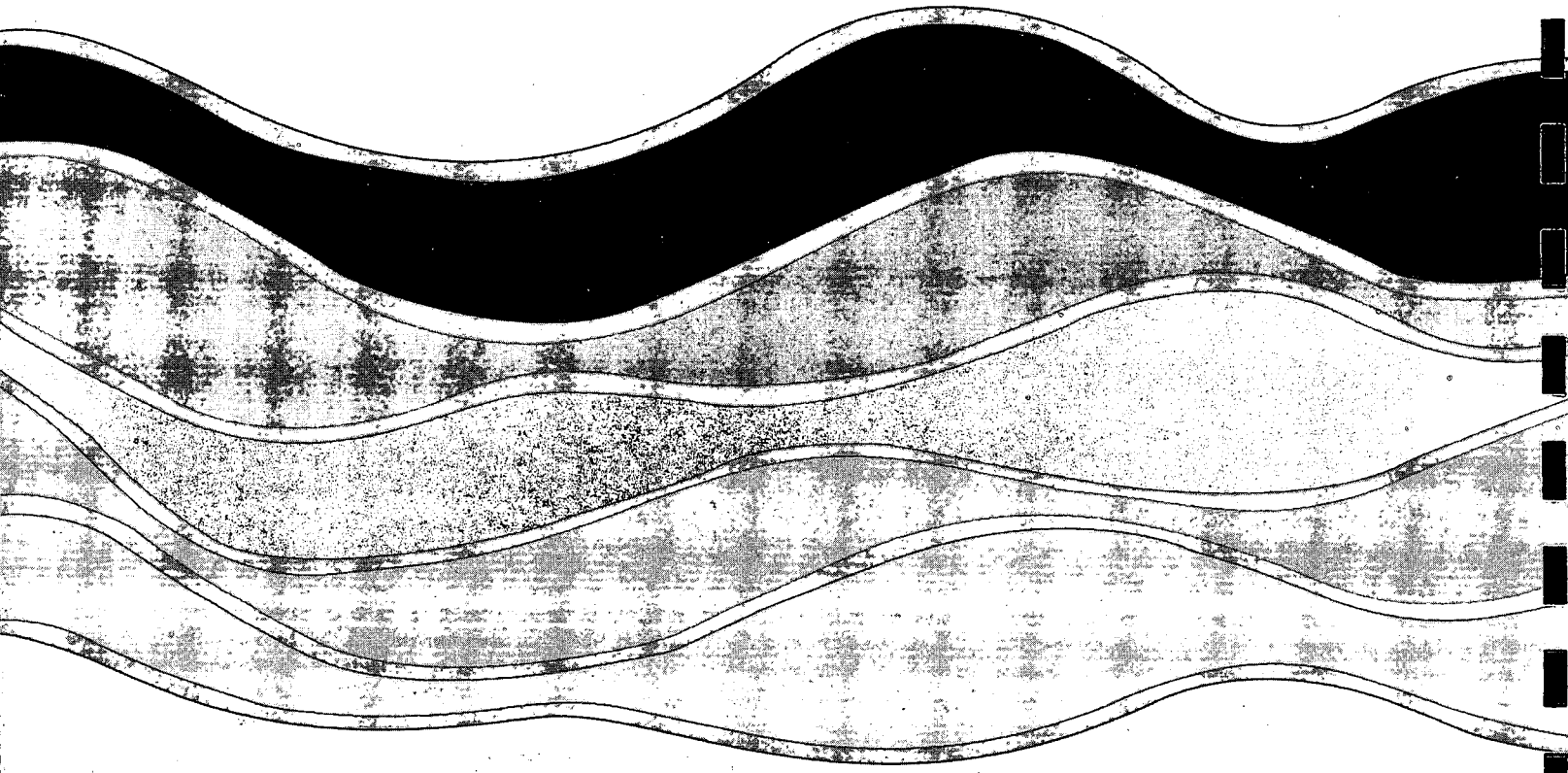

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