Division Control No. AP262

OBSERVATIONS OF SUSPENDED SEDIMENT FLUX OVER A TIDAL CYCLE IN THE REGION OF THE TURBIDITY MAXIMUM OF THE UPPER ST. LAWRENCE RIVER ESTUARY

by

P.F. Hamblin, K.R. Lum, M.E. Comba and K.L.E. Kaiser

National Water Research Institute
Canada Centre for Inland Waters
Burlington, Ontario, Canada L7R 4A6

December 1986

NWRI Contribution #86-205

ABSTRACT

Suspended sediment distributions and salinity gradients have been shown to exert a strong influence on the distributions and environmental mobility of such contaminants as lead, cadmium and volatile hydrocarbons in the St. Lawrence Estuary. A series of four 36-hour anchor stations were occupied along the axis of the Upper St. Lawrence Estuary from the freshwater zone near Quebec, across the turbidity maximum and finally to near sea water salinities at the mouth of the Saguenay Fjord. The anchor stations reveal that in the region of the turbidity maximum near surface suspended sediment concentrations are maximum during and just following the ebb phase of the tidal cycle while near the bottom sediment concentrations are greatest shortly after the occurrence of maximum current speeds. The intense near surface maximum in turbidity coincides with the reduced vertical stratification during the ebb which is considered to increase the upward vertical diffusion of suspended sediment from lower depths. It appears that the turbidity maximum is not maintained by advection according to the classical two-layer estuarine circulation but by upstream Reynolds transport in the lower portion of the water column. Thus contaminants may be recycled through the turbidity maximum by means of tidal pumping. A bulk vertical settling velocity of 2.1 mm/s was estimated at one station near the turbidity maximum from equilibrium settling theory and is in reasonable agreement with turbidity fluctuations observed during the tidal cycle.

RÉSUMÉ

Il a été montre que les distributions des sédiments en suspension et les gradients de salinité exercent une forte influence sur la distribution et la mobilité environnementale de polluants tels que le plomb, le cadmium et les hydrocarbures volatils dans l'estuaire du Saint-Laurent. Quatre stations à l'ancre de 36 h ont été occupées le long de l'axe de la partie supérieure de l'estuaire, dans la zone d'eau douce près de Québec, en travers du maximum de turbidité, et enfin dans des salinités proches de celle de l'eau de mer à l'embouchure du fjord du Saguenay. Les stations rélèvent que, dans la région de turbidité maximum, les concentrations de sédiments en suspension près de la surface sont au maximum pendant et juste après le reflux de la marée, tandis que les concentrations de sédiments près du fond sont les plus élevées peu de temps après l'occurrence des vitesses de courant maximum. Le maximum de turbidité intense près de la surface coincide avec la réduction de la stratification verticale pendant le reflux, qui augmenterait la diffusion verticale vers le haut du sédiment en suspension des zones inférieures. Il semble que le maximum de turbidité ne se maintienne pas par advection, selon la circulation estuarienne classique à deux couches, mais par transport de Reynolds vers l'amont dans la partie inférieure de la colonne d'eau. Les polluants peuvent donc ainsi se recycler dans le maximum de turbidité grâce au pompage maréal. On a estimé à 2,1 mm/s le taux global de sédimentation verticale à une station proche du maximum de turbidité, en utilisant la théorie de la sédimentation à l'équilibre, et ce chiffre concorde raisonnablement bien avec les fluctuations de la turbidité observées pendant le cycle maréal.

MANAGEMENT PERSPECTIVE

This manuscript has been prepared from data collected during and in support of the contaminant chemistry study of the Upper St. Lawrence Estuary, June 1986. This work contributes additional knowledge on the processes connected with contaminant transport in the St. Lawrence system. The results discussed in this manuscript should lead to improved sampling strategies in future sampling programs.

PERSPECTIVE DE GESTION

Ce manuscrit a été préparé à partir de données recueillies dans le cadre de l'étude sur la chimie des polluants menée en juin 1986 dans la partie supérieure de l'estuaire du Saint-Laurent. L'étude enrichit la connaissance des processus liés au transport des polluants dans le système du Saint-Laurent. Les résultats examinés ici devraient permettre d'améliorer les stratégies d'échantillonnage dans les futurs programmes d'étude.

INTRODUCTION

A study of the distribution and transport of trace metals and organic contaminants was undertaken in the upper estuary of the St. Lawrence River during the field seasons of 1986. In a prior study of trace metal chemistry in the estuary, Cossa and Poulet (1978) found that suspended sediments played a crucial role in determining trace metal concentrations through adsorption-desorption processes. Similarly, Bewers and Yeats (1979) pointed out that a region of very high suspended sediment concentration known as the turbidity maximum of the St. Lawrence estuary has a profound influence upon the distributions of total iron, manganese and cobalt. The present paper is concerned with the description of the dynamics of the suspended sediments that were measured concurrently with the contaminant chemistry in the hope that knowledge of the suspended sediments will provide useful information on the processes responsible for the distribution and transport of such contaminants as cadmium, lead and volatile hydrocarbons in the St. Lawrence Estuary.

There have been a number of earlier studies of suspended sediments. Notably, Soucy et al. (1976) gave a detailed description of the residual circulation in the vicinity of the turbidity maximum and related this circulation to the sediment concentration and showed the importance of the bathymetric configuration of the estuary in controlling the residual circulation. Furthermore, they found a close correspondence between upper limit of the highly turbid zone and the null velocity zone of the residual flow which is in agreement with the mechanism for the formation of the estuarine turbidity maximum postulated by Postma (1967). In an important study of suspended matter in the estuary, d'Anglejan and Ingram (1976) took simultaneous current profiles and suspended sediment measurements over a tidal cycle at a number of stations approximately 100 km downstream from the turbidity maximum. They were the first to calculate the along and cross-channel components of suspended sediment flux and noted the importance of horizontal advection of sediment in the study area. Silverberg and Sundby (1979) observed sediment concentrations in the region of the turbidity maximum and related the horizontal position of the turbidity maximum to seasonal changes in river discharge. While they had no measurements of flow accompanying the sediment measurements, they provided valuable data on size and mineralogy of the particles and noted the presence of sand waves. Finally, Anglejan (1981) reviewed the past work and pointed out the importance of lateral banks of mud in supplying the turbidity maximum as opposed to local resuspension.

In the present study, the novelty lies in concurrent measurement of dissolved and particulate concentration of contaminants along with suspended sediments and other supporting data such as profiles of salinity and current. The approach followed in a discussion of the sediment dynamics is similar to that of d'Anglejan and Ingram (1976) except that we include additional stations just upstream of the turbidity maximum.

METHODS

A series of four anchor stations along the axis of the estuary were occupied aboard the research vessel, CSS Limnos, for periods of a day or longer at the end of June and beginning of July, 1986 (Figure 1). As the flow at station 6E200 was too swift to permit secure anchorage, a limited set of data was taken under conditions of controlled drift. At all stations, suspended sediment concentrations were taken at the depths of 3 and approximately 12 m by centrifuging 600 l of water over a 100 minute interval. Additionally, profiles of optical transmission at hourly intervals were taken at most stations by a 25 cm path-length transmissometer. The instantaneous transmission readings at the continuous sampling depths provided an in situ relation between transmission and suspended sediment concentration. Vertical profiles of salinity were measured with an Applied Microsystems CTD (Model 12 probe) and current speed, direction and temperature by a Neil Brown direct reading acoustic current meter which was calibrated prior to field deployment. Salinity and current profiles were taken at 30 minute intervals and at 10 depth levels while the ship was anchored. Special attention was given to the magnetic field disturbance by the hull of ship on the magnetometer of the current meter. This error was eliminated by profiling about 4 m from the hull. Suspended sediment flux was determined from the product of current components along and across the local direction of the river channel averaged over the 100 minute sampling interval of the suspended sediments. Flux is taken as positive in the downstream and northward directions. Shipboard meteorological readings supplemented the oceanographic and chemical data collections.

The current meter data were sufficiently complete at most stations to permit an accurate determination of the residual circulation. In previous work in the estuary (i.e. Soucy et al., 1976), residual circulation had been determined by simply averaging the maximum and minimum of each component of flow. This method is subject to error, particularly if the samples are infrequent or overtides are strong. Instead we chose to determine the average value by the method outlined by Bloomfield (1976) for a time series dominated by a harmonic component. This method is simple to use and does not require the interpolation of data to lunar hours as is often the case with estuarine data. At station 6E300 suspended sediment and flux data were sampled sufficiently often to permit the residuals of these quantities to be determined.

RESULTS

At the start of sampling period the tides were in the middle of the spring and neap cycle and at the end of the survey neap tides were present. The river flow was about 10% larger than the past five year average for this period. From the hydrological data of d'Anglejan (1981), the river flow was estimated to be from 12 to 13 [10^3 m^3/s]. At all stations slack water occurs from 1 to 2 hr after high tide indicating that the tidal wave is between a progressive and standing wave in character.

(a) Residual Circulation

Figure 2 shows the residual along-channel flow at a station just upstream of the turbidity maximum, 6E100, another downstream of the most turbid water and finally at a station near the seaward end of the upper estuary. Clearly, the well-defined downstream flow of 6E100 is in agreement with other studies in this region such as Soucy _et al._ (1976) but it is surprising that the flow remains unidirectional downstream from the turbidity maximum at 6E300, in disagreement with the two-layer model of Postma (1967). Soucy _et al._ (1976) show that upstream flow downstream of the turbidity maximum is in general confined to the deep lateral channels. In the case of 6E300 we may have the situation that the station is located on a central bank where unidirectional downstream residual flow is observed (Soucy _et al._, 1976).

At station 6E400 near the Saguenay River mouth, the residual circulation demonstrates a three-layer structure. It is possible that the bottommost layer is influenced by local topography since it was necessary to anchor on shallow bank for operational purposes.

(b) **Suspended Sediment Flux**

(1) **Station 253**

Suspended sediment concentration, limited components of sediment flux and their relation to salinity are shown for the river station 253 in Figure 3. The concentration of suspended matter ranges from 8 to 16 mg/l which is close to that observed by Silverberg and Sundby (1979) at a river location during the high runoff period. The highest levels of suspended sediment are seen at mid-depth levels during the ebb phase of the tidal cycle. The salinity is not appreciably different from the upper reaches of the river.

(2) **Station 6E100**

By far the highest suspended sediment concentrations and horizontal fluxes are evident in Figure 4 at station 6E100 which is assumed to be located close to and upstream of the turbidity maximum. Maximum concentrations near the surface lag maximum current by about 90° and occur only on the ebb tide phase where vertical mixing is not reduced by vertical stratification due to the absence of the salt wedge, whereas sediment concentrations near the bottom are maximum following both the ebb and flood current. The transverse sediment flux likely plays a minor role in the overall sediment dynamics at this point since it is such a small fraction of the longitudinal flux. As is the case with the residual flow, the net along channel flux is downstream at both depths.

(3) **Station 6E300**

Station 6E300 is located well within the high turbidity region but downstream of the turbidity maximum. Lower levels of suspended sediment permit the use of the transmissometer data which augment the centrifuge readings at lower depths in Figure 5. With the use of additional data there is no evidence of a mid-depth maximum in suspended sediment concentration as reported at several stations further downstream by d'Anglejan and Ingram (1976). They interpreted this maximum as an indication of the importance of horizontal advection as opposed to local resuspension as a factor controlling the distribution. With reference to the studies reported by Silverberg and Sundby (1978) and d'Anglejan (1981) no mid-depth turbidity maxima were found.

Instead of mid-depth maxima we find a pattern of sediment concentration and longitudinal flux similar to station 6E100; surface maximum suspended sediment levels during the ebb associated with minimum vertical stratification and maxima near the bottom following peaks in the current speed on both the ebb and flood phases of the tide. It may be noted that due to a reduction in flow near the bottom, the sediment flux is highest at approximately two thirds of the depth. The cross-channel component sediment flux is still a small fraction of the longitudinal component but not as small as at station 6E100.

The tidally-averaged suspended sediment profile at station 6E300 which is computed from hourly transmission data exhibits a considerable stratification in sediment concentration in Figure 6. The concentration difference between top and bottom nondimensionalized by the average concentration is 1.4. Following the arguments of Teeter (1984) we may estimate the average vertical settling velocity of 2.(1) mm/s under the assumption of equilibrium conditions. This calculation is based upon the peak measured speed of 0.70 m/s, a bed friction velocity of 2.2×10^{-2} m/s and an average vertical eddy diffusivity of 2.0×10^{-2} m^2/s. Again we may employ the settling theory conveniently presented by Teeter (1984) to estimate the percent of sediment remaining in suspension at various times after a resuspension event. For the above parameters there ought to be 75% remaining after an hour, 48% after two hours and 32% after three hours. While the theory does not take account of the highly variable tidal conditions such a settling rate results in reasonable concentration fluctuations over the tidal cycle. This settling velocity is about an order of magnitude larger than that which may be computed from the Stokes settling law and the dominant particle size of 16 μm observed in this region of the estuary by Silverberg and Sundby (1979).

The accompanying longitudinal flux is subdivided into two components, one, the residual advective flux and the other, the tidally-averaged Reynolds flux. While the net downstream sediment flux is near zero at a value of 0.26 g/m^{2}s, there is a close balance between the advective flux which is downstream and the Reynolds flux which is upstream, particularly at the lower levels. Thus we see that the turbidity maximum is maintained, at least at this station, not by the classical two-layer circulation but by the upstream Reynolds transport of suspended sediment. The cross-channel flux is to the southwest at all depths and averages 3.8 g/m^{2}s. The bottommost point in the mean transport profile indicates a small upstream residual current which does not agree with the residual flow shown in Figure 2. The data of Figure 2 are based upon one tidal cycle employing 30 minute profiles whereas Figure 5 has been prepared from hourly profiles averaged over two tidal cycles.

(d) **Station 6E400**

At the end point in our series of anchor stations, station 6E400, the salinity has nearly attained open sea values and the suspended sediment concentrations are near those of the Gulf of St. Lawrence of about 1 mg/l (Figure 7). Fluctuations of sediment concentration are much less than those at the two upstream stations and do not appear to be so clearly related to the current strength and stratification as is the case in the high turbidity region. The cross-channel component of sediment flux corresponds to a clockwise rotation of the flux which is not clearly evident at the other stations.

Again, the residual sediment flux is similar to residual circulation, downstream at the surface and upstream at mid-depth.

SUMMARY AND CONCLUSIONS

Suspended sediments are sampled in this study principally through continuous sampling at fixed depths over sampling intervals of 100 minutes. This method averages irregular and short-term fluctuations of suspended concentrations shown to exist in the transmission data of d'Anglejan (1981) and thus permits the underlying relations between concentration and the determining factors, namely flow speed and stratification, to be examined more readily than in earlier studies employing individual sediment samples. Moreover, sufficient suspended material is collected to allow chemical analysis and particle size distribution to be determined.

The residual flow and the residual sediment flux along the channel were in similar directions in the upper portion of the water column. This residual circulation did not agree with the classical picture of two-layer estuarine circulation downstream from the turbidity maximum postulated by other investigators of this region. Our observations indicate that upstream sediment flux was maintained by tidally related Reynolds transport in the lower portion of the water column. The upstream tidal pumping mechanism is consistent with flood dominance of the estuarine system.

Time-depth distributions of suspended sediment within the region of elevated turbidity did not demonstrate the influence of horizontal advection as hypothesized by d'Anglejan and Ingram (1976). Instead, the large fluctuations observed in suspended sediment appeared to be related to local resuspension coupled with changing vertical diffusion which in turn was related to rapidly fluctuating rates of vertical stratification arising from the horizontal advection of the salt wedge. The dominance of vertical processes over horizontal processes suggests that a simple one-dimensional model of suspended sediment dynamics may provide useful results in the upper estuary of the St. Lawrence River.

REFERENCES

Bewers, J.M. and P.A. Yeats. 1979. The behaviour of trace metals in estuaries of the St. Lawrence Basin. Naturaliste Can., 108:149-161.

Bloomfield, P. 1976. Fourier analysis of time series: An introduction. John Wiley & Sons, pp 258.

Cossa, D. and S.A. Poulet. 1978. Survey of trace metal contents of suspended matter in the St. Lawrence Estuary and Saguenay Fjord. J. Fish. Res. Board Can., 35:338-345.

d'Anglejan, B. 1981. On the advection of turbidity in the Saint Lawrence Middle Estuary. Estuaries, 4:2-15.

d'Anglejan, B. and R.S. Ingram. 1976. Time-depth variation in tidal flux of suspended matter in the St. Lawrence estuary. Estuarine and Coastal Marine Sciences, 4:401-416.

Postma, H. 1967. Sediment transport and sedimentation in the estuarine environment, p 159-179, G.H. Lauff (ed.) Estuaries - AAAS, Pub. No. 83.

Silverberg, N. and B. Sundby. 1979. Observations in the turbidity maximum of the St. Lawrence Estuary. Can. J. Earth Sci., 16:939-950.

Soucy, A.Y., Y. Bérubé, J.P. Fronde and P. Meric. 1976. Evolution des suspensions et sédiments dans l'estuarie moyen du Saint Laurent, Le Cahier de Centreau, 1(5):67.

Teeter, A.M. 1984. Vertical transport of fine-grained suspension and newly-deposited sediment. Estuarine Cohesive Sediment Dynamics, A.J. Mehta (Ed.) Springer-Verlag, Berlin, pp 170-428.

FIGURE CAPTIONS

(1) Station locations in the upper St. Lawrence Estuary.

(2) Longitudinal component of residual circulation, positive downstream.

(3) Tidal variations at station 253 of (a) suspended sediment concentration, (b) horizontal sediment flux and (c) salinity (mg/l).

(4) Tidal fluctuations at station 6E100 of (a) suspended sediment concentration, (b) horizontal sediment flux and (c) salinity (g/l).

(5) Tidal fluctuations at station 6E300 of (a) suspended sediment concentration, (b) horizontal sediment flux and (c) salinity (g/l).

(6) Residual suspended sediment, $\overline{SS}$, product of residual along-channel flow, $\overline{U}$, and $\overline{SS}$, and longitudinal Reynolds sediment transport, $\overline{U'SS'}$.

(7) Tidal fluctuations at station 6E400 of (a) suspended sediment concentration, (b) horizontal sediment flux and (c) salinity (g/l).

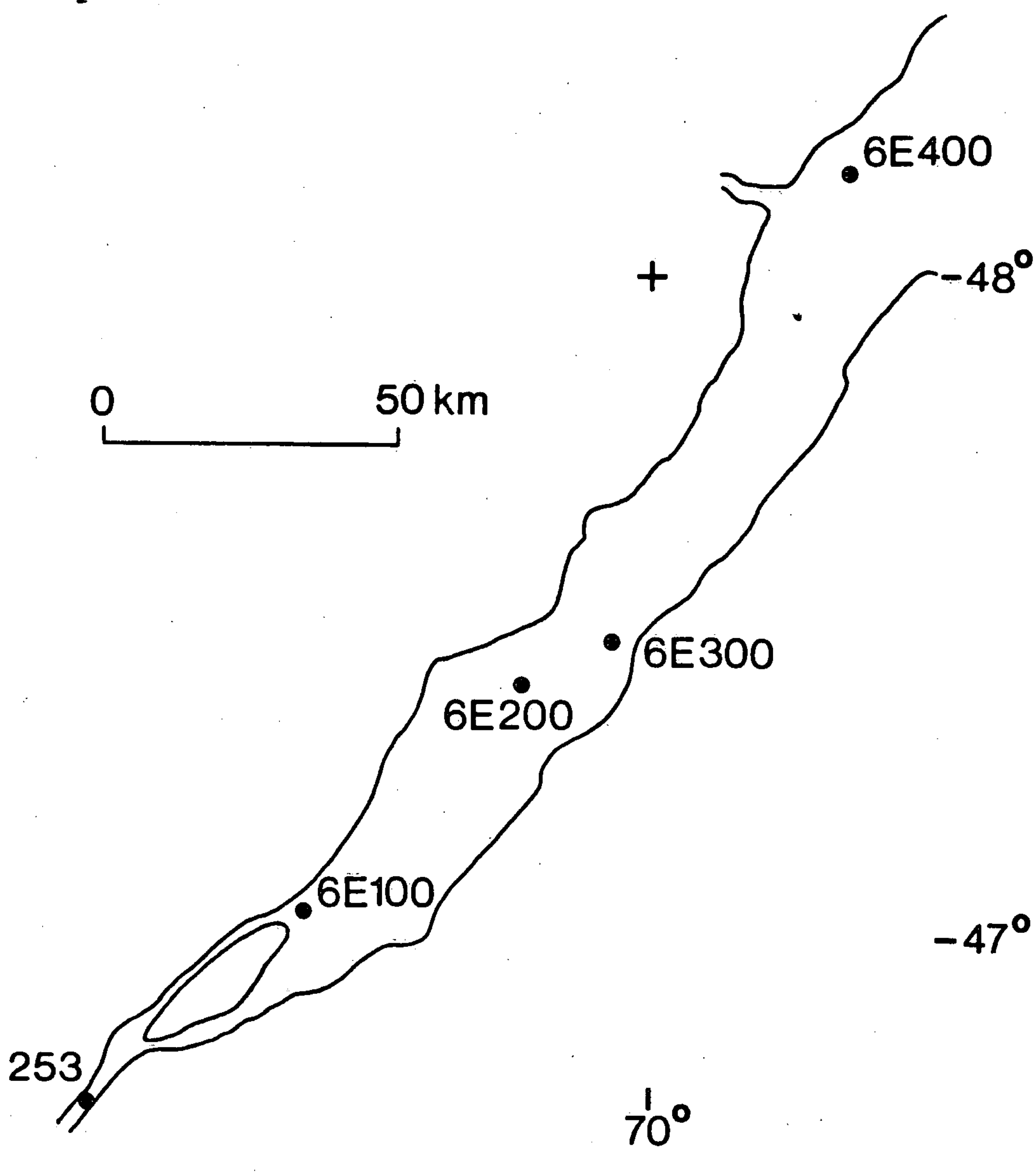


Fig 1

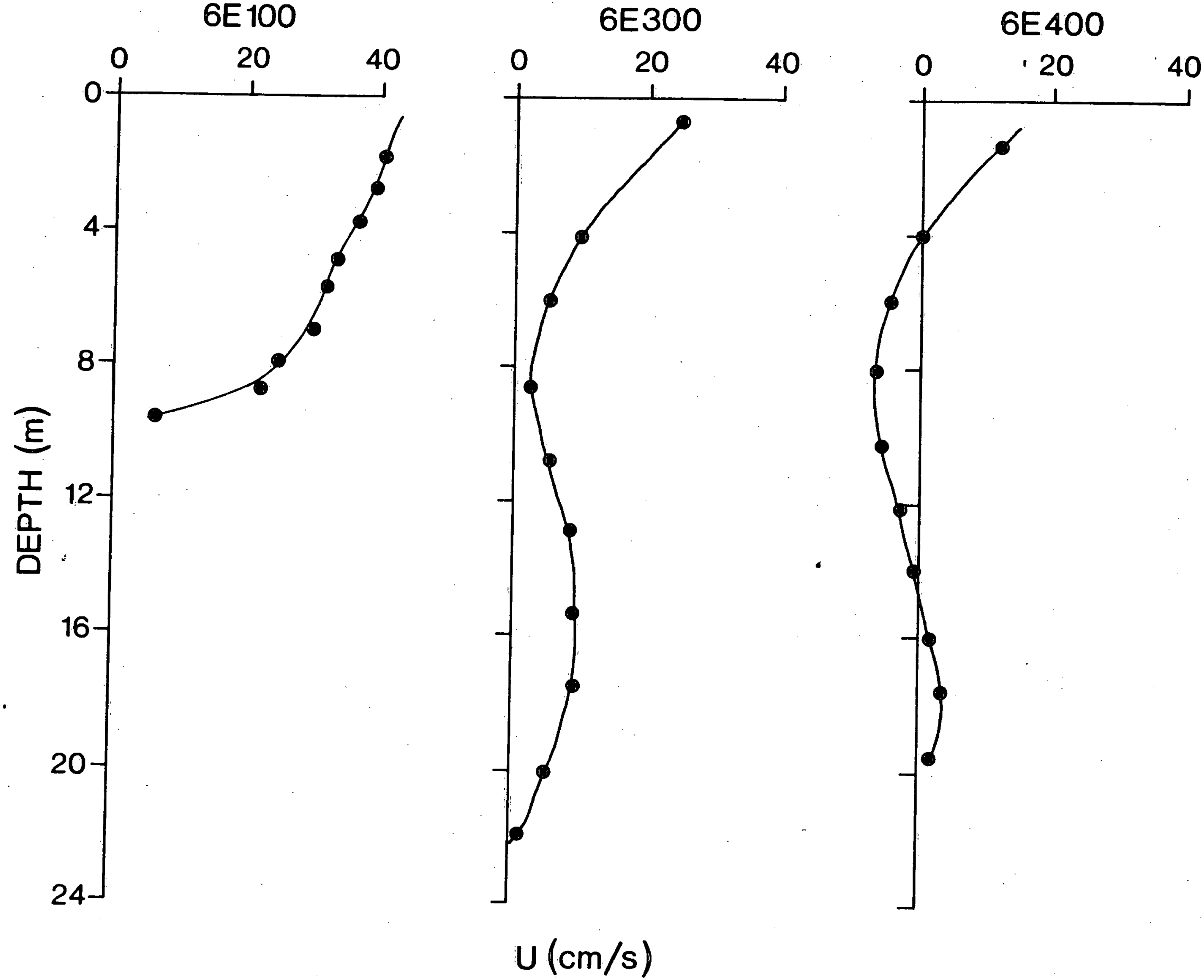


Fig. 2

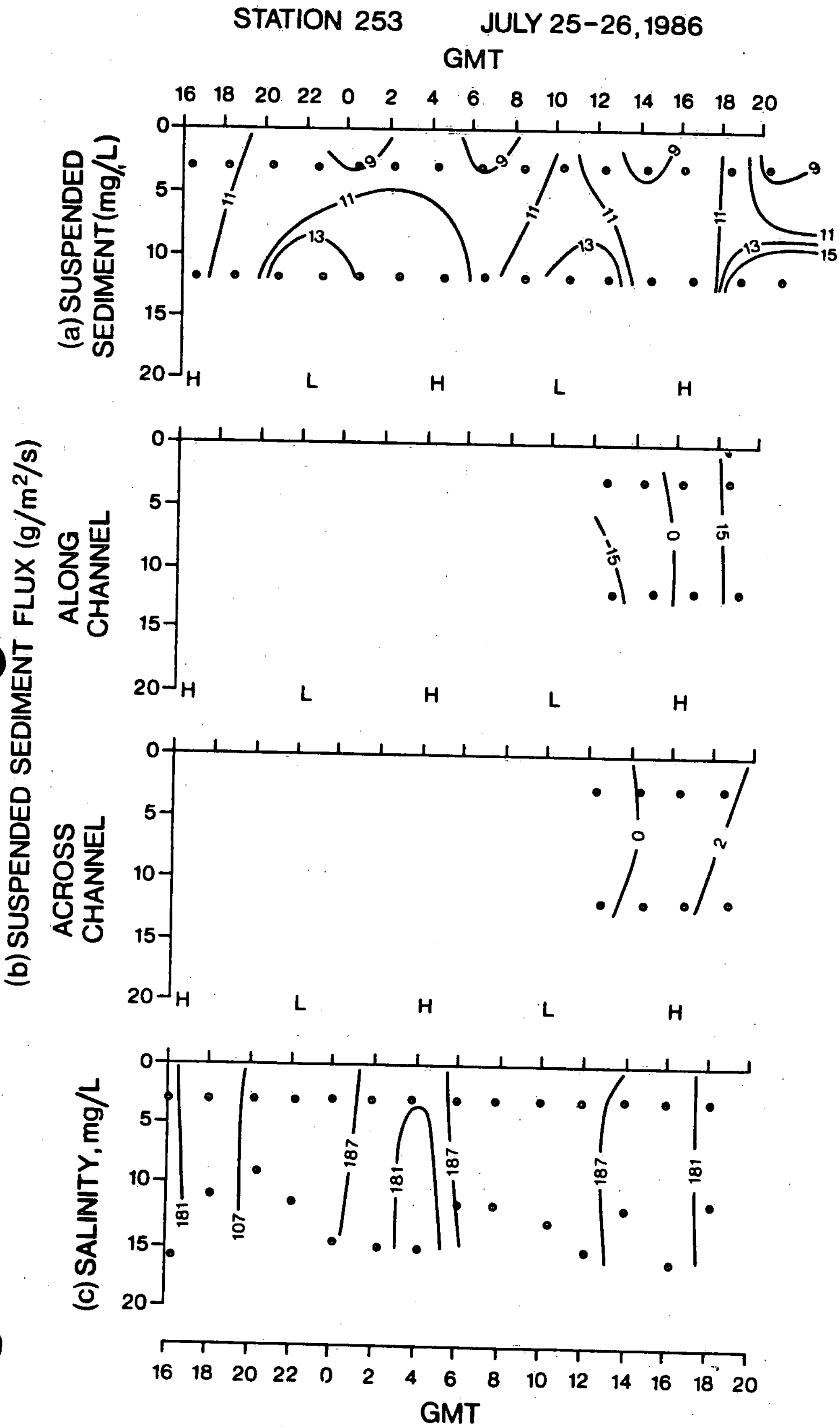

STATION 253
JULY 25-26,1986
GMT
(a) SUSPENDED SEDIMENT (mg/L)
(b) SUSPENDED SEDIMENT FLUX (g/m²/s)
ALONG CHANNEL
ACROSS CHANNEL
(c) SALINITY, mg/L
H
L
H
L
H
GMT

Fig 3

STATION 6E100 JUNE 27 & 28, 1986

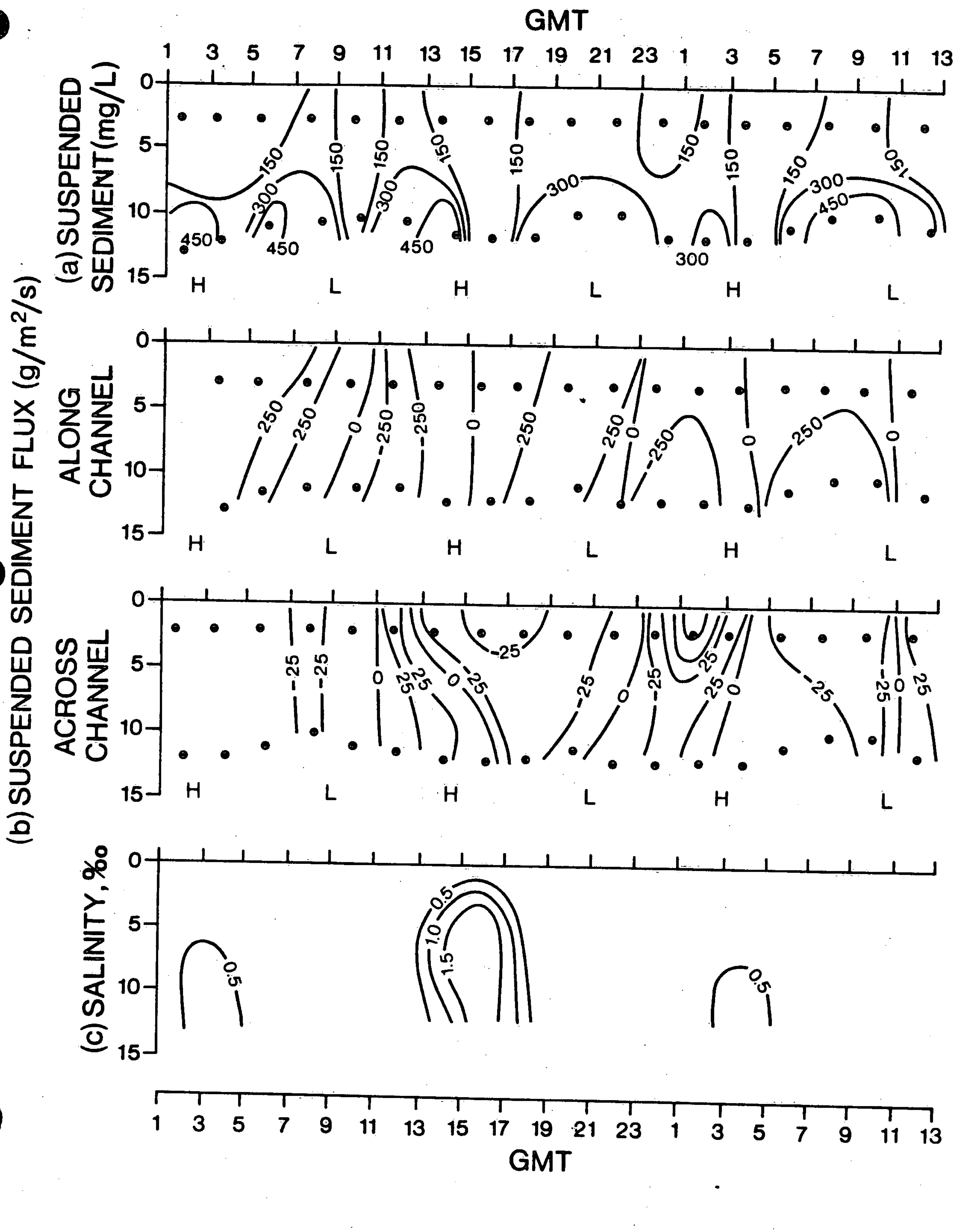
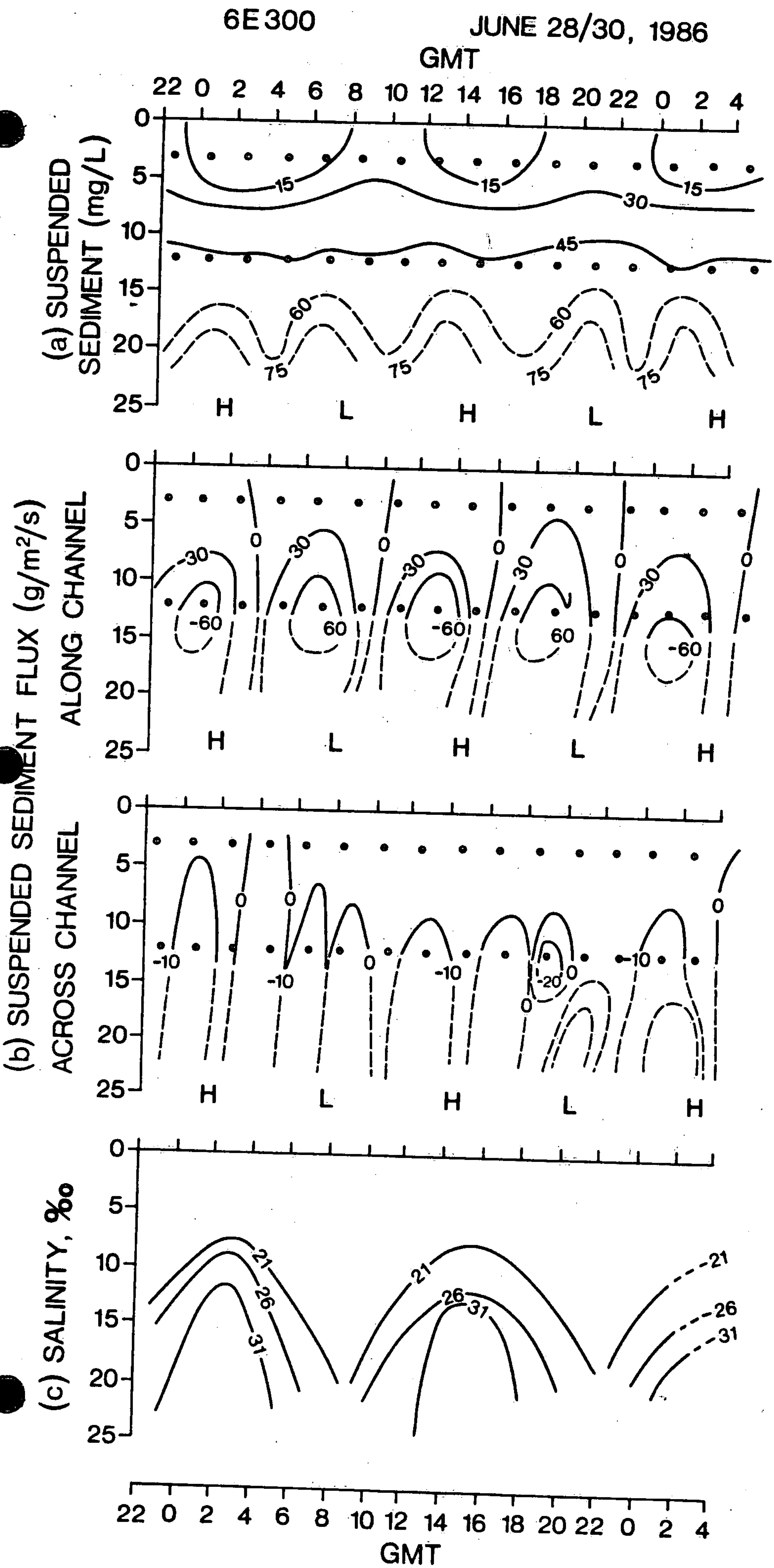
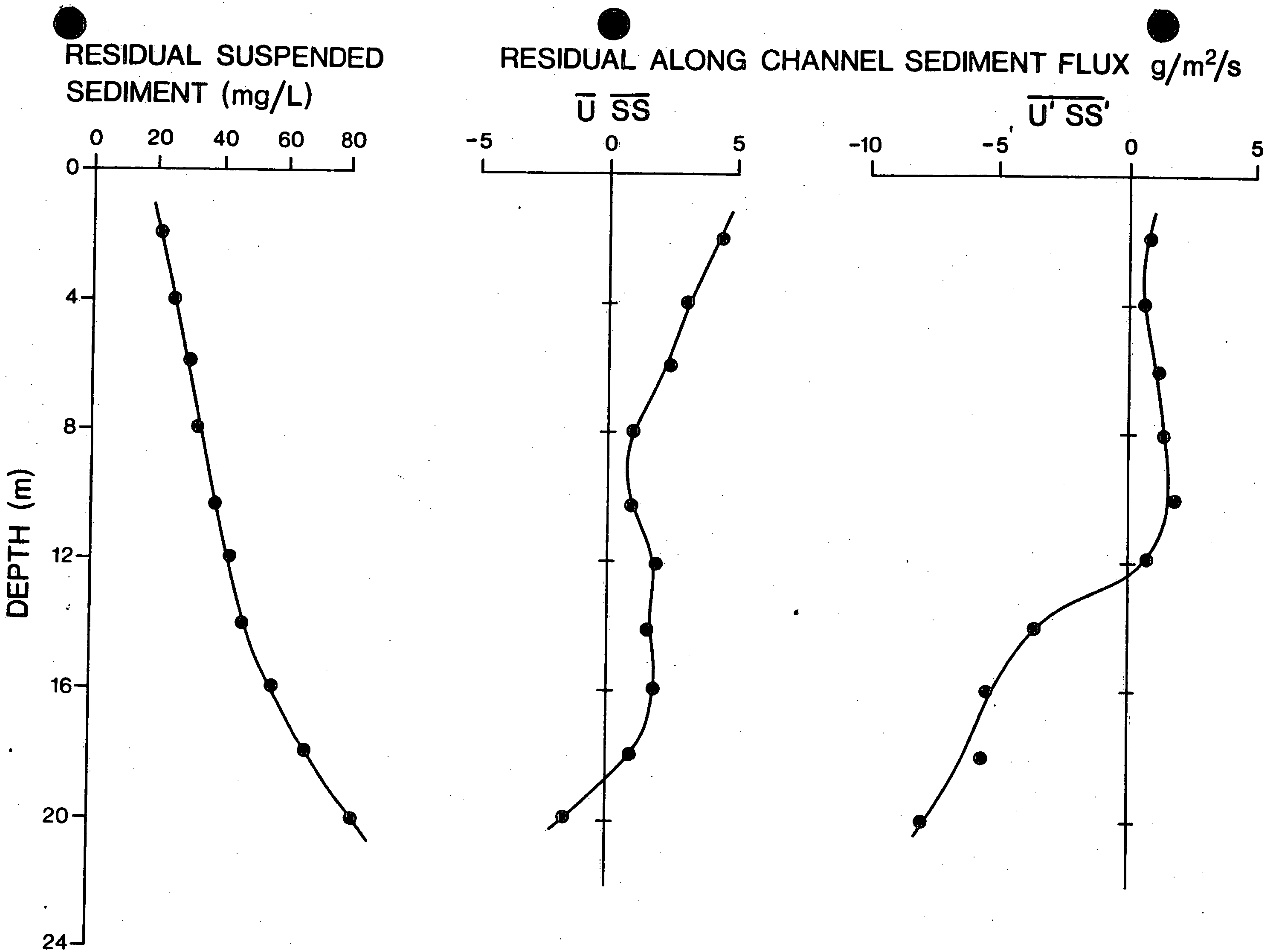


Fig 4



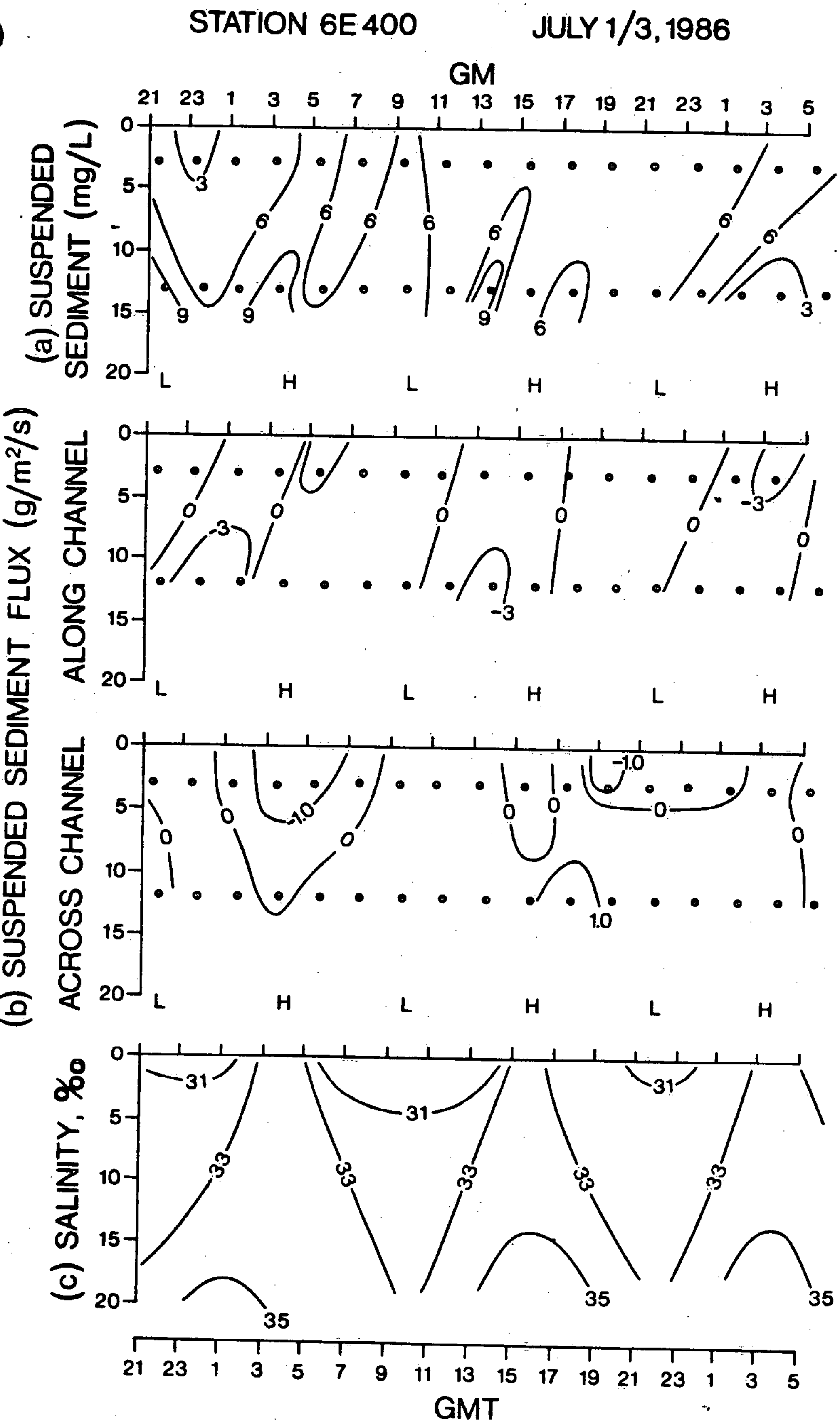
6E300
JUNE 28/30, 1986
GMT
(a) SUSPENDED SEDIMENT (mg/L)
(b) SUSPENDED SEDIMENT FLUX (g/m²/s)
ALONG CHANNEL
ACROSS CHANNEL
(c) SALINITY, ‰
H
L
GMT

Fig 5



RESIDUAL SUSPENDED SEDIMENT (mg/L)
RESIDUAL ALONG CHANNEL SEDIMENT FLUX g/m²/s
$\overline{U}\ \overline{SS}$
$\overline{U'SS'}$
0
20
40
60
80
-5
0
5
-10
-5
0
5
DEPTH (m)
0
4
8
12
16
20
24

Fig 6



STATION 6E400
JULY 1/3, 1986
GM
(a) SUSPENDED SEDIMENT (mg/L)
(b) SUSPENDED SEDIMENT FLUX (g/m²/s)
ALONG CHANNEL
ACROSS CHANNEL
(c) SALINITY, ‰
GMT

Fig 7