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Temporal & Spatial Variations in Hydrographic Conditions of Mandovi Estuary

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Variations in temperature, salinity, suspended matter and currents at mouth, middle and upstream regions of Mandovi estuary were studied in relation to tides for 3 seasons, viz. premonsoon, monsoon and postmonsoon. Waters attained maximum temperature of 31·5°C during premonsoon and minimum of 25·5°C during postmonsoon. Maximum salinity variation over a tidal cycle was in the middle region of the estuary during monsoon (2 to 34‰) and minimum was at the mouth during premonsoon (34 to 36‰). Horizontal gradient in salinity was maximum (2·0‰/km) during monsoon and minimum (about 0·2‰/km) during premonsoon. The estuary changed from a stratified type during the wettest season (monsoon) to a well-mixed type in premonsoon. The sediment load was generally low (<25 mg/litre) in the waters of the upstream region during postmonsoon. Higher values of suspended load were generally associated with strong currents. At the mid region of the estuary strong currents of about 150 cm/sec were encountered with flood during premonsoon and with ebb during monsoon.

MANDOVI estuary, situated on the northern side of Panaji, is one of the two main estuaries of Goa. This estuary is very narrow in the upstream and broadens considerably before joining the Arabian Sea. The width at the mouth is about 3 km. A number of tributaries join Mandovi estuary. The tide in this area is of a mixed semidiurnal type. The fresh water supply which is maximum during monsoon period gradually decreases during postmonsoon and becomes negligible during premonsoon. At a distance of about 14 km from its mouth, Mandovi is connected to Zuari estuary by a narrow canal, Cumbarjua canal.

The navigation channel near the mouth of the estuary is open during fair weather season. During monsoon this channel is closed because of the formation of sand bar near its entrance. Some studies on the hydrography of this estuary near its mouth were carried out during premonsoon season[1] and during February and August[2]. Bhargava[3], while presenting the seasonal variations of phytoplankton pigments, discussed the two parameters, temperature and salinity, near the mouth and mid-reaches of the estuary. In view of the navigational importance of this estuary a detailed study of the variation in the hydrographical conditions in relation to tidal currents has been made.

Methods

Observations were made during April, September and January. Each of these months depicts conditions which are by and large typical for the premonsoon, monsoon and postmonsoon respectively. Hourly observations of hydrographical parameters over tidal cycles were made at some fixed stations located at the mouth, middle and upstream regions of the estuary either on the same day or on successive days to cover the situations associated with similar tidal conditions. Dates of observation and distances of the stations from the mouth are given in Table 1. Altogether 8 tidal cycle observations were carried out as per the detail given in Table 1. As the present work is oriented mainly to study the temporal and spatial variation in parameters in relation to tidal currents, more emphasis was laid on conducting simultaneous observations over tidal cycles at different regions of the estuary, and days with high tidal ranges only were chosen for observations in each season. Data from station B located in the middle of the estuary were collected in all the seasons. Station A located at the mouth of the estuary could not be worked during the monsoon due to rough weather conditions and hence station A_1 located very close to the

TABLE 1 — DISTANCES FROM THE MOUTH AND DATES OF OBSERVATION

Season	Station	Distance from mouth (km)	Date of observation
Premonsoon	A	0	15-4-72
	B	9	15-4-72
Monsoon	A_1	4	7-9-72
	B	9	8-9-72
	C	26	9-9-72
Postmonsoon	A	0	15-1-73
	B	9	15-1-73
	C_1	31	19-1-73

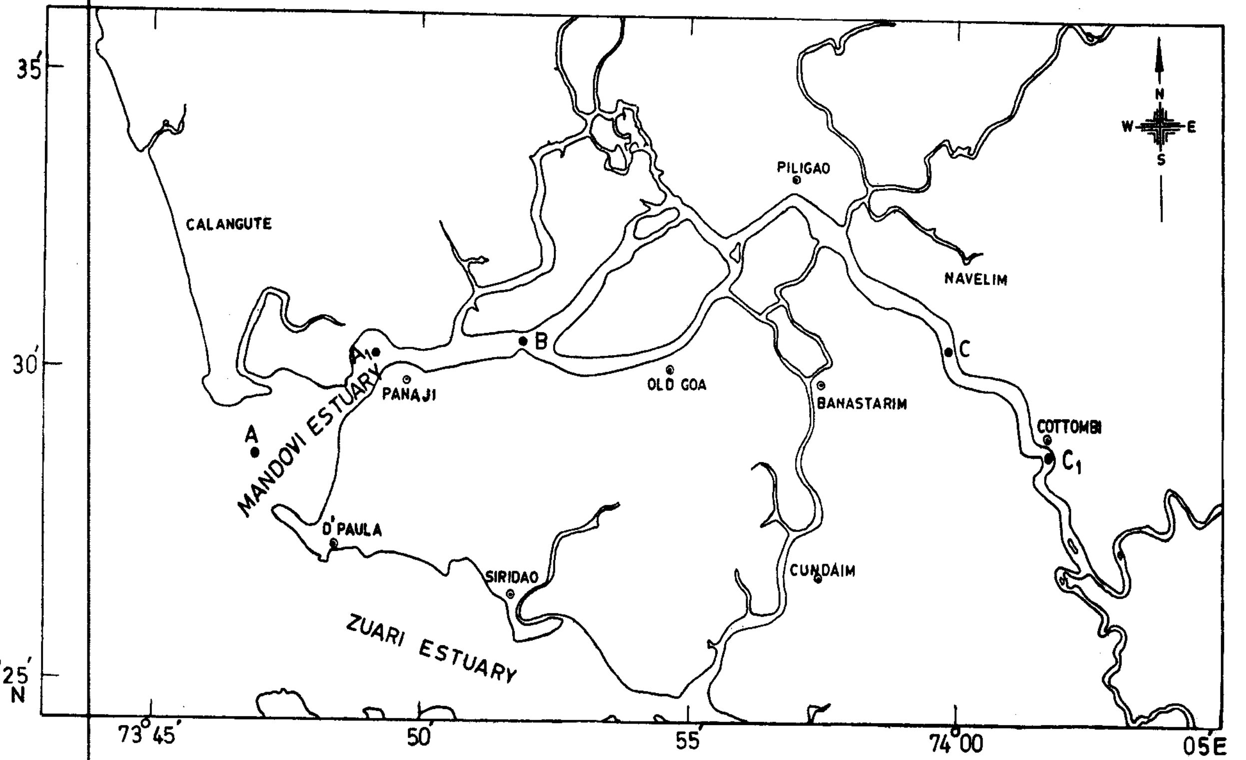


Fig. 1 — Location of stations

mouth was investigated. The upstream station was fixed as near the salt water boundary as possible. Locations of the stations are shown in Fig. 1. The average depths at stations A, A_1, B, C and C_1 are 7, 6, 7·5, 4·5 and 9 m respectively.

Surface currents (1 m below the surface) and bottom currents (1 m above the bottom) were measured using the Ekman type current meter. Water samples were collected from 3 depths, viz. upper ½ m, the mid-depth of the water column prevailing at the time of observation and about ½ m above the bottom, to represent the waters in surface, middle and bottom layers respectively. For measuring surface and subsurface temperature, bucket thermometer and reversing thermometers were used. Water samples were analysed for salinity by the titration method. Sediment load was estimated using standard filtration technique. Variations of different parameters with tide during premonsoon, monsoon and postmonsoon seasons are shown in Figs. 2(a, b), 3(a, b, c) and 4(a, b, c) respectively.

A comparison of recorded tide at the Mormugao Harbour with tide pole data collected in Mandovi estuary has shown that even in upstream region of the estuary there is no significant difference in tidal ranges. So the recorded tide at Mormugao Harbour was plotted for the days of observations wherever tide pole data could not be collected due to field difficulties at respective stations.

Results and Discussion

Premonsoon (*Fig.* 2) — Temperature varied between 29·2° and 30·6°C at the mouth and between 30·2° and 31·5°C in the middle region of the estuary. In general, there was a depthwise decrease in temperature at the mouth of the estuary. In the middle reaches of the estuary, even though there was diurnal variation of temperature due to solar heating, it was slightly obscured by a fall in temperature at all levels in association with the flood tide.

At the mouth of the estuary salinity varied from 34 to 36·0‰. There was an increase in salinity at all levels till flood reached its maximum. In the middle region, salinity variation was about 5‰ (from 29·5 to 35·0‰). The waters attained high salinity at the maximum flood. Between the peak flood and the peak ebb, waters of nearly same salinity were present. This feature appeared to be due to considerable mixing of the waters in this region and the bifurcation of the river at the upstream side of this station. However, there was a depthwise increase in the salinity during the other phases of the tide.

At the mouth of the estuary, the suspended sediment load at the surface and middle layers was generally less than 50 mg/litre. In general, a depthwise increase in sediment load was observed. There was a marked increase in the sediment load of the bottom layer towards the afternoon hours, when wave action is greater due to strong sea breeze. This appeared to be associated with the transport of coarse grained particles near the bottom and apart from currents wave action often seemed to be required to set this into motion[4]. Semitidal fluctuations in sediment load associated with currents were observed in the middle region of the estuary. The sediment load was found to vary between 25 and 95 mg/litre. Maximum values were encountered in the middle and bottom waters during the peak flood, when the bottom currents were considerably

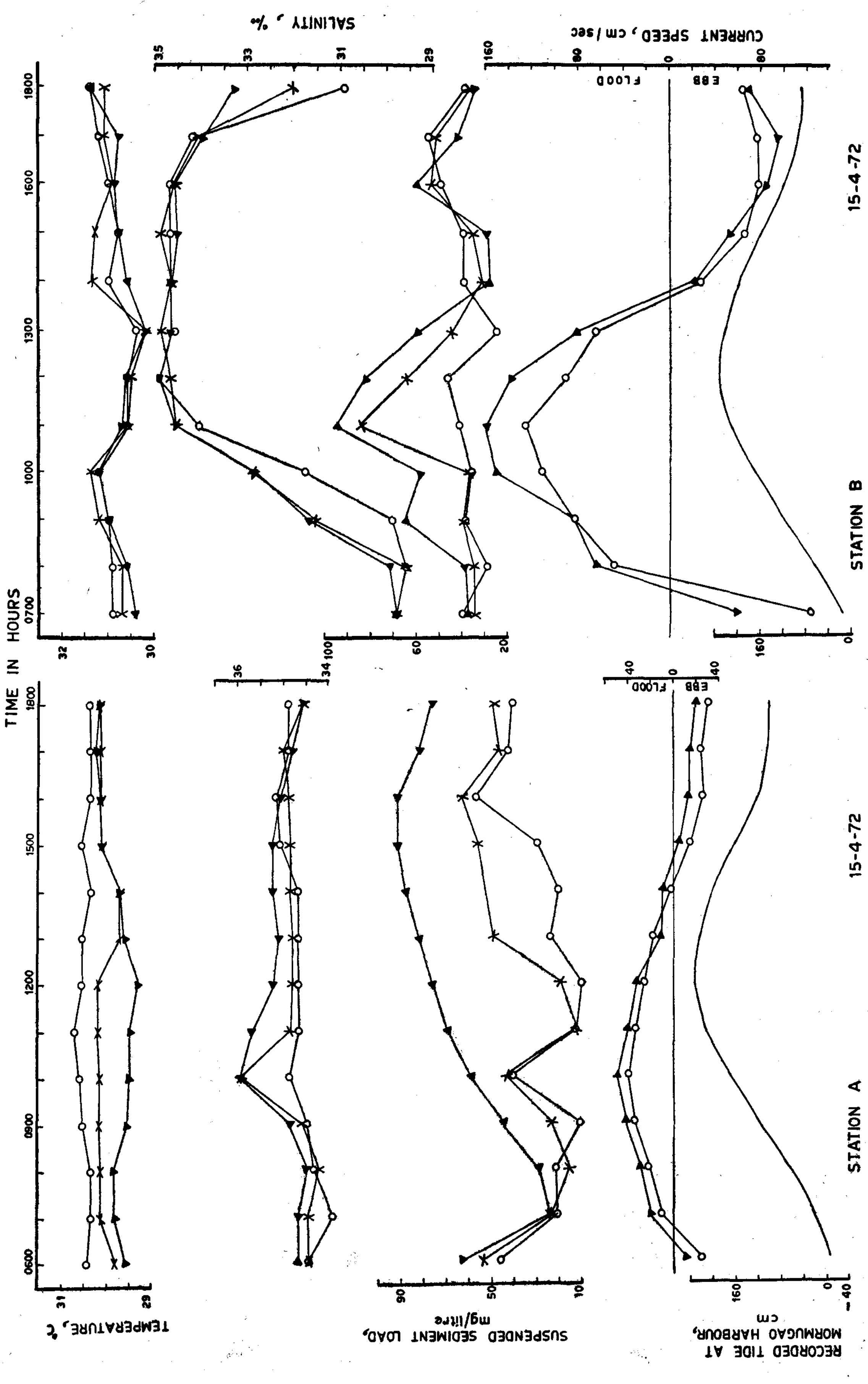


Fig. 2 — Variation of temperature, salinity, suspended sediment load and current with tide at the (station A) mouth and (station B) middle regions of the estuary during premonsoon [○—○, surface; ×—×, middle; ▲—▲, bottom]

strong. During the ebb, the sediment load did not show much variation with depth.

At the mouth of the estuary, maximum surface currents associated with the peak flood and peak ebb were found to be about 40 and 30 cm/sec respectively. Maximum bottom current during flood was of the order of 50 cm/sec while that during ebb was about 20 cm/sec. In the middle region of the estuary, bottom currents were faster than those at the surface during flood, peak values being 160 and 125 cm/sec at the bottom and surface layers respectively. During the ebb, maximum current speeds observed were of the order of 90 cm/sec and there was not much variation in the current speed between the surface and the bottom. Higher current speeds observed during flood than during ebb were in agreement with the findings of Murthy and Das[1] for the same season. Relatively low values of current speed at the mouth were the result of considerable widening of the channel in this region.

Monsoon (*Fig.* 3) — Near the mouth and in the middle region of the estuary, the temperature varied between 26° and 30°C. Surface and bottom layers were generally warmer than the middle layer. In the upstream region, the variation in temperature was less (28·5° to 30·0°C). At this region bottom waters were warmer than those at surface and mid depth. Near the mouth and in the middle region of the estuary, lower temperature was encountered with the high tide which brought in colder water from the sea. Similar tide-controlled temperature variations have been reported by Qasim and Gopinathan[7] in Cochin backwater during this season. In the upstream region, diurnal variation associated with the solar heating appeared to be more predominant than fluctuations associated with the tides.

Salinity ranged from 10 to 35‰ near the mouth and from 2 to 34‰ in the middle reaches of the estuary. Waters in the upstream region (station C) were free of salt. Increase in the range of salinity and steep vertical gradient encountered in the middle region of the estuary reflected the stratification caused by appreciable runoff during this season. Decrease in vertical salinity gradient with incoming waters and increase in the gradient with outgoing waters, observed near the mouth (station A_1), appeared to be associated with the up and down movement of the salt wedge.

Near the mouth and in the middle and upstream regions of the estuary, suspended sediment load was generally found to increase with depth. Near the mouth of the estuary suspended sediment showed a semitidal fluctuation and maximum values were about 100 mg/litre. In the middle region of the estuary even though the suspended sediment was generally less than 60 mg/litre, in the bottom waters sediment load was more than 100 mg/litre during strong currents. In the upstream region, suspended sediment load was, in general, less than 70 mg/litre and showed fluctuations associated with tidal currents. Suspended sediment load in the upstream region was high in this season compared to that during postmonsoon. This was presumably due to high river discharge during this season.

Maximum speeds of surface currents observed during the flood were about 110, 120 and 40 cm/sec near mouth, middle and upstream regions respectively of the estuary. Corresponding values for the ebb were 140, 150 and 65 cm/sec. Ebb currents were stronger than flood currents presumably due to the runoff which augmented the outgoing tide. Similar feature was observed in Zuari estuary during the same season[6]. At the upstream station (station C) even though the waters were free of salt, influence of tidal currents was experienced indicating that this station was located in the 'tidal section of river'.

Postmonsoon (*Fig.* 4) — Temperature varied from 26·5° to 27·4°C at the mouth, from 25·5° to 28·6°C in the middle region and from 27·6° to 28·4°C in the upstream region of the estuary. At the mouth and upstream regions of the estuary, temperature of the middle layer was less than that of the surface and bottom waters. In the middle region of the estuary, no significant depthwise variation in temperature was noticed, and the variation in the temperature of the waters during the day-time was comparatively high (about 3°C). This appeared to be the cumulative effect of tides and insolation.

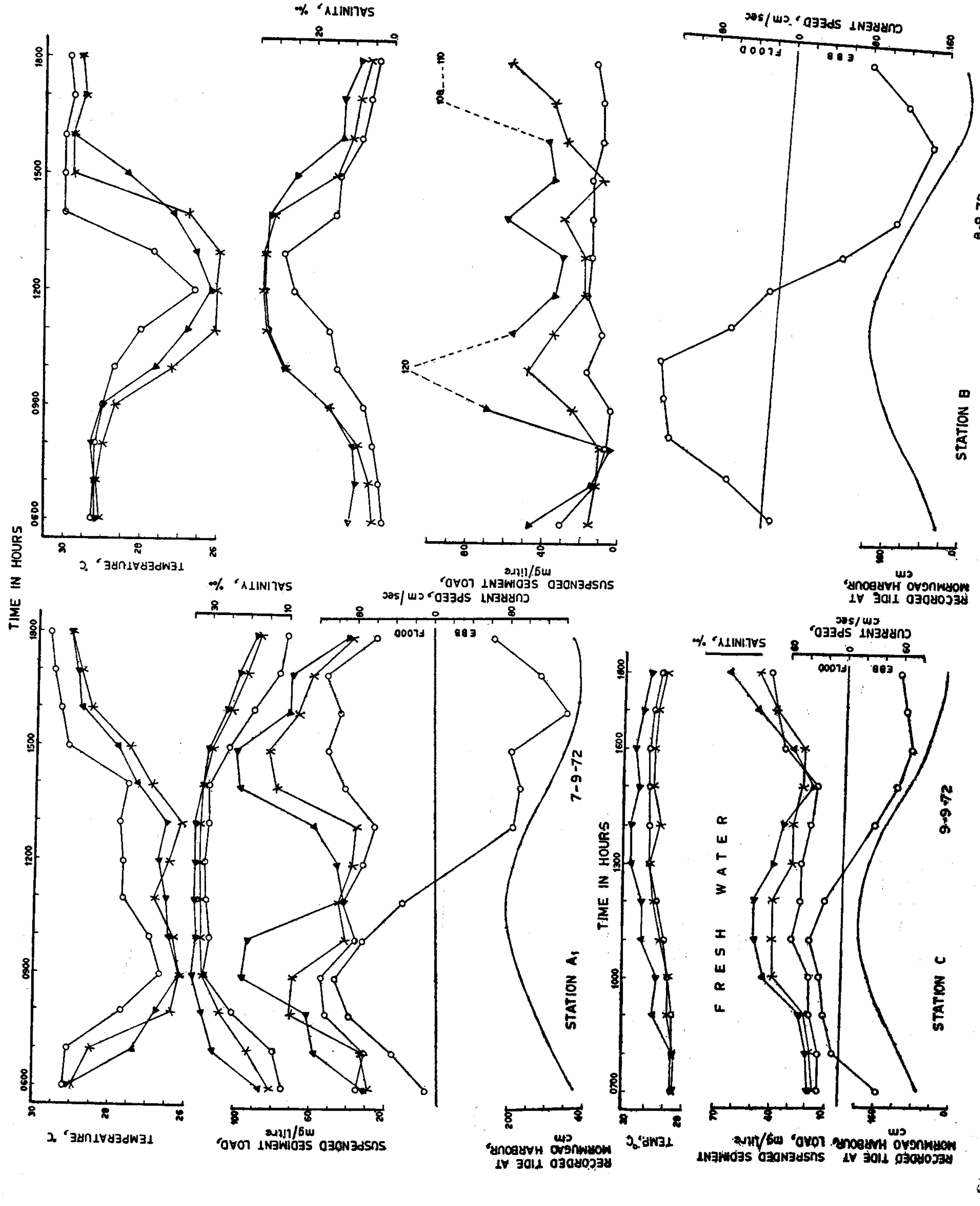
Variation in salinity was from 32·2 to 35·6‰ at the mouth, 23·0 to 34·5‰ in the middle region and 2·5 to 7·5‰ in the upstream region of the estuary. At the mouth, range of salinity over a tidal cycle decreased with depth from about 3‰ at the surface to about 0·5‰ in the bottom waters. Minimum salinity was encountered during low slack. In the middle region of the estuary the salinity variations at the surface, middle and bottom layers were similar, the ranges being comparatively high. In the upsteam region, even though the salinity was more or less the same at all depths during the rising tide, slight increase in salinity with depth was noticed during the falling tide.

At the mouth of the estuary suspended sediment load was found to vary, in general, between 5 and 50 mg/litre except near the bottom where it was higher during the low slack and flood. Low values of suspended load encountered with the ebb appeared to be caused by the divergence of currents in the adjacent regions. It is possible that flocculation of particles also contributed to this feature. In the middle region of the estuary, suspended sediment load was found to fluctuate, generally, between 10 and 55 mg/litre and it did not show any regular variation with currents. In the upstream region, sediment load of the waters was comparatively low (5 to 25 mg/litre).

During the ebb, maximum speeds were found at the surface (40, 75 and 40 cm/sec in the mouth, middle and upstream regions respectively). At the mouth and in the middle region of the estuary bottom currents attained higher speeds than surface currents during flood. Bottom currents attained a maximum speed of about 25 cm/sec at the mouth and 70 cm/sec in the middle region of the estuary.

Commencement of flood/ebb currents — This was studied in different regions of the estuary in relation to the recorded tide at Marmugao Port. In the premonsoon season, flood current was found to commence in the mouth of the estuary about the same time as the low water at the harbour whereas ebb current started about 2 hr after the high water. In

Fig. 3 — Variation of temperature, salinity, suspended sediment load and current with tide at the (station A_1) mouth, (station B) middle and (station C) upstream regions of the estuary during monsoon [○—○, surface; ×—×, middle; ▲—▲, bottom]



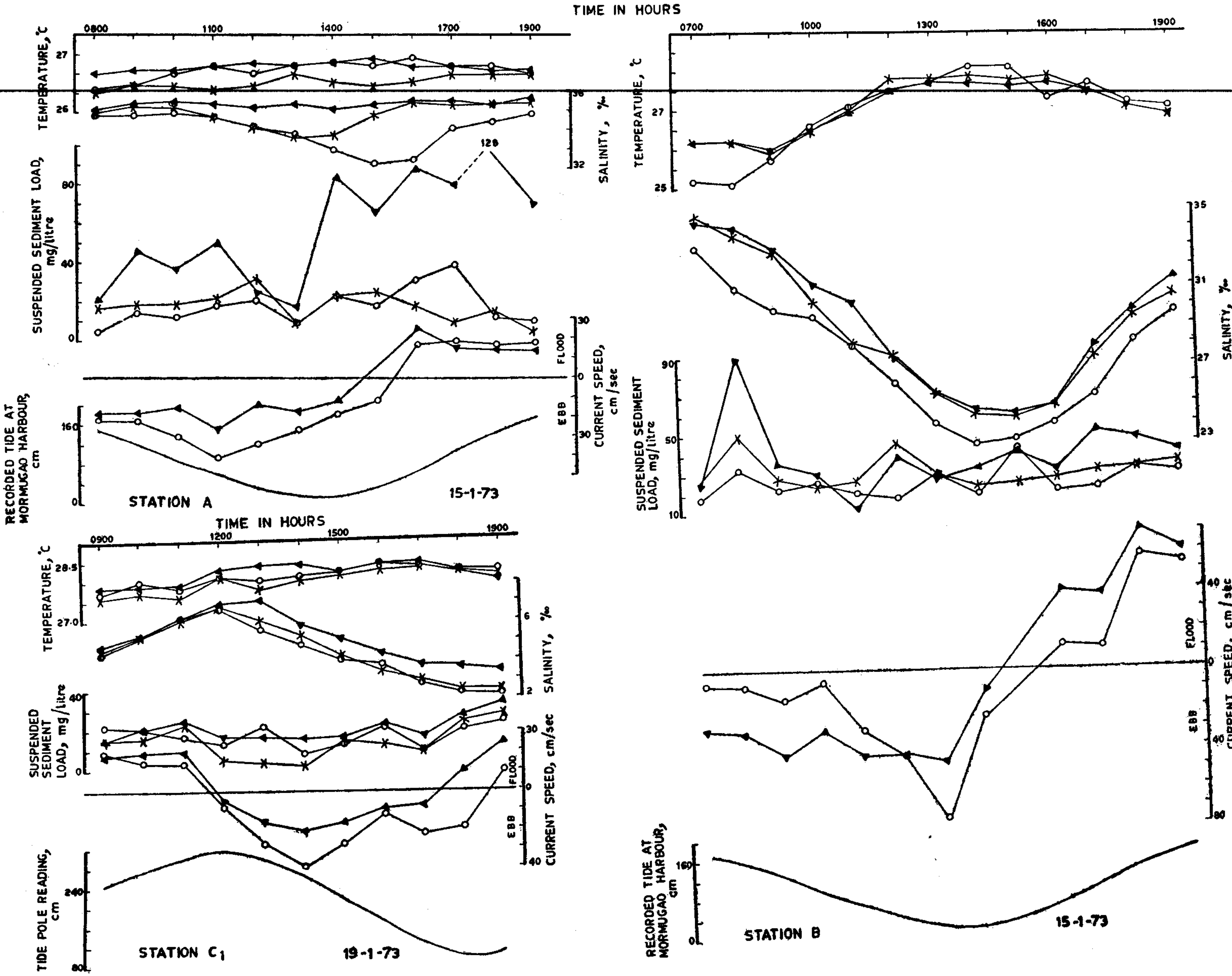


Fig. 4 — Variation of temperature, salinity, suspended sediment load and current with tide at the (station A) mouth, (station B) middle and (station C_1) upstream regions of the estuary during post-monsoon [O—O, surface; ×—×, middle; ▲—▲, bottom]

the middle region of the estuary flood current showed a slight lag from that at the mouth, while ebb started at about the same time. During monsoon, ebb current at the station near the mouth started more or less at the time of high water in the harbour. The start of ebb current at the middle and upstream regions of the estuary exhibited a lag of about 1 hr from the time of high water in the harbour. During postmonsoon, flood current was found to start at the mouth of the estuary about 1 hr after the low water in the harbour. In the mid region, flood did not show much time lag from that at the mouth. Tide pole readings in the upstream region indicated that high and low waters in this region exhibit a lag of about 1 hr from those at the harbour. Ebb current started at the time of high water in this region.

Horizontal salinity gradient — Horizontal salinity gradient (‰ per km) in the surface, middle and bottom layers was calculated for different seasons and presented in Table 2. For this, the temporal mean values over a tidal cycle were used.

Maximum horizontal gradient in salinity of 2·35‰/km during monsoon, minimum of 0·19‰/km in premonsoon and an intermediate value of about 1·0‰/km during postmonsoon clearly indicated the diminishing effect of freshet from monsoon through premonsoon. Vertical variation of horizontal gradients decreased from monsoon through premonsoon. The estuary was stratified during monsoon, and well mixed during the premonsoon while it was partially mixed during postmonsoon as per the definition[7]. Reduction of fresh water discharge, as the case here is, changes the estuary from a stratified type to a partially mixed or well mixed type[8]. In monsoon the horizontal gradient in the downstream region (between stations A_1 and B) decreased from surface to bottom presumably due to the intrusion of salt water in the form of a wedge. However, between stations B and C, the horizontal gradient in salinity increased with depth. This was because station C was situated beyond the salt water intrusion.

The salient features inferred from the preceding discussion are given below:

Temperature of the waters attained highest value (31·5°C) in premonsoon and lowest (25·5°C) during postmonsoon. Influence of tides on temperature was prominent in the downstream region of the estuary while that of insolation was predominant in the upper reaches.

The salt water boundary which was found at a distance of about 36 km from the mouth (as observed by the authors) in premonsoon, receded rapidly to less than 25 km from the mouth during monsoon and migrated gradually upstream reaching a distance of about 31 km during the postmonsoon. Distribution of salinity indicated that the estuary was stratified during monsoon, partially mixed in postmonsoon and well mixed during the premonsoon.

TABLE 2 — HORIZONTAL SALINITY GRADIENT

Season	Depth	Horizontal sal. gradient between mouth and middle of estuary (‰/km)	Horizontal sal. gradient between middle and upstream of estuary (‰/km)
Premonsoon	Surface	0·21	—
	Middle	0·19	—
	Bottom	0·19	—
Monsoon	Surface	2·35	0·75
	Middle	1·80	1·20
	Bottom	1·75	1·35
Postmonsoon	Surface	0·75	1·02
	Middle	1·01	1·08
	Bottom	1·11	1·06

Waters in the upstream region in general bear less sediment material compared to those at the mouth and mid reaches of the estuary.

Tidal currents were stronger in the middle region than at the mouth and the upper reaches of the estuary. This can be attributed to the location of this station (station B) where the estuary narrows first before it branches (Fig. 1). It is interesting to note that, in general, maximum speeds were attained by surface and bottom currents during ebb and flood respectively.

In the upsteam region (about 30 km from the mouth), during postmonsoon, high and low waters occurred about 1 hr after their occurrence at the harbour.

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