

## Flow Characteristics of Combarjua Canal Connecting Mandovi & Zuari Estuaries

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A comparative study of the tidal flow patterns at the two terminals of the Combarjua canal which connects the estuaries of the two rivers, Zuari and Mandovi, is presented. It is shown from the analysis of tidal currents and vertical tides together with the variations in salinity over complete tidal cycles that the postmonsoon flow pattern in Combarjua, when there is little freshwater discharge through the river Zuari and very little through Mandovi, is controlled primarily by the tidal conditions at the Zuari side of this connecting canal. The distribution of the tidal energies reaching the two ends of the canal is shown to be 77 and 23% respectively at the Zuari and Mandovi openings whose relative magnitudes appear to be the deciding factors for the flow characteristics of the canal. Differences in the salinity at the Zuari and Mandovi ends of the canal suggest that the larger volume of freshwater storage in the Mandovi river system may account for the appreciable lower salinity at the Mandovi side of the canal. The salinity gradients in the Combarjua canal reveal a net salinity influx from the Zuari side to the Mandovi side of the canal and to the upper reaches of the Mandovi river. Variations in the suspended sediment loads in the surface and near bottom waters in relation to the tidal stages, during the postmonsoon period, are also discussed. The sediment loads do not show much dependence on the speeds of the tidal current but they seem to be a little dependent on the salinity of the waters. This study suggests that the problems of sedimentation and pollution through waste disposal in this canal should be viewed in the context of the circulation features of the canal.

THE rivers Mandovi and Zuari run nearly parallel to each other before meeting the Arabian Sea where the two estuary openings are delineated by a promontory between them. The widths of Zuari and Mandovi estuaries here are 5.5 and 3.2 km respectively (Fig. 1). Combarjua canal connects the Mandovi and the Zuari at the upstream distances of 14 and 11 km from their mouths respectively. From the canal, the Zuari has an appreciably increasing width and is much larger in area than that of the Mandovi which has a meandering course before streaming into the sea. The Mandovi has a larger tributary system and, compared to the Zuari, shows lower average salinity throughout the year<sup>1</sup>. Both the rivers are fed by the monsoon precipitation and the discharge data available for the Zuari (Fig. 2) for the years 1963, 1964 and 1966 show negligible freshwater discharge during the premonsoon and postmonsoon periods. The discharge characteristics of the Mandovi, under reasonable assumptions, should be similar to that of the Zuari. In both the estuaries, therefore, the premonsoon and postmonsoon flows must be tide dominated. The tides here are of a mixed semi-diurnal type and have a maximum range of 230 cm. The predicted tides used in this study are for Mormugao harbour near the mouth of the Zuari estuary and, for reasons of geographical proximity, are assumed to hold good for the Mandovi estuary also.

Combarjua canal is a navigable canal and during the monsoon the entire traffic of barges, carrying iron ore, goes through it. There are plans to dredge it deeper for this reason. Moreover, in the near future, some industrial waste might be discharged

into this canal which necessitates a study of the water circulation in it along with its hydrographic features. The present study is a beginning towards this aim. The Combarjua canal is an interesting example of two estuaries interacting dynamically through a common channel.

The general outline of the estuarine system is shown in Fig. 1. Stations A and B are at Zuari and Mandovi sides of the canal. The canal is narrow and shallow at the Mandovi side while it is appreciably wider and deeper on the Zuari side. The northern side of the canal has two other narrow channels that merge together before meeting the river Xandovi further upstream.

Practically no information is available on the flow characteristics and hydrographic features of the canal which has become a vital channel for barge traffic in recent years in view of the increasing iron ore transport from the Mormugao harbour. Some studies on currents near the mouth of the Mandovi under typical premonsoon conditions were made recently<sup>1</sup>.

### Materials and Methods

Observations at Stations A (mean depth 7.5 m) and B (mean depth 3.5 m) consisted mainly of measuring the surface (0.5 m below the surface) and near bottom (1 m above the bottom) currents with an Ekman type current meter and of collecting water samples for determining the salinities and suspended sediment loads.

Three sets of observations were made at anchor Stations A and B in November 1969, March 1970 and November 1970, over complete tidal cycles

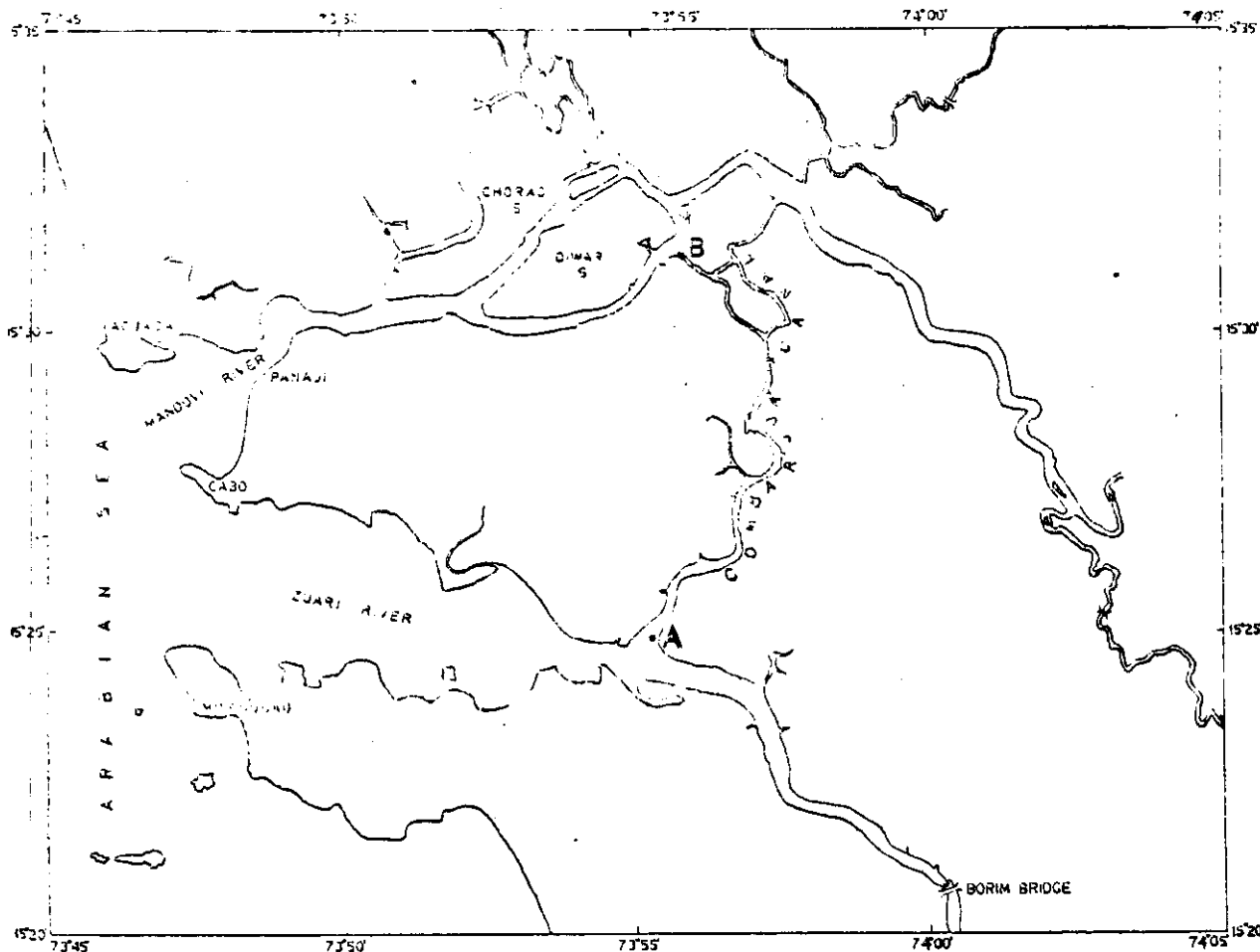


Fig. 1 -- Map showing the location of stations

under typical postmonsoon and premonsoon conditions.

Vertical tide was observed through a 30 min reading of a graduated pole fixed near Stations A and B during the observations taken in November 1970, and the lags or leads from the tides predicted for Mormugao Port were checked against these. The differences being small, it has been assumed that the predicted tide is a good enough index for the vertical tides at the two ends of the Combarjua canal (Stations A and B). Water samples were collected with a Hytech water sampler. The salinities of the water samples were determined by the standard method of titration against silver nitrate. The suspended sediment load was determined by taking the dry weights of the sediments after filtration.

**Results and Discussion**

Table 1 shows the maximum values of the tidal currents for surface and bottom waters at Stations A and B. It also shows the salinity ranges observed at these stations during November 1970 and March 1970. Figs. 3, 4 and 5 present the predicted tides, observed vertical tides, near surface and near bottom currents, salinities and a few estimations on suspended sediment loads. The velocity-salinity diagrams for these stations, for November 1970, are shown in Fig. 6. Fig. 7 gives the best fits of

correlation between tide range and mean maximum velocity for these stations.

*Tides* — The tide is semidiurnal. Observations on vertical tide during November 1970 show a time lag of about 1 hr at Station A for the occurrence of high and low waters, from the predicted tide for Mormugao harbour. There was, however, virtually no difference in the range. While the latter statement holds good for Station B also, the time lag of the observed tide at this station is irregular and may, on an average, be taken as 75 min. This can be explained by the fact that the water level at Station B is not only dependent on the time of arrival of the high and low of the tidal sinusoid from the Mandovi side on the one hand and from the Zuari side on the other but also on their relative amplitudes.

*Currents* — The variations of the current with tide at the two ends of the canal, in general, show smooth profiles near the surface and near the bottom except when the tide range is very low, when some irregularities in the current pattern show prominently (Fig. 4, Station B). In the case of Station A, the times of occurrence of peak and zero velocities in the current bear a clear-cut relationship to those of highs and lows of the tide predicted for the Mormugao harbour, while at Station B they are irregular. In general, the magnitude of the current velocities is more at Station A compared

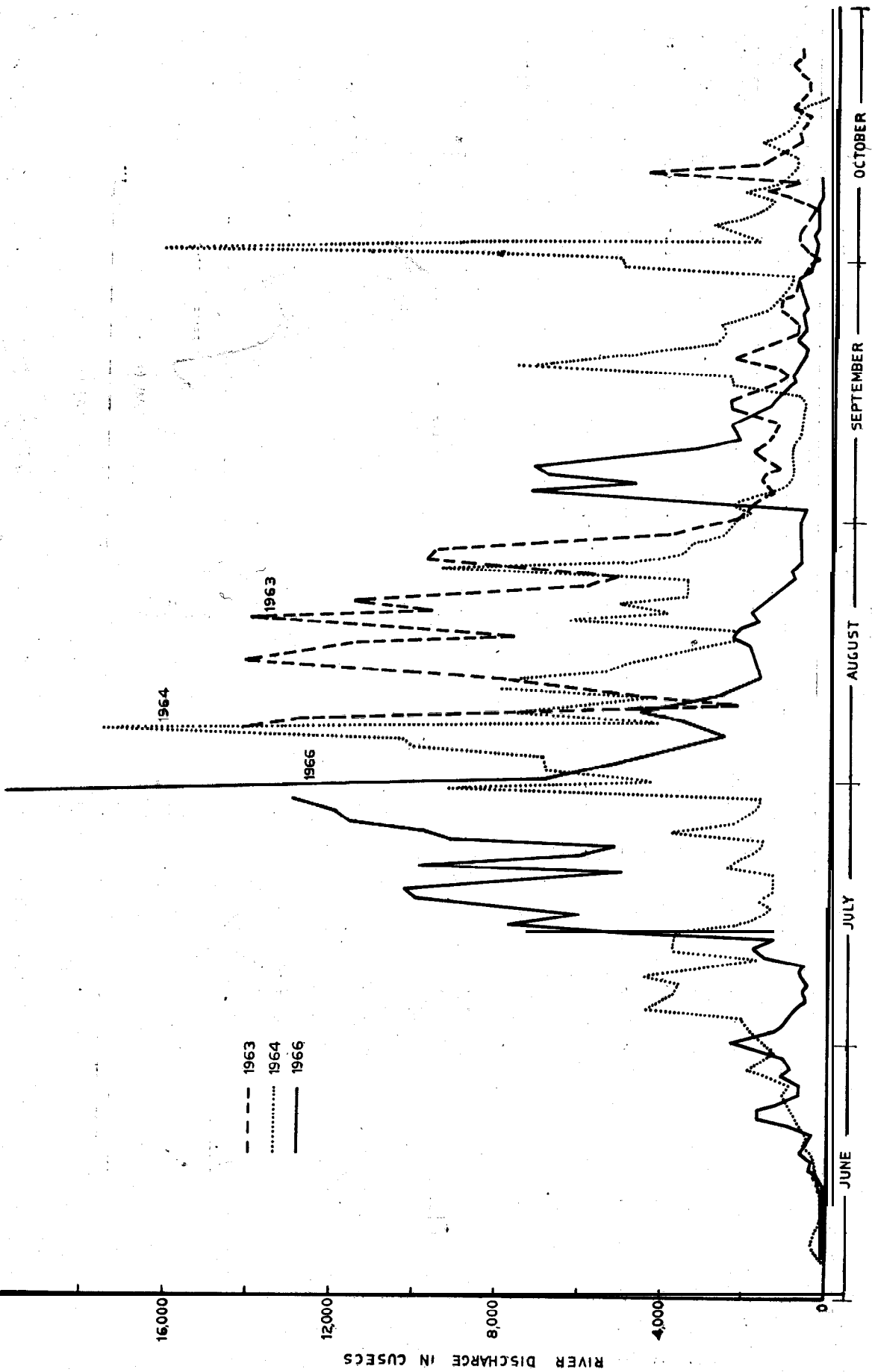


Fig. 2 — River discharge diagram for the Zuari river (1963, 1964 and 1966)

TABLE 1 - MAXIMUM CURRENT SPEEDS AND SALINITY VARIATIONS WITH TIDE OBSERVED IN COMBARJUA CANAL DURING PREMONSOON AND POSTMONSOON PERIODS

Month	Tide range (cm)		Current speed (cm/sec)						Salinity (‰)									
	Stn A Stn B		Flood			Ebb			Maximum			Minimum						
	Stn A	Stn B	Stn A	Stn B	Stn A	Stn B	Stn A	Stn B	Stn A	Stn B	Stn A	Stn B						
Nov. 1970	172	200	n.s.	n.b.	n.s.	n.b.	n.s.	n.b.	n.s.	n.b.	n.s.	n.b.	n.s.	n.b.	n.s.	n.b.		
March 1970	54	36	109	100	104	091	71	71	44	30.25	31.5	19.35	19.45	23.90	24.05	7.05	9.1	
Nov. 1969	110	110	67	57	55	51	72	47	48	11	35.2	32.6	33.3	33.3	34.90	27.4	31.2	
			68	124	91	—	68	72	61	—	—	—	—	—	—	—	—	—

n.s. — near the surface (0.5 m below surface).  
 n.b. — near the bottom (1.0 m above bottom).

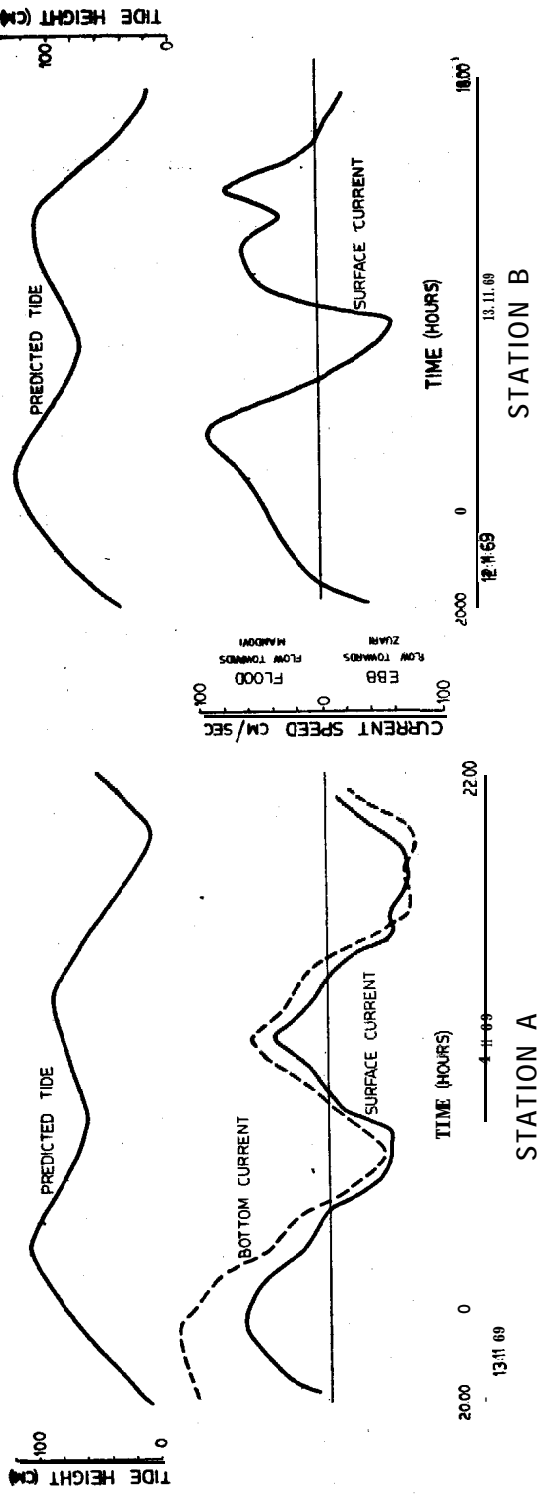


Fig. 3-Variation of current with tide at Stations A and B during November 1969

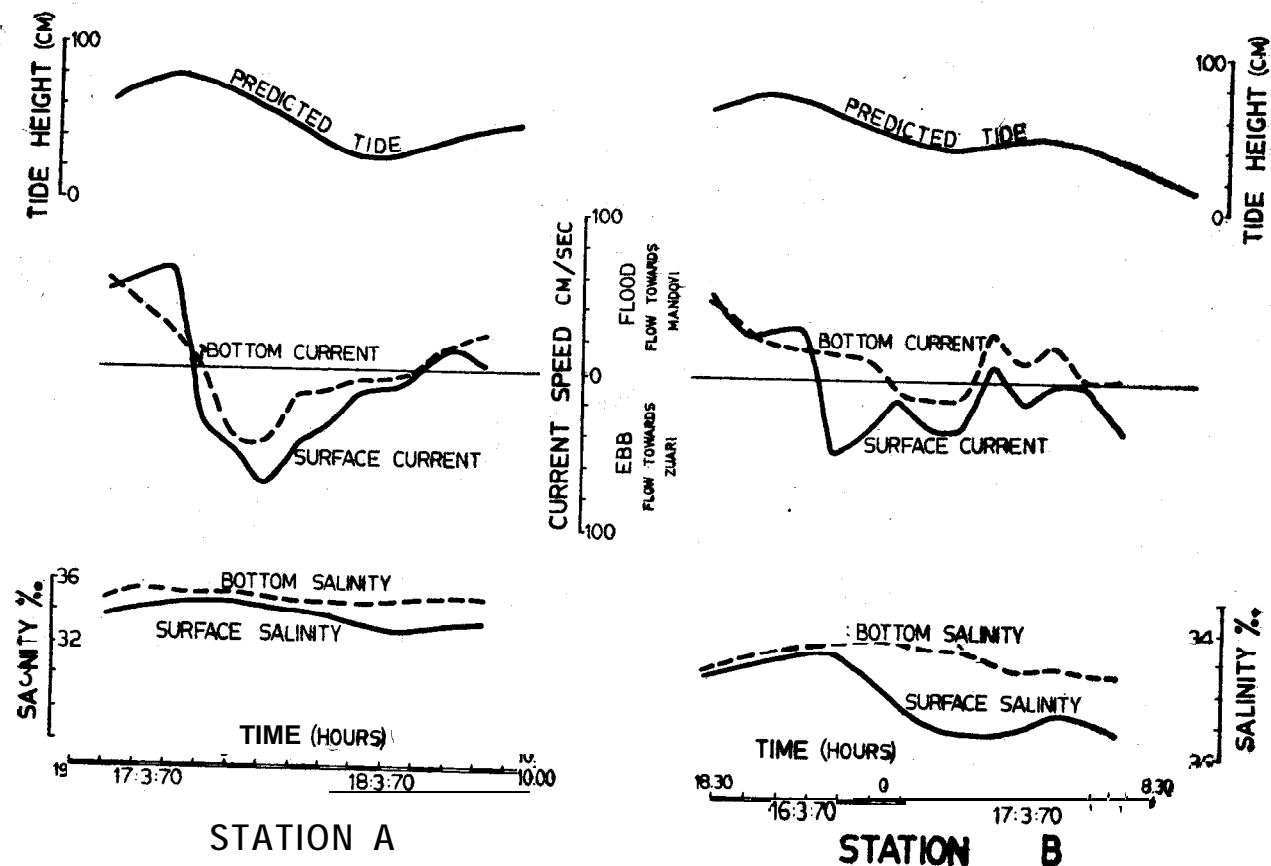


Fig. 4—Variation of current and salinity with tide at Stations A and B during March 1970

to that at Station B. Further, in the case of Station A, ebb velocities are higher than flood velocities. The observations at Station A, for November 1969 and 1970 show in general a negative shear in the flood current (higher current near the bottom than near the surface) and positive shear during the ebb. This may be explained by the fact that the flood current is opposed by the freshwater discharge particularly at the surface giving rise to a weaker surface flow. During the ebb, the surface flow is aided by the freshwater discharge. The presence of mud flats near Station A is also partly responsible for the occurrence of higher velocities near the bottom than near the surface, since the effective cross-sectional area increases considerably during the rising tide.

Station B consistently shows a flow towards the Mandovi during rising tide and towards the Zuari during the falling tide. This may look paradoxical because the station being nearer the Mandovi river should normally be controlled by the tide conditions near the Mandovi. The influence of the river Zuari seems to be considerable even on the Mandovi side of the Combarjua because of large influx of water. The currents at this station are due to the combined influence and the relative magnitudes of tides in the Zuari and the Mandovi and any fresh water discharge from the upstream side of the Mandovi river system. The complicated nature of currents at this place during March 1970, by way of opposing flows at the near surface and bottom, during certain phases of the tide (Fig. 4, Station B) is possibly due to the interaction of the tidal

energies received from the Mandovi and the Zuari sides and also due to lower tidal range during the period of observation.

The tidal energies reaching Stations B and A through the Mandovi and the Zuari respectively should normally be proportional to the sea-side widths of the estuary openings which are in the ratio of 2.1 : 3.5 (Mandovi: Zuari). The Mandovi, however, forks out further upstream in almost 1:1 ratio. Hence, the energy reaching from the Mandovi side would be reduced to half its value. Thus the ratio of the tidal energies arriving at Station B through A from the Zuari side and from the Mandovi side directly would, therefore, be 3.5:1.05 or expressed as percentages the energies available at B from the Zuari and the Mandovi side should be 77% and 23% assuming ideal conditions (i.e. no reduction of energies due to friction and other effects).

The excess flood flow (towards Mandovi) found at station B (Figs. 3 and 5) can be accounted for by the freshwater discharge from the Mandovi river system into the canal through the two intermediate canals near Station B (Fig. 1). The velocity curve for Station B shows an interesting double peak during the rising tide which must be due to the relative increase or decrease of the net tidal force as a result of the tidal energies supplied through the Zuari and the Mandovi.

Table 1 shows the maximum flood and ebb currents at Stations A and B. The magnitude of current velocities is more at Station A compared to that at Station B. While at Station A, the maximum velocities precede the corresponding observed high

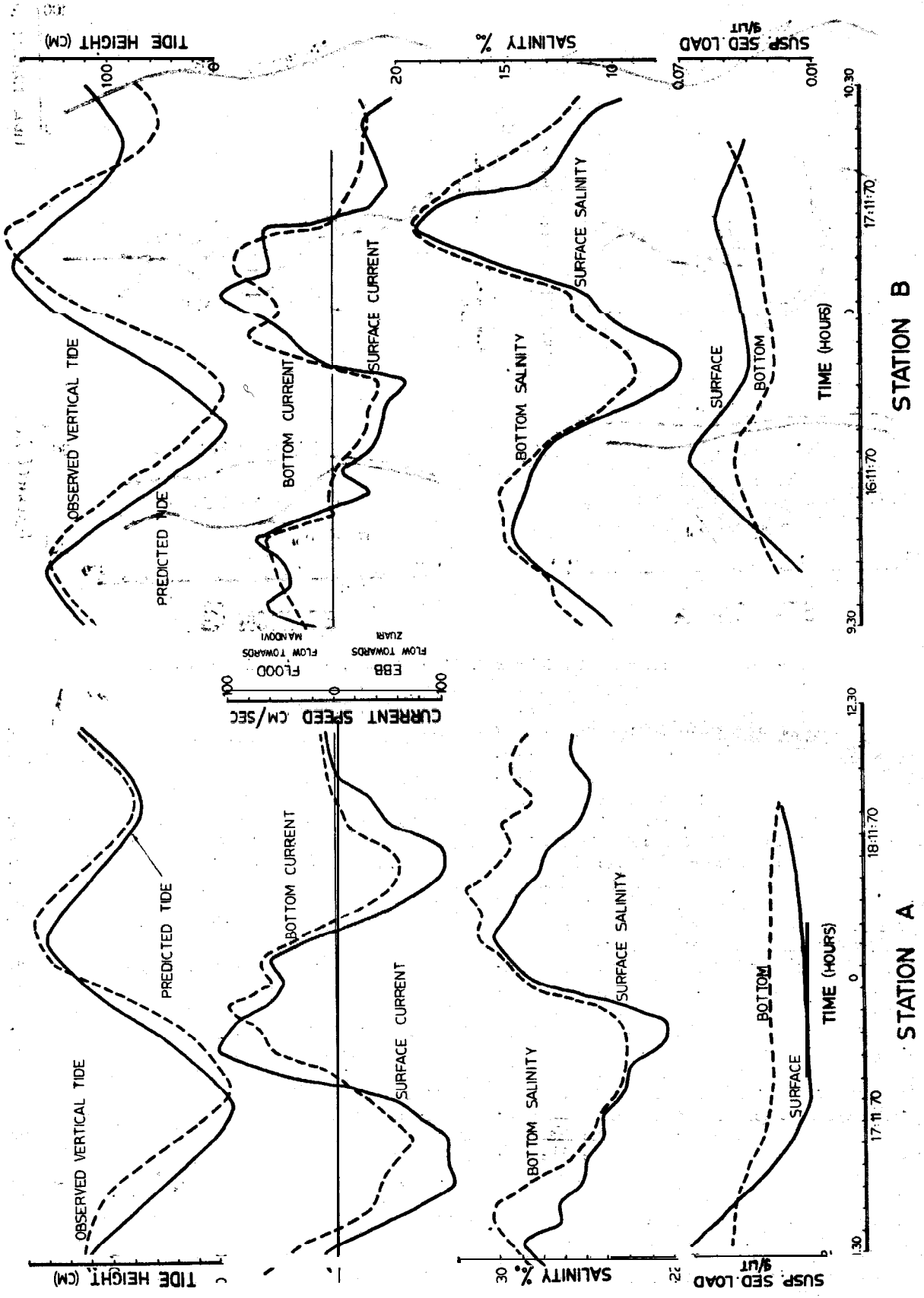


Fig. 5 — Variation of current, salinity and suspended sediment load with tide at Stations A and B during November 1970

and low waters by about 3 hr with a fair degree of regularity (Figs. 3-5), no such regularity is found at Station B. As already explained, the irregularities in the currents at Station B are due to the combined action of the tidal energies from the Mandovi and the Zuari.

Fig. 7 gives the relationship between tidal range and the mean maximum-current velocity for Stations A and B. The velocities show large dependency on the tidal range, higher velocities being associated with higher tidal ranges. At Station A, for the same tide range, the ebb velocity is found to be more than the flood velocity. This is probably due to the fact that the station has been fixed on the eastern side of the deeper channel while on the western side there is a mud flat which gets flooded during the rising tide. A similar case of such differential ebb and flood velocities in the presence of tidal flats was reported by Postma<sup>3</sup>. Unlike the conditions found at Station A, the tidal range plays a complex role at Station B. When the tidal range is less than 0.5 m, the ebb (flow towards the Zuari) dominates the flood flow while the reverse is the case when the tide range exceeds 0.5 m (flood more than ebb).

Under normal circumstances, it would be expected that the narrowness of the Combarjua canal at Station B would give rise to higher current velocities compared to those at Station A which has a much larger cross-sectional area (area at A: area at B, 12:2.5). Observations reveal exactly an opposite situation. More striking is the fact that during the rising tide, the current at this station flows towards the Mandovi and during the falling tide it flows towards the Zuari. Obviously the tidal energy ratio, as already discussed above, available at Station B from the Zuari and the Mandovi sides (77% and 23%) play a vital role here where the tidal currents are due to the resultant of the two opposing forces.

**Salinity** — The variations in salinity at the Stations A and B bear a good relationship with the stages of the tide. The maximum and minimum values observed during flood and ebb have been shown in Table 1. The salinity values for Station A are higher than those for Station B during the different stages of the tide indicating that Station B is more influenced by the fresh water locked up in the

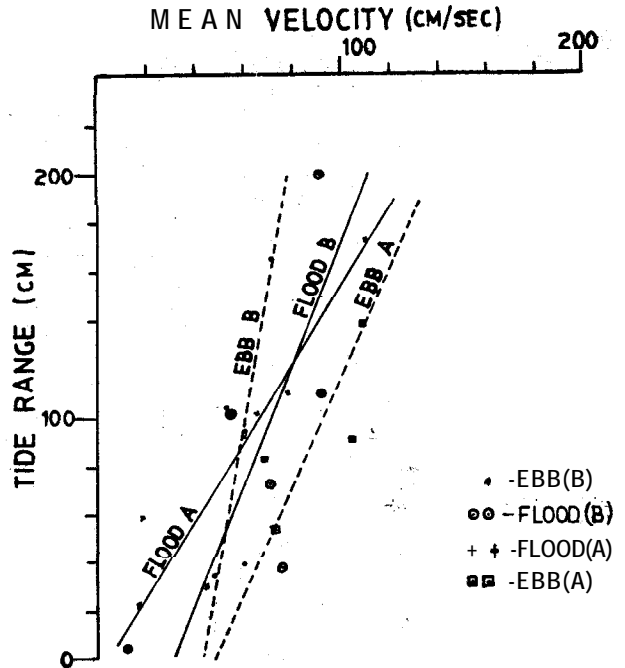


Fig. 7 - Lines of best fit between the range of tide and the average of the maximum currents near the surface and near the bottom

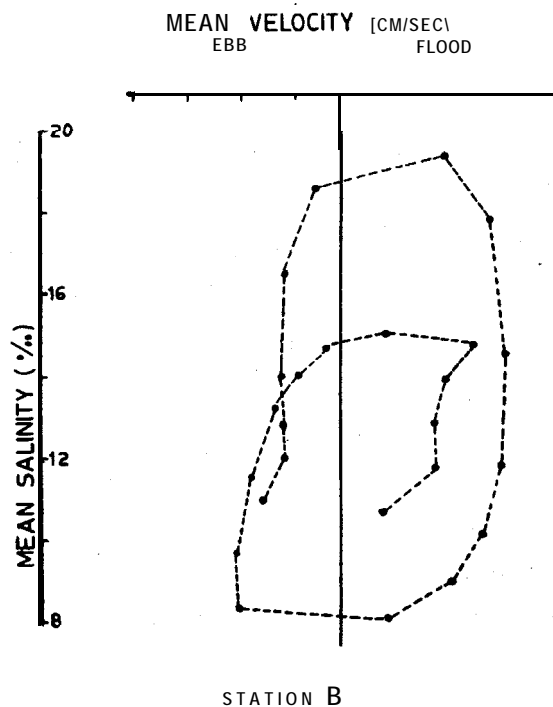
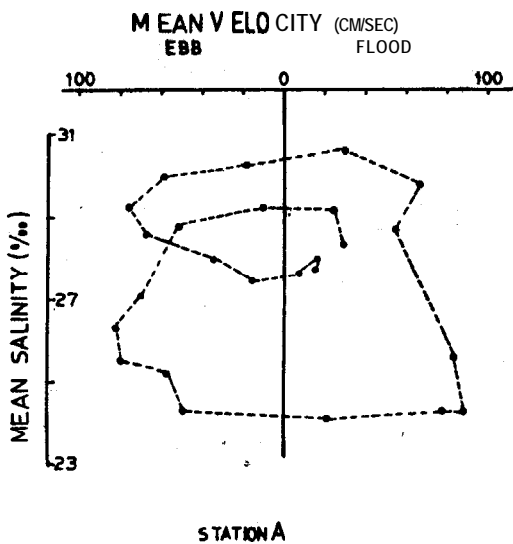


Fig. 6 — velocity-salinity diagram for Stations A and B for November 1970

upper reaches of the Mandovi river system. The premonsoon conditions show a lower salinity gradient from Station A to Station B, being of the order of about  $3.7^{\circ}/_{\infty}$  while the postmonsoon gradient is much higher (about  $13.7^{\circ}/_{\infty}$ ). The approximate average increases in salinity from postmonsoon to premonsoon at the Zuari and the Mandovi sides of the canal are  $7.4$  and  $17.4^{\circ}/_{\infty}$  respectively. The general hydrographic features of the estuarine systems are variable and some fluctuations in salinity may occur associated with the fluctuations in the freshwater discharges<sup>4</sup>.

Qualitatively, the average salinities observed at Stations A and B, during the postmonsoon and premonsoon seasons clearly demarcate the two estuaries of the Zuari and the Mandovi in the following way: The Zuari estuary has always a higher average salinity compared to that of the Mandovi which has a larger proportion of freshwater during the postmonsoon period, but, which, none the less, shows a rapid rate of increase in salinity from post to premonsoon period — the increase being  $7.4$  and  $17.4^{\circ}/_{\infty}$  for the Zuari and the Mandovi respectively from November to March. The evolution of the Mandovi estuary from a stratified one during the monsoon period to a completely mixed type during the premonsoon period was discussed<sup>2</sup>. In November (Fig. 6), there is a net salinity influx from Station B towards the Mandovi. This would be justified in view of the high salinity gradients from Stations A and B. Comparing the cross-sectional areas at Stations A and B, which are in the ratio  $4.8 : 1$ , it is obvious that an insignificant net flux of salinity at A would be magnified about  $4.8$  times at Station B.

**Suspended sediment load** — The suspended sediment loads determined for the different stages of the tide (high, low and slack periods) for the observations made during November 1970 are shown in Fig. 5. The sediment loads vary from  $0.02$  to  $0.08$  g/litre at Station A and  $0.015$  to  $0.07$  g/litre at Station B. The values give a fair estimate of the sus-

pended sediment loads for the postmonsoon period but they do not show much dependence on the speeds of the tidal currents. There was very little sand fraction in the sediment, most of it being fine clay. The absence of sand fraction in these suspended sediments may be responsible for the lack of correlation of sediment loads with the stages of the tide and the tidal currents. For Station A, the sediment load for the surface waters is, in general, lower than the load for the waters near the bottom. The reverse is the case for Station B. The sediment load of the surface waters for Station B is slightly higher than those of Station A. The salinities are generally lower than  $20^{\circ}/_{\infty}$  at all stages of the tide (Fig. 5) for Station B, while they are more than  $22^{\circ}/_{\infty}$  at Station A, indicating that the surface waters which are less saline have a greater chance of carrying more sediment in suspension than at Station A where the higher salinities of the waters may lead to some flocculation and lower sediment loads for the surface waters.

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### References

1. DEHADRAI, P. V., *Proc. Indian Acad. Sci.*, **72B** (1970), 56.
2. MURTY, C. S. & DAS, P. K., *Indian J. mar. Sci.*, **1** (1972), 148.
3. POSTMA, H., *Neth. J. Sea Res.*, **2** (1965), 566.
4. BOWDEN, K. F., in *Estuaries*, edited by G. H. Lauff (Publ. No. 83, American Association for the Advancement of Science, Washington), 1967, 15.