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Variations in Physical Characteristics of the Waters of Zuari Estuary

THOMAS CHERIAN, L. V. GANGADHARA RAO & K. K. VARMA
National Institute of Oceanography, Dona Paula, Caranzalem 403301

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Based on data collected over tidal cycles at 3 selected stations in Zuari estuary, seasonal changes and temporal variations in hydrographic conditions were studied in relation to tidal currents. In general, temporal variations in different hydrographic parameters were minimum during summer and maximum during monsoon. Water temperature, in general, attained higher values (>30°C) in summer and monsoon and lower values (<27°C) in winter. Maximum range of salinity over a tidal cycle (about 16°/₀₀) was observed during monsoon in middle and upstream regions of the estuary, the minimum range being in the mouth during summer (34·8 to 35·2°/₀₀). Salinity structure indicated the transformation of the estuary from a mixed one during summer to a stratified one during monsoon. Compared to that at the mouth, the suspended sediment load was generally high in middle and upstream regions of the estuary, where the maximum values encountered were of the order of 200 mg/litre in the monsoon. Tidal currents were, in general, stronger in middle and upstream regions than at the mouth. During monsoon, the predominance of ebb flow bearing high sediment load, the probable flocculation due to large salinity variation in the downstream part and the reduction of current speed due to widening of the estuary appear to contribute to higher rate of siltation in the harbour area.

RIVER Zuari debouches into the Mormugao Bay, which joins the Arabian Sea near the Mormugao Harbour. Zuari estuary is narrow and has a meandering course in the upstream region. It widens considerably near the mouth and has a free access with the open sea throughout the year. Tides of mixed semidiurnal type with a maximum range of about 2·3 m are encountered in this estuary causing the exchange of appreciable amount of salt water into the system from the adjacent sea, the rate of which varies considerably with seasons. The freshwater discharge into this estuary during the monsoon season is considerably high. During the winter and summer seasons, the estuary is primarily tide dominated due to meagre or negligible runoff.

Mormugao Harbour is situated on the southern side of the Mormugao Bay. There is a dredged navigation channel at the mouth of the bay to facilitate the entry of ships into the harbour. Zuari estuary is open throughout the year for the traffic of barges carrying iron ore to the harbour from a number of mines located in the hinterland. At about 11 km from the mouth of the estuary, Cumbarjua canal, which connects this estuary with Mandovi estuary, is located. In view of the navigational importance of the estuary and the problems connected with the high rate of siltation in the harbour area, a comprehensive study on the physical characteristics of this estuary has been taken up. The present work is an attempt to elucidate the spatial and temporal variations of the hydrographical conditions, including currents and suspended sediment load in this estuary during summer, monsoon and winter seasons.

No previous account has appeared regarding the variations over tidal cycle of different hydrographic parameters and currents at the mouth, middle and upstream regions of this estuarine system for different seasons. Observations on certain environmental features including temperature, salinity, turbidity and light penetration from a jetty at the Dona Paula point near the mouth of the estuary[1], some studies on the variations of current and salinity with the tides under postmonsoon and premonsoon conditions at a station near the middle region of the estuary[2], and observations on the diurnal variations of temperature and salinity during different seasons in the middle of the estuary[3] are perhaps the only previous works concerning the physical characteristics of the waters in this estuary.

Materials and Methods

In the present work, 3 stations, viz. stations 1, 2 and 3 located in the mouth, middle and upstream regions of the estuary respectively (Fig. 1), were selected for observations. Stations 2 and 3 were situated at about 10·5 and 24 km from the mouth respectively. Average depths at stations 1, 2 and 3 were 8·5, 7 and 11·5 m respectively.

Observations were made in April 1972, September 1972 and January 1973 to study the hydrographic conditions prevailing in summer, monsoon and winter seasons. Data were collected from the stations once in each season. As far as possible the stations were occupied simultaneously (the same day) during each season. In cases where this could not be done, the observations were carried out on successive days during which the tidal conditions were more or less similar. In general, days with high tidal ranges were chosen for observation. Data from station 1 could not be collected in monsoon because of rough sea and ban on anchoring in this region. Station 2

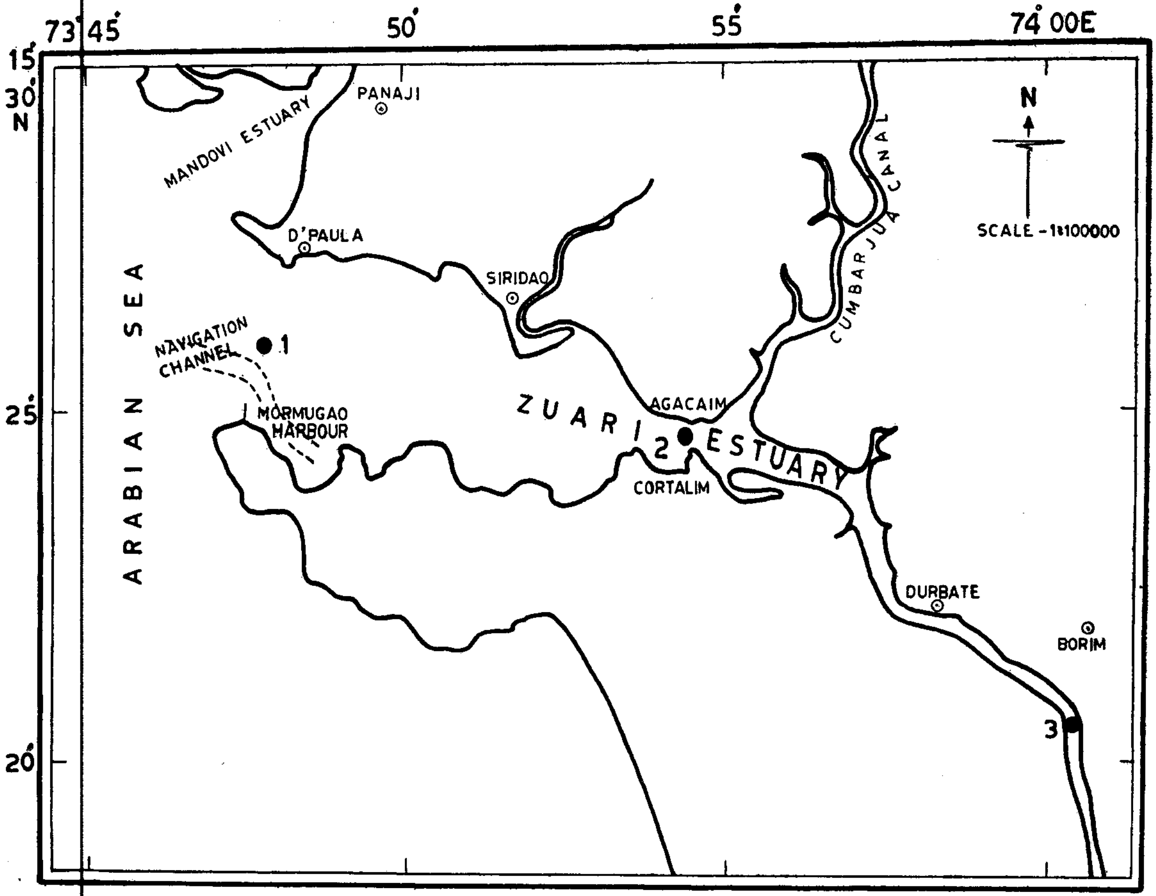

Fig. 1 — Location of stations

was occupied in all the seasons while station 3 could be covered in monsoon and winter periods only. Tide gauge data for Mormugao Harbour were made use of while comparing the variation of the parameters with tides. For the upstream region, the tide pole data, wherever available, was used.

Hourly observations over tidal cycles were carried out at stations 1, 2 and 3. Surface (1·0 m below the surface) and bottom (1·0 m above the bottom) currents were measured using an Ekman current meter. Surface temperature was recorded using a bucket thermometer and subsurface temperatures measured employing reversing thermometers. Water samples were collected from 3 depths, viz. the surface, the mid depth of the water column at the time of observation and about ½ m above the bottom to represent waters in surface, middle and bottom layers respectively. Salinity of the water samples was determined by the titration method and suspended load was estimated using the standard filtration technique.

Results and Discussion

Summer — Variations of different hydrographic parameters are shown in Fig. 2.

Waters at the mouth of the estuary showed a temperature variation between 29·2° and 30·0°C. Temperature structure indicated a slight decrease with depth and the temporal variations were not significant. In the mid-estuary, water temperature varied between 30·0° and 31·2°C. In this region, thermal variations reflected the effect of both insolation and tide. In general, waters in the middle estuary were warmer than those at the mouth of the estuary.

The range of salinity at the mouth of the estuary was slightly less (34·8 to 35·2‰) compared to that in the mid-estuary (34·1 to 35·2‰). In general, salinity structure showed a slight depthwise increase in the mid-estuary and a thoroughly mixed condition at the mouth. In the middle estuary a drop in salinity was observed at all layers about 3 hr after peak flood current.

An interesting feature observed was a decrease in the amount of suspended sediment load from the middle region (9-90 mg/litre) to the mouth (5-45 mg/litre) of the estuary. This is in agreement with the earlier work in this region regarding spatial[4] distribution of various hydrographic parameters. In general, the suspended load increased with depth and also with current speed. In the mid reaches of the estuary, the depthwise increase in suspended load was well marked and it exhibited a semitidal fluctuation. Maximum sediment load was encountered in the bottom waters during peak flood, when the bottom currents attained maximum speed.

At the mouth of the estuary, maximum speed of the current was observed during flood (55 cm/sec) while the maximum speed observed during ebb was only about 20 cm/sec. One remarkable feature was that bottom current was stronger during flood while surface current was faster during ebb. Flood started

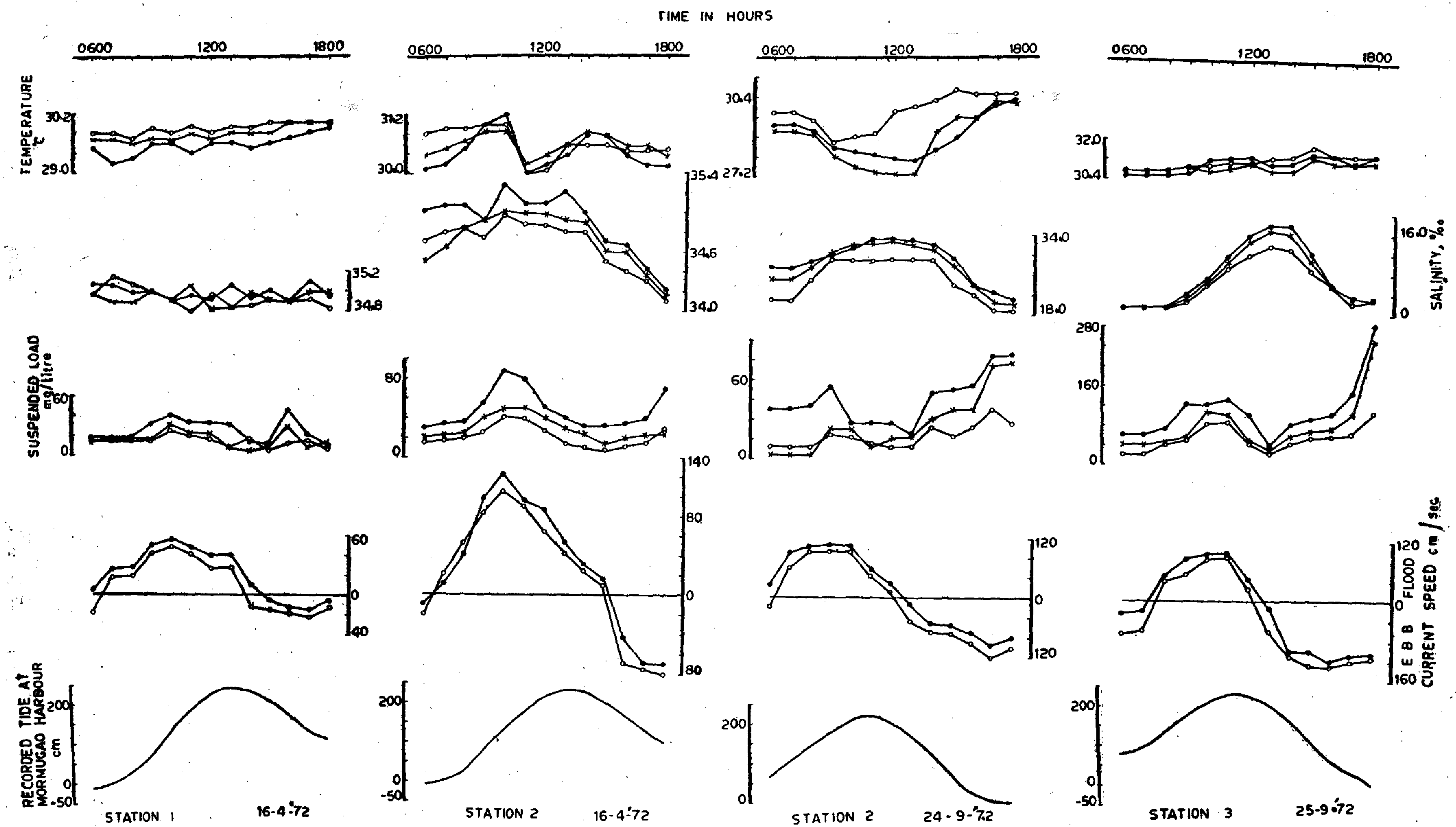

Fig2

Fig3

Figs. 2 and 3 — Temporal variation of temperature, salinity suspended load and current velocity during summer (2) at the mouth (station 1) and the middle (station 2) regions and during monsoon (3) at the middle (station 2) and the upstream (station 3) regions of the estuary and tide at Mormugao Harbour [○—○, surface; ×—×, middle; ●—●, bottom] first at the bottom waters while ebb commenced first at surface. In the mid region of the, estuary current speeds were comparatively high, maximum values associated with the flood and ebb being of the order of 120 and 80 cm/sec respectively. There was no time lag from surface to bottom in the commencement of ebb or flood currents. During this season generally the flood current was faster than the ebb current. This feature can be related to the dominance of tide resulting from negligible runoff in this season. Similar features were observed in Mandovi estuary also during the same season[5].

In general, during premonsoon season variations in all the parameters were found to be more in the middle region of estuary than at the mouth.

Monsoon — Monsoon influences various hydrographic parameters considerably as large amount of fresh water is added to the system. Fig. 3 shows the variations in the parameters at the middle and head of the estuary respectively.

Temperature varied between 27·3° and 30·7°C in the middle region and 30·4° and 31·5°C in the upstream region of the estuary. In the mid-estuary during flood surface and bottom water were generally warmer than waters at mid depth. Temperature variation in this region clearly indicated the influence of tide. Such tide-controlled changes in temperature during the same season were observed in Mandovi estuary[5] also. The comparatively large vertical temperature gradient associated with the outgoing tide could be attributed to the 2-layer flow, characteristic of the season. In the upstream region, temperature variation showed a combined effect of tide and insolation, and generally in the middle layer, temperatures were slightly low compared to those in the surface and bottom layers.

Drastic changes in salinity structure were observed with the onset of monsoon. Salinity variation over tidal cycle was considerably high during this season compared to winter and summer seasons. Salinity of waters varied from 19·0 to 33·5‰ in the middle and from 2 to 18‰ in the upstream regions of the estuary. One general feature observed both in the middle and upstream regions of the estuary was the depthwise increase in salinity. In the mid-estuary, vertical salinity gradient was large suggesting a stratified condition. Comparatively low salinity waters at the surface and nearly isohaline waters in subsurface layers during flood indicated that the salt wedge moving upstream did not reach the surface in this region. In the upstream region of the estuary, very low salinity (<4‰) waters observed in all layers during ebb and relatively high vertical salinity gradient noticed during high slack were indicative of the up and down movement of the salt wedge.

Maximum amount of suspended sediments encountered in this estuary was during monsoon season. This agrees with the finding that most intense period of suspended sediment transport in estuaries occurs during times of high river discharge[6-8]. Suspended load ranged from 6·5 to 214 mg/litre in the middle region of the estuary while in the upstream region it varied between 20 and 280 mg/litre. In general, the suspended load was found to increase with depth. Semitidal fluctuation in the suspended sediment load was well marked in the middle and upstream regiosn of the estuary. Another significant feature was that the waters contained more suspended sediments during the falling tide.

In the middle estuary, maximum speeds of surface and bottom currents were about 90 and 100 cm/sec respectively during flood, while during ebb maximum speeds of about 120 and 95 cm/sec were encountered in the surface and bottom layers respectively. In the upstream region, maximum speeds attained by surface and bottom currents during flood were 90 and 95 cm/sec respectively, whereas during ebb they were comparatively high, values being of the order of 130 and 125 cm/sec respectively in the surface and bottom layers. A conspicuous feature was that in the upstream and middle regions of the estuary, the ebb predominated during this season with the ebb currents attaining higher speeds than the corresponding flood currents and flowing for longer periods. This was due to the effect of considerable runoff during this season. Another interesting feature was that during high slack surface currents reversed first, whereas during low slack bottom currents changed direction prior to to the surface currents.

Winter — Variation in different parameters during this season are shown in Fig. 4.

Temperature varied from 26·6° to 27·8°C at the mouth, 26·7° to 28·1°C in the middle and 27·2° to 28·4°C in the upstream regions of the estuary. At the mouth, surface waters were generally warmer than the subsurface waters and showed a diurnal variation. Minimum temperatures were encountered with the waters at mid depth. However, temperatures of middle and bottom waters did not show any significant variation. In the middle estuary, temperature structure indicated combined effect of insolation and tide at all levels. In the upstream region, temperatue variation exhibited the influence of diurnal heating and tide. The depthwise decrease in temperature was well marked in this region.

Salinity range at the mouth of the estuary was low (34·8-35·5‰) compared to those in the middle (29·7-34·3‰) and in the upstream (19·5-27·0‰) regions of the estuary. In the mouth and middle regions of the estuary salinity did not show any significant depthwise variation, whereas in the upstream region the depthwise increase in salinity was well marked. Increase in salinity variation over tidal cycle in the upstream direction was significant.

Suspended sediment load was low (between 4 and 50 mg/litre) at the mouth, high in the middle (between 8 and 168 mg/litre) and in the upstream (between 20 and 120 mg/litre) regions of the estuary. In the middle and upstream regions higher values of sediment load were found in association with strong currents. Larger fluctuation in values of sediment load in the middle region of the estuary might be the result of resuspension of bottom sediment by tidal scour as the estuary is relatively shallow in this region. This is analogous to the observations by Schubel[9] in shallow regions of northern Chesapeake Bay. Depthwise increase in suspended load was well marked in the middle and in the upstream regions of the estuary.

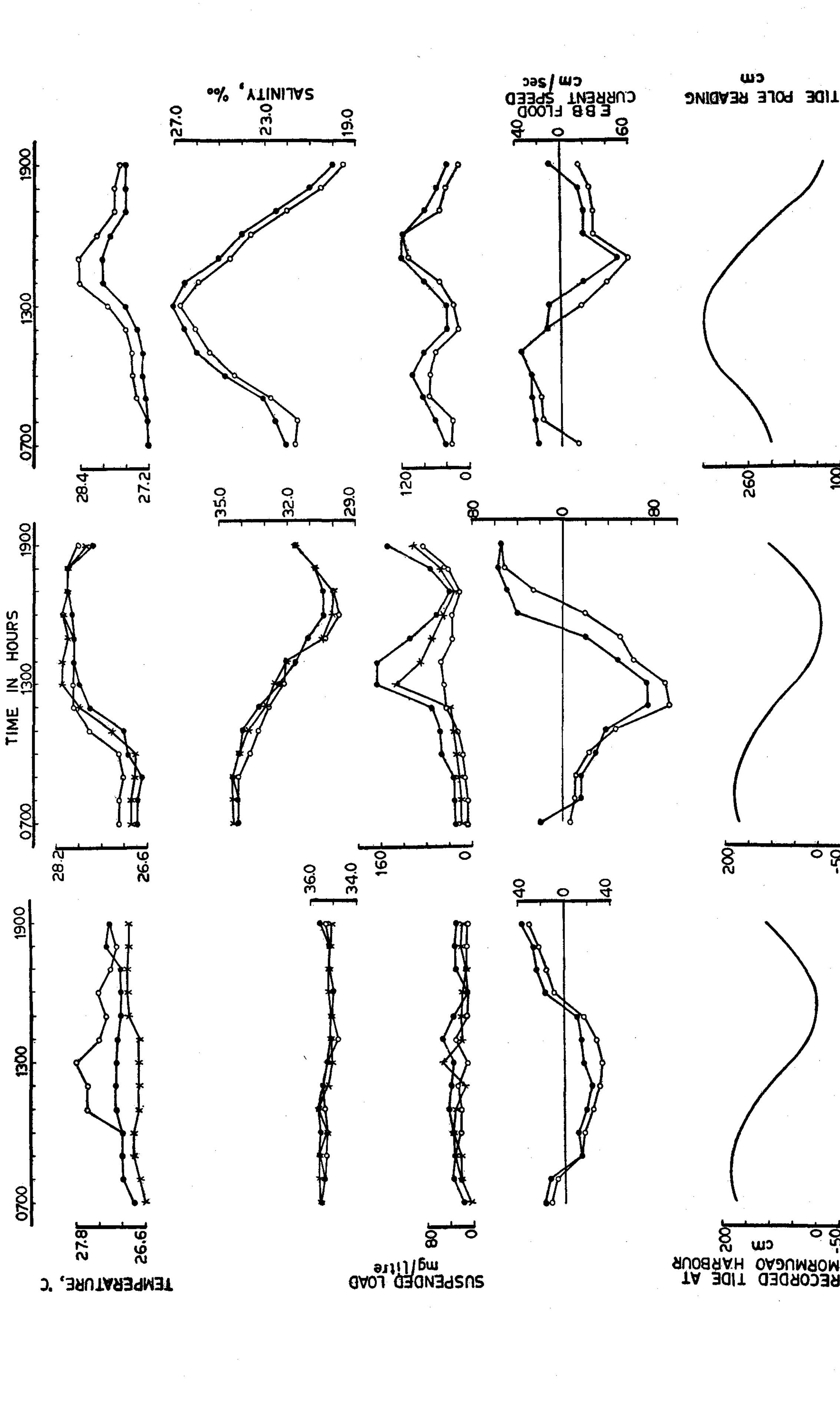

Fig. 4 — Temporal variation of temperature, salinity, suspended load and current velocity at the mouth (station 1), the middle (station 2) and the upstream (station 3) regions of the estuary and tide at Mormugao Harbour and upstream region during winter [○—○, surface; ×—×, middle; ●—●, bottom]

During ebb, surface and bottom currents attained maximum speeds of about 30 and 25 cm/sec at the mouth, about 95 and 75 cm/sec in the mid-estuary and 60 and 50 cm/sec in the upstream region of the estuary respectively. At the mouth, both ebb and flood were found to start at more or less the same time in the surface and bottom layers. In the middle region of the estuary, though there was not much lag from surface to bottom for the commencement of ebb, a lag of about 1 hr was observed from bottom to surface for the commencement of flood. In the upstream region during low slack, bottom currents reversed before surface currents, while during high slack the reversal took place first in surface waters. In general, at the mouth and mid-estuary bottom currents were stronger during flood while surface currents were faster during ebb.

Variation in salinity along the longitudinal axis of the estuary and also the vertical variation in salinity at different regions of the estuary were maximum during monsoon. Vertical salinity structure during monsoon indicated stratification caused by freshet. Minimum vertical variation in salinity (about 0·4‰) encountered in summer showed appreciable mixing. Reduction in fresh water supply changed the estuary from a stratified one to a partially mixed or a well mixed type[10].

Commencement of tidal currents in different regions of the estuary — As the observations were carried out either on the same day or on successive days when the tidal ranges were similar, an attempt has been made to study the differences in the commencement of ebb/flood current in different regions of the estuary in relation to the recorded tide near the mouth.

In summer, no appreciable time lag was observed between the occurrence of low water and the commencement of flood current and between the occurrence of high water and the starting of ebb current at the mouth of the estuary. In the middle region of estuary the ebb exhibited a lag of about 1 hr from the mouth while the flood started almost simultaneously at the mouth and mid reaches of the estuary.

During monsoon, in the middle region of the estuary ebb started about 1 hr after the occurrence of high water at the mouth of the estuary. In the upper reaches of the estuary, ebb current and flood current exhibited a lag of about 1 and 1½ hr from the occurrence of high water and low water respectively at the mouth of the estuary.

In winter, at the mouth of the estuary ebb and flood currents commenced at about the times of high water and low water respectively. At the mouth and middle regions of the estuary, the flood started about the same time, while ebb commenced about 1 hr earlier in the middle region. On comparing the tide pole data for station 3 with the recorded tide at Mormugao Harbour for the same day it was found that the low water and high water occurred in the upstream region about 1 hr after their occurrence at the mouth. Further, ebb current and flood current started about the same time as high water and low water respectively in this region.

The following features can be inferred from the preceding discussion:

In the Zuari estuary, temperature in general increased from the mouth towards the upstream in all the seasons. Higher values of temperature (> 30°C) were encountered in the summer and monsoon periods and lower values (< 27°C) in the winter season.

An analysis of salinity structure in different seasons revealed that the estuary was well mixed during summer and stratified during the monsoon.

In general, waters in the upstream and middle regions have more sediment load compared to those at the mouth. Maximum values of suspended sediment load (> 200 mg/litre) were encountered during the monsoon season.

Tidal currents attained higher speeds (> 100 cm/sec) in the middle and upstream regions of the estuary compared to those at the mouth. During monsoon period, dominance of ebb currents (with higher speeds and longer duration) over flood currents was noticed in the middle and upstream regions.

Higher values of sediment load were observed in the waters of middle and upstream regions of the estuary. Reduction in current speed during ebb in the downstream part due to widening of the estuary facilitated settling of suspended sediments in the harbour bay. This conclusion is substantiated by the relatively low values in sediment load observed in the waters near the mouth of the estuary.

During monsoon season, the time lag between high water at the mouth and commencement of ebb in the middle and upstream regions was less (about 1) compared to that between low water at the mouth and commencement of flood (about 1½ hr) in the upstream region of the estuary.

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