

Environmental Characteristics of the Mandovi-Zuari Estuarine System in Goa

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Two rivers, the Mandovi and the Zuari, with their interconnecting canal, form an estuarine system in Goa on the west coast of India. Physical, chemical and biological features of this estuary are adapted to a seasonal rhythm induced by the annual cycle of the monsoon. Heavy precipitation and land runoff from June to September bring about large changes in temperature, salinity, flow pattern, dissolved oxygen and nutrients when the estuary becomes freshwater dominated. The monsoon season (July-September) is followed by a recovery period during the post-monsoon season (October-January) and thereafter a stable period of the pre-monsoon season (February-May) when the estuary becomes marine dominated. During the pre-monsoon (dry) season, the water in the estuarine system remains well mixed and the intrusion of salt water is felt as far as 65 km upstream in both the rivers; but during the monsoon season the rivers become stratified and a salt wedge is formed in each river which extends up to about 10 km upstream in the Mandovi and 12 km in the Zuari. The flow of the estuarine system is regulated by the entry of seawater with the incoming tide through Zuari which reaches Mandovi through the canal. The flow is reversed during the outgoing tide when the estuarine system is flushed. Dilution factors in both the estuaries are similar and vary from 1.2 to 8; highest values occur during the pre-monsoon season. Two shoals/sand bars occur permanently in Mandovi (Aguada Bay) close to a ramp-like inlet to the sea. This inlet poses no navigational problems for about 9 months during the dry season; but for a 3-month period during the monsoon, the waterway becomes hazardous and is closed to boat traffic. Heavy swell and intense wave activity lead to the transfer of sediments into the navigational inlet and the calm season brings the materials back to their original position with practically no overall change in the bathymetry of the bay.

The oxygen cycle in the estuarine system is closely related to seasonal changes in temperature and bears an inverse relationship with salinity. In both the estuaries, the sulphate/chlorinity relationship remains uniform and similar to that of the sea except during the monsoon months when the relationship gets disturbed. Changes in phosphorus, nitrogen and silicon are largely regulated by rainfall and land runoff. There is no significant difference in the phytoplankton counts between Mandovi and Zuari which follow a rhythm similar to that of nitrate. Zooplankton biomass is higher in Zuari because of its greater marine influence. No seasonal variation was observed in the density of microflora in the two rivers. Bacterial counts were higher in the lower reaches of the estuarine system and decreased upstream.

From its environmental features, the estuarine system can be classified as a tide-dominated coastal plain estuary.

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Introduction

Studies on the Mandovi–Zuari estuarine system began in 1970 and several interim reports on short-term observations have been published from time to time. Some of the earlier works have been reviewed recently (Qasim, 1979). However, because of the navigational difficulties associated with the bar formation near the mouth of the river Mandovi, the entire estuarine system has not been studied for a continuous period of 1 year. Nevertheless, one of the important findings emerging from the earlier studies has been that it is a tidal-stream estuarine system in which the water from surface to bottom remains well mixed for most of the year. The only period when a stratification appears in the two rivers is the monsoon period (June–September). In this season the seawater underneath the stratified layer keeps moving up and down with the tides in the form of a salt wedge up to some distance from the mouths of both the rivers.

During 1977–78 an extensive survey was undertaken in these two rivers for the preparation of a master plan for pollution control and this communication gives some of the results of this survey.

Description of the area

The Mandovi–Zuari estuarine system is located along Lat. $15^{\circ}25'$ to $15^{\circ}31'N$ and Long. $73^{\circ}45'$ to $73^{\circ}59'E$ on the west coast of India (Arabian Sea). The two rivers, Zuari and Mandovi, are influenced by the seawater inflow up to a considerable distance inland and receive large volumes of freshwater during the south-west monsoon season.

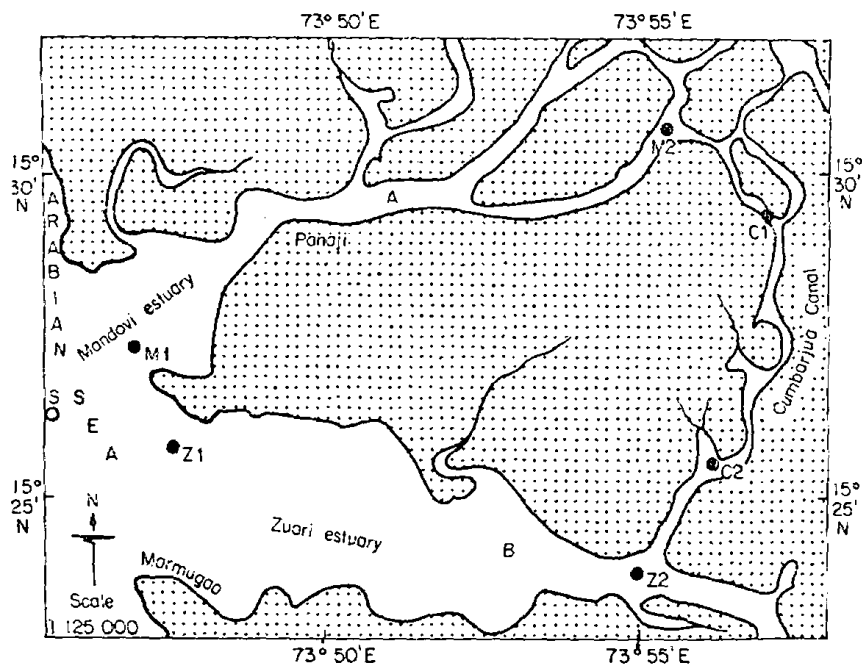


Figure 1. The Mandovi–Zuari estuarine system of Goa with its marine and main riverine connections. Solid circles indicate the main stations where seasonal measurements of environmental characteristics were made. Z1 and Z2 refer to Zuari stations while M1 and M2 are Mandovi stations and C1 and C2 are stations in Cumbharjua Canal. A and B indicate sites where current measurements were made. Station S (open circle) refers to the source stations for computation of dilution factors.

Both rivers have their sources in the Western Ghats. The Mandovi river extends about 75 km and the Zuari up to 70 km before meeting the Arabian Sea. The width at the mouth of Mandovi estuary is about 3.2 km and that of Zuari approximately 5.5 km (Figure 1). The former narrows down to less than 0.25 km and the latter to about 0.5 km upstream.

The average rainfall in Goa is 3000 mm year⁻¹, of which nearly 80% occurs in 3 months (June–August). Both the rivers are fed largely by the monsoon precipitation and receive a large amount of land runoff from the catchment areas and forest land. The catchment areas of the Mandovi and Zuari basins are 1150 and 550 km² respectively.

The two rivers are interconnected by the Cumbarjua Canal (Figure 1). This canal, from the mouths of Mandovi and Zuari estuaries, is 14 and 11 km away respectively. Thus, the two estuaries with their rivers and the Cumbarjua demarcate the island of Panaji (Panjim) (Figure 1). The canal is about 17 km in length and 0.5–0.7 km in width.

During the monsoon period (June–September), all boat traffic is suspended in Mandovi because of the occurrence of shoals/bars in this estuary. These shoals are popularly known as the Aguada bar and the Reis Magos bar; the former is located in the Aguada Bay which is a part of the Mandovi estuary and the latter is located opposite to an old Portuguese fort (Reis Magos Fort) situated on top of an adjoining hill; for details see page 567. Because of these sand bars, navigation is rendered hazardous and Panaji port is declared closed for all boat traffic from June to August.

The river Zuari and Cumbarjua Canal remain free from any such navigational problems and the mining activities, although far less intense, continue in these two waterways uninterrupted throughout the year.

Material and methods

Although during the survey many stations were worked practically throughout the year in each of the two rivers, the present communication deals largely with the results obtained at two stations in each river—one at the mouth of the estuary and the other in the upper reaches of the river. These two stations show a marked contrast in the environmental features downstream and upstream. However, wherever necessary, a reference has been made to the other stations in the two rivers. In the Mandovi estuary the two main stations have been marked as M1 and M2. In the Zuari estuary, the stations are Z1 and Z2 and in the Cumbarjua Canal, C1 and C2 (Figure 1). Since the water from surface to the bottom in both the estuaries remains fairly well mixed practically throughout the year except during the peak monsoon season, observations were made once every month at mid-depth at all the six stations. For the analysis of chemical components, sampling was done every 4 h over one tidal cycle of 12 h at all the stations once a month. The depth range, from the mean sea level or chart datum, in the Mandovi and Zuari is 3–11 m and in the Cumbarjua Canal the average depth is about 3 m.

The environmental parameters examined were temperature, salinity, flow pattern and related aspects, oxygen, sulphate, phosphate-phosphorus, nitrate-nitrogen and dissolved silicon. Biological features investigated were phytoplankton counts, zooplankton biomass and microbial load (total plate counts) in the water. Standard techniques were used for all the estimations. Salinity, sulphate and nutrients were estimated from the mixed samples of all collections over one tidal cycle. Observations on the estuarine system began in October 1977 and ended in September 1978.

Results

A. Physical features

Seasonal variability of different environmental features in the estuarine system demands an understanding of the freshwater discharge into the system which is chiefly controlled by the spectacular regime of the rainfall during the monsoon thus making the year divisible into three distinct seasons: (1) pre-monsoon (February–May), (2) monsoon (June–September), (3) post-monsoon (October–January).

(a) *Temperature.* Seasonal changes in temperature of water at mid-depth of the six stations in the estuarine system are given in Figure 2(a). At all the six stations there was a progressive

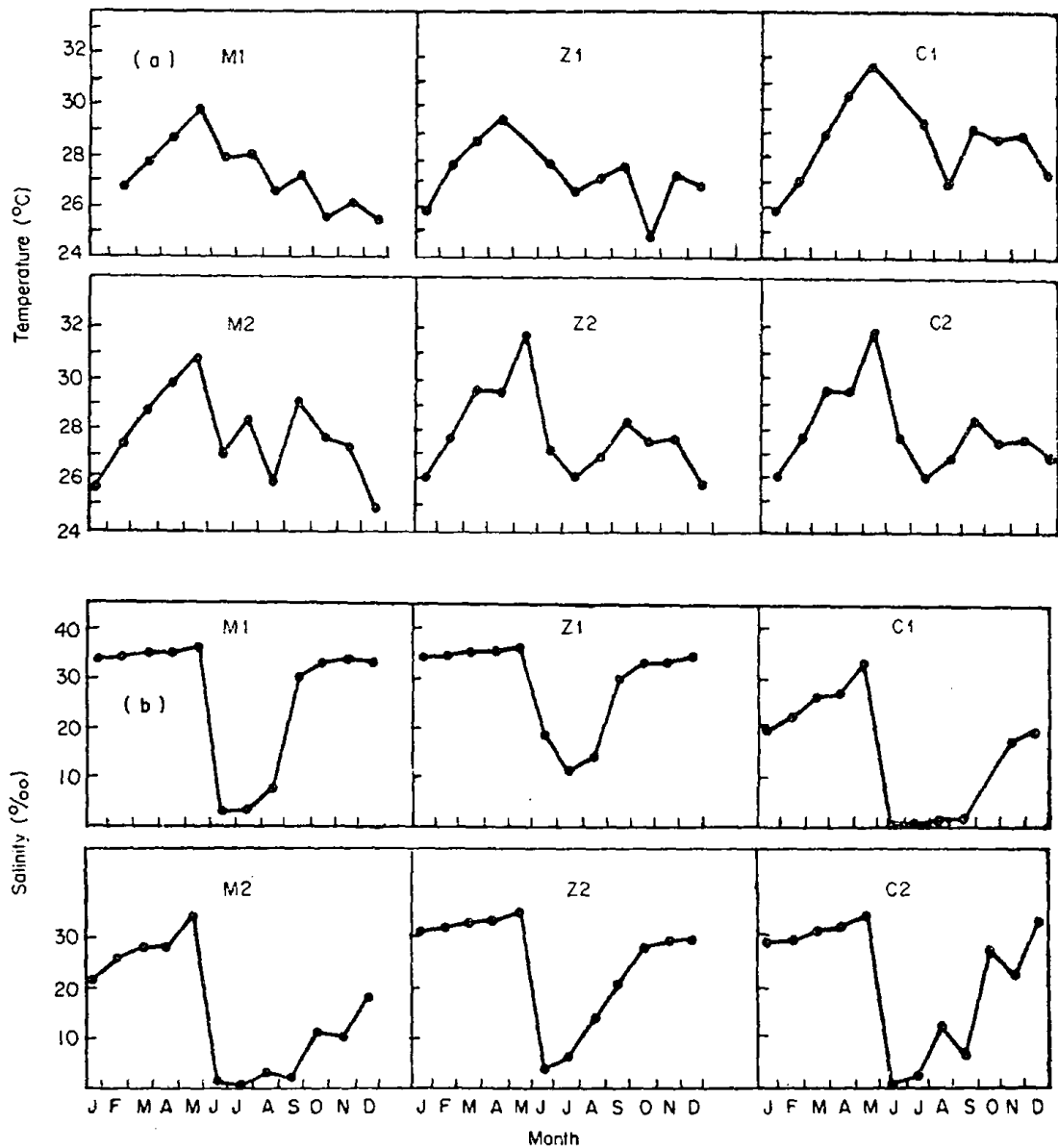


Figure 2. Seasonal variations in (a) temperature and (b) salinity at Mandovi Zuari and Cumbarjua stations.

increase in temperature from January to May followed by a decline during the peak monsoon months and again an increase thereafter at some stations. The two estuarine stations M₁ and Z₁ showed a similar seasonal variation in temperature. Similarly, the two riverine stations M₂ and Z₂ behaved somewhat alike and the case at the two stations C₁ and C₂ in Cumbarjua was almost identical. The difference in temperature from surface to bottom was about 2 °C at deeper stations, and the annual variation in temperature at all stations was from 5–6 °C [Figure 2(a)].

(b) *Salinity*. Seasonal variation in the salinity of the estuarine system was very large [Figure 2(b)]. From January to May the two estuaries simply become an extension of the sea with salinity reaching 35‰ [see Figure 2(b)—Stations M₁ and Z₁]. At the two riverine stations M₂ and Z₂, the salinity also remains fairly high from January to May. The Mandovi station (M₂) showed an increase in salinity from 29 to 34‰ during the period January to May, whereas the salinity at the Zuari station (Z₂) remained uniformly high and ranged between 31 and 35‰. From January to May the Zuari side of the estuarine system and of the Cumbarjua Canal thus has a higher salinity than that of the Mandovi portion [Figure 2(b)].

With the onset of the monsoon in June, the salinity of the entire estuarine system decreases sharply. At M₁, it falls down to 5‰ whereas at Z₁ the lowest salinity recorded in July was 10.5‰. At these two stations (M₁ and Z₁), salinity remains low for about 3 months (June–August) and from September onwards it begins to increase. In the upper reaches of the two estuaries (Stations M₂ and Z₂), a similar feature was noticed—the major difference between the two is that M₂ remains largely freshwater dominated during a greater part of the post-monsoon period (October–January) than Z₂. The lowest salinity recorded at M₂ in July was almost zero whereas at Z₂ the lowest was 6‰. The two Cumbarjua stations also behave in a similar fashion. The Mandovi end of the canal (Station C₁) has very low salinity (nearly zero) from June to September and shows no influence of seawater in these months, whereas in the Zuari end of the canal (C₂), freshwater conditions prevail only for about 3 months (June–August) and salinity begins to rise again recording high values from October onwards [Figure 2(b)].

The Mandovi estuary has a lower average salinity than that of Zuari because the Mandovi river receives considerable amount of runoff through a larger tributary system and along its course it has a number of islands, narrow bends and shallow mangrove swamps (Figure 3).

From the predicted tides at Marmugao harbour, the tidal time-lag in the Mandovi from M₁ to M₂ is approximately 75 min and in the Zuari, from Z₁ to Z₂ it is about 60 min. The average tidal range at Goa is about 2.0 m. At any given time of the year, a large horizontal salinity gradient exists from the Zuari-end to the Mandovi-end of the estuarine system (Z₂ to M₂) via the Cumbarjua Canal (C₂ and C₁). From Z₂ to M₂ via the two estuaries (Station Z₁ and M₁), the horizontal salinity gradient is small.

(c) *Flow pattern*. Measurements of the speed and direction of currents at several places in the estuarine system in different seasons showed that the maximum current speed during ebb and flood tides was in the middle region of the two estuaries (points A and B in Figure 1) and the minimum at the mouth of the two estuaries (Stations M₁ and Z₁). The average current speed was stronger during the flood tide in the pre-monsoon and post-monsoon months practically everywhere in the estuarine system whereas during the monsoon months the currents become stronger during the ebb tides as the river runoff accelerates the flow (Varma *et al.*, 1975). The current velocity in both the rivers during the flood tide is maximum and the currents are directed upstream and largely towards the left sides of the rivers. The

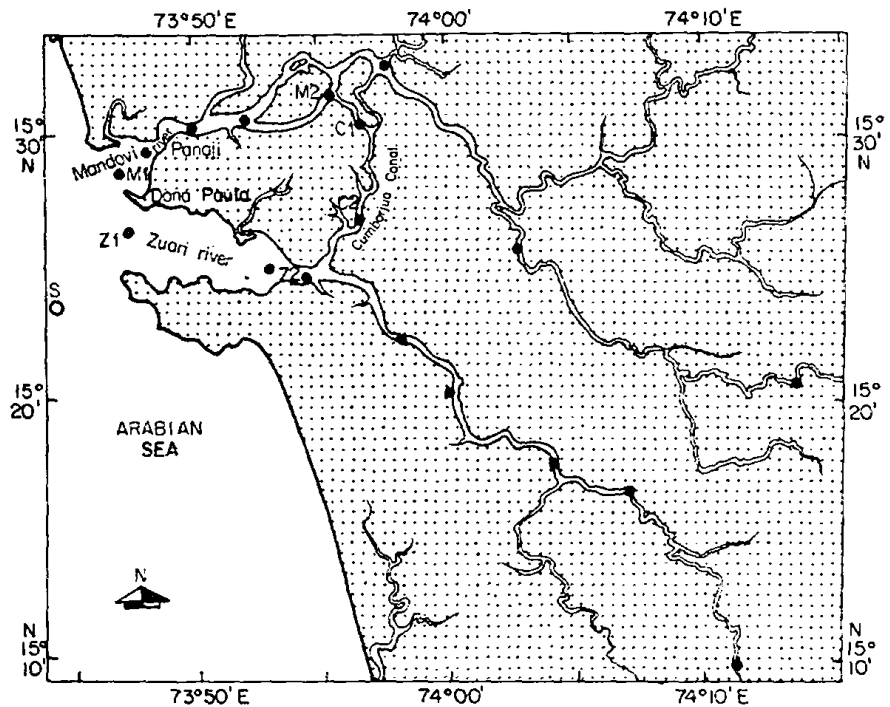


Figure 3. Map showing the Mandovi-Zuari river systems. Solid circles indicate location of stations where salinity measurements were made to study salt-water intrusion.

speed of currents varies from station to station and with the state of tides. During the ebb tide the currents are reversed. Thus, to an observer who is travelling seaward during the incoming tide, the seawater would appear to enter the two rivers along their left banks and with the outgoing tides it seems to flow into the sea along the right banks. The water in the estuaries remains well mixed when the freshwater runoff is small. However, during the monsoon season, because of the formation of two salt wedges (described in the following section), the rivers became stratified 2–3 m below the surface depending upon the depth in the estuary.

Apart from the distance up to which the salt-wedge formation in the two estuaries occurs (10 km in the Mandovi and 12 km in the Zuari) during the peak monsoon period, the rest of the estuarine system remains filled with freshwater with practically no salt-water incursion anywhere. Immediately after the monsoon, when the runoff remains still high, partial mixing of salt and freshwater occurs but some stratification continues to remain at a few places in the estuarine system (Murty & Das, 1972). In the pre-monsoon season (February–May), there is no stratification anywhere and the water remains well mixed throughout the water column, and the entire estuarine system, far beyond Cumbarjua, has tidal influence with salt water incursion.

The extent of seawater intrusion into the riverine system was studied at many more stations fixed into the riverine network and these are shown in Figure 4.

Adopting the index of seawater penetration as 1‰ salinity, it can be seen from Figure 4 that the distance varies from a maximum of about 65 km in May to a minimum of about 11 km in the Mandovi in July and 20 km in the Zuari in June. Examining the salinity gradients in Figure 4, it becomes apparent that at any given time of the year there is a much greater amount of salt water in the Zuari than in the Mandovi.

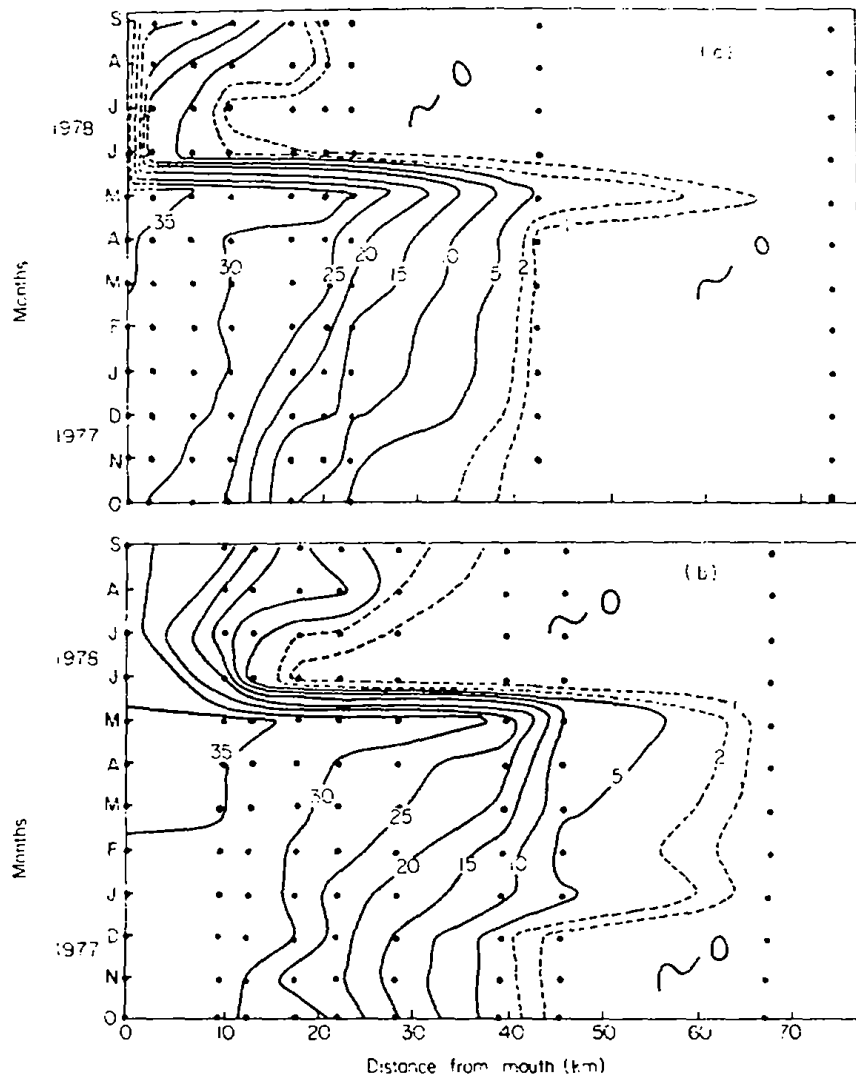


Figure 4. Diagrammatic representation showing the extent of salt-water penetration from the mouth of (a) the Mandovi river and (b) Zuari river upstream in different months of the year. Continuous isohalines give the salinity at 5‰ intervals, broken lines indicate salinities of 2 and 1‰.

The general flow pattern in Cumbarjua is regulated by the entry of seawater during the incoming tide through the Zuari side. The Mandovi flow has little influence in Cumbarjua. The Zuari water reaches the Mandovi region via the canal. However, during the outgoing tide the flow in the canal is reversed (Das *et al.*, 1972), i.e. the water rushes out through the Mandovi side first and thereafter through the Zuari side. In this way the estuarine system gets flushed. During the dry season (pre-monsoon) there is hardly any variation in the salinity either from surface or bottom or from high to low tides at the Zuari-end of Cumbarjua (C₂). The entire estuarine system becomes salt water dominated from October to May and at no place in the area, shown in Figure 1, was the salinity found to be less than 15‰ during this period [see Figure 2(b)].

(d) *Salt wedge*. A salt wedge is formed in such perennial rivers which are filled with fresh-water nearly up to their mouths during the period of heavy precipitation and runoff. For the

rest of the year, the estuarine regions of these rivers become an arm of the adjoining sea with homogenous conditions prevailing vertically. The only account of salt-wedge formation in an Indian river has been reported from the Vellar estuary on the east coast of India (Dyer & Ramamoorthy, 1969). The salt-wedge formation in this estuary occurs for a period of about 2 months during the north-east monsoon.

In Mandovi, the salt-wedge formation can be studied from a section of the estuary taken a few kilometres away from the river mouth (Station M1) during the peak monsoon month (July). This is shown in Figure 5. It is clear from the figure that while the freshwater dominates the water column, seawater, with varying salinities of 2.5 to 15‰, is found at the bottom and in the uneven pockets of the sea bed in the form of a salt wedge (Figure 5). Although no clear demarcation of the maximum distance of the salt-wedge extension into the river Mandovi could be made due to lack of observations during the monsoon months, it can be concluded from the salinity data obtained from the bottom that it extends up to about 10 km upstream.

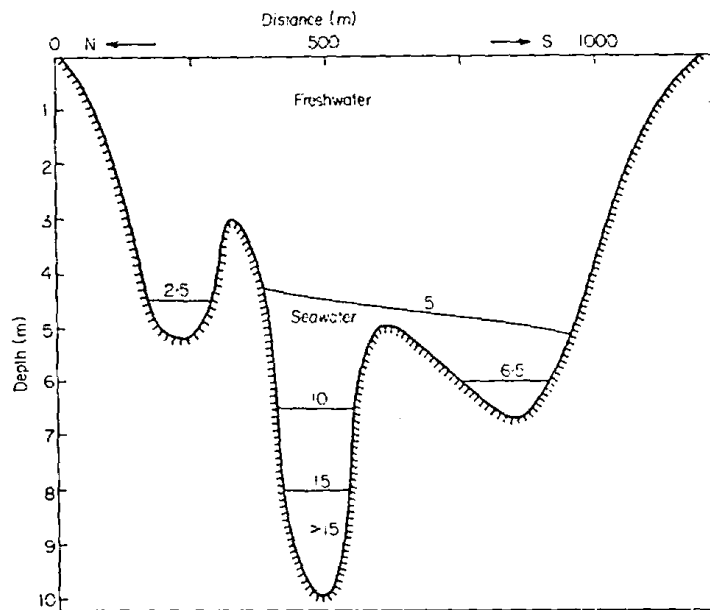


Figure 5. Diagrammatic representation showing the presence of salt wedge at the bottom in a section across the Mandovi. Values indicate salinity (‰) of water in July 1978.

In the Zuari, on the other hand, the salt-wedge formation can be studied in relation to distance more easily because there are no navigational problems in the river throughout the year. This was investigated in July from the mouth of the river (Station Z1) to a considerable distance upstream and the results are shown in Figure 6. It can be seen from the figure that the salt wedge extends up to a distance of about 12 km into the river and the water column remains clearly demarcated into distinct salinity layers with freshwater flowing seaward from the top and the salt water invading into the river from the bottom; both remaining quite distinct (Figure 6).

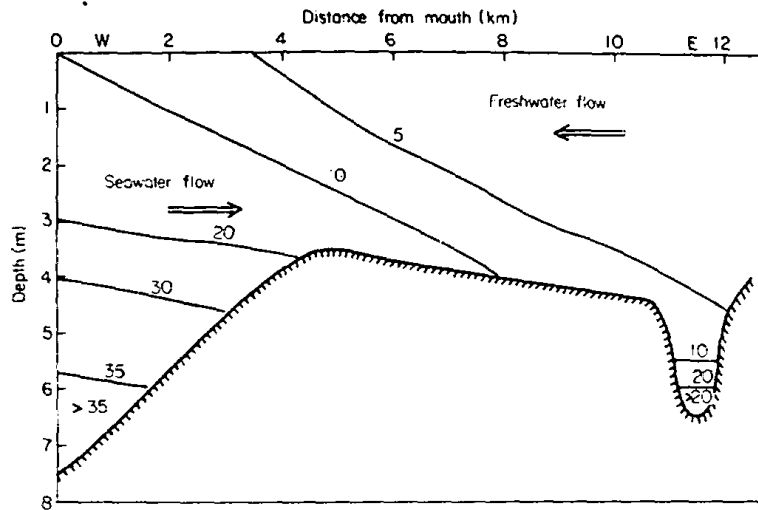


Figure 6. Diagrammatic representation of the occurrence of seawater and freshwater flow in a longitudinal section along the Zuari. Values indicate salinity (‰) of water in July 1978.

(e) *Longitudinal dispersion coefficient.* The longitudinal dispersion coefficient (K_x) can be computed from the relationship

$$K_x = \frac{RA^{-1}S}{dS/dx},$$

where R is the tidal mean downstream transport across each section (four sections were maintained in each river), A is the cross-sectional area normal to the flow, S is the salinity at the point of interest and dS is the change in salinity with distance dx .

In Zuari, K_x values ranged from 1337 to $119 \times 10^6 \text{ cm}^2 \text{ s}^{-1}$, decreasing with increasing distance from the mouth. The corresponding values in Mandovi were from 550 to $10 \times 10^6 \text{ cm}^2 \text{ s}^{-1}$. K_x values remained high up to 50 km upstream in Zuari but in Mandovi they started decreasing 20 km upstream.

The K_x values in both the rivers are several orders of magnitude higher than those recorded from the English rivers which range from $0.5\text{--}4 \times 10^6 \text{ cm}^2 \text{ s}^{-1}$ (Dyer, 1973) or from the Columbia River, U.S.A. where it was $50 \times 10^6 \text{ cm}^2 \text{ s}^{-1}$ (Hansen & Rattray, 1965). The higher values in the Zuari and the Mandovi are due to the wide variation in the downstream transport of water during the seasons.

(f) *Stability characteristics.* Stability characteristics were defined by the dimensionless Richardson's number R_i , which is expressed as

$$R_i = \frac{g \frac{\partial \rho}{\rho \partial z}}{(\partial u / \partial z)^2},$$

where g is the acceleration due to gravity, ρ is the density of seawater, u is the velocity of water layer and z is the vertical distance.

In Zuari, R_i ranged from 6 to 39 in different regions and seasons and from 0.06 to 48 in Mandovi. R_i values during the monsoon months were zero or near-zero since in most of the sections, except close to the mouth, the salinity of water was almost nil. The highest values

were obtained when the velocity difference between surface and bottom was very small and of a transient nature. Vertical density gradients near the mouths of the two estuaries were of the order of 10^{-4} during the pre-monsoon season and 10^{-3} during the monsoon. This difference indicates that an unstable stratification exists in the otherwise labile water mass. The ranges in R_t also indicate that due to turbulent diffusion, mixing remains uniform throughout the entire water column which is the characteristic feature of a one-layer estuary; or the flow is turbulent but there is little mixing across the steep gradients.

(g) *Dilution and flushing.* The amount of freshwater contained in any given sample of brackish water can be calculated from the salinity, since

$$F = (1 - S_1/S_2),$$

where F is the fraction of freshwater in the sample, S_1 is the salinity of the sample and S_2 is the salinity of the 'source' water (Ketchum, 1969).

In this calculation the entire estuarine region has been treated as one system. Some longitudinal variations may exist from the mouth to the upper reaches of the estuary, but it is assumed that they may not be very significant as the estuary is tide dominated and remains almost homogenous vertically for a greater part of the year. Therefore, the salinity values at all the stations during the three different seasons were averaged and used as an approximation of the general conditions.

For the salinity of the 'source' water, the values at a station 5 km away from the mouths of the estuaries (see Figure 1) were taken and these were separately averaged for the three seasons. The exception was in the monsoon period which is represented only by the September data. The salinity values in the open sea off the river mouths do not change appreciably from the average value during the period June to September (Dr J. S. Sastry, personal communication). Therefore, the assumption that salinity during September may be taken to represent the average monsoon conditions appears to be valid.

The results obtained from the equation noted above are given in Table 1. It can be seen that the dilution factors are approximately of a similar magnitude in both the estuaries during the three seasons, maximum values occurring during the pre-monsoon season when the freshwater flow is almost absent. Any pollutant therefore released to the estuarine system during this season will be diluted more than six times by seawater before it finally reaches the open sea. During the monsoon season; dilution by seawater would be minimum.

Preliminary calculations based on the data noted above give the flushing-out time (residence time) of the water in the Mandovi as 5-6 days during the monsoon period and about 50 days in the dry season (Das & Bhattathiri, unpublished results). For Zuari the residence time would be somewhat longer.

TABLE 1. Average values of freshwater fractions (F) and dilution factors in the Mandovi and the Zuari during the three seasons. The dilution factor relates to seawater

Season	Salinity (‰)			F		Dilution factor	
	Sea	Mandovi	Zuari	Mandovi	Zuari	Mandovi	Zuari
Pre-monsoon	36.27	30.49	30.43	0.16	0.16	6.2	6.2
Monsoon	31.09 ^a	5.73	7.97	0.82	0.74	1.2	1.3
Post-monsoon	34.45	23.64	25.70	0.31	0.25	3.2	4.0

^a September data only.

(h) *Formation of shoals/sand bars.* The occurrence of shoals/sand bars, popularly known as Aguada and Reis Magos bars, near the entrance of the Mandovi has been known for centuries. The map of Manuel Godinho de Eredias published in 1610 (Bois Penrose, 1960) shows the bars as a single patch of shoal at the entrance of Mandovi. Since then, over a few centuries, little appears to have changed, and even today the shoals/bars have neither grown nor have reduced in size. For about 9 months during the dry season, these shoals pose no serious navigational problems but during the 3-month period of the monsoon, the waterway is completely closed for boat traffic. The mechanisms of sand transport, wave action and circulation pattern have been studied by Murty *et al.* (1976).

Figure 7 shows the two shoals and the inlet to the sea. The important feature is the presence of a ramp-like structure in the navigational channel with a depth gradient from 10 to 4 m. The depth over the shoals ranges from 1.5 to 2 m. Aguada Bay is exposed to swells

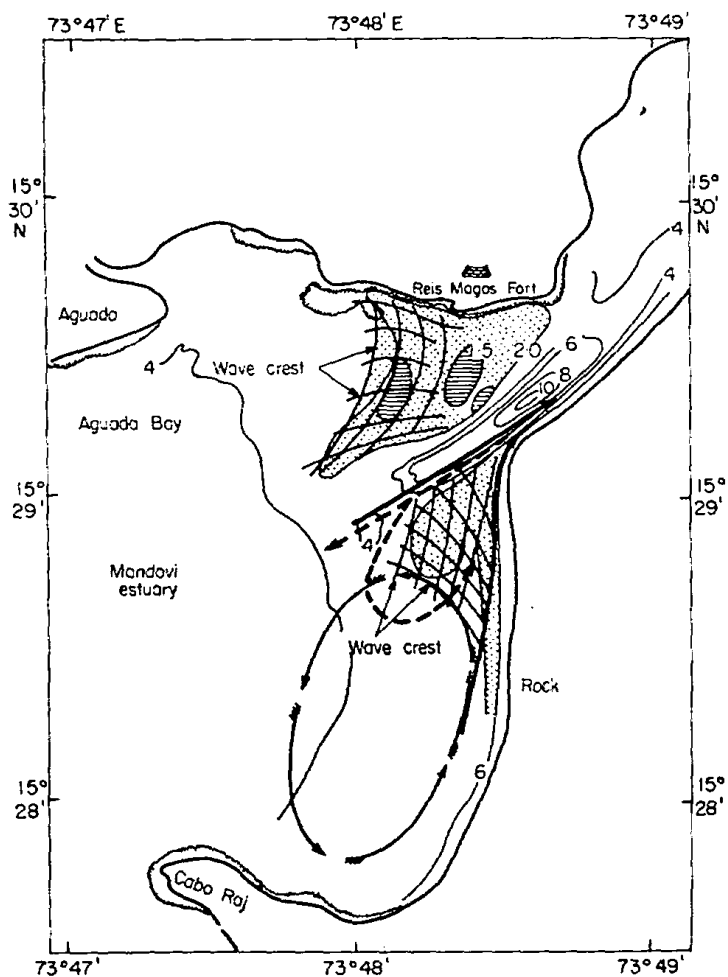


Figure 7. Schematic representation (modified from Murty *et al.*, 1976) of the Aguada Bay in Mandovi estuary and bathymetry of the inlet of the sea (navigational channel) and waves over the shoals. Stippled areas indicate the two shoals (Aguada and Reis Magos) on either side of the inlet; solid arrows indicate the current direction; broken arrows indicate the possible course of the movement of sediments along the shoal and in the inlet. Wave crests are marked by arrows over the shoals where maximum wave breaking occurs. Numbers over the shoal and in the navigational channel indicate depth in metres. 1.5-m depth contours over Reis Magos shoal have been ruled with close-spaced lines.

from the south, south-west, north-west and north. The two shoals shown in Figure 7 become the main sites for wave breaking.

The water circulation follows the current directions shown in the figure which leads to movement of the sediments probably in the same direction. During the fair weather season, the waves in the Aguada Bay are small with a significant period of 6.8 s and a significant wave height of 0.38 m. Heavy swells and intensification of wave activity by several folds during the monsoon season lead to highly turbulent conditions over the shoals, resulting in the removal of large quantities of material from the beaches and their transfer close to the navigational channel. During the fair weather the lost material is returned and the original profiles of the beaches are restored. From October–May at the lowest low water, the shoals are clearly exposed, but during the monsoon, even at the lowest spring tides, the bars are never seen and the boat traffic is closed. This is because the water over the bars probably gets deepened due to removal of material from the shoals.

There appears to be some similarity in the circulation pattern between the Mandovi and the Georgia estuary reported by Oertal (1972). Using Oertal's terminology, it would be incorrect to describe the Mandovi phenomenon as 'sand bar formation', and it can appropriately be termed 'ramp margin shoals'. According to Hayes (1972), this type of accumulation near the tidal inlets could be termed an 'ebb tidal delta' and the Aguada bar a 'linear sand bar'. However, as the monsoon recedes, their original shape and size are restored and such a cycle of sedimentary processes is maintained with utmost regularity every year.

B. Chemical features

(a) *Oxygen*. Before examining the values of oxygen concentrations in detail two points need to be mentioned (Barrett, 1972). Firstly, the oxygen content of any waterbody shows wide fluctuations over each tidal cycle and secondly, the concentration of oxygen varies with the varying flow rates in an estuary.

Observations were taken every 4 h over one tidal cycle of 12 h. Figure 8(a) gives the mean of three estimations in each month along with the measured values.

Seasonal variations in dissolved oxygen concentrations ranged from 0.95–5.16 ml l⁻¹ at M1, 3.77–6.24 ml l⁻¹ at M2, 2.39–6.77 ml l⁻¹ at Z1, 2.95–6.97 ml l⁻¹ at Z2, 3.60–5.77 ml l⁻¹ at C1, and 3.33–5.71 ml l⁻¹ at C2 during the year.

During all the tidal cycles the oxygen concentration decreased with the rising tide and increased with the falling tide. The annual range of variation showed a decrease with increasing distance from the mouth in both the rivers. Variations during the pre-monsoon months were smaller in range as compared to those of the monsoon months. Evidently this is due to the varying flow rates during the two seasons.

The average oxygen concentrations in both the rivers increase with distance from the river mouths. Temperature variations [Figure 2(a)] are similar to those of oxygen while salinity [Figure 2(b)] decreases with distance. Decreasing salinity increases the solubility of oxygen in water which probably appears to be the main cause for the increase in the concentration of dissolved oxygen upstream.

A very low mean value of 1.74 ml l⁻¹ was recorded at Station M1 in September. Most probably this is a temporary effect of the local sewage discharge. The Mandovi receives about 5.21×10^6 m³ of sewage and other effluents per year and Station M1 is not very far from the main sewage pipeline of Panaji town opening into Mandovi.

(b) *Sulphate and chlorinity*. Seawater maintains a sulphate : chlorinity ratio very close to 0.1400 at 35‰ salinity in all the oceans (Wilson, 1975). Geographical variations have been reported to be very small (less than $\pm 0.4\%$).

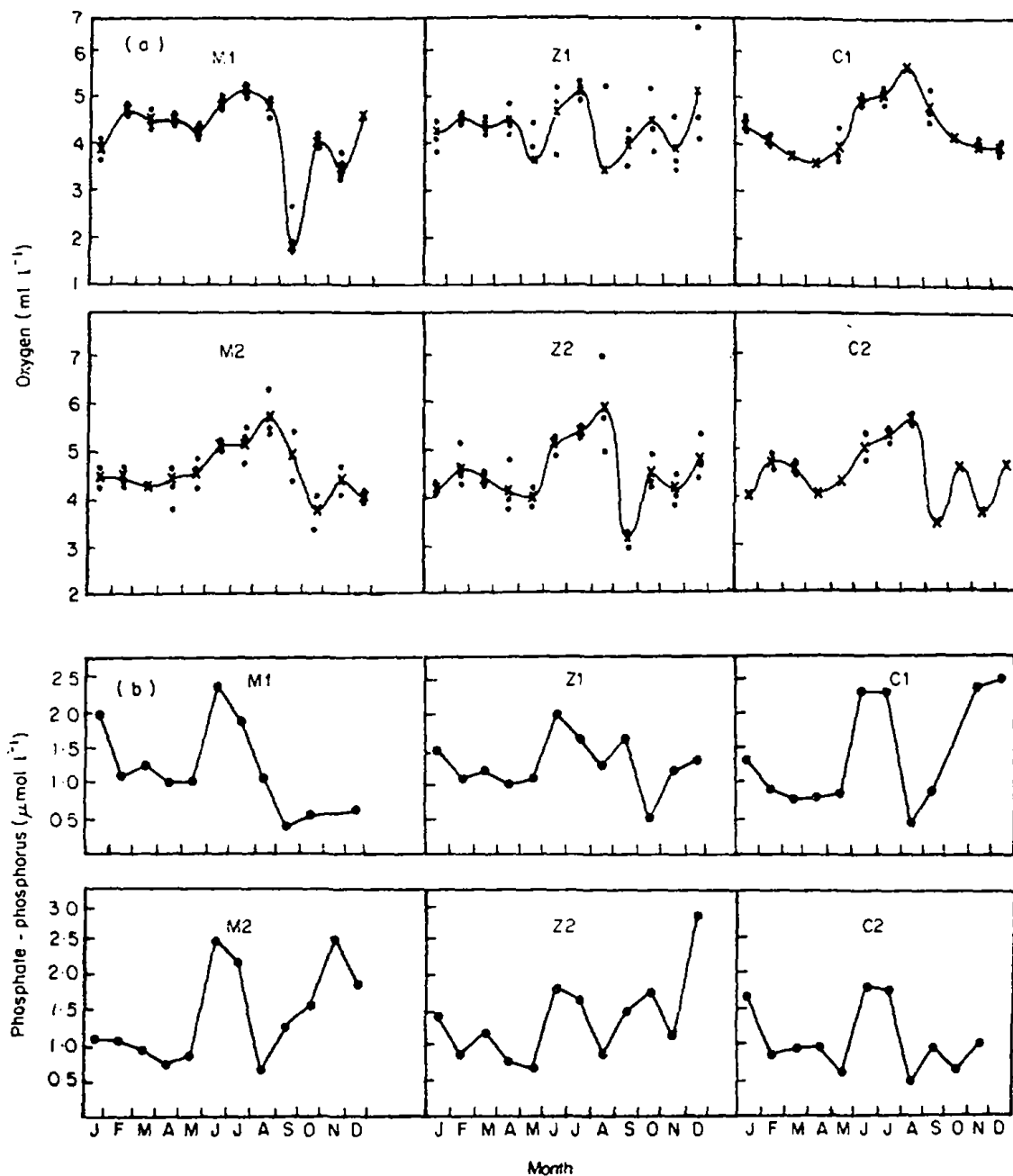


Figure 8. Seasonal variations in (a) oxygen and (b) phosphate-phosphorus at Mandovi, Zuari and Cumbarjua stations. Each dot represents an actual value and crosses give the monthly means.

In the waters of the Mandovi and the Zuari, the sulphate : chlorinity ratio remains similar to that of the open sea for 9 months in the year (Table 2). The ratio in the Mandovi ranges from 0.1322 to 0.1490 with a mean of 0.1409 ± 0.0011 , while that in the Zuari has a range from 0.1340 to 0.1525 with a mean of 0.1404 ± 0.0015 . However during the monsoon months (June-August), dilution due to river runoff disturbs this relationship. The global mean of sulphate concentration in rivers is $11.2 \text{ parts } 10^{-6}$ while the mean for the Asian rivers is $8.4 \text{ parts } 10^{-6}$ (Livingstone, 1964). In the freshwater zones of the Mandovi and the Zuari,

TABLE 2. Sulphate and chlorinity values taken as average values of all the stations of the Mandovi-Zuari estuarine system and their relationships

Months	Mandovi			Zuari		
	Chlorinity (g kg ⁻¹)	Sulphate (g kg ⁻¹)	SO ₄ ²⁻ : Cl ⁻	Chlorinity (g kg ⁻¹)	Sulphate (g kg ⁻¹)	SO ₄ ²⁻ : Cl ⁻
January	14.65	2.04	0.1392	14.30	1.99	0.1392
February	15.32	2.14	0.1397	15.18	2.12	0.1396
March	16.48	2.42	0.1468	16.38	2.35	0.1435
April	16.58	2.47	0.1490	16.95	2.55	0.1504
May	19.13	2.53	0.1322	18.87	2.61	0.1383
June	1.27	0.08	0.0630	2.04	0.18	0.0882
July	1.12	0.005	0.0045	2.13	0.005	0.0023
August	3.00	0.06	0.0210	5.43	0.22	0.0405
September	7.25	1.03	0.1421	8.00	1.22	0.1525
October	11.85	1.71	0.1443	16.79	2.25	0.1340
November	12.26	1.70	0.1387	12.31	1.69	0.1373
December	13.62	1.86	0.1366	13.48	1.74	0.1291
Mean of SO ₄ ²⁻ : Cl (excluding the values from June to August)			0.1409 ± 0.0011			0.1404 ± 0.0015

the sulphate concentration ranged from 0.17 and 0.22 parts 10⁻⁶ respectively at zero or near-zero chlorinity.

Using sulphate as a conservative element the dilutions in the two rivers were studied, applying the following 'simple mixture' relationship of Carpenter *et al.* (1975):

$$A_1/A_2 = F/(1-F),$$

where

$$F = (X - X_2)/(X_1 - X_2) \text{ and } F < 1.$$

X_1 is the concentration of a component in solution 1 while X_2 is the concentration of the same component in solution 2 and X is the concentration in the resulting mixture of solutions 1 and 2; A_1 is the amount of solution 1 in the resulting mixture, A_2 is the amount of solution 2 in the same mixture and F is a constant to be calculated for each season.

With the same assumptions as described under 'Dilution and flushing', and averaging the values for the river water at stations where chlorinity is zero or near-zero throughout the year, the results obtained for the three seasons in both the rivers are presented in Table 3.

It can be concluded from the values in Table 3 that both the rivers undergo an almost similar amount of dilution by seawater during the three seasons. The magnitudes of dilution range from 6-8 times in pre-monsoon, 1.2-1.3 times in monsoon and 3-5 times in post-monsoon.

(c) *Phosphate-phosphorus*. Normally, one would expect an anomalous cycle of dissolved inorganic phosphate in such estuaries which are influenced by heavy seasonal rainfall and in which the suspended load is fairly high (Phillips, 1972). Because of adsorption and dissolution at the sediment-water interface there is hardly any estuary which can be completely depleted of dissolved phosphate (Pomeroy *et al.*, 1965).

The seasonal cycle of the distribution of PO₄³⁻-P at all the six stations in the estuarine system is shown in Figure 8(b). From January to May in the two estuaries (Stations M1 and Z1) the PO₄³⁻-P values were almost similar and showed a decrease. This is the period when both the estuaries remain salt-water dominated. Presumably the decrease in PO₄³⁻-P is

TABLE 3. Values of the mixing ratio $A_1 : A_2$ and the seawater dilution factor calculated from the mean sulphate concentrations in the Mandovi and the Zuari during the three seasons. F is a constant to be determined for each season

Seasons	Mean sulphate ($g\ l^{-1}$) at sample Cl ‰			Mean sulphate ($g\ l^{-1}$) at $\sim 0\ Cl\ ‰$			F		$A_1 : A_2$		Dilution factor	
	Sea	Mandovi	Zuari	Mandovi	Zuari	Mandovi	Zuari	Mandovi	Zuari	Mandovi	Zuari	
	Pre-monsoon	2.74	2.39	2.41	0.017	0.007	0.87	0.88	6.7	7.3	7.7	8.3
Monsoon	2.68 ^a	0.32	0.43	0.001	0.002	0.12	0.16	0.14	0.19	1.1	1.2	
Post-monsoon	2.52	1.84	1.88	0.010	0.015	0.73	0.74	2.7	2.8	3.7	3.8	

^a September data only.

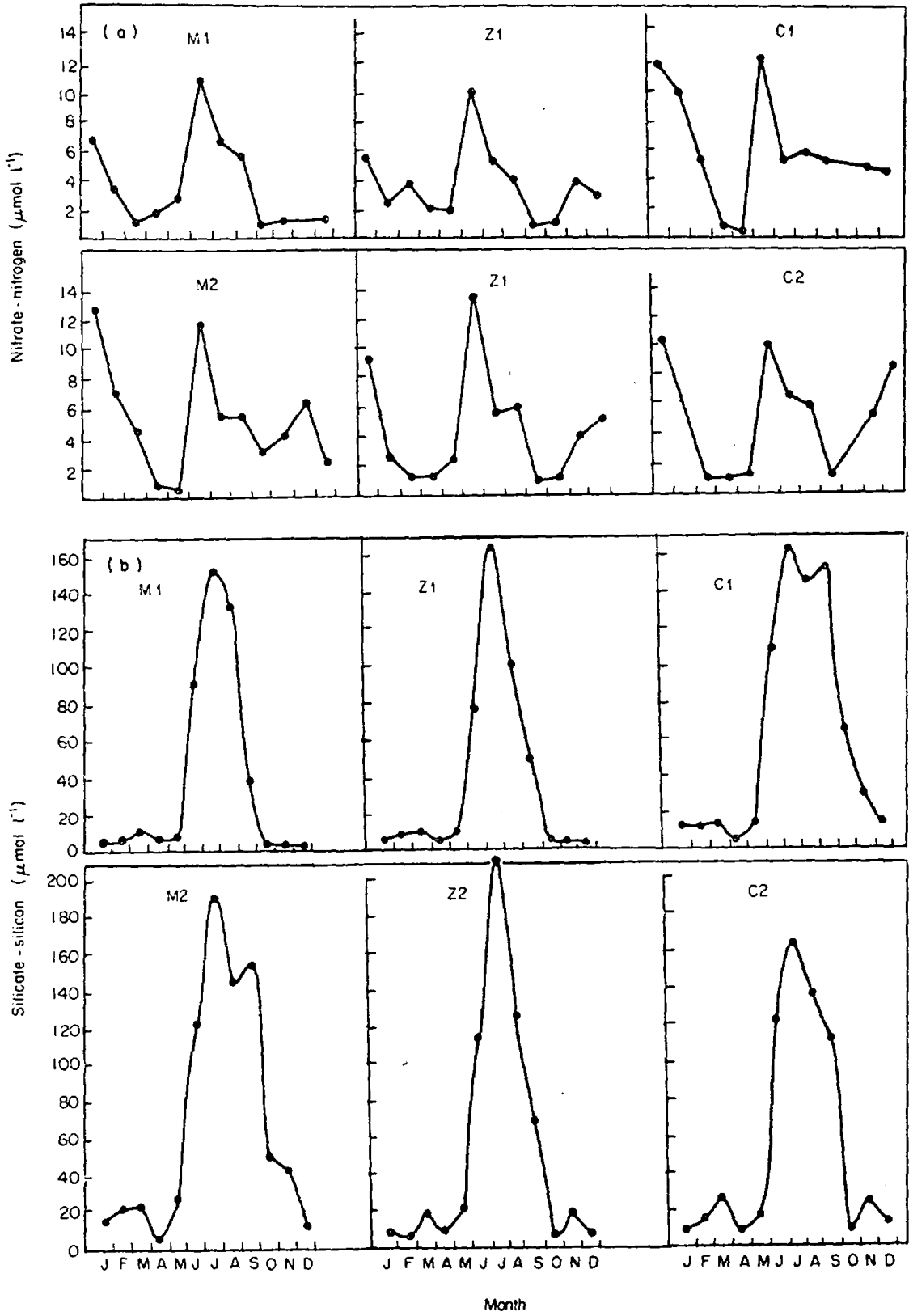


Figure 9. Seasonal variations in (a) nitrate-nitrogen and (b) silicate-silicon at Mandovi, Zuari and Cumbarjua stations.

because of its utilization by phytoplankton. In June, because of the monsoon precipitation and land runoff, $\text{PO}_4^{3-}\text{-P}$ values suddenly increase to almost the maximum. This increase is less pronounced in the Zuari (Station Z1) which is not as much influenced by runoff as the Mandovi (Station M1). Similar seasonal variations were seen in the upper reaches of the Mandovi and the Zuari (Stations M2 and Z2). Seasonal variation at Z2 was not as large as at M2 [Figure 8(b)]. The two stations in Cumbarjua also showed a similar seasonal trend.

High salinity in the estuaries associated with low $\text{PO}_4^{3-}\text{-P}$, indicates that $\text{PO}_4^{3-}\text{-P}$ comes largely from the freshwater source and land runoff whereas the seawater contribution of $\text{PO}_4^{3-}\text{-P}$ is small and remains almost uniform throughout the year.

Earlier information on phosphate-phosphorus in the Mandovi-Zuari estuarine system indicated a range of $0.24\text{--}2.6 \mu\text{mol l}^{-1}$ during the monsoon of 1971 (Dwivedi *et al.*, 1974) and $0.3\text{--}1.9 \mu\text{mol l}^{-1}$ during monsoon of 1972 (Sankaranarayanan *et al.*, 1978) with similar temporal variations, as shown in Figure 8(b). In the present investigation the range was from $0.42\text{--}2.5 \mu\text{mol l}^{-1}$ during the monsoon of 1978.

(d) *Nitrate-nitrogen.* From January to May, there was a progressive decrease in the $\text{NO}_3^-\text{-N}$ concentration at all the six stations in the estuarine system [Figure 9(a)]. This decrease was far more pronounced at the riverine stations than at the mouths of the two estuaries and probably indicates that the nitrogen is being utilized rapidly by the photosynthetic activity of phytoplankton. With the onset of rainfall and land runoff, $\text{NO}_3^-\text{-N}$ values suddenly increase at all the stations and fall again in subsequent months. Atmospheric precipitation has been reported to contain large amounts of ammonia-nitrogen and nitrate-nitrogen (Sen Gupta, 1973). At some stations, however, there was a secondary increase towards the end of the year signifying localized enrichment of land origin.

Nitrate-nitrogen and ammonia-nitrogen were also measured together with the total nitrogen content of water. It was thus possible to determine both inorganic and organic fractions of nitrogen in the two rivers and these are given in Table 4. In both rivers, seasonal variations in nitrogen fractions were similar except in October, November and December. High organic fractions from January to May in both the rivers probably indicate higher productivity during this period and/or sewage influence. Similarly, high organic fractions during the monsoon months are a result of heavy rainfall and land runoff. The last 3 months of the year constitute a transition period when freshwater addition gradually reduces to

TABLE 4. Nitrogen fractions based on average values of all the stations in the Zuari-Mandovi estuarine system

Months	Zuari		Mandovi	
	Inorganic N (%)	Organic N (%)	Inorganic N (%)	Organic N (%)
January	29	71	38	62
February	62	38	71	29
March	20	80	19	81
April	18	82	14	86
May	21	79	26	74
June	82	18	83	17
July	61	39	62	38
August	48	52	53	47
September	24	76	29	71
October	50	50	62	38
November	50	50	69	31
December	53	47	24	76

small quantities and the river system becomes progressively marine dominated. Such a transition in the Mandovi probably takes longer than in the Zuari. It is perhaps for this reason that both inorganic and organic fractions in the two rivers are not comparable from October to December.

Concentrations of phosphate and nitrate are generally known to show a negative correlation with salinity (Phillips, 1972). Such a relationship was observed here between nitrate and salinity for the pre- and post-monsoon periods. During the monsoon the salinity decreases sharply while the nitrate concentration does not show a proportionate increase.

(e) *Dissolved silicon.* The range in dissolved silicon during the year was from 3 to 210 $\mu\text{mol l}^{-1}$ in the Mandovi and from 3 to 196 $\mu\text{mol l}^{-1}$ in the Zuari for all the nine stations in each river [Figure 9(b)]. Silicon concentrations were lower in the estuarine region than upstream. There was remarkable agreement in the values between the two estuaries at all the stations including Cumbarjua. Peaks in the seasonal cycle of silicon were attained during the monsoon period indicating that silicon is contributed by the river and land runoff. This is in agreement with the situation in Cochin backwaters—another estuarine system of the west coast of India (Qasim, 1973). At all stations very little silicon is present in water during the non-monsoon months [Figure 9(b)].

C. Biological features

(a) *Phytoplankton.* Phytoplankton was studied at Stations M₁ and Z₁. Water samples were collected from the surface and preserved in 2–3% formalin. After shaking the bottles thoroughly, a 50-ml aliquot from each was transferred to a sedimentation chamber and allowed to settle for 2 days. The supernatant was removed and the organisms were counted under an inverted microscope. Cell counts at the two stations (Z₁ and M₁) are given in Table 5 for a period of 6 months. In the Mandovi the counts varied from 6500 to 26 000 cells l^{-1} while in Zuari the range in the counts was from 6500 to 12 600 cells l^{-1} . Both the minimum and maximum values in the two estuaries occurred in the same months. Bhattachari *et al.* (1976) studied the phytoplankton crop during the monsoon months in the Zuari, Mandovi and Cumbarjua and reported large blooms in Cumbarjua during the monsoon season (June–September) when the salinity was extremely low. The occurrence of massive blooms in Cochin backwaters (Kerala) during the monsoon months has been reported earlier

TABLE 5. Phytoplankton counts and zooplankton biomass at two stations in the Zuari–Mandovi estuarine system in some months

Months	Phytoplankton (cells l^{-1})		Zooplankton biomass (ml m^{-3})	
	M ₁	Z ₁	M ₂	Z ₂
January	6500	6500	0.0085	0.0074
February	12 040	10 030	0.04021	0.04592
March	12 000	14 400	0.04831	0.06334
April	26 000	12 600	0.0088	0.411
May	6500	8800	0.0892	0.0674
June	—	—	—	—
July	—	—	—	—
August	—	—	—	—
September	8500	6500	0.0851	0.0133
October	—	—	0.1067	0.01
November	—	—	0.0087	0.05
December	—	—	—	0.021

(Devassy & Bhattathiri, 1974) and a similar feature occurring in the estuarine system of Goa indicates that the peak production of most of the tropical phytoplankton organisms coincides with large dilution of seawater during the monsoon season which is invariably associated with enrichment with nutrients. Probably the phytoplankton crop in the Mandovi (Table 5) is larger because of its greater dilution than the Zuari's. Laboratory experiments on many organisms collected from the inshore waters of the south-west coast of India have shown that optimum photosynthesis occurs at salinities ranging from 10 to 20‰ (Qasim *et al.*, 1972).

An important factor in the phytoplankton cycles seems to be the concentration of nitrate which begins to increase in both the rivers from September onwards and reaches its peak by about January. Such an increase in nitrate may be the result of the use of fertilizer in low-lying wetlands which are often flooded with riverine water. Such farms are quite common in inland areas which remain free from salinity incursion. A comparison of Table 5 with Figure 9(a) shows that phytoplankton production starts increasing till it reaches a maximum when nitrate values are the lowest. A similar feature has been observed in the Pamlico River in North Carolina (Hobbie *et al.*, 1975). Our findings agree with the earlier reports that the Mandovi estuary is more productive than the Zuari (Devassy & Bhargava, 1978).

(b) *Zooplankton*. Zooplankton samples were also collected at Stations M1 and Z1 except during the monsoon period. Horizontal surface tows were made for five minutes using Heron-Tranter net with a mesh width of 300 μm . The speed of the boat during each tow was kept at 1 knot. The volume of water filtered through the net was determined by a TSK flow meter attached to the net. The total volume of plankton in each haul was estimated by the displacement method as total biomass in ml m^{-3} .

Zooplankton biomass, as given in Table 5, was found to be somewhat inconsistent in the two estuaries. In both the Mandovi and the Zuari, the lowest values were recorded in January, but in the Mandovi the highest value was in April and in the Zuari it was in October.

In general, the biomass values were high during the pre-monsoon months as compared with the monsoon months. Salps and siphonophores were quite abundant during the pre-monsoon months particularly during April and May, whereas fish eggs and larvae were abundant in October. Zooplankton population begins to increase in the post-monsoon months following the peak in phytoplankton production during the monsoon period and maximum zooplankton abundance occurs in the pre-monsoon period when the salinity in both the

TABLE 6. Total plate count (organisms ml^{-1}) at six stations in the Zuari-Mandovi estuarine system

Months	Mandovi		Zuari		Cumbarjua	
	M1	M2	Z1	Z2	C1	C2
January	174×10^6	131×10^6	178×10^6	94×10^6	92×10^5	180×10^5
February	168×10^6	69×10^6	92×10^6	20×10^5	82×10^6	40×10^6
March	144×10^6	100×10^5	17×10^6	16×10^6	12×10^6	5×10^6
April	—	—	—	—	—	—
May	—	—	—	—	—	—
June	49×10^6	5×10^5	26×10^6	3×10^6	4×10^5	3×10^6
July	—	32×10^6	41×10^6	66×10^6	7×10^6	91×10^6
August	74×10^5	29×10^6	9×10^6	25×10^6	26×10^6	5×10^6
September	22×10^6	213×10^6	81×10^6	55×10^6	142×10^6	94×10^6
October	3×10^6	12×10^4	10×10^4	18×10^6	—	—
November	3×10^6	8×10^6	100×10^6	43×10^6	5×10^6	15×10^4
December	12×10^6	2×10^6	100×10^4	18×10^4	1×10^5	11×10^6

rivers is maximum. During this period, purely marine forms dominate the estuarine system. Average secondary production in the estuarine system has been reported to be $21.4 \text{ mg dry wt. m}^{-3} \text{ day}^{-1}$ (Selvakumar *et al.*, 1980).

(c) *Microbes*. Microbial activity in the water was determined at all six stations by total plate counts (Table 6). There was no seasonal variation in the total number of organisms and their numbers varied between 12×10^4 and 213×10^6 organisms ml^{-1} in the Mandovi, 10×10^4 and 178×10^6 organisms ml^{-1} in the Zuari and 15×10^4 and 142×10^6 organisms ml^{-1} in Cumbarjua Canal. In both the estuaries, the total population was greater in the lower reaches and showed a decreasing trend upstream (Table 6). In general, the Mandovi had a higher microbial count than the Zuari and Cumbarjua Canal.

Discussion

The changes in the Mandovi–Zuari estuarine system reported above make the entire estuarine regime dependent upon the monsoon cycle. The monsoon brings about changes from typically marine to typically brackish-water conditions. This is followed by a general reduction in the freshwater discharge during the post-monsoon period and the restoration of stable marine conditions in the pre-monsoon months.

Diurnal variations in the physico-chemical conditions in both the Mandovi and Zuari estuaries (Singbal, 1973, 1976) and of the phytoplankton pigments (Dehadrai & Bhargava, 1972) are reported to be controlled by the tides. Other ecological studies conducted in this estuarine system during the monsoon period (June–September) of 1971 (Dwivedi *et al.*, 1974) give several features which do not fully agree with the present investigation. The distributions of phosphorus, nitrogen and silicon in the estuarine system are greatly influenced by the rainfall and land runoff.

Primary production during the monsoon period was measured earlier by Bhattathiri *et al.* (1976) using ^{14}C technique. These authors give the average production as $247 \text{ mg C m}^{-2} \text{ day}^{-1}$ in the Mandovi, $249 \text{ mg C m}^{-2} \text{ day}^{-1}$ in the Zuari and $316 \text{ mg C m}^{-2} \text{ day}^{-1}$ in Cumbarjua Canal. Higher production in Cumbarjua Canal was probably because of prevailing lower salinity as compared to the other two rivers. Zooplankton biomass has been reported to be greater in the Zuari than in the Mandovi and the faunal composition and species diversity were also greater in the Zuari (Goswami & Singbal, 1974). Some of these observations are in agreement with the present study.

According to the definition for the estuaries given by Pritchard (1967), the Mandovi–Zuari estuarine system can be classified as a coastal plain estuary which remains homogenous vertically for about 8 months and gets moderately stratified for about 3 to 4 months during the year. The water in this estuarine system penetrates up to a considerable distance upstream and the semidiurnal tides of M_2 type occur twice a day raising and lowering the water level by about 2 m. The rivers, being shallow, get dominated by the tidal flow. There is, however, a strong longitudinal variation in salinity at almost all the depths from the mouths of the rivers upstream, which gives rise to a range in the longitudinal dispersion coefficients probably due to advective flux. Longitudinal variation in salinity would provide a decreasing slope seaward of the pressure surfaces with increasing depth. As is usual for this type of estuaries, because of the effect of Coriolis force, the seaward flow of the water always appears to be on the right to an observer, looking downstream, while the compensating flow of salt water appears to be on his left. There always exists a horizontal or lateral salinity gradient,

however small it may be, from the left to the right banks of the two rivers, except during the monsoon months when due to large influx of freshwater, a compensatory salt-water flow occurs below the freshwater in the form of a salt wedge. This gives rise to stratification in the water column, which extends only up to a short distance from the mouths of the two rivers as the volume of river runoff is very large.

Thus, the Mandovi-Zuari estuarine system can be classified as a tide-dominated coastal plain estuary which is homogenous vertically but has lateral variation in salinity and also develops a salt wedge. Geomorphologically both the Mandovi and the Zuari have been identified as drowned river valley estuaries (Murty *et al.*, 1976).

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References

- Barrett, M. J. 1972 The effects of pollution in Thames estuary. In *Estuarine Environment* (Barnes, R. S. K. & Green, J., eds). Applied Science, London. pp. 119-122.
- Bhattathiri, P. M. A., Devassy, V. P. & Bhargava, R. M. S. 1976 Production at different trophic levels in the estuarine system of Goa. *Indian Journal of Marine Sciences* **5**, 83-86.
- Bois Penrose 1960 *Goa—Queen of the east (Eredias, M. G. de, 1610)* Commemoracoes Do V Centenario Da Morte De Infante De Henrique. Commissao Ultramarina, Lisboa.
- Carpenter, J. H., Bradford, W. L. & Grant, V. 1975 Processes affecting the composition of estuarine waters (HCO₃, Fe, Mn, Zn, Cu, Ni, Cr, Co and Cd). In *Estuarine Research Volume 1* (Cronin, L. E., ed.). Academic Press, New York. pp. 188-214.
- Das P. K., Murty, C. S. & Varadachari, V. V. R. 1972 Flow characteristics of Cumbarjua Canal connecting the two estuaries Mandovi and Zuari. *Indian Journal of Marine Sciences* **1**, 95-102.
- Dehadrai, P. V. & Bhargava, R. M. S. 1972 Distribution of chlorophyll, carotenoids and phytoplankton in relation to certain environmental factors along the central west coast of India. *Marine Biology* **17**, 30-37.
- Devassy, V. P. & Bhargava, R. M. S. 1978 Diel changes in phytoplankton population in the Mandovi and Zuari estuaries of Goa. *Mahasagar—Bulletin of the National Institute of Oceanography* **11**, 195-199.
- Devassy, V. P. & Bhattathiri, P. M. A. 1974 Phytoplankton ecology of Cochin backwater. *Indian Journal of Marine Sciences* **3**, 46-50.
- Dwivedi, S. N., Bhargava, R. M. S., Parulekar, A. H., Selvakumar, R. A., Singbal, S. Y. S. & Sankaranarayanan, V. N. 1974 Ecology and environmental monitoring of Mandovi, Zuari and Cumbarjua Canal complex during monsoon months. *Journal of Indian Fisheries Association* **3**, 4, 113-130.
- Dyer, K. R. 1973 *Estuaries: A Physical Introduction*. John Wiley, London. 140 pp.
- Dyer, K. R. & Ramamoorthy, K. 1969 Salinity and water circulation in the Vellar estuary. *Limnology and Oceanography* **14**, 4-15.
- Goswami, S. C. & Singbal, S. Y. S. 1974 Ecology of Mandovi and Zuari estuaries: plankton community in relation to hydrographic conditions during monsoon 1972. *Indian Journal of Marine Sciences* **3**, 51-57.
- Hansen, D. V. & Rattray, M. 1965 Gravitational circulation in straits and estuaries. *Journal of Marine Research* **23**, 104-122.
- Hayes, M. O. 1972 Forms of sediment accumulation in the beach zone. In *Waves on Beaches* (Meyer, R. E., ed.). Academic Press, New York. pp. 297-356.
- Hobbie, J. E., Copeland, B. J. & Harrison, W. G. 1975 Sources and fates of nutrients of the Pamlico River estuary, North Carolina. In *Estuarine Research Volume 1* (Cronin, L. E., ed.). Academic Press, New York. pp. 287-302.
- Ketchum, B. H. 1969 Eutrophication of estuaries. In *Eutrophication: Causes, Consequences, Correctives*. National Academy of Sciences, Washington D.C. pp. 197-209.

- Livingstone, D. A. 1964 Chemical composition of rivers and lakes. *Geological Survey of U.S.A. Professional Paper* 440-G. 64 pp.
- Murty, C. S. & Das, P. K. 1972 Pre-monsoon tidal flow characteristics of Mandovi estuary. *Indian Journal of Marine Sciences* 1, 220-225.
- Murty, C. S., Das, P. K., Nair, R. R., Veerayya, M. & Varadachari, V. V. R. 1976 Circulation and sedimentation processes in and around the Aguada Bar. *Indian Journal of Marine Sciences* 5, 9-17.
- Oertel, G. F. 1972 Sediment transport of estuary entrance shoals and the formation of swash platforms. *Journal of Sedimentary Petrology* 42, 858-863.
- Phillips, J. 1972 Chemical processes in estuaries. In *Estuarine Environment* (Barnes, R. S. K., & Green, J., eds). Applied Science, London. pp. 35-50.
- Pomeroy, L. R., Smith, F. E. & Grant, C. M. 1965 The exchange of phosphate between estuarine water and sediments. *Limnology and Oceanography* 10, 167-172.
- Pritchard, D. W. 1967 Observations of circulation in coastal plain estuaries. In *Estuaries* (Lauff, G. H., ed.). American Association for the Advancement of Science, Washington D.C. pp. 37-44.
- Qasim, S. Z. 1973 Productivity of backwaters and estuaries. In *The Biology of the Indian Ocean* (Zeitzschel, B., ed.), *Ecological Studies* 3, 143-154. Springer Verlag, Berlin.
- Qasim, S. Z. 1979 Primary production in some tropical environments. In *Marine Production Mechanisms* (Dunbar, M. J., ed.). International Biological Programme Series No. 20. Cambridge University Press, Cambridge. pp. 31-63. 69.
- Qasim, S. Z., Bhattathiri, P. M. A. & Devassy, V. P. 1972 The influence of salinity on the rate of photosynthesis and abundance of some tropical phytoplankton. *Marine Biology* 12, 200-206.
- Sankaranarayanan, V. N., Rao, D. P. & Antony, M. K. 1978 Studies on some hydrographical characteristics of the estuarine and inshore waters of Goa during the south-west monsoon 1972. *Mahasagar—Bulletin of National Institute of Oceanography* 11, 125-136.
- Selvakumar, R. A., Nair, V. R. & Madhupratap, M. 1980 Seasonal variations in the secondary production of the Mandovi-Zuari estuarine system of Goa. *Indian Journal of Marine Sciences* 9, 27-34.
- Sen Gupta, R. 1973 A study on nitrogen and phosphorus and their inter-relationships in the Baltic. Doctoral Dissertation, Göteborgs Universitet, Sweden (mimeo).
- Singbal, S. Y. S. 1973 Diurnal variation of some physico-chemical factors in the Zuari estuary of Goa. *Indian Journal of Marine Sciences* 2, 90-93. ✓
- Singbal, S. Y. S. 1976 Diurnal variation of some physico-chemical factors in the Mandovi estuary of Goa. *Mahasagar—Bulletin of National Institute of Oceanography* 9, 27-34. ✓
- Varma, K. K., Rao, L. V. G. & Cherian, T. 1975 Temporal and spatial variations in hydrographic conditions of Mandovi estuary. *Indian Journal of Marine Sciences* 4, 11-17.
- Wilson, T. R. S. 1975 Salinity and major elements in sea water. In *Chemical Oceanography* Volume 1, 2nd edition (Riley, J. P. & Chester G., eds). Academic Press, London. pp. 365-414.