

Seasonal patterns of phytoplankton biomass and productivity in a tropical estuarine complex (west coast of India)

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MS received 10 October 1988; revised 5 June 1989

Abstract. Phytoplankton cell numbers and chlorophyll *a* determinations were made during the premonsoon, monsoon and postmonsoon periods in the Mandovi-Zuari estuarine complex (west coast of India). Primary productivity estimates agreed well with chlorophyll *a* and phytoplankton cell numbers. The consequent decline in salinity with the onset of monsoon was found to be an important factor controlling the distribution, abundance and productivity of phytoplankton. As compared to the Zuari estuary, the Mandovi retained typical estuarine conditions and a greater phytoplankton biomass. Based on primary productivity estimations, the potential fishery resource of this estuarine complex has been computed.

Keywords. Phytoplankton; biomass; productivity; environmental interrelationship; tropical estuary.

1. Introduction

Estuaries are unique ecosystems because of their continually changing environmental conditions. They form the transition areas between more stable marine and limnetic regions and exhibit wide ranges in hydrographical conditions (Kinne 1967). This feature warrants special adaptations, such as osmoregulatory adjustments and the organisms inhabiting the estuaries form an interesting class by themselves. The economic importance of estuaries has long been understood, although intensive studies on their environmental aspects commenced only recently.

The Mandovi-Zuari estuarine complex on the west coast of India is a highly dynamic and variable environment with considerable tidal influence. The perennial connections of this estuarine complex with the Arabian sea, results in a rhythmic ingress and egress of marine and estuarine plankton populations. Except during the monsoon months, both the Mandovi and Zuari estuaries maintain well mixed conditions (Das *et al* 1972; Qasim and Sengupta 1981). There have been few investigations in the past from these estuaries on phytoplankton pigments (Bhargava 1973, 1974; Bhargava and Dwivedi 1976) and primary production (Bhattathiri *et al* 1976; Devassy 1983).

An important account of the environmental characteristics of the Mandovi-Zuari estuarine ecosystem has already been published (Qasim and Sengupta 1981). The present investigation forms the first comprehensive account on the distribution patterns of phytoplankton, chlorophyll *a* and primary production in relation to the hydrographical and chemical features of this estuarine complex. An attempt has also been made to estimate the zooplankton biomass. Based on primary productivity data, the potential fishery resource of the estuarine complex has been computed.

2. Materials and methods

Investigations were carried out at 5 stations located in the estuarine complex (figure 1)

from November 1979 to October 1980. Monthly samples were collected from 3 predetermined light depths during the high tide phase (100, 30 and 1%) using 5 liter Niskin PVC samplers. The sampling depths were established after measuring the transparency by a Secchi disc. The 1% light depth varied during the nonmonsoon and monsoon periods. Inorganic $\text{PO}_4\text{-P}$, $\text{NO}_2\text{-N}$, $\text{NO}_3\text{-N}$ and alkalinity were estimated by standard methods (Strickland and Parsons 1968). Samples for phytoplankton enumeration were fixed in 1% Lugol's iodine and preserved in 3% formaldehyde. The cells were counted in a Sedgwick-Rafter counting chamber. For chl *a* estimation, 500 ml of water sample was filtered on to GF/C filters that was pretreated with a few drops of 1% magnesium carbonate suspension. The filters were extracted overnight under cold and dark conditions in 90% acetone. Chl *a* and phaeopigments were estimated in a precalibrated Turner Designs Fluorometer.

The [^{14}C] method (Steemann Nielsen 1952) was used for measurements of primary productivity. All samples were prescreened through a 300 micrometer nybolt net to minimise the possibility of grazing of phytoplankton cells by zooplankton during incubations. Two light and one dark 125 ml bottles from each depth were spiked with $5 \mu\text{Ci}$ of $\text{NaH}^{14}\text{CO}_3$ obtained from Bhabha Atomic Research Centre, Bombay and incubated for 6 h. Phytoplankton cells were collected on a $0.45 \mu\text{m}$ membrane filter paper and the radioactivity was measured in a liquid scintillation counter (ECIL), using the channels ratio method for quench correction. Primary productivity rates were expressed as $\text{mgC m}^{-3}\text{h}^{-1}$ and as $\text{mgC m}^{-3}\text{d}^{-1}$ assuming an average 10 h of daylight.

3. Results and discussion

3.1 Hydrography and chemistry

The monsoon cycle is a major factor which influences the hydrographical features of the Mandovi-Zuari estuarine complex. Based on this, the year has been divided into 3 seasons viz. premonsoon (Feb–May), monsoon (June–Sept) and postmonsoon (Oct–Jan). Generally, maximum rainfall occurs from June to August and in the postmonsoon the rains decline. The influence of the northeast monsoon is not so pronounced and the premonsoon is practically dry. This classification is a rather generalized one and hence the length of the seasons may vary from year to year depending on the onset, intensity and duration of the monsoon.

Salinity fluctuated widely at all the stations varying from 0.45–36.43‰ (figure 2). The annual average salinity values in the Mandovi, Cumbarjua and Zuari were 23.39, 17.58 and 28.52‰ respectively. The lowest salinity values were encountered during the monsoon season. The Mandovi estuary has a lower average salinity than that of the Zuari because the former receives considerable amount of runoff from several tributaries (Qasim and Sengupta 1981).

In general, nutrients ($\text{NO}_3\text{-N}$ and $\text{NO}_2\text{-N}$) were low in the premonsoon months and relatively high in the monsoon and postmonsoon seasons. $\text{NO}_2\text{-N}$ values showed a very fluctuating trend and varied from undetectable levels to $3.56 \mu\text{g at l}^{-1}$ (figure 3). $\text{NO}_3\text{-N}$ ranged from below detection levels to $10 \mu\text{g at l}^{-1}$ and in general high concentrations were recorded in the lower reaches of the estuaries (figure 4). Highest concentration of $\text{PO}_4\text{-P}$ recorded in this environment was $4.5 \mu\text{g at l}^{-1}$ during October (figure 5).

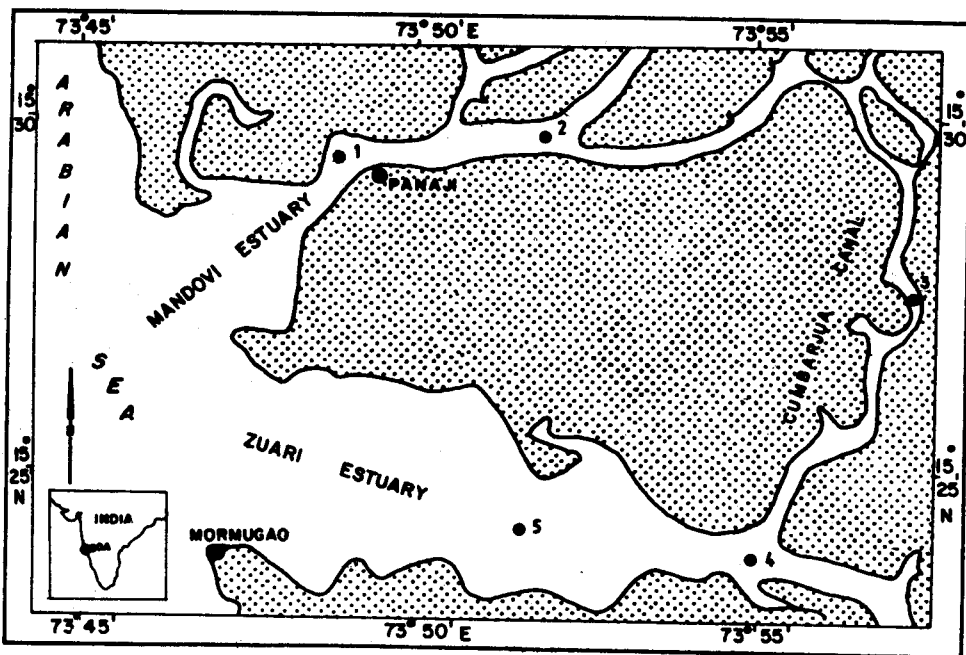


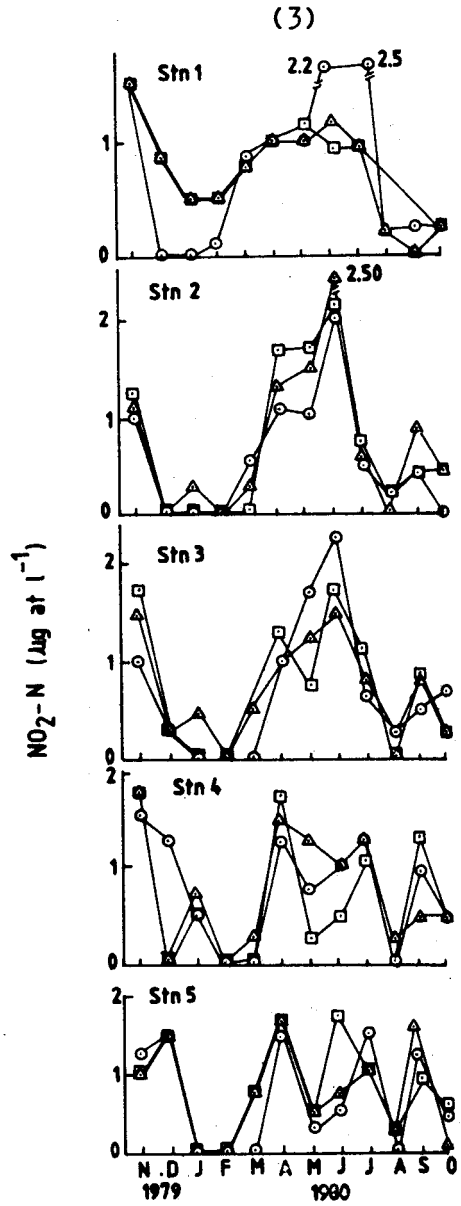
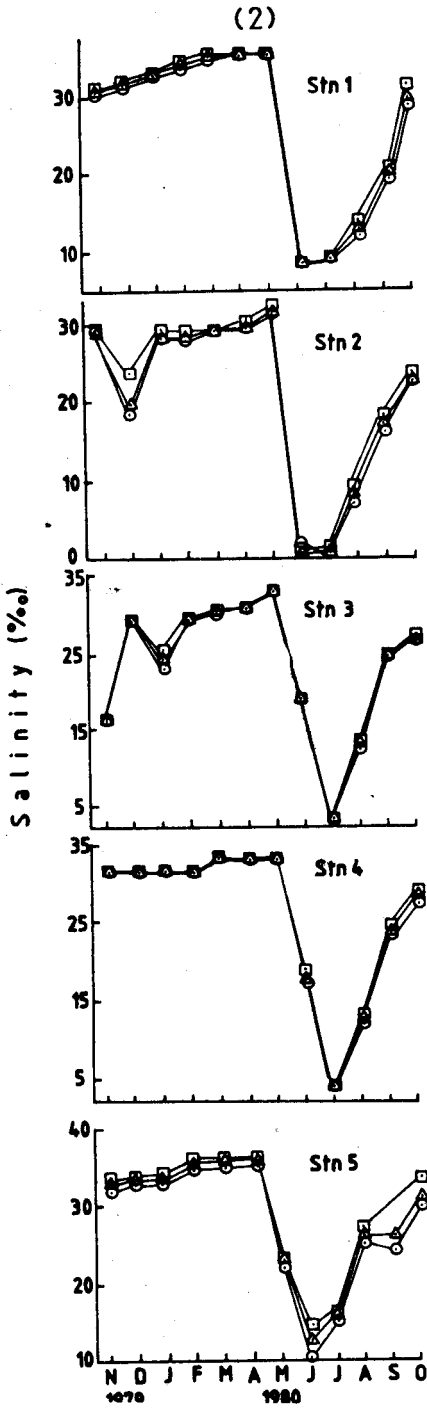
Figure 1. Mandovi-Zuari estuarine complex showing stations.

3.2 Biological features

Chl *a* concentrations in the estuaries remained high at the surface as compared to the subsurface layers (figures 6a, 7a, 8a, 9a, 10a). Higher concentrations of chl *a* were recorded at most of the stations during the pre- and postmonsoon seasons, the maximum being in the latter season. Surface concentrations varied from 0.1–14.2 mg m⁻³. The earlier recorded values of chl *a* (Bhargava and Dwivedi 1976) varied from 0.56–11.86 mg m⁻³ in these estuaries.

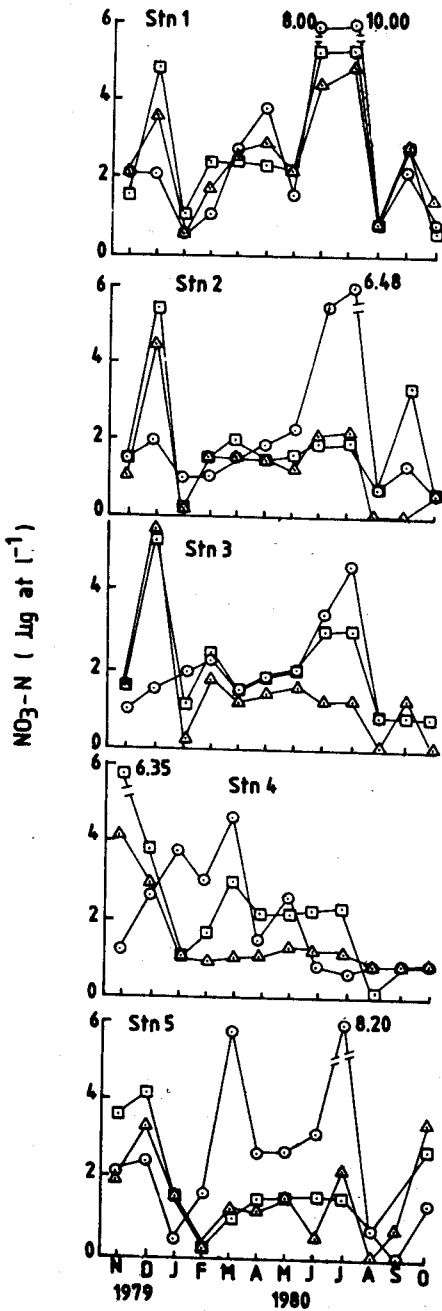
In the Mandovi estuary, chl *a* exhibited 3 peaks at stn 1 (figure 6a) and two peaks at stn 2 (figure 7a). Very high column concentrations (integrated for the euphotic column) viz. 30.30 and 16.80 mg m⁻² were observed at stn 1 during October and November respectively. The Cumbarjua canal exhibited a fluctuating pattern until June, followed by a sudden decline till August (figure 8a). Chl *a* showed a fluctuating trend (0.22–3.7 mg m⁻³) from November to April in the Zuari estuary (figures 9a, 10a). A sharp decline was noticed in the monsoon months at all the stations. The highest concentrations were observed in October.

Surface and column phytoplankton concentrations observed are shown in figures 6b, 7b, 8b, 9b, 10b. The cell concentrations at the surface fluctuated from 4.75 (July) to 1369 × 10³ l⁻¹ (Oct) in the Mandovi, 7.5 (Aug) to 489.5 × 10³ l⁻¹ (May) in the Cumbarjua canal and 10.5 (Aug) to 356 × 10³ l⁻¹ (Dec) in the Zuari. The Mandovi-Zuari estuarine complex sustains very high phytoplankton populations during the pre- and postmonsoon seasons as compared to the Cochin backwater, the latter being a highly polluted environment (Qasim and Madhupratap 1979). One conspicuous difference found was the very poor phytoplankton crop observed in the Mandovi-Zuari estuarine complex during the peak monsoon season. The paucity of phytoplankton in the monsoon months was due to the scarcity of freshwater species.

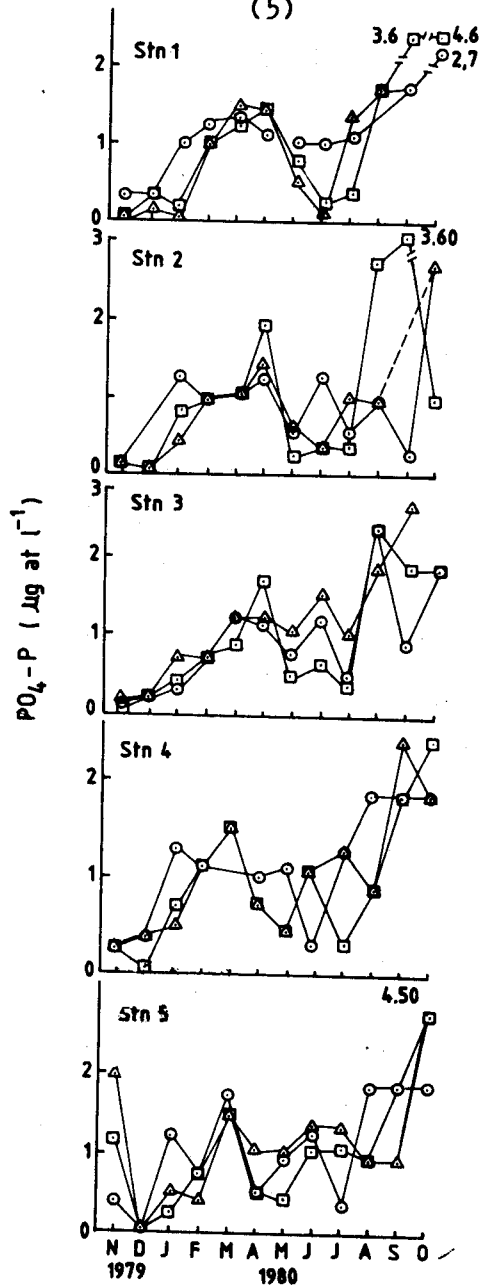


Figures 2 and 3. 2. Monthly variations in salinity (‰). 3. Monthly variations in NO₂-N (µg at l⁻¹). (○), Depth of 100% incident light; (△), depth of 30% incident light; (□), depth of 1% incident light.

(4)



(5)



Figures 4 and 5. 4. Monthly variations in $\text{NO}_3\text{-N}$ ($\mu\text{g at l}^{-1}$). 5. Monthly variations in $\text{PO}_4\text{-P}$ ($\mu\text{g at l}^{-1}$). (○), Depth of 100% incident light; (△), depth of 30% incident light; (□), depth of 1% incident light.

that would have been expected to occur at the lower salinities associated with increased river flow as was observed in the Cochin backwater (Devassy and

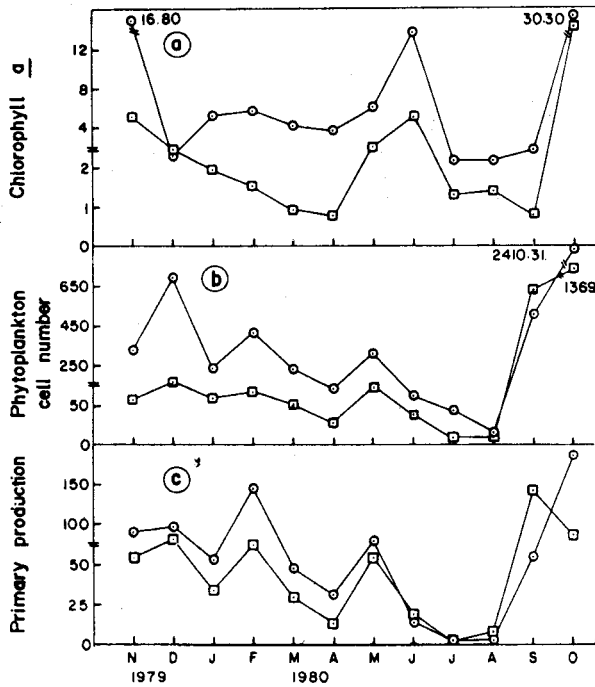


Figure 6. Monthly variations at stn 1 of (a) column chl *a* (mg m^{-2}) (○) and surface chl *a* (mg m^{-3}) (□); (b) column cell numbers (no. m^{-2}) (○) and surface cell number (no. l^{-1}) (□); (c) Column primary production ($\text{mgC m}^{-2} \text{h}^{-1}$) (○) and surface primary production ($\text{mgC m}^{-3} \text{h}^{-1}$) (□).

Bhattathiri 1974). Monthly variations in the surface phytoplankton (diatoms, dinoflagellates and other algae) counts, along with the species diversity indices are presented in figure 11. A total of 63 diatom species belonging to 38 genera, 14 dinoflagellate species belonging to 8 genera, 3 species of blue-green algae and 2 green algae were encountered in the present studies.

Diatoms were by far the predominant organisms and in general, maximum concentrations were recorded during the postmonsoon period. The distribution of dinoflagellates was erratic and no definite pattern could be observed. The other algae (3 species of blue-green algae and 2 species of green algae) formed only an insignificant component of the phytoplankton population, except for an unidentified filamentous blue-green alga which surpassed all other phytoplankters in May and contributed to as much as 65.4, 90.2 and 90.6% at stns 1, 2 and 3 respectively (figure 11). The cell counts in the column indicated an overall greater concentration in the Mandovi with an annual average of 372.83×10^3 cells m^{-2} , compared to 261.83 and 230.03×10^3 cells m^{-2} in the Zuari and Cumbarjua canal respectively (table 1). This is in agreement with the findings of the earlier studies conducted in the same area by Devassy and Bhargava (1978). A general pattern in the seasonal abundance of various components of phytoplankton was noticed as follows:

3.3 Premonsoon

In the Mandovi estuary, the unidentified blue-green algal form and the diatom

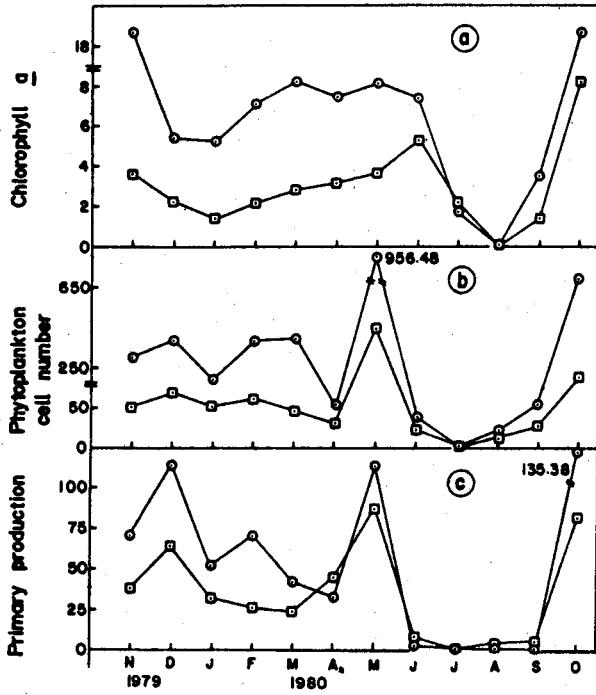


Figure 7. Monthly variations at stn 2 of column and surface chl a, cell numbers and primary production (other details as in figure 6).

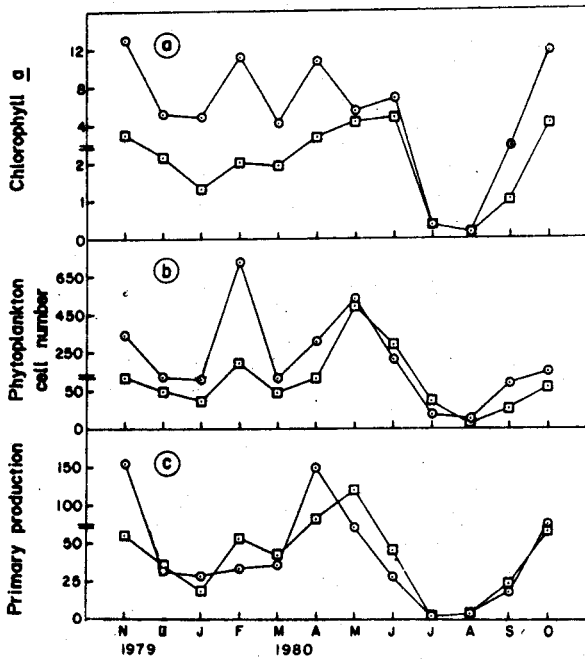


Figure 8. Monthly variations at stn 3 of column and surface chl a, cell numbers and primary production (other details as in figure 6).

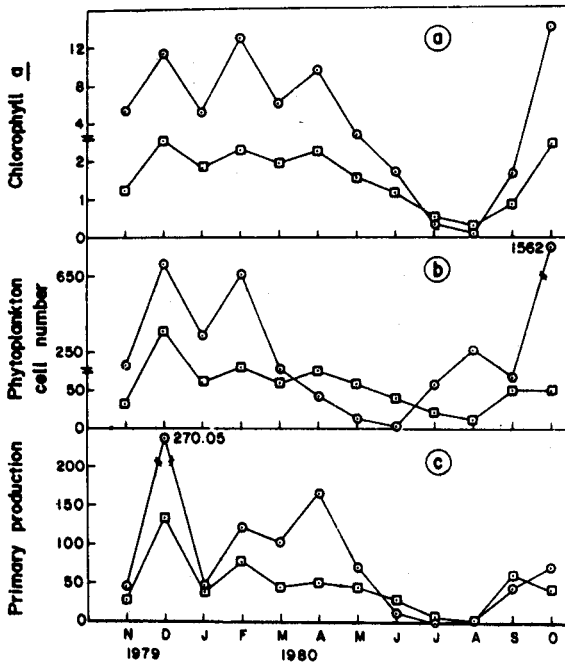


Figure 9. Monthly variations at stn 4 of column and surface chl *a*, cell numbers and primary production (other details as in figure 6).

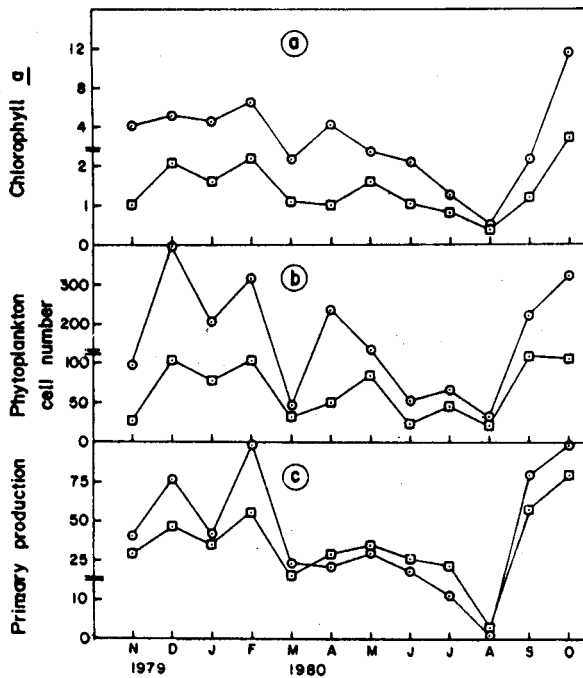


Figure 10. Monthly variations at stn 5 of column and surface chl *a*, cell numbers and primary production (other details as in figure 6).

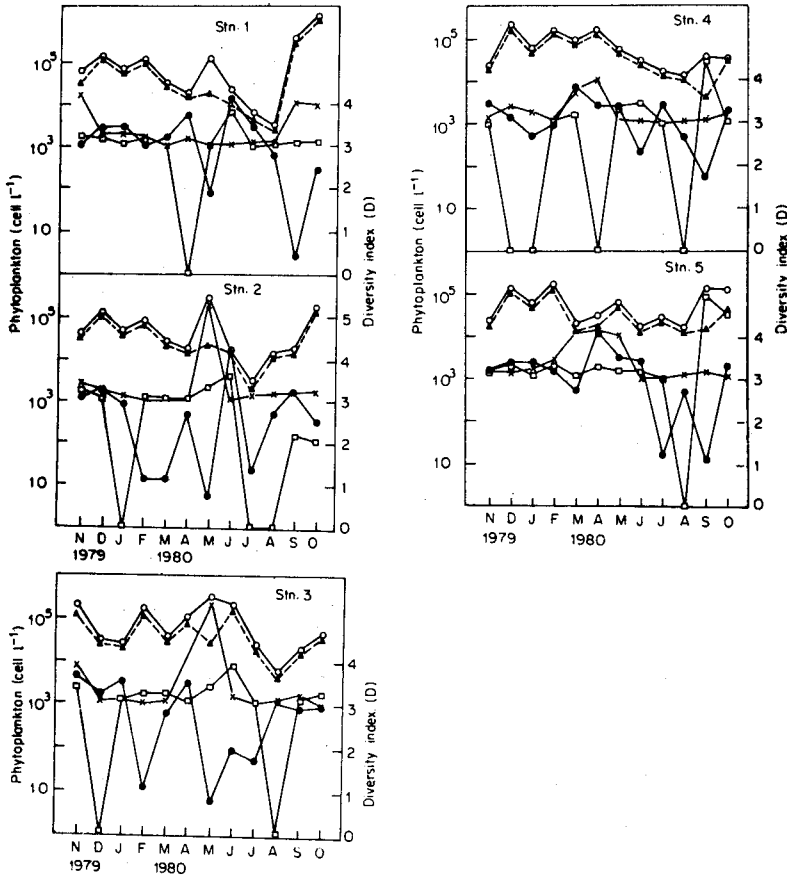


Figure 11. Monthly variations in surface phytoplankton cell number and diversity index. (○), Total phytoplankton; (▲), diatoms; (□), dinoflagellates; (×), other algae; (●), diversity index.

Table 1. The seasonal variations in chl *a*, phytoplankton cell numbers and primary production.

		Premonsoon	Monsoon	Postmonsoon
Chl <i>a</i> mg m ⁻²	Mandovi	6.62	4.25	13.64
	Cumbarjua	7.51	2.51	8.73
	Zuari	5.97	1.28	7.76
Phytoplankton cell numbers × 10 ³ m ⁻²	Mandovi	364.82	146.02	655.30
	Cumbarjua	415.61	90.27	184.22
	Zuari	5.97	1.28	7.76
Primary production mgC m ⁻² h ⁻¹	Mandovi	65.75	10.20	99.11
	Cumbarjua	72.49	11.97	71.49
	Zuari	43.83	21.31	64.48

Delphineis surelloides dominated the population and contributed 90.3% (May) and 82.2% (Mar) of the numbers respectively. Other dominant forms were *Coscinodiscus* spp., *Nitzschia* spp., *Melosira sulcata* and *Rhizosolenia stolterfothii*. In the

Cumbarjua canal, dense populations of the unidentified blue-green alga contributed to the extent of 90.6% (May) while *Coscinodiscus marginatus* accounted for 83.5% (Feb). *Nitzschia* spp., *Skeletonema costatum* and *R. stolterfothii* were the other principal species present. The most abundant forms in the Zuari were *Nitzschia* spp., *Coscinodiscus* spp., *Pleurosigma* spp., *S. costatum*, *Hemiaulus sinensis*, *Ditylum sol*, *Bacillaria paxillifer*, *Navicula membranacea*, *Trichodesmium erythraeum* and flagellates.

3.4 Monsoon

Towards the close of the monsoon (Sept) in the Mandovi (stns 1 and 2), heavy blooms of *D. surirelloides* occurred (600×10^3 cells l^{-1}), which alone accounted for 94.4% (Sept) of the phytoplankton crop. Other abundant forms were, species of *Coscinodiscus*, *Nitzschia*, *Navicula* and the dinoflagellate *Ceratium furca*. During the peak monsoon months (July and Aug), when the rains were heavy, phytoplankton composition, both quantitatively and qualitatively was found to be poor (figure 11). In the Cumbarjua canal, the diatoms viz. *Nitzschia closterium*, *D. surirelloides*, *Leptocylindrus danicus* and species of *Coscinodiscus* and *Navicula* were also moderately abundant. Blooms of *S. costatum* (83.5%) (July) and *C. furca* (77.6%) (Sept) appeared in the Zuari. At times, *Pleurosigma* spp., and an unidentified pennate diatom and *D. surirelloides* also could be noticed in appreciable quantities but during the heavy monsoon period, phytoplankton population declined considerably.

3.5 Postmonsoon

This period was very conducive for maximum proliferation of both diatoms and dinoflagellates. Maximum diversity of dinoflagellates was observed during October. Other species viz. *D. surirelloides* and species of *Nitzschia*, *Pleurosigma* and *Tetraselmis gracilis* also dominated. In the Cumbarjua canal *L. danicus*, species of *Nitzschia*, *Coscinodiscus* and *Rhizosolenia* were predominant. In the Zuari at the stn 5, a bloom of *Noctiluca scintillans (miliaris)* occurred during October and contributed 40.7% of the total population. Diatoms, viz. *Chaetoceros curvisetus*, species of *Nitzschia*, *Coscinodiscus* and *Rhizosolenia* and the flagellate *T. gracilis* were also abundant during this period.

The occurrence of phytoplankton blooms in relation to salinity along with Shannon Weaver diversity indices and percentages of different phytoplankters is shown in table 2. *D. surirelloides* was found to be the most frequent bloom-forming phytoplankton. It is evident from the table, that this euryhaline diatom can thrive and often bloom under wide ranging salinities (2.5–31.5‰). An unidentified pennate diatom occurred in appreciable numbers when the salinity was very low (1‰) during July at the stn 2. Diatoms such as *N. closterium* bloomed at 19‰ (June), *N. seriata* (stn 3) at higher salinity of 30‰ (Mar) and *C. marginatus* and *N. seriata* (stn 3) exhibited bloom conditions at a salinity of 29‰ (Feb). Based on experimental evidences, Desikachary and Rao (1972) suggested that variations in salinity in natural environments can also influence the productivity of diatom populations. The dinoflagellate *C. furca* (stns 4 and 5) formed blooms when salinity levels were between 24 and 24.5‰ during September. The unidentified blue-green alga (stns 1–3) preferred 32–32.5‰ and were dominant during May. Studies off Madras in the

Table 2. Concentration of phytoplankton (10^3 cells or filaments l^{-1}) during bloom situation along with salinity and diversity index in the Mandovi-Zuari estuarine complex.

Species	Month	Cells or filaments	Total cells or filaments	Percentage in total	Salinity (%)	Diversity index
<i>Leptocylindrus danicus</i>	November	22.0	86.0	25.6	30.9	3.10
<i>Nitzschia bilobata</i>	November	15.5	62.0	25.0	29.0	3.10
<i>Chaetoceros curvisetus</i>	December	140.0	356.0	39.3	31.7	3.20
<i>Bacillaria paxillifer</i>	January	24.0	76.0	31.6	33.0	2.70
<i>Nitzschia longissima</i>	January	25.0	85.3	29.3	35.0	3.00
<i>Coscinodiscus marginatus</i>	February	167.0	200.0	83.5	29.0	1.07
<i>Delphineis surirelloides</i>	March	40.5	49.3	82.2	28.0	0.77
<i>Nitzschia seriata</i>	March	16.0	49.0	32.7	27.3	2.80
Unidentified blue-green	May	439.8	485.5	90.6	82.5	0.75
Unidentified blue-green	May	93.0	142.3	65.4	35.0	1.90
Unidentified blue-green	May	408.0	453.3	90.2	32.0	0.77
<i>Nitzschia closterium</i>	June	148.0	296.5	49.9	19.0	1.98
<i>Leptocylindrus danicus</i>	June	109.5	296.5	36.9	19.0	1.98
<i>Delphineis surirelloides</i>	June	26.5	43.0	61.6	18.0	2.30
<i>Delphineis surirelloides</i>	July	25.0	36.0	69.4	2.5	1.70
<i>Skeletonema costatum</i>	July	38.0	45.5	83.5	15.0	1.20
Unidentified pennate diatom	July	2.0	4.8	42.1	1.0	1.30
<i>Pleurosigma angulatum</i>	August	5.0	19.8	25.3	15.6	2.70
<i>Delphineis surirelloides</i>	September	597.5	633.0	94.4	18.5	0.49
<i>Ceratium furca</i>	September	39.5	54.5	72.5	24.5	1.70
<i>Ceratium furca</i>	September	95.0	122.5	77.6	24.0	1.10
<i>Delphineis surirelloides</i>	October	96.0	166.5	57.7	31.5	2.10
<i>Nitzschia closterium</i>	October	747.5	1369.0	54.6	28.2	2.50

Bay of Bengal indicated that sizeable euryhaline component of the diatom population in the Bay contributed substantially to the abundance of nearshore phytoplankton (Ragothaman and Rao 1978). Further, they observed that the occurrence of phytoplankton bloom in the nearshore regions of the Bay very often coincides with a marked decrease in salinity of the nearshore waters. The predominant plankton diatoms involved in such blooms, in several instances, have been traced to be of estuarine origin.

In the Mandovi estuary, the species diversity indices ranged from 0.49 (Sept) to 4.2 (June) and in the Cumbarjua canal it was between 0.75 (May) and 3.65 (Nov). In the Zuari estuary (see figure 11), the indices for the surface phytoplankton varied from 1.1 (Sept) to 4.1 (April).

Primary productivity exhibited seasonal and spatial heterogeneity as was observed with chl *a* concentrations and phytoplankton cell counts. Higher values were generally encountered at the surface or slightly below the surface at all the stations. Figures 6c, 7c, 8c, 9c and 10c show the monthly fluctuations at the surface and in the column production. In the Mandovi estuary, 3 peaks (Dec, May and Oct) were recorded at stn 2. The highest production of $82 \text{ mgC m}^{-3} \text{ h}^{-1}$ was recorded at the surface and $135 \text{ mgC m}^{-2} \text{ h}^{-1}$ in the column during October. The dominant phytoplankters contributing to the higher production values were *L. danicus* in December, *S. costatum* and *Leptocylindrus minimus* in October and the unidentified blue-green alga in May. At stn 1, similar trimodal peaks were observed

in February, May and October—the highest surface production ($140 \text{ mgC m}^{-3} \text{ h}^{-1}$) being in September and the highest column production ($185 \text{ mgC m}^{-2} \text{ h}^{-1}$) in October. Primary production was high during October at both the stations in the Mandovi. *C. marginatus* dominated in February, the unidentified blue-green alga in May and *N. closterium* predominated in June and October.

In the Cumbarjua canal, at the stn 3 also, 3 peaks of column primary production were observed in November, April and October. However, the highest surface production was in May ($120 \text{ mgC m}^{-3} \text{ h}^{-1}$) which was due to a bloom of the unidentified blue-green alga. The highest column primary production ($152 \text{ mgC m}^{-2} \text{ h}^{-1}$) was observed in November. The lowest production values were recorded during the months of July and August (figure 8c).

In the Zuari estuary at stn 5, the highest surface and column production values were $79 \text{ mgC m}^{-3} \text{ h}^{-1}$ and $100 \text{ mgC m}^{-2} \text{ h}^{-1}$ respectively during October, whereas at stn 4, they were found to be $134 \text{ mgC m}^{-3} \text{ h}^{-1}$ and $270 \text{ mgC m}^{-2} \text{ h}^{-1}$ respectively during December. The latter was the highest value observed during the present study and was evidently due to the occurrence of a mixed diatom bloom, mainly comprising of *C. curvisetus*, which contributed 39.3% of the total phytoplankton population during that month. Lowest values were recorded during July and August when turbidity was the highest and light penetration minimum (figures 9c, 10c).

Average primary productivity rates per day calculated for the entire year were 0.58, 0.52 and $0.43 \text{ gC m}^{-2} \text{ d}^{-1}$ for the Mandovi, Cumbarjua canal and Zuari estuaries respectively. An overall average value for the estuarine complex works out to be $0.51 \text{ gC m}^{-2} \text{ d}^{-1}$. This value is similar to the estimate arrived for the Cochin backwater by Qasim *et al* (1969). The annual primary production value works out to be $186 \text{ gC m}^{-2} \text{ yr}^{-1}$ and is close to the figure arrived at by P M A Bhattathiri (unpublished results) following identical methods ($205 \text{ gC m}^{-2} \text{ yr}^{-1}$) for the same estuarine complex.

The relationship between different hydrobiological parameters in the Mandovi, Cumbarjua canal and Zuari estuaries has been arrived at by simple correlation coefficients (table 3). The significance of r has been tested by the T test at 5 and 1% significance levels.

The correlation coefficients of phytoplankton with primary production and chl *a* were highly significant in all the 3 areas. Primary production correlated significantly with chl *a* in the Cumbarjua canal and Zuari estuary.

The relationship of phytoplankton biomass and production with nitrate and phosphate were insignificant in all the 3 areas except for the Mandovi estuary where phytoplankton and phosphate concentrations showed positive correlation. These findings suggest that the instantaneous concentrations of nutrients are not very important in determining the standing crop or the production of phytoplankton in this estuarine complex.

The correlation coefficients of phytoplankton, chl *a* and primary productivity with salinity were significant in all the 3 areas. The scatter diagrams of chl *a*, phytoplankton cell numbers and primary production versus salinity presented in figure 12 show that very low saline waters (<10‰) cannot sustain high phytoplankton populations. Apparently, the scatter diagrams of phytoplankton assimilation numbers against salinity presented in figure 13 show that phytoplankton present in very low saline conditions are under physiological stress.

Table 3. Simple correlation coefficient matrix of hydrobiological features of the Mandovi-Zuari estuarine Complex.

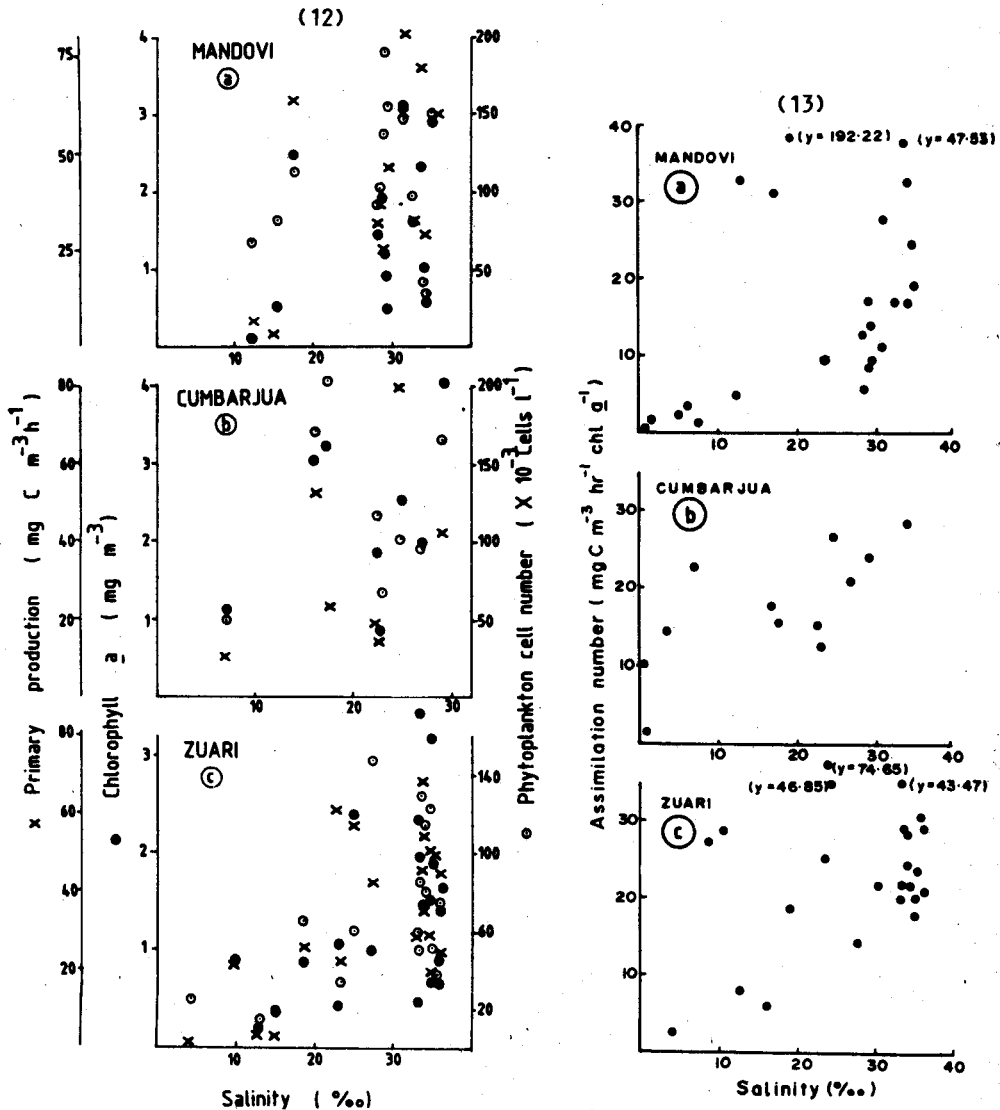
Variables	Phyto-plankton	Primary productivity	Chloro-phyll <i>a</i>	Zoo-plankton	Nitrate-nitrogen	Phosphate-phosphorus	Salinity
Mandovi (n = 24)							
Phytoplankton	—						
Primary productivity	0.635**	—					
Chlorophyll <i>a</i>	0.694**	0.324	—				
Zooplankton	0.135	0.239	0.093	—			
Nitrate-nitrogen	-0.230	-0.370	-0.076	-0.200	—		
Phosphate-phosphorus	0.513**	0.212	0.488*	-0.007	-0.190	—	—
Salinity	0.214	0.467*	0.068	0.307	-0.590**	-0.004	—
Cumbarjua (n = 12)							
Phytoplankton	—						
Primary productivity	0.772**	—					
Chlorophyll <i>a</i>	0.673**	0.817**	—				
Zooplankton	0.212	0.443	0.278	—			
Nitrate-nitrogen	0.229	-0.183	-0.066	-0.399	—		
Phosphate-phosphorus	-0.150	-0.132	-0.095	0.138	-0.361	—	
Salinity	0.332	0.698**	0.368	0.446	-0.260	-0.288	—
Zuari (n = 24)							
Phytoplankton	—						
Primary productivity	0.907**	—					
Chlorophyll <i>a</i>	0.700**	0.774**	—				
Zooplankton	0.164	0.304	0.498**	—			
Nitrate-nitrogen	0.021	-0.012	-0.046	-0.210	—		
Phosphate-phosphorus	-0.130	-0.007	0.074	0.217	-0.140	—	
Salinity	0.397*	0.471*	0.548**	-0.010	0.112	0.008	—

n = 24

n = 12

 $P < 0.05 = 0.3890$ $P < 0.05 = 0.53$ $P < 0.01 = 0.4969$ $P < 0.01 = 0.66$ Significant at * $P < 0.05$, ** $P < 0.01$.

This feature is conspicuous during the monsoon period in the Mandovi and Zuari estuaries. In the Cumbarjua canal however, phytoplankton populations appear to be better adapted to very low saline conditions. This is understandable, taking into consideration that during the nonmonsoon months, the salinity values averaged only about 22.9‰ as compared to 30.07‰ for the Mandovi and 34.33‰ for the Zuari estuary. In the Cochin backwater, in contrast to the observations made here, a negative correlation was observed between cell numbers and salinity. The most probable reason for such a difference between these two regions is the non-replacement of euryhaline phytoplankton by freshwater forms during the monsoon as was observed in the Cochin backwater by Devassy and Bhattathiri (1974). Another interesting feature noted in this study was that at salinities between 10–25‰ chl *a*, phytoplankton cell, primary production and assimilation numbers recorded were higher. Based on experimental studies with unialgal cultures as well as observations in natural phytoplankton, Qasim *et al* (1972) and Desikachary and Rao (1972) con-



Figures 12 and 13. 12. Correlation of salinity with primary production, chl *a* and cell number. 13. Correlation of salinity with assimilation number.

cluded that within limits, tropical estuarine waters with moderately low salinities support a greater abundance of phytoplankton.

A comparison between the Mandovi and Zuari estuaries showed that for most of the time typical estuarine conditions prevailed in the former which promoted optimum salinity regimes for higher phytoplankton production (Qasim *et al* 1972). Bhargava and Dwivedi (1976) noticed that the Mandovi waters were significantly different from those of the Cumbarjua canal and Zuari estuary. In the Zuari estuary however, higher salinity regimes and lower phytoplankton standing crops were observed.

Seasonal variations in chl *a*, phytoplankton cell numbers and primary production

have been summarised in table 1. It is obvious that the onset of monsoon results in a spontaneous increase in phytoplankton production. However, following heavy rainfall, enormous quantities of freshwater input result in extensive dilution and stratification. The resulting high turbidity along with the cumulonimbus cloud cover in the monsoon restrict light penetration in the water column limiting phytoplankton production. Thus, although increased nutrients are introduced into the system by land runoff, there is no effective utilization of nutrients till September. A gradual repopulation of the estuary following a recovery of salinity regime begins in the postmonsoon resulting in enhanced production.

It is obvious that salinity plays an important role in the distribution and abundance of phytoplankton in the Mandovi-Zuari estuarine complex than do nutrients. Since nutrient concentrations were never seriously limiting at any time, no pronounced effect on the phytoplankton standing crop could be observed as is evidenced by the r values derived for phytoplankton indices and nutrients.

Zooplankton biomass values fluctuated from 0.01–0.478 ml m⁻³. The annual average biomass values were 0.07 and 0.06 and 0.09 ml m⁻³ in the Mandovi, Cumbarjua canal and Zuari estuaries respectively. Qasim and Sengupta (1981) observed higher zooplankton biomass in the Zuari as compared to the Mandovi because of its greater marine influence. Copepoda followed by Cladocera and invertebrate larvae were the dominant groups in this estuarine complex. Zooplankton counts varied from 3–1,017 m⁻³. The highest counts were recorded in the premonsoon and postmonsoon periods. Similar results were also obtained by Goswami and Selvakumar (1977) and Selvakumar *et al* (1980).

Macrobenthic fauna of the Mandovi-Zuari estuarine complex was dominated by a polychaete-bivalve combination, these are filter-feeders and mainly subsist on particular organic matter sinking to the bottom (Parulekar *et al* 1980). Highest benthic biomass (5.2 gC m⁻² yr⁻¹) was obtained in the Mandovi estuary which, as pointed out earlier sustained the highest phytoplankton biomass. Lowest benthic biomass was observed in the monsoon season. Studies on phytoplankton distribution, primary productivity, chl *a* and zooplankton showed lowest concentrations during the monsoon. Although it is tempting to attribute the decline in benthic faunal abundance during the monsoon to a decline in phytoplankton production, Parulekar *et al* (1980) have ascribed the sparsity in benthic fauna to the salinity linked stress factor.

Based on the primary and secondary production values obtained in this study, the estimate of coefficient of energy transfer (defined as the rate of yield in one trophic level to the next trophic level) from the primary to secondary level works out to 6.3%. In this computation, the presence of carnivorous zooplankton has been ignored as they represented a very small percentage of the total zooplankton populations in this estuarine environment. Further, no attempt has been made to include benthic production as a component of the secondary trophic level in this computation (the benthic population does not subsist exclusively on phytoplankton production). The other important inputs of organic matter probably utilized by the benthic population, such as the production rate at the substratum and organic matter derived from the rich fringing mangrove vegetation bordering the estuarine system, were not measured in the present study. The value of 6.3% coefficient of energy transfer obtained in the present study, however, compares well with 6.6% (Selvakumar *et al* 1980) and 7% (Qasim 1977).

Bhattathiri *et al* (1976) have reported that the metabolic requirement of zooplankton in the estuarine complex varies between 0.1 and 7.2% of the total primary production. Therefore it is reasonable to believe that an excess stock of phytoplankton is available for alternate pathways in the Mandovi-Zuari estuarine complex. Studies from the Cochin backwater also revealed that phytoplankton production is surplus when compared to zooplankton grazing pressure and this excess food material culminates in alternate pathways in the trophic chain (Qasim and Madhupratap 1979; Qasim *et al* 1969).

From the primary productivity data collected, it is possible to arrive at an approximate estimate of fish yield of this estuarine complex. Tertiary production in carbon equivalents is estimated as 1% of primary production, which can then be converted into wet weight by using a factor of 10 (Qasim 1977).

The total area of the Mandovi-Zuari estuarine complex is estimated to be 92.14 km^{-2} whilst the annual mean primary production has been computed as 186 tonnes C km^{-2} . The total primary production for the whole complex therefore works out to be 17,138 tonnes C yr^{-1} . From these estimates of primary production, the potential fishery resource has been computed as 18.6 tonnes $\text{km}^{-2} \text{ yr}^{-1}$ or 1,714 tonnes yr^{-1} for the entire estuarine complex. The estimate of wet weight of fish obtained by Selvakumar *et al* (1980) based on the secondary production rates in this estuarine complex was 1,078 tonnes yr^{-1} . Studying the production at different trophic levels in the Mandovi-Zuari estuarine complex, during the southwest monsoon period, Bhattathiri *et al* (1976) estimated the tertiary production for monsoon as 0.15 tonnes C km^{-2} , which is very close to the present estimate of 0.174 tonnes C km^{-2} for the monsoon and can be considered as a representative value for this period.

Acknowledgements

The authors are grateful to Dr B N Desai for encouragement and to Dr P M A Bhattathiri for the help rendered during the course of this work.

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