

THE ENVIRONMENTAL CHARACTERISTICS OF THE GANGA ESTUARY

R. Sengupta

C. S. Murty

P. M. A. Bhattathiri

ABSTRACT

This report presents physical, chemical and biological observations in the last 160 km stretch of river Ganga for a period of 3 years.

In the one-layer estuary the mixing is brought about by the horizontal gradient of the flow field closely associated with tides. Direction of the axis of the ellipse at the mouth indicate the possibility of the return of part of the outflow along with the inflow. Penetration of the salt front never goes beyond Diamond Harbour, clearly demarcating the estuarine limits.

A significant chemical reaction zone exists between Diamond Harbour and Haldia resulting in precipitation of a good amount of nutrients and some dissolved metals. A zone of addition of nutrients could be noted from observations between Haldia and Sagar Island. About 85% of the dissolved metals settle within the river leaving only 15% to flow out. Only 10% of the suspended and particulate metals settle within the estuary, 50% at the confluence of river water with sea water and 40% finally flows out to the open Bay of Bengal.

Photosynthetic productivity and chlorophyll *a* decrease down stream. High zooplankton standing stock is observed. *Copepods* form the dominant constituent and numerous larvae and juveniles of commercially important fishes and prawns are observed. Occurrence and distribution of bacteria of health significance can be expected to be fairly high in the estuary. Significant numbers of the bacteria, which is the etiologic agent for food-borne *gastroenteritis*, are present in the waters and sediments at Sandheads and off the newly formed New Moore Island.

These observations would indicate that the estuarine region of river Ganga, as of now, has poor water quality and consequently weak resilient capacity.

INTRODUCTION

River Ganga rises from the Himalayan glacier Gangotri and reaches the plain at Rishikesh. Thereafter, flowing through the plains it bifurcates at Rajmahal. One branch flows further east and is known as Padma. The other branch flows south and is known as Bhagirathi upto Nabadwip and thereafter, as Hooghly upto Sagar Island where it opens out into the Bay of Bengal. To avoid confusion in nomenclature we have used the name Ganga even to denote the downstream and estuarine region.

The tidal limit of the river stretches from Sagar Island downstream to Nabadwip upstream, a distance of about 300 km. The estuarine region, defined by the intrusion of salt water to a minimum of about 1 ppt, is, however, restricted from Sagar Island to Diamond Harbour, a distance of approximately 100 km.

The runoff from Ganga is 493 km^3 every year, which is roughly about 30% of the total annual runoff, 1645 km^3 , from all the Indian rivers (Rao, 1979). This volume of water from Ganga annually adds 616×10^6 tonnes of suspended solids and 94×10^6 tonnes of dissolved solids to the Bay of Bengal.

This river is influenced by semi-diurnal tides of type M_2 . The maximum spring tide is about 5.5 m. This river is also visited occasionally by 'bores' during spring tides, periodically almost throughout the year because of the funnel - shape of the estuary and shallower depths. Considering its physical characteristics, the Ganga estuary can be classified as a 'coastal plain estuary' (Pritchard, 1967).

The estuarine stretch of the river is densely populated and a place of intense industrial activity. As a result of these, a total of $396 \times 10^6 \text{ m}^3$ of wastes, including $122 \times 10^6 \text{ m}^3$ industrial effluents, are added to this stretch every year (Ghosh *et al* 1973), which can be expected to be higher, as of now. The effects of this pollution are becoming significant and more detrimental to the water quality of the river.

Research in this estuary is an on-going process since a long time (Ghosh & Basu, 1968; Basu & Ghosh, 1970; Ghosh *et al*, 1973; Gopalkrishnan *et al*, 1973; Ray 1981; Nandi *et al*, 1983). The organisations who are carrying out almost regular observations in the river, are: Hydraulic Study Department of the Calcutta Port Trust, Central Inland Capture Fisheries Research Institute, National Environmental Engineering Research Institute and Marine Science Department of Calcutta University.

Several dams and barrages have been raised along the courses of almost all the major rivers of India. A barrage has been built across the Ganga at Farakka. However, our observations, though at the down-stream

reaches, attempt to delineate a picture of water characteristics without making any attempt to evaluate the effect of the Farakka barrage, which seems to have changed the ecological characteristics of the river, considerably, for the better (Nandi *et al*, 1983).

Available literature data on environmental parameters from the Ganga estuary are only from samples collected once during high and low tides. In a tide-dominated estuary with wide range in M_2 tides such observations will hardly indicate either the tidal fluctuations of the components or their residual effects. Samples collected at a mid-depth every 3 hours over two tidal cycles for a total of about 25 hrs, and equal aliquots from each collection when integrated and analysed for chemical components gives only the residual tidal effect on the components, which is vital for all pollution studies. We, therefore, applied the same methodology to our study of the Ganga estuary.

MATERIAL AND METHODS

Observation stations were fixed at off-Diamond Harbour, Haldia and Sagar Island within the estuary and at Sandheads outside it (Fig. 1). One station was also worked off-New Moore Island at the easternmost extreme of Indian territorial waters (Fig. 2). R V GAVESHANI was used whenever available. On one occasion, R V ANUSANDHANI was chartered. During the rest of the samplings-hired boats were used. Physical, chemical and biological observations were carried out over two tidal cycles from the research vessels while only chemical and biological sampling over one tidal cycle could be conducted from the boats. Basically, the sampling procedures were as follows :

(i) Physical

The ships were anchored at the stations over 13 to 25 hrs. Depending on the mean depth of the stations, 3-4 self recording Aanderaa current-meters were suspended with weights and sinkers using the heavy duty winches of the ships at depths from 3m below the surface to about 1m above the bottom. These current meters recorded speed and direction of the flow as well as temperature and conductivity of water at prefixed intervals. Currents at the upper layer were measured using a Direct Reading Current- Meter designed at NIO.

(ii) Chemical

Integrated samples collected by using Niskin PVC water samplers, from mid-depths were analysed on board for salinity, pH, dissolved oxygen, phosphate-phosphorus, nitrite-nitrogen, nitrate-nitrogen and silicate-silicon. A part of the samples were also filtered on board for analysis of heavy metals for suspended and particulate matter.

The analytical methods followed were the same as described by Grasshoff *et al* (1983). Accuracy and reproducibility of the data were checked by replicate analysis occasionally. The quality of all such data were controlled by participating in the International Inter-calibration exercises organised by IOC of UNESCO and in the NIO/DOD/SCOR National Intercalibration exercises.

(iii) Biological

Water samples were injected with ^{14}C and incubated on board for estimation of photosynthetic productivity. Part of the water was also filtered for measurement of chlorophyll *a*.

A Heron-Tranter net was kept suspended for 3 hours, between two samplings, for the collection of zooplankton.

Benthic samples were collected using a LaFond - Diatz snapper or a Van-Veen grab.

INTERPRETATION OF DATA

A. Physical Observations

i) Currents and tides

Three stations, off-Diamond Harbour, Haldia and Sagar Island, were selected to collect time series data on all the time-variable physical parameters. The distances of these stations from Calcutta Port point, measured along the navigation channel presently in use are : 75 km, 105 km and 145 km respectively. Data were collected at all the stations for durations varying from 16 to 43 hours at two to four depths.

Broadly, changes in the properties are not conspicuous in the vertical at any given time and place. The general trend is one of tidal variations. The absence of measurable gradient along the vertical indicates that near-homogenous watermass undergoes turbulent mixing under the influence of tides up or down the river and bathymetric status of the estuary. However, spatial gradients indicate clearly the decreasing quantity of freshwater downstreams, irrespective of the seasons, which show wide range in salinity during the 'freshet' period, when the freshwater runoff is at its maximum.

The general flow pattern is mainly tide-induced. The funnel shape of the Ganga estuary is well suited for the optimum tidal flux which is the prime factor governing the channel regime and navigability in the downstream reaches. Currents, in general, show variations in magnitude, depending upon the location of the stations within the estuary. The duration of the flood and ebb flows and the occurrence of the maximum and

minimum current velocities present some time lag. The current shear in the vertical did not exhibit significant changes at any of the stations. The nature of mixing, particularly during the dry seasons, has been observed to be dependent on the weak stratification of waters. The salinity in the estuarine environment, during the 'freshet' period is around 2 ppt at the entrance (Sandheads) and decreases progressively with distance upstream. Values as low as 0.1 ppt could be recorded at Diamond Harbour. The mean salinity value drops by 21 ppt during February and by 13 ppt during August from Sandheads to Diamond Harbour.

The estuary being shallow, the tides keep the water well-mixed from surface to bottom. This could be observed by the low values of Richardson's number, indicating turbulent mixing. Residence time could not be computed due to lack of data on runoff, bathymetry, etc. Some indirect conclusions have, however, been drawn. The estuary is shallow and is subjected to tidal flushings twice every day. Richardson's numbers are low, indicating turbulent mixing and near homogeneity. Under these conditions the residence time of water particles cannot be high.

Flow patterns at Sandheads and off-New Moore Island show certain interesting features (Figs. 3 & 4). The major axis of the ellipse is oriented towards the north-south direction at Sandheads and the ratio of the major to minor axis increases with depth indicating a non-linear flow in the north-south direction. The flow off-New Moore Island is completely dominated by tides. The major axis of the ellipse is about 3 times the minor axis and tilted a little towards the axis of the river Ganga. These directional orientation of the ellipses towards the axis of the river would indicate that part of the outflow during low tides may return to the river with the inflow during high tides.

Summing up the observations at all the major river mouths on the east coast the following conclusions have been arrived at. In the coastal boundary drift values are low. Water particles move in a nearly-closed cyclic pattern with marginal separations. These would indicate high residence time which need to be examined in greater detail for studies pertaining to the discharge of any unwanted substance into the environment.

(ii) Dilution and salt front

Using the data on salinity, recorded during the current measurements at anchor stations, we made an attempt to compute the dilution and sea water fractions during different stages of the tide during different seasons of the year.

The amount of freshwater, contained in a 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).

The river Ganga can be considered as a vertically homogenous estuary, at least as far as its salt content is concerned. We, therefore, averaged the salinity values at periods of 'low to high water' and 'high to low water' during three series of observations in February, July and September, coinciding roughly with pre-monsoon, monsoon and 'freshet' periods. The inflow and outflow of the river are regulated by water movements at Sandheads. We have, therefore, used the salinity values at Sandheads as those of 'source water' and have used them to compute the freshwater fractions at Diamond Harbour, Haldia and Sagar Islands. The results are presented in Table I.

It is clear from Table I, that seawater during both the tidal phases gets almost equally diluted by freshwater by the time it reaches around Sagar Island. A significant dilution takes place between Sagar Island and Haldia during the wet season. However, during the dry season that dilution is only twice that at Sagar Island. At or around Diamond harbour, the water remains almost fresh throughout the year.

We then tried to calculate the extent of penetration of the salt front, considering the suitability of the river water for public water supply. The maximum permissible chloride concentrations for public water supply are : 200 mg/l according to WHO; 250 mg/l according to USPHS and ICMR; and 600 mg/l according to ISI (Sengupta and Singbal, 1985). We assumed the ICMR standard of 250 mg/l as the limit to study the penetration of the so called 'salt front' inside the river.

The following have been deduced by applying linear interpolation and extrapolation, wherever needed, between the values at the relevant stations. The salt front oscillates, on an average, from 2.7 km upstream of Diamond Harbour to 3.3 km down stream during low to high tides in non-monsoon and early monsoon months. Similar figures during high to low tides are 2 km upstream to 1.7 km downstream of Diamond Harbour. However, during the 'freshet' period this salt front hardly penetrates beyond Haldia. These conclusions broadly agree with those of Nandi *et al* (1983) about the receding of the euryhaline zone of the river due to the freshwater release from the Farakka barrage.

B. Chemical Observations

i) Nutrients

In an attempt to present a generalized picture of the variations of the nutrients inside the estuary and its confluence with the sea, we have

reduced the voluminous data by dividing the observation period into three seasons, e. g. pre-monsoon (February-May), monsoon (June-September) and post-monsoon (October-January). The east coast of India is also influenced by the North-East monsoon during the conventional post-monsoon period.

For all practical purposes, this estuary can be considered as a one-layer estuary. However, tidal and seasonal variations of properties do take place inside the estuary caused, mainly, by volume fluctuations of inflow and outflow. To generalise the picture, we have averaged all the values during the same months of the season for high and low tides throughout the observation period.

a) Qualitative analysis

We have tried to keep the qualitative and descriptive examination of the data to a minimum, as these will only increase the volume of the report without adding much to its substance. The examinations have been restricted only to those features which might warrant a quantitative analysis, as have been done later.

One set of observations of the time-variable chemical parameters during 4-9 July, 1983 at Diamond Harbour, Haldia and Sagar Island over 24 hours at each station is presented at Table II, as an example. The data, as expected, indicate diurnal and spatial variations of many of a chemical parameter. $T^{\circ}C$, pH and O_2 , however, hardly indicate any change, the estuary being shallow and well-mixed. Salinity variations have been detailed earlier. Data on total alkalinity (TA) being scanty have been excluded. We have, therefore, restricted our attempt to examine the data on PO_4 -P, NO_3 -N, and SiO_4 -Si in some detail.

Figures 5-7 present the values of the essential nutrients at all the stations over the stretch Diamond Harbour to Sandheads. The Theoretical Dilution Lines (TDL) between the lowest chlorinity value at the innermost station (Diamond Harbour) and the highest chlorinity value at the outermost stations (Sandheads) have been super-imposed on all the figures. This, no doubt, has its limitations as the chlorinity fluctuates, sometimes widely, at individual stations over the seasons. Hopefully, this generalized picture will help to delineate the very broad features of these chemical variables.

The general picture of all the nutrients is one of loss in the estuarine stretch of the river. Phosphate is lost by chemical and biological processes. Nitrate, being soluble in all forms, is lost only by biological assimilation. The estuary has always an excess of dissolved oxygen and, hence, nitrate

loss due to denitrification can be ruled out. At the upper reaches of the estuary, values of phosphate and nitrate would indicate addition. But the entire stretch of the estuary indicates a zone of precipitation for silicate. Observations at the river mouths and inshore regions of India indicate very low values of dissolved silicate (Rejendran *et al*, 1980). This, coupled with the present observations, would lead to the conclusion that insignificant amount of silicate in dissolved form, is added to the Bay of Bengal through river runoff.

Features in figures 5-7 tempt us to conclude that the nutrients, phosphate, nitrate and silicate, which are added to the river Ganga at its source and the civilization on its banks along its course, do not reach the sea. They either settle to the bottom of the river or are incorporated in biological systems within the river, part of which may be transported by the outflow ultimately. The only addition to the lower reaches of the estuary seems to be partly by the inflow of water from the Bay of Bengal, but mostly by anthropogenic additions, since concentrations in the inflow is very low as compared to the values within the estuary.

b) Quantitative analysis

Assuming a simple mixing relation between fractions of river water and sea water within the estuary, we tried to calculate the expected quantities of the nutrients during the three seasons for both high and low tides, applying the relation (Carpenter *et al*, 1975) :

$$X_{\text{sample}} = X_{\text{river}} + \frac{X_{\text{sw}} - X_{\text{r}}}{Cl_{\text{sw}}} \times Cl_{\text{sample}}$$

If the difference between the observed and the calculated concentrations is zero then the particular component remains unaltered and is in a steady state. When the difference is positive the component is added and when it is negative the component is removed.

For such calculations in a tide-dominated estuary, the ideal river value should be from non-tidal and uncontaminated reaches of the river. In the absence of such a value from Ganga we assumed the concentrations at Diamond Harbour as river values. Values of the variables at Sandheads upto 20 m have been considered as sea water concentrations, and are presented in Table III.

Values at all the stations for the months comprising of the three seasons both during high and low tides were averaged individually and taken as observed values. The 'expected' values were calculated applying the above relation and are presented as Tables IV to VI.

Phosphate - Phosphorus

It is clear from Table IV that concentrations of phosphate-phosphorus decrease seawards from Diamond Harbour and are always higher during the low tide than during the high tide. At Haldia, observed phosphate values are always lower than the calculated ones and those at Diamond Harbour during all the seasons. This would indicate a removal of phosphate in this stretch of the river. The mean removal is - 9%.

At Sagar Island, however, the observed phosphate values are higher than the calculated ones with a maximum during monsoon (mean addition + 25%). There should be some source of addition of phosphorus between Haldia and Sagar Island to cause this increase. In the absence of any definite information we presume that the sources for addition of phosphorus to this stretch of the river could be, the runoff from any or all of the tributaries, atmospheric precipitation and human activities along its shores. The influence of the concentrations in the 'source water' can be ignored as they are about an order of magnitude lower than all the observed and calculated values.

The processes of removal could also be only apparent. There should be a considerable tidal oscillation within the river because of the large tidal amplitude. This percentage removal can be the manifestation of the tidal oscillation as well. In addition, biological productivity and suspended particulates also act as sources and sinks for phosphates in estuaries.

Nitrate-Nitrogen

Similar to phosphate-phosphorus, nitrate-nitrogen also decreases seawards from Diamond Harbour (Table V). However, the average peak in concentration appears during pre-monsoon, which decreases through the seasons. An almost equilibrium condition seems to exist at Haldia during low tides except in monsoon when there appears to be a substantial removal. At Sagar Island, however, the difference between observed and calculated values of nitrate is positive throughout indicating addition, which could be due to the same reasons as phosphate-phosphorus.

In estuaries nitrate can be removed through biological productivity and denitrification while it can be added through river runoff, rainfall, oxidation of organic matter and human activities. Since the estuary is well-oxygenated, nitrate loss due to denitrification can be ruled out. The process of nitrification would rather take place resulting in addition to nitrate. Photosynthetic productivity in the Ganga estuary is fairly high, particularly during monsoon and postmonsoon. Hence, it could be inferred that biological productivity is the main process for nitrate removal.

In general, except during the low tides at Haldia, the mean values of difference between observed and calculated values of nitrate are positive throughout indicating a net addition. This is with reference to Diamond Harbour, where the concentration of nitrate is already fairly high. Rain water is known to contain a high amount of ammonia (Sengupta, 1973). This ammonia can get oxidised by the excess oxygen in the river adding to its nitrate pool. Here again, addition from the 'source water' can be ruled out as the concentration of nitrate at Sandheads is very low, sometimes more than an order of magnitude lower than that inside the river.

Although some nitrate will remain inside the estuary as a result of nutrient entrapment due to tidal oscillations, yet it appears that other sources may also add to it. Thus, it is clear that the estuarine reaches of river Ganga contain an excess of nitrate which is not conducive to good water quality, consequently limiting its recipient capacity.

Silicate - Silicon

The observed and calculated values of silicate-silicon along with the quantum of addition and removal are presented in Table VI. Compared to the other two inorganic nutrients, silicate-silicon shows a completely different behaviour. However, it also decreases seawards and increases with season with a maximum during post-monsoon.

River runoff is the main source of silicate to the estuary, whereas biological utilization and abiological removal of dissolved silicate by absorption onto suspended and particulate matter are the chief processes of its removal from water. High biological productivity coupled with high sediment load appear to be responsible for the removal of dissolved silicate throughout the year in this estuary, during both high and low tides, with a few exceptions.

In contrast to phosphate and nitrate, the general features of silicate in the Ganga estuary is one of removal from the water column throughout the entire stretch from Diamond Harbour to Sandheads. The removal is at its maximum near the Sagar Island during post-monsoon. Although a high concentration was observed at Sandheads during this season (Table III) this does not seem to be adequate to off-set the sedimentation loss of silicate.

We have now attempted to sum up these quantitative analyses of the nutrients. For this, instead of the percentage addition and removal during the individual seasons, we have considered only the overall mean values. This will help us, hopefully, to arrive at a general picture which

might be expected to manifest itself from the prevailing situation during the different seasons. The data are summed up in Table VII. It is apparent from Table VII that there is a removal between Diamond Harbour and Haldia with addition between Haldia and Sagar Island. Combination of these two results is a net removal, though of a small magnitude. Chemical, biological and abiological processes are responsible for this removal.

We shall, however, make some reservations about our conclusions. In the absence of data from non-tidal and uncontaminated reaches, values at Diamond Harbour have been assumed as river concentrations. The latter values can be expected to be order (s) of magnitude higher than the former. Such high concentrations of 'river water' resulted in negative values indicating nutrient losses. We are almost sure that with respect to uncontaminated river water, all the values would be positive and, instead of the net removal, a net addition could be expected.

C. Geochemical Observations

Estuarine regions are important sinks for several elements since the accumulation rates are very high and physico-chemical conditions are different from those in the open sea. Most of the riverine dissolved and particulate matter can be expected to settle to the bottom at the confluence of river water with sea water. We, therefore, made an attempt to compute the quantities of metals in different forms, which can be expected to be lost to the sediments.

We restricted our observations to the transition group of metals viz., Cu, Cd, Fe, Mn, Pb, Ni and Co. These would constitute the major bulk of the settleable metals, other than the alkali and alkaline-earth metals, at least as a first approximation. Presumably the concentrations of other minor metals may not affect the total quantity to any appreciable extent.

i) Dissolved metals

From Table VIII it can be seen that the total concentrations at Diamond Harbour, Haldia, Sagar Island and Sandheads are to 515, 171, 174 and 44 ppb respectively. It is clear that a considerable part of these metals settle inside the river. A significant chemical reaction appears to take place between Diamond Harbour and Haldia as has been observed for the nutrients also. This chemical reaction results in a loss of 67% of these metals from the water column.

The difference in concentration between Haldia and Sagar Island is almost negligible, but the difference in salinity between these two stations is over 10 ppt. Combination of the values at these two places

would give an addition of only 2% to the river water. This could as well be due to analytical error and can be ignored. It appears that between Haldia and Sagar Island, there is not much change in chemical factors as far as the trace metals are concerned. A look at Table II would indicate that the oxidation-reduction characteristics show hardly any change between these two stations.

We can, therefore, take the mean concentration of the metals at all the stations to arrive at a generalized picture. The mean comes to 287 ppb. Combining this with the concentration of 44 ppb at Sandheads gives us a figure of 85% precipitation of these metals at the river mouth. Thus, only 15% of the dissolved metal ultimately is expected to flow out into the Bay of Bengal.

ii) Suspended and particulate metals.

From the available data (Tables IX & X) we made an attempt to compute the amounts of Suspended and Particulate Metals (SPM) which can be expected to settle at or near the confluence of river water with sea water. The moisture content of SPM has been assumed to be around 75% to convert the dry weight data to wet weight basis. A significant amount of resuspension of sediments can be expected to take place at the sediment-water interface. We, therefore, based our calculations on the surface values only, since the surface SPM can be expected to be transported with the freshwater outflow and hence would, mostly, be of terrestrial and/or anthropogenic origin.

The percentage of SPM at Diamond Harbour is 1.86. Similar figure at Haldia is 1.95. This small difference could be due to analytical error. Therefore, it appears that very little or insignificant precipitation of SPM takes place between these two stations and the major settling would occur downstream Haldia. It has also been observed that there is hardly any difference in salt content between Haldia and Diamond Harbour, particularly during the 'freshet' period.

The per cent SPM at Sagar Island is 1.82. Combining this with the value at Haldia we get a figure of about 7% as the settling amount of SPM in this stretch. However, if the mean value of Diamond Harbour and Haldia (1.91%) is combined with that at Sagar, the settling rate becomes 5%. Hence, about 5 to 7% of SPM settles to the bottom in the stretch of the river between Haldia and Sagar Island.

The values at Sagar Island and Sandheads are 1.82 and 1.73% respectively. Earlier similar difference between Diamond Harbour and Haldia has been ignored. Salinity at Sandheads is about 10 ppt higher than

that at Sagar. This difference can be of significance for the settling of SPM. However, the percentage settlement, based on these values, comes to only 5%. If the mean value of Diamond Harbour and Haldia is combined with the Sandheads value the settling rate becomes 9%. Therefore, only 5 to 9% of SPM settles within the estuarine stretch from Diamond Harbour to Sandheads and the major settling can be expected to take place at the mouth region of the river. Of course, a part of this would oscillate with the tides within the river.

It has been mentioned under 'physical observations' that the major axis of the ellipse of the tidal flow at New Moore Island is directed towards the estuarine region of river Ganga and the direction of the flow is from northwest to southeast. Similar observations at Sandheads imply that the SPM transported with the outflow from the river will follow the southeasterly course, the direction of the mean current. We, therefore, made an attempt to compute the amount of SPM which can be expected to settle to the bottom at the mouth region between Sandheads and New Moore Island.

The per cent SPM at Sagar Island, Sandheads and New Moore Island are 1.82, 1.73 and 0.9 respectively. Combining the values at Sagar and New Moore Island we get a figure of about 50% for the rate of settlement. Similar figures for Sandheads and New Moore Island comes to about 48%. Thus, about 10% of the suspended and particulate metals, transported by Ganga, settles in the lower estuarine region between Diamond Harbour and Sandheads, about 50% in the mouth region and the remaining 40% would ultimately find its way into the Bay of Bengal proper.

We based our calculations only on our observations during the 'freshest' period in September. Some difference in this rate can be expected during the rest of the year, due to the varying amounts of inflow and outflow and higher difference between their salinities. We, naturally, do not claim accuracy in our calculations beyond first approximation.

This high rate of depositions in the mouth region of Ganga has resulted in the formation of a number of banks and shoals. In fact, the New Moore Island itself and several other fast growing mudbanks in this region are manifestations of this interaction of river water and sea water.

D. Biological Observations

i) Primary production and chlorophyll *a*

Measurements of primary production and chlorophyll *a* were

carried out at Diamond Harbour, Haldia, Sagar Island and Sandheads during September 1980.

At Diamond Harbour measurements of primary production were made twice during 13 hours. The values at surface, 2 m and 7 m below surface varied from 0.44 to 23.9, 0.30 to 9.2 and 0.20 to 4.8 $\text{mgCm}^{-3}\text{d}^{-1}$. The column values were between 2 and 68 $\text{mg Cm}^{-2}\text{d}^{-1}$. At Haldia the values of primary production at 0, 2 and 4 m were 11.50, 5.43 and 0.80 $\text{mg Cm}^{-3}\text{d}^{-1}$ while the column value was 29.3 $\text{mgCm}^{-2}\text{d}^{-1}$. Observations at Sagar Island were made twice. The values at 0, 2 and 7 m below surface varied from 14.3 to 16.3, 9.7 to 19.4 and 1.6 to 2.8 $\text{mg Cm}^{-3}\text{d}^{-1}$. Column values were 52 and 110 $\text{mgCm}^{-2}\text{d}^{-1}$ respectively on the two occasions.

From the above it could be seen that the average column production at Diamond Harbour, Haldia and Sagar Island were 34, 29, 81 $\text{mg Cm}^{-2}\text{d}^{-1}$ respectively.

Measurements of chlorophyll *a* were made four times in 13 hours at Diamond Harbour. The values at surface, 2 and 7m below surface showed variation from 0.87 to 1.83, 0.9 to 2.74 and 0.69 to 1.57 mg m^{-3} respectively. The average values were 1.4, 1.73 and 1.10 mgm^{-3} . The column values were found to be between 4.18 and 14.05 with an average of 9.82 mgm^{-2} . During a 12 hour cycle chlorophyll *a* was measured five times at Haldia. Variation in values (mgm^{-3}) of chlorophyll *a* at 0, 2 and 6m below surface were as : 0m : 0.81 to 1.41; 2m : 0.65 to 1.27; 6m : 0.94 to 1.57. The respective average values were 1.14, 0.85 and 1.25 mgm^{-3} . Column values showed variation from 5.32 to 8.70 mgm^{-2} (av. 6.45). At Sagar Island also observations were made five times during two tidal cycles. The values of chlorophyll *a* at surface, 2 m below surface and near the bottom were found to be between 0.29 to 0.82, 0.49 to 1.06 and 0.48 to 0.98 mgm^{-3} . The corresponding average values were 0.62, 0.64 and 0.64 mg m^{-3} . Column values showed variation from 2.72 to 6.09 mgm^{-2} (av. 4.72).

Variations in chlorophyll at these three stations indicated that in general the average values at different depths decreased in the order: Diamond Harbour, Haldia and Sagar Island.

The values of primary production indicate that they are less than some of the values reported for other estuarine systems. Nutrients are not limiting in the estuarine regions. The lower values could be due to the high turbidity and the consequent reduction in light with depth.

ii) Zooplankton

Seasonal, diel and tidal variability studies on the occurrence and

abundance of zooplankton were carried out at Sagar Island, Haldia and Diamond Harbour every month from June 1983 to March 1984. Observations were also carried out at Sandheads and at New Moore Island where the biomass values ranged from 36 to 125 ml/1000 m³ (mean 79 ml/1000m³) and 44 to 147 ml/1000 m³ (mean 88 ml/1000 m³).

Eighteen zooplankton *taxa* were recorded in the collections. Faunal and species diversity values were more for the zooplankton samples collected at the river mouths. *Cirripedia*, *Siphonophora*, *Ctenophora*, *Polychaeta*, *Cumacea*, *Isopoda*, *Cladocera*, *Copepoda*, *Amphipoda*, *Sergestidae*, *Decapoda*, including prawn larvae, *Chaetognaths*, *Pteropoda*, *Veliger* larvae, *Stomatopod* larvae, *Tunicata*, fish eggs and fish larvae were the common groups observed in the samples. Seasonal, tidal and diel variations in the distribution of zooplanktonic groups were discernible. *Copepods*, *Ostracods*, *Medusae*, *Chaetognaths* and *Lucifers* were abundant in samples collected during premonsoon; *Polychaetes*, *Mysids*, *Amphipods*, *Cirripede* larvae during post-monsoon and *Isopods*, *Decapod* larvae and fish larvae during monsoon season. *Siphonophores*, *Ctenophores*, *Cladocerans*, *Amphipods*, *Sergestids* and fish eggs were numerous in the samples taken at high tide and during day-time (0600 - 1800 hrs), while *Polychaetes*, *Decapod* larvae, *Cumaceans*, *Mysids*, *Veliger* larvae and fish larvae during low tide and in night collections (1800 - 0600 hrs). Spatial variability in the occurrence and abundance of zooplankton *taxa* was also noticed. *Hydromedusae*, *Copepods*, *Chaetognaths*, *Mysids*, *Decapod* larvae, *Amphipods* and *Ostracods* were abundant at Sagar Island; *Lucifers* and *Polychaete* larvae at Haldia and *Isopods* and fish larvae at Diamond Harbour.

Copepods were dominant at all the stations (Table XI). *Copepod* species belonging to genera *Paracalanus*, *Acartia*, *Pseudodiaptomus* and *Oithona* were common. *Paracalanus dubia* (Sewell), *Acrocalanus gracilis* (Giesbrecht), *Acartia plumosa* T. Scott, *Temora turbinata* Dana and *Oithona rigida* (Giesbrecht) were abundant. Larvae and juveniles of commercially important penaeid prawn species viz., *Metapenaeus monoceros* (Fabricius), *M. dobsoni* (Miers), *M. affinis* (Milne Edwards), *Penaeus merguensis* de man, and *P. indicus* (M. Edwards,) occurred invariably in the collections.

iii) Microbiology

Total Heterotrophic Bacteria (THB), Total Coliforms (TC), *Escherichia coli* (E.C.), *Faecal Streptococci* (F.S), *Vibrio* like organisms (V. L. O), *V. parahemolyticus* like organisms (V.P.L.O) and *Salmonella* like organisms were enumerated in water and sediments at Sandheads and

New Moore Island. Due to technical difficulties such studies could not be conducted inside the river.

The tidal variations of the THB population in water at Sandheads and New Moore Island were 12.48 - 62.5 x 10³/100 ml and 11.4 - 37.2 x 10³/100 ml respectively. The same in the sediments at Sandheads were 3.8-4.2x 10⁸/g dry weight.

TC and EC variations over a tidal cycle in water at the same stations were 2960 - 6720 and 2682 - 4650 per 100 ml respectively. Sandheads sediment contained 720 - 2340 and 166 - 920 per gram of these bacterial strains.

F.S were not detectable either in water or in sediments. However, *Salmonella* concentrations ranged from 20 - 110 and 11 - 85 per 100 ml of water respectively at both the stations. The sediments at Sandheads had 68 - 120 per gram.

Marine *Vibrio* species could be recovered in varying quantities. At Sandheads their ranges were 158 to 3406/100 ml in water and 23 — 67 x 10⁴/g in sediments. Waters at New Moore Island indicated 167 — 2340/100 ml.

One of the significant findings of this study was the occurrence of VPLO, the etiologic agent in food-borne gastroenteritis, in water and sediments at both Sandheads and New Moore stations. The number varied in water from 110 - 1860 and 56 - 1400 per 100 ml over one tidal cycle at the two stations respectively. In sediments at Sandheads their number ranged from 30.5 — 73 x 10³/g.

It is evident from these observations that Sandheads and New Moore Island areas are fairly polluted bacteriologically. These are transported with the outflow and part of it can be expected to return to the river as is evident from the flow patterns in figures 3 and 4.

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Legends to Figures

- FIGURE 1 : Locations of the observation stations in the Ganga estuary.
- " 2 : Locations of the observation stations at the mouth of some of the major rivers on the east coast of India.
- " 3 : Progressive vector diagram of movement of water at 14, 16, 18 and 20 m at Sandheads.
- " 4 : Progressive vector diagram of movement of water at 22, 23 and 24 m at the station off New Moore Island.
- " 5 : Variations of the concentrations of phosphate-phosphorus at surface, mid-depth and bottom at stations in the stretch Diamond Harbour and Sandheads in the Ganga estuary. The Theoretical Dilution Line (TDL) between the lowest chlorinity at the innermost station and the highest chlorinity at the outermost station is super-imposed on the figure.
- " 6 : Variations of the concentrations of nitrate-nitrogen at surface, mid-depth and bottom at stations in the stretch Diamond Harbour and Sandheads in the Ganga estuary. The Theoretical Dilution Line (TDL) between the lowest chlorinity at the innermost station and the highest chlorinity at the outermost station is super-imposed on the figure.
- " 7 : Variations of the concentrations of silicate-silicon at surface, mid-depth and bottom at stations in the stretch Diamond Harbour and Sandheads in the Ganga estuary. The Theoretical Dilution Line (TDL) between the lowest chlorinity at the innermost station and the highest chlorinity at the outermost station is super-imposed on the figure.

TABLE I

Stations	Low to High Water			High to Low Water		
	S ‰	DF	DF (%) Sea Water	S ‰	DF	DF (%) Sea Water
February 1983						
Diamond Harbour	0.94	0.97	3	1.0	0.97	3
Haldia	6.36	0.79	21	9.08	0.71	29
Sagar Island	13.22	0.97	43	14.75	0.52	48
July 1983						
Diamond Harbour	0.14	0.99	1	0.17	0.99	1
Haldia	2.90	0.91	9	5.11	0.84	16
Sagar Island	11.47	0.85	35	12.33	0.62	38
Sandheads	32.53	-	-	32.52	-	-
September 1983						
Diamond Harbour	0.09	0	0	0.09	0	0
Haldia	0.24	0.99	1	0.35	0.99	1
Sagar Island	11.21	0.51	49	13.13	0.51	49
Sandheads	22.99	-	-	25.85	-	-

DF - Dilution Factor

TABLE II

Variations in Chemical Parameters at 3 stations in Hooghly River in relation to periods, tide and depth as observed during each tidal cycle

Station	Date	Time	Depth of Collection	Temp °C	pH	TA		S ‰	O ₂ /l		PO ₄ -P		NO ₃ -N		SiO ₂ -Si			
						Mequiv/l	Max.		Min	Max.	Min	Max.	Min	Max.	Min	Max.	Min	Max.
Diamond Harbour	0700 of 9.7.83	to	Surface	36.36	8.34	8.11	1.97	1.82	0.52	0.37	4.98	4.46	10.73	7.53	8.88	6.76	64.88	32.1
			mid-depth (1m)	36.50	8.34	8.13	1.96	1.82	0.52	0.41	4.87	3.57	13.41	3.02	8.86	8.05	72.52	37.6
			mid-depth (5m)	36.90	8.34	8.13	3.98	1.82	0.48	0.34	4.89	2.16	19.58	3.25	8.75	8.05	66.80	25.1
Haldia	0930 of 4.7.83	to	Surface	29.30	8.32	7.77	2.13	1.91	8.80	3.84	5.30	4.84	10.37	2.60	17.02	10.46	100.43	39.4
			mid-depth (1m)	29.30	8.34	8.18	2.21	2.04	9.56	3.75	5.28	4.73	10.19	3.96	15.37	9.11	107.86	26.0
			mid-depth (5m)	29.20	8.40	8.33	2.16	2.03	9.03	3.64	5.23	4.79	2.08	1.77	13.15	10.41	112.69	30.8
Sagar	0600 of 6.7.83	to	Surface	31.40	8.18	8.15	2.41	2.08	28.33	8.56	5.36	2.36	7.45	1.82	13.26	4.00	56.79	23.9
			mid-depth (1m)	29.80	9.20	8.17	2.26	2.00	28.62	7.71	5.18	2.42	6.27	2.63	14.05	4.41	77.52	22.9
			mid-depth (5m)	29.50	8.17	8.12	2.24	2.10	26.32	8.35	5.51	2.15	11.48	1.73	13.31	4.24	81.47	24.0
			Bottom (11m)															

TABLE III
Chlorinity (‰) at all the stations and nutrients ($\mu\text{mol. dm}^{-3}$) of 'Source' water

Stations	Haldia (Cl‰)		Sagar Island (Cl‰)		Sandheads Nutrients							
					Cl‰		P		N		Si	
	HT	LT	HT	LT	HT	LT	HT	LT	HT	LT	HT	LT
Pre-monsoon	5.03	3.52	8.16	7.32	17.13	16.98	0.44	0.54	0.99	1.03	18.7	49.7
Monsoon	0.19	0.13	7.27	6.20	14.30	12.73	0.45	0.63	0.97	0.98	25.1	37.7
Post-monsoon	2.83	1.60	8.82	6.35	18.30	18.00	0.35	0.36	0.20	0.21	32.2	91.8

TABLE IV
Average Observed Concentrations of Phosphate-Phosphorus and Expected Values ($\mu\text{g at. l}^{-1}$)

Seasons	Diamond Harbour		Haldia						Sagar Island						
	HT	LT	P _{obs}		P _{calc}		P _{obs} P _{calc} (%)		P _{obs}		P _{calc}		P _{obs} P _{calc} (%)		
			HT	LT	HT	LT	HT	LT	HT	LT	HT	LT	HT	LT	
Pre-Monsoon	3.81	5.34	2.73	4.13	2.82	4.34	4.34	-3	-5	2.71	4.71	2.20	3.27	+19	+30
Monsoon	4.53	6.38	4.34	6.17	4.47	6.32	6.32	-3	-2	3.44	5.45	2.45	3.58	+33	+24
Post-monsoon	2.24	4.96	2.16	3.60	1.94	4.55	4.55	+10	-26	2.11	3.37	1.52	3.3	+28	+1
		Mean :	3.08	4.63	3.08	5.07	5.07	±0	-9	2.75	4.51	2.06	3.3	+25	+25

TABLE V
Average Observed Concentrations of Nitrate-nitrogen and Expected Values ($\mu\text{g at. l}^{-1}$)

Seasons	Diamond Harbour		Haldia				Sagar Island								
	HT	LT	N_{obs}	N_{calc}	N_{obs}	N_{calc}	N_{obs}	N_{calc}	N_{obs}	N_{calc}	N_{obs}	N_{calc}			
					($\%$)				($\%$)						
Pre-Monsoon	11.29	13.65	10.95	11.64	8.26	11.92	+25	-1	8.61	10.25	6.38	6.32	+26	+19	
Monsoon	12.30	18.43	9.15	11.43	12.15	18.25	-33	-60	7.29	10.07	6.54	9.93	+10	+1	
Post-monsoon	8.00	11.16	7.68	10.30	6.77	10.15	+12	+1	6.06	7.45	5.04	8.41	+17	-12	
			Mean:	9.26	11.19	9.06	13.45	+2	-20	7.32	9.27	5.99	8.99	+16	+4

TABLE VI
Average Observed Concentrations of Silicate-silicon and Expected Values ($\mu\text{g at. l}^{-1}$)

Seasons	Diamond Harbour		Haldia				Sagar Island							
	HT	LT	Si _{obs}	Si _{calc}	Si _{obs} - Si _{calc} (%)	HT	LT	HT	LT	Si _{obs}	Si _{calc}	Si _{obs} - Si _{calc} (%)	HT	LT
Pre-Monsoon	59.4	70.5	58.0	62.5	47.4	66.2	+18	-6	30.0	57.9	40.0	61.6	-33	-6
Monsoon	78.0	105.8	68.7	78.4	77.3	105.1	-12	-34	44.0	77.8	51.1	72.6	-16	+7
Post-monsoon	82.09	104.7	60.0	99.0	74.9	103.5	+6	-4	42.1	73.4	63.9	100.1	-52	-36
	Mean:		68.9	80.0	66.5	91.6	+3	-14	38.7	69.7	51.7	76.1	-33	-12

TABLE VII
Percentage of the mean tidal addition and removal of phosphate, nitrate and silicate at Haldia and Sagar Island with reference to Diamond Harbour

	Haldia			Sagar Island				
	P	N	Si	Total	P	N	Si	Total
High Tide	0	+2	+3	+5	+25	+18	-33	+10
Low Tide	-9	-20	-14	-43	+25	+4	-12	+17
	Net			-38				+27
								-11

TABLE VIII
Concentrations of dissolved trace metals in the integrated samples in the
estuarine region of the river Hooghly in $\mu\text{g l}^{-1}$ (September 1980)

Station	Depth (m)	Salinity ‰	Cu	Cd	Fe	Mn	Zn	Pb	Ni	Co
Diamond Harbour	Mid-depth 7	0.09	17.5	2	237.5	39.3	173.8	14.5	30.3	0.5
Haldia	Mid-depth 7	0.81	7.1	1.5	62.3	4.3	75	5	14.8	1
Sagar	Mid-depth 7	10.99	5.5	0.25	38.5	7.8	105	9.8	6.3	1.3
Sandheads	Mid-depth 20	30.84	4.8	0.75	11.5	2.3	14.8	1.5	6.8	1.8

Table IX
SURFACE PARTICULATE MATTER (Mean values-September 1980)
 (Mn, Cu, Ni, Zn, Cr in ppm)

	Fe (%)	Mn	Cu	Ni	Zn	Cr
Diamond Harbour	7.32	954	88	93	105	120
Haldia	7.68	1068	100	105	115	130
Sagar	7.15	985	89	103	103	118
Sandheads	6.90	992	85	100	99	95
New Moore Island	3.50	375	46	53	72	50
1740	4.00	470	55	62	75	45
Mahanadi	5.62	725	65	76	85	92

Table X
SURFACE PARTICULATE MATTER (Mean values-
September 1980) (in dry weight basis)
(Mn, Cu, Ni, Zn, Cr in ppm)

	Fe (%)	Mn	Cu	Ni	Zn	Cr
Diamond Harbour	8.15	1098	100	115	118	120
Haldia	8.38	1090	105	112	120	113
Sagar	8.45	1210	112	123	125	130
Sandheads	8.20	1140	106	120	118	123
New Moore Island	3.80	440	53	58	65	53
1740	4.25	483	56	62	82	65
Mahanadi	5.60	525	65	73	85	73

Table XI
Occurrence of common groups (average No. l/m³) at the 3 stations
during June 1983 – March 1984

Groups	Sagar Island	Haldia	Diamond Harbour
<i>Copepoda</i>	79786.3	48330.4	25999.8
<i>Decapoda</i>	163.0	90.7	69.7
<i>Lucifera</i>	41.8	105.1	87.3
<i>Chaetognatha</i>	85.1	13.8	21.0
<i>Polychaeta</i>	18.4	51.7	15.8
<i>Ostracoda</i>	37.4	6.0	2.6
Fish larvae	12.4	9.1	21.9
<i>Hydromedresae</i>	19.1	51.7	15.8
<i>Isopoda</i>	13.2	8.9	13.4
<i>Amphipoda</i>	3.8	1.6	2.3
<i>Mysiaeea</i>	1.7	0.0	0.6
Total	80183.2	48668.4	26249.6

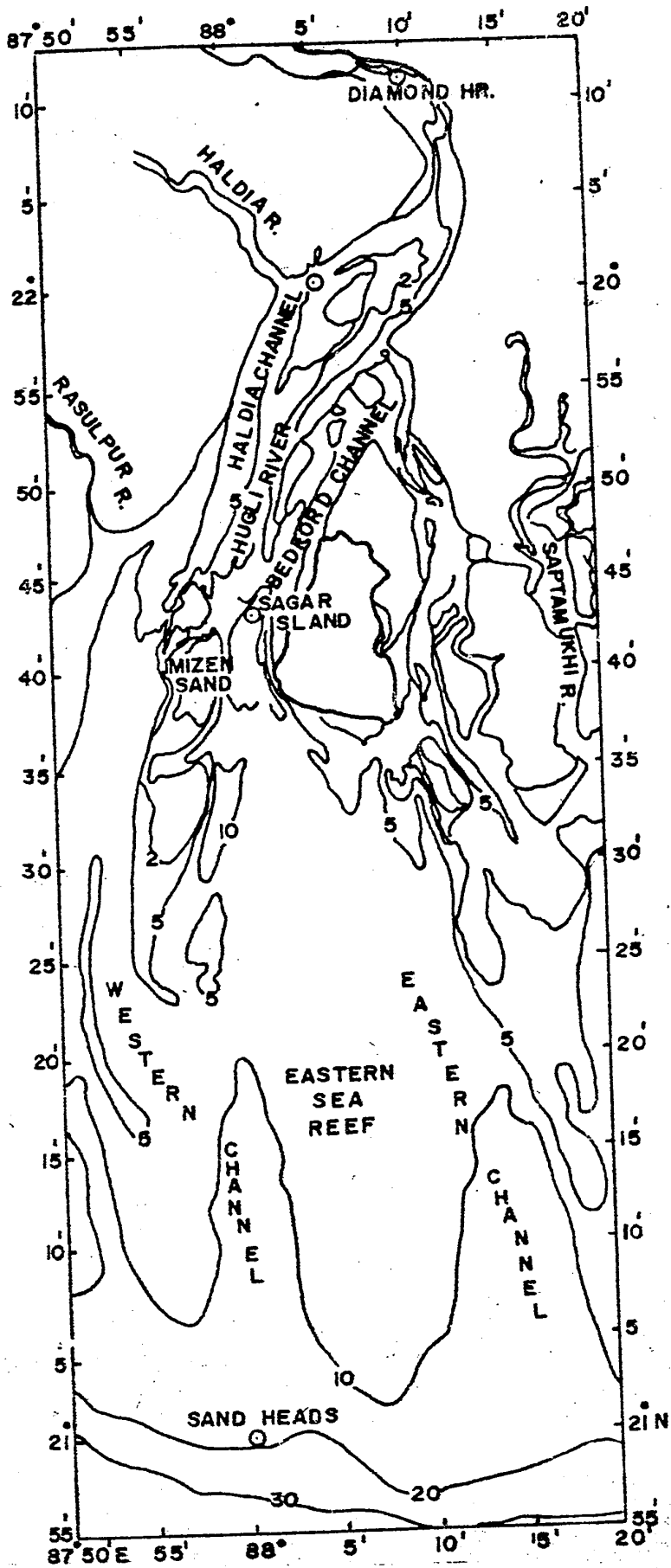


Fig.1 Ganga estuarine system. Closed circles indicate the position of four stations. Numbers give the depth contour. in metres

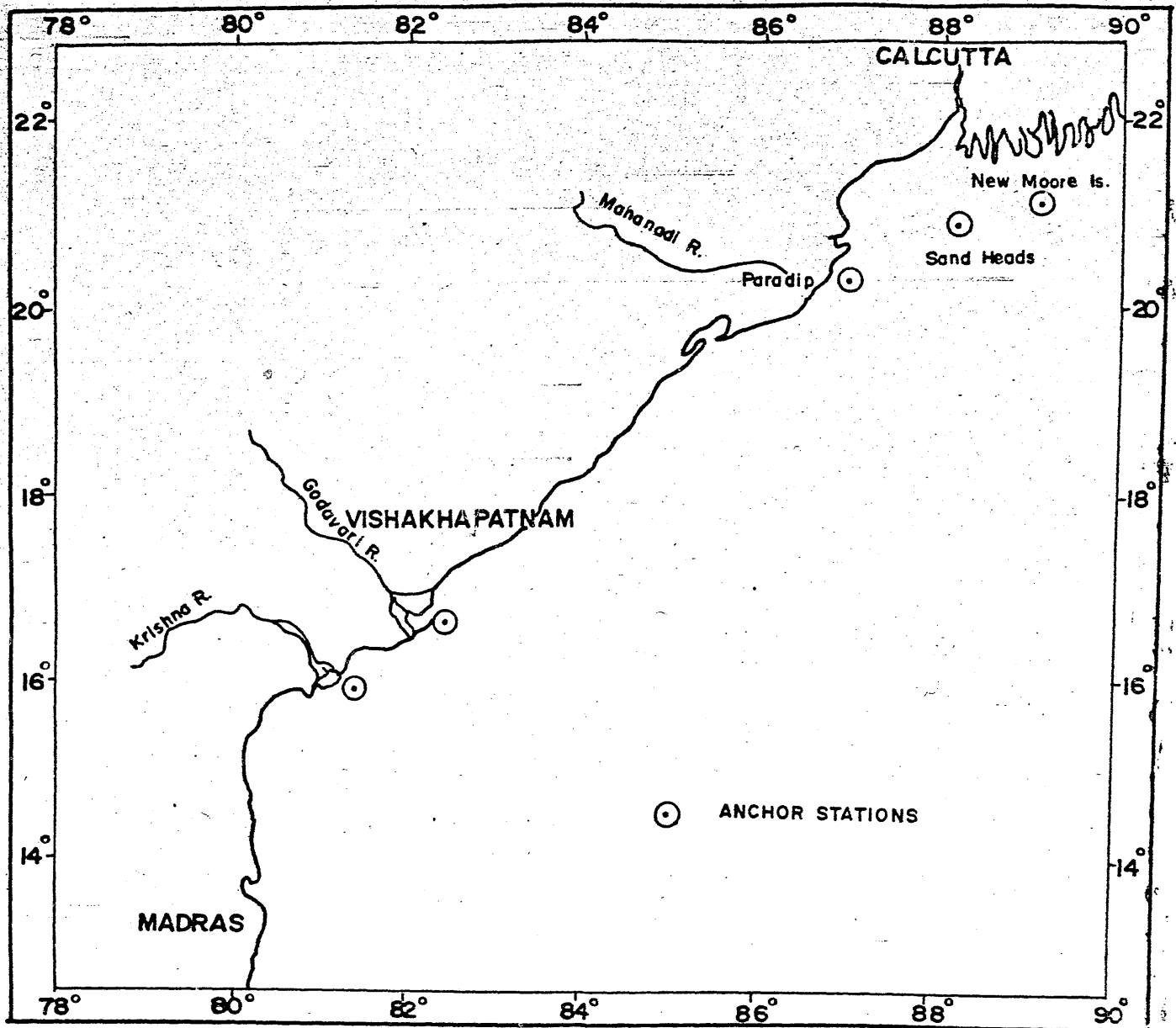


FIG. 2