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PHYSICOCHEMICAL AND BIOLOGICAL CYCLES IN A TIDE DOMINATED, NITROGEN-POLLUTED TEMPERATE ESTUARY

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ABSTRACT

Spatio-termporal variations in the physicochemical and biological parameters in the Morlaix estuary on the Brittany coast of France were studied. The estuary is characterized by strong tidal currents and low freshwater flow. Hydrographically, the estuary can be classified into 3 segments: the upper estuary where stratification always persists, the *lower estuary where vertical homogeneity is permanent*, and a middle estuary where there is a regular oscillation of stratification and homogeneity during every tidal cycle, stratification being associated with slack waters and homogeneity, with ebb and flood. Nitrogen pollution in the estuary is very intense. The average concentration of nitrate in river waters was 397 ug-at N 1^{-1} (range: 5-125). Because of the heavy nitrogen pollution, NO_3:PO_4 ratios in the estuary range from 44 to 322, the highest known for world estuaries. However, the rapidly alternating stratification-homogeneity cycle, predominance of tidal prism volume over freshwater flow, and the short flushing time of 7 tidal cycles, counteract effectively the nitrogen pollution in the estuary. In spite of the strong mixing and tidal dominance, chemical and biological cycles evolve rapidly in the estuary, preceding those in the coastal waters by a month. Ammonium cycle is unique, as in the coastal waters, in that it accumulates in the estuary in spring and is utilised only in summer when nitrate is limiting. Calculations of the relative importance of nitrate and ammonium to primary production show that the winter-spring production is based on new nitrogen and summer-autumn production is sustained mainly by recycled nitrogen.

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INTRODUCTION

The estuaries along the west Brittany coast of France are unique in several respects (Wafar, 1981). Geomorphologically they are shallow coastal plain estuaries (rias) and open into a coastal body of water known for strong tidal action where tidal range at spring tides attains 9.5 m; the freshwater flow from the rivers is very low, less than 10 m^3 s^{-1} even at the highest river discharge; all rivers drain a hinterland known for intensive agricultural practices and consequently are selectively and heavily enriched with nitrate, with typical winter concentrations in the order of 400 ug-at Nl^{-1} and above; and almost all of them are interrupted in their upper reaches by man-made barriers. In addition, all these estuaries sustain rich clam beds, and several of them are being used for commercial oyster farming. These unique features, combined with a paucity of data on the physicochemical and biological processes in these estuaries, led to the present study on the hydrology, nutrients and productivity of the Morlaix estuary.

MATERIAL AND METHODS

Fig.1 shows the Morlaix estuary, and the sampling stations worked out in different sampling series. These are detailed below.

(a) *Transect stations :*

Eight stations, numbered 1 to 8 in Fig.1, from Morlaix dam down to Roscoff were sampled, in that order, at monthly intervals from February 1979 to June 1980. All field trips were made under same tidal conditions, midway between a neap tide (NT) and the succeeding spring tide (ST). Stn. 1 was sampled at high water slack, and the rest of the stations were sampled successively with the turn of the tide. Stns 1-4 were sampled only at the surface, 5 at the surface and bottom, and 6-8 at the surface, bottom and an intermediate depth.

(b) *Synoptic survey stations :*

A single synoptic survey essentially consisted of two field trips, made a week apart, one at ST and the other at NT. In both instances, sampling was done both at high water (HW) and low water (LW), thus covering four different tidal phases. Three series of synoptic surveys were made in October-

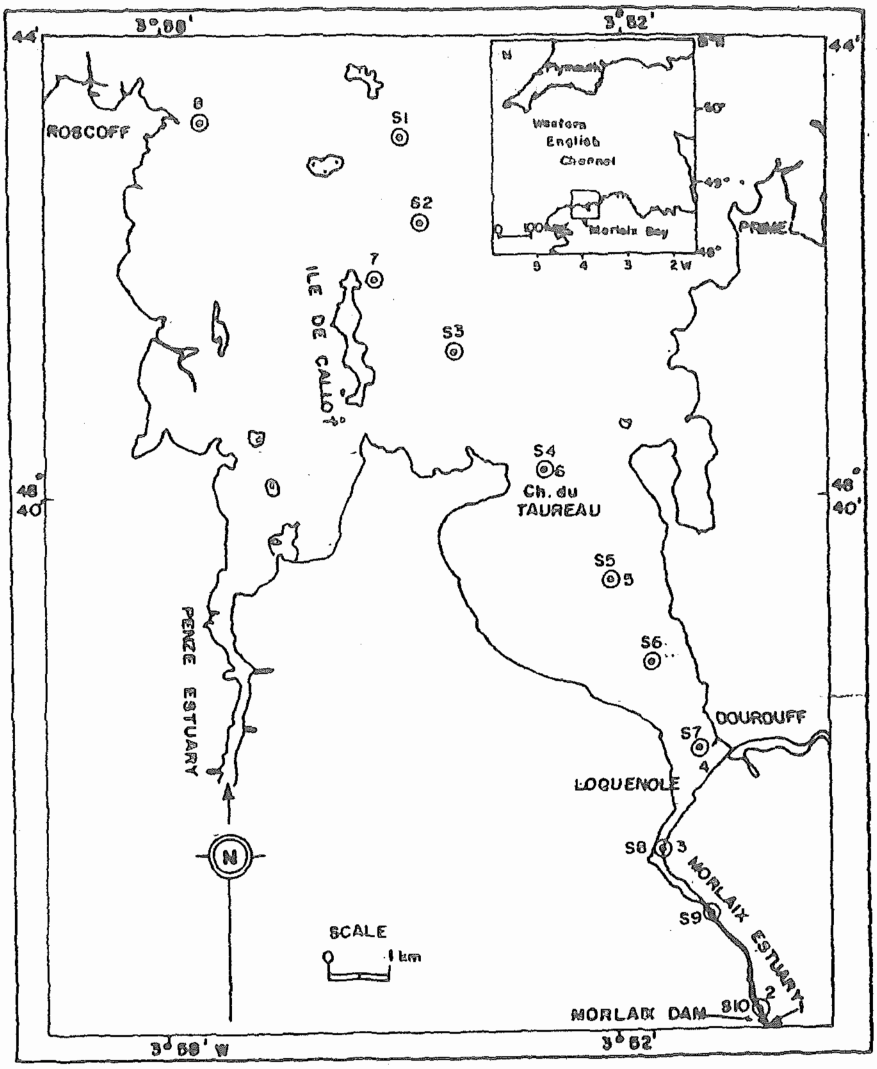

Fig. 1 : Morlaix estuary showing the position of the stations in transact and synoptic surveys.

November, 1978, January and May 1979.

The 10 stations covered under this study, prefixed with S in Fig. 1, were worked out in a reverse order beginning from the seaward end. Both at HW and LW sampling began at S1 75 minutes before the slack and the stations were sampled rapidly using two fast boats so that the last station S10 was reached at when the tide was at its slack. Sampling depths varied from three to only surface, depending on the state of the tide and the depth over the stations.

c) *Tidal cycle - fixed stations :*

4 stations, S4, S5, S7 and S8 were selected for measurements of changes of salinity and current velocity over tidal cycles. A total of 8 such measurements were made at various combinations of tides and river discharge. In all these studies,

sampling was at hourly intervals over a continuous 14 h duration. Current velocity measurements were obtained with a Braystoke current meter.

At all stations, water samples were obtained with 5 1 Niskin water samplers. Salinity was calculated from the conductivity ratio of the sample measured in a Guildline Autosal model 8400 salinometer. Particulate matter separated on GF/C filter pad not treated with $MgCO_3$ (Holm-Hansen and Riemann, 1978) was used for the fluorometric termination of Chl *a* and phaeopigments and their concentration calculated using Lorenzen's (1966) equations. Nutrients were analysed in a Technicon auto-analyser following the methods given by Treguer and Le Corre (1975).

RESULTS

(a) *Physical features*

Transect stations :

Salinity distribution (Fig.2) shows that the estuary downstream

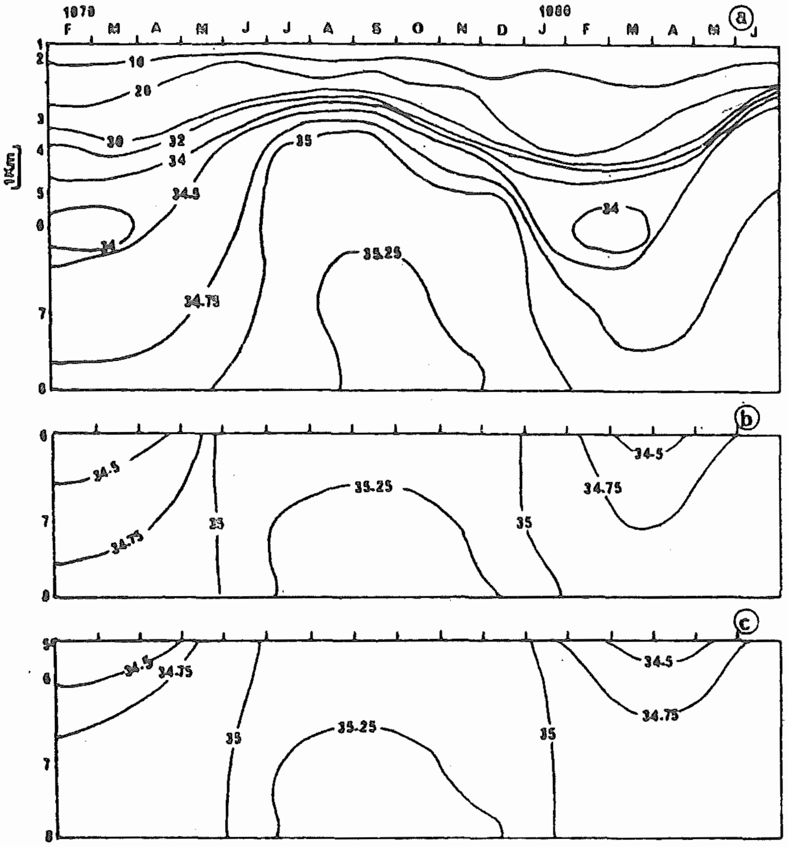

Fig.2 : Spatio-temporal variations of salinity measured at transect stations. a) surface; b) mid-depth and c) bottom.

to stn 5 preserves essentially a neritic character (> 34.5%), with vertical homogeneity prevailing throughout the year. At stn 5, the salinity decreased to between 34 and 34.5% in late autumn - early spring, but surface-to-bottom salinity differences were still within 0.5%, indicating vertical homogeneity (Haas, 1977). Stn 4 and the other upstream stations kform the gradient zone. when the river flow was at its lowest, this zone was limited to upstream of stn 3. With increased river flow this extended down to stn 4 but was never as far as stn 5.

Synoptic survey stations :

Figures 3-5 show the salinity distribution in the Morlaix

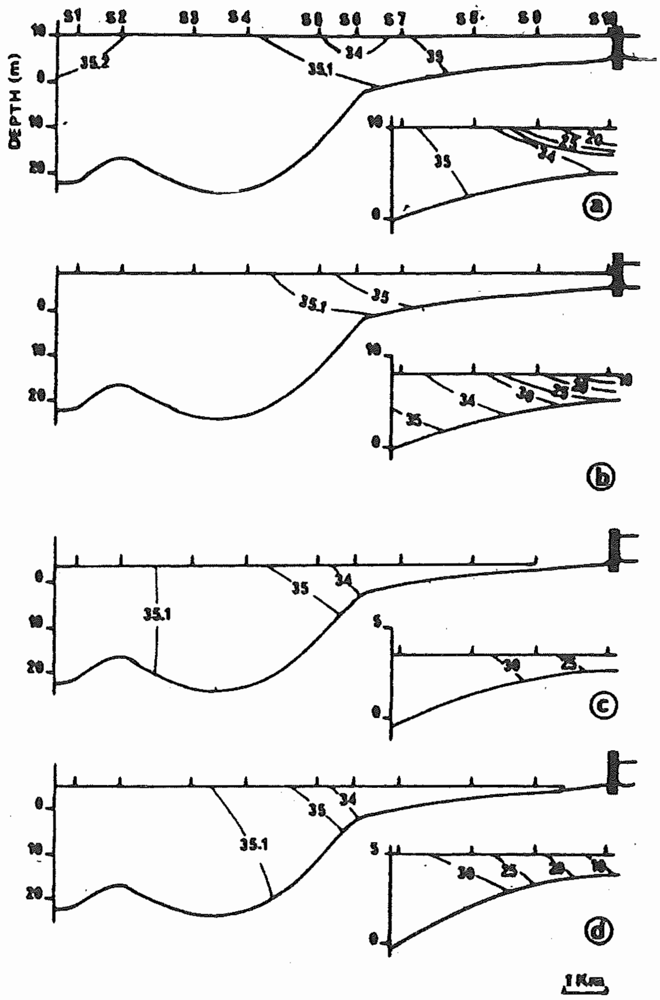

Fig.3 : Salinity distribution in the synoptic survey in October-November, 1978. a) STHW; b) NTHW; c) STLW and d) NTLW. Stations S7-S10 with different depth scale.

estuary as a function of tides and river flow. The October-November survey (Fig.3) was during low river discharge (LRD) (0.35 m^3 s^{-1}), January survey (Fig.4) during high

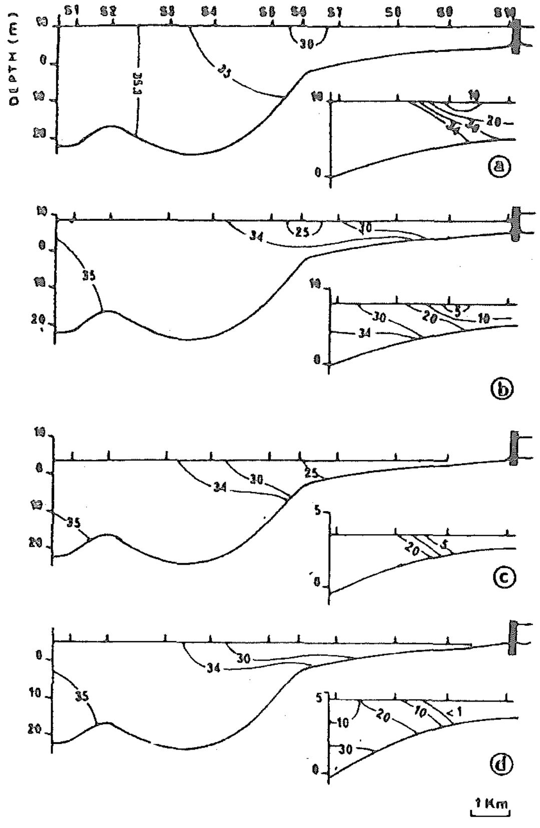

Fig.4 : Salinity distribution in the synoptic survey in January, 1979. Other details as in Fig.3.

river discharge (HRD) (2.42 - 2.46 $m^3 s^{-1}$) and the May survey (Fig.5) during moderate river discharge (1.61-2.37 m^3 s^{-1}). While the salinity distributions shown in Figs. 3-5 are self-explanatory, the salient results can be summarized as follows :

Vertical homogeneity prevails upto, and sometimes beyond, S7 at STHW irrespective of the strength of river flow. At NTHW, the extent to which homogeneity prevails in the estuary is a function of river flow; at LRD, vertical homogeneity is seen upto S7, and at HRD, only upto S4. At low water, irrespective on spring of neap tide, the extent to which homogeneity prevails is again a function of river flow. At LRD, it is upto S6. At HRD, stratification develops at S6 and extends down to S4. Regardless of the tidal conditions and river flow, stations S1-S3 show complete vertical homogeneity.

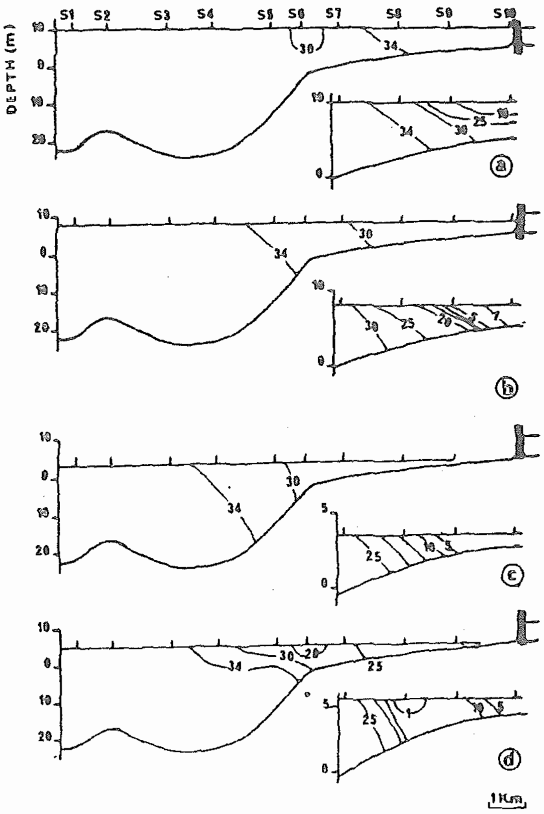

Fig.5 : Salinity distribution in the synoptic survey in May, 1979. Other details as in Fig.3.

Stratification-circulation diagram :

For a classification of the Morlaix estuary according to the concept of Hansen and Rattray (1966), measurements of salinity and current velocity obtained over several tidal cycles at 3 stns (S5, S7 and S8), covering combinations of HRD, LRD, ST and NT, were used. A plot of these parameters on the relevant portion of the stratification-circulation diagram of Hansen and Rattray (1966) is shown in Fig.6.

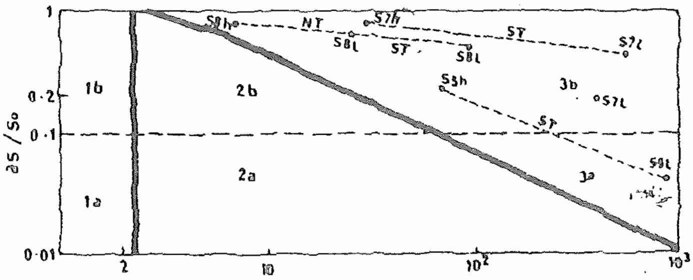

Fig.6: Stratification-circulation diagram for 3 stns. in the Morlaix estuary. H-high river discharge. L - low river discharge.

The data points for stns S7 and S8 classify this stretch of the estuary as belonging to class 3 characterized by appreciable stratification which persisits regardless of spring and neap tides or the strength of river flow. Stn S5, while still belonging to class 3, shows vertical homogeneity at LRD and very slight stratification at HRD.

Flow ratio :

Flow ratio, defined as the ratio of the volume of river water entering the estuary during a tidal cycle to its tidal prism volume, can also be used to classify the estuary. Thus, when the ratio is 1 or above, the estuary is highly stratified, when it is about 0.25, it is a partially mixed type, and when it is less than 0.1, it is a well-mixed type (Schultz and Simmons, 1957). Flow ratios were calculated for different segments of the estuary, and for different rates of river discharge and tidal heights. These were consistently less than 0.2 suggesting a vertical homogeneity which does not conform with the observed pattern of salinity distribution in the estuary (Figs 3-5) and the stratification-circulation diagram (Fig.6). This shows that the flow ratio is not a dependable index in classifying the Morlaix estuary but, on the other hand, it does serve to illustrate the influence of tides as the major environmental factor in the estuary.

(b) *Chemical features :*

Nitrogen pollution of the estuary :

The Morlaix river is selectively and heavily polluted with NO_3 arising from intensive agriculture in the hinterland, which tends to increase NO_3 to levels higher than 400 ug.at Nl^{-1} throughout the year (Fig.7). The annual mean NO_3 concentration in the Morlaix river is 397 ug-at N 1^{-1} which is about 56 times higher than in unpolluted rivers (average 11.4 ug-at N 1^{-1}) and still several times higher than in many polluted rivers (Meybeck, 1982). Similarly, ammonium pollution in the Morlaix estuary is also intense. Annual mean ammonium concentration in river waters was 65 ug-at N 1^{-1} (range 5-125 ug-at N 1^{-1}) which is about 59 times higher than in unpolluted rivers and 10-20 times higher than in many polluted rivers.

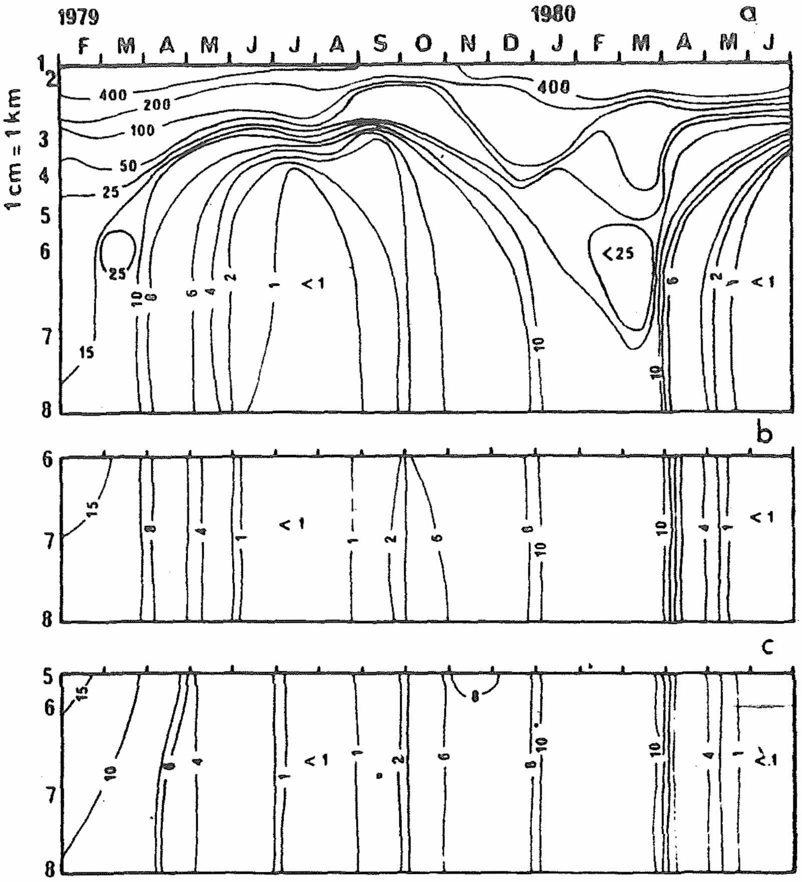

Fig.7 : Spatio-temporal variations of nitrate measured at transect stations. a) surface, b) mid-depth and c) bottom.

The nitrogen pollution of the Morlaix river increases the NO_3 - N:PO_4-P ratios in the estuary, which range from about 50 at the downstream stns to 200-300 at upstream stns in winter. Maximum N:P ratios for the world estuaries (Boynton *et al.*, 1982) are generally about 10-60; by comparison, in the Morlaix estuary, these were 44-322, and even at stns 6-8 which are neritic throughout the year (Figs. 2-5), were between 44 and 192. These ratios are probably the highest known for any estuary in the world and their persistence over the whole of the estuary, inspite of it being tide-dominated, are clearly demostrative of the impact of nitrogen pollution.

Seasonal changes of nutrients :

Seasonal changes of the major nutrients at stn 5, located in the middle of the estuary and taken as a representative station, are shown in Fig.8. These are characteristic of what might be expected in temperate estuaries, but are different in comparison with those obtained in the nearly well-mixed coastalwaters Wafar *et al.*, 1983) in that the consumption of the major nutrients, nitrate, phosphate and silicon, begins much earlier in the estuary and is much more intense. Spring nitrate decrease in 1979 and 1980 in the estuary was much faster, and lowest concentrations (<1 ug-at N 1^{-1} were attained in late June-early July whereas in the coastal waters it was in August. Phosphate, both in 1979 and 1980, decreased rapidly in spring to <0.1 ug-at P 1^{-1} as early as in May and remained so till July; by contrast, in the coastal waters, it was never below 0.1 ug-at P 1^{-1} nor its consumption was as rapid as in the estuary. Similarly, silicon consumption in the estuary in 1979 began in February whereas in coastal waters it was not before March. In 1980 also, silicon at estuarine stations, decreased to < 2 ug-at Si 1^{-1} in April whereas in the coastal waters it was 3.3 ug-at Si 1^{-1}, and by June, silicon was already at its seasonal minimum of <1 ug-at Si 1^{-1} in the estuary but in the coastal waters it remained closer to 2 ug-at Si 1^{-1}. These clearly demonstrate that the consumption of these three major nutrients in the estuary begins earlier and is intense, the latter conclusion being amply supported by the initial winter reserves of these nutrients in the estuary which were higher than in the coastal waters, and the relatively shorter time interval in which these are exhausted.

The ammonium cycle in Morlaix Bay costal waters is unusual in that ammonium accumulates in the euphotic zone when primary production increases, and is consumed only after nitrate has been exhausted from the water column in summer (Wafar *et al.*, 1983). This is evident in the Morlaix estuary also. Ammonium at the estuarine stns attained a peak of about 1.5 ug-at N 1^{-1} in May-June 1979 when chl *a* was also increasing (Fig.8). However, only after nitrate has decreased to < 1 ug-at N^{-1}, its consumption began, and this sustained the second chl *a* peak in August. Similarly, in 1980, consumption of ammonium in the estuary began only when nitrate has decreased to < 1 ug-at N 1^{-1} in June, and this sustained high chlorophyll concentrations, > 6 ug 1^{-1}, encountered at the estuarine stations. Again, as with other nutrients, consumption of ammonium was at least a month earlier than in the coastal waters; in 1979, ammonium peak in the estuary was in May-June whereas in coastal waters it was in July, and in 1980, by June, ammonium has already begun to decrease in the estuary whereas in the coastal waters, it was still increasing.

Biological features :

Chlorophyll a :

Seasonal changes of chl *a* in 1979 (Fig.8) show two peaks of 3 ug 1^{-1} and above in May and August. These are similar to those in the coastal waters but with a difference that the first peak in the estuary was in May whereas in the latter it was in June (Wafar *et al.*, 1983). Similarly, in 1980 also chl *a* increased by 4 or more ug 1^{-1} at the estuarine stations between March and June, whereas in coastal waters,

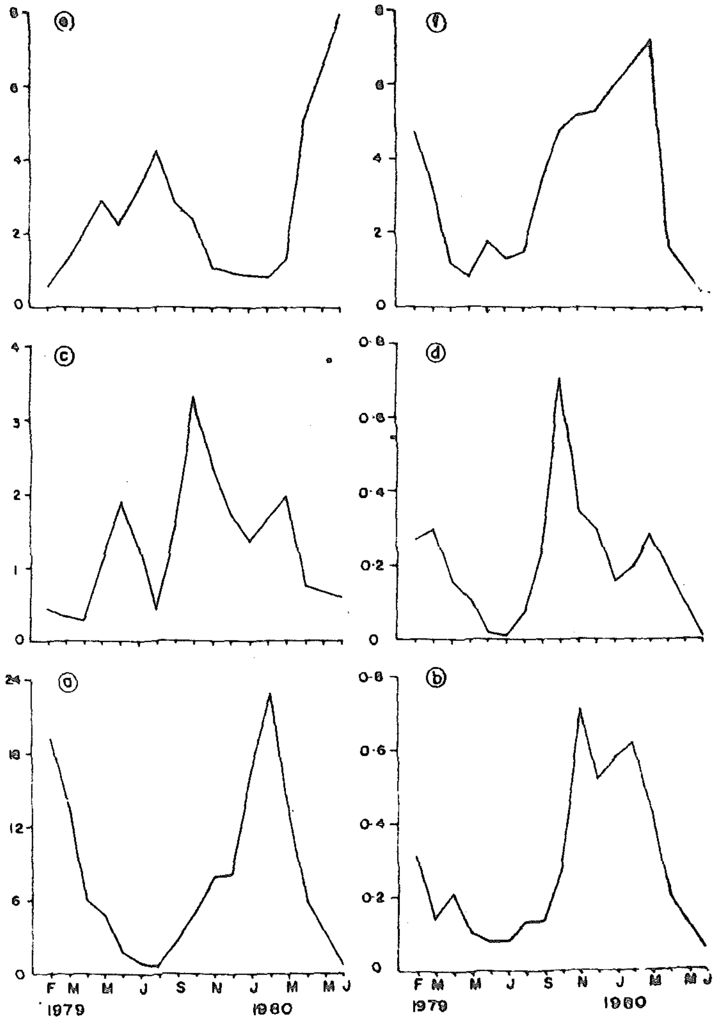

Fig.8 : Seasonal changes of nutrientss and chl a at stn 5 in the Morlaix estuary. a) Nitrate, b) phosphate, c) ammonium, d) nitrite, e) chl a and f) silicon. Units for untrients i ug-at 1^{-1} and for chl in ug 1^{-1}

the increase was only 0.6 ug 1^{-1}. These show that the phytoplankton production in the estuary begins earlier than in the coastal waters and proceeds at a faster rate, a conditin that conforms with early and relatively rapid utilisation of nutrients.

DISCUSSION AND CONCLUSIONS

Distribution of salinity, tides, geomorphology and the stratification-circulation plot show that the Morlaix estuary can be classified into 3 segments based on its dynamic nature. The fisrst is the stretch upstream of Dourduff up to Morlaix city where the freshwater flow and tidal currents are relatively balanced, leading to a moderate stratification which persisits throughout the year. Changes of salinity over tidal cycles at stns S7 and S8 during ST, NT, HRD and LRD (Figures in Wafar, 1981) also confirm this. The third segment comprises the stations downstream of S4 where salinity at all depths was identical to that measured in coastal waters throughout the year, and a vertical homogeneity prevails at any state of the tide or river flow.

Of particular interest is the intermediate section of the estuary, from Dourduff to Chateau du Taureau, not only from the hydrological characters but also from their influence on biological and chemical cycles. At HRD, a STHW slack produces vertical homogeneity and a STLW slack, a stratification; during NT, at both HW and LW slacks, stratification occurs (Fig.4). However, the salinity distribution during the transect survey which was done at the ebb, was always vertically homogeneous. This shows that stratification is limited to slack waters and homogeneity prevails in the intervening period. Predominance of homogeneity over stratification is more manifest during LRD (Fig. 3); at any state of the tide, the surface-to-bottom salinity difference was $< 0.5\%$, a limit taken to definite vertical homogeneity (Hass, 1977). Changes of salinity over tidal cycles at stns S4 and S5 (Figures in Wafar, 1981) also confirm this; the only instance stratification was significant was during LW slack at stn 5 when river flow was high, but even at this time, stratification persisted for only about 4 hrs. To our knowledge, a large section of the estuary, oscillating thus between stratification and vertical homogeneity during every tidal cycle, has not been reported so far. The only other instance where such oscillations were shown is in the case of Chesapeake Bay estuaries (Hass, 1977) which oscillate between vertical homogeneity and stratification in conjunction with spring-neap cycles. In Morlaix estuary, however, such oscillations occur at much shorter time intervals, at every tide, slack waters being associated with stratification and ebb and flood with homogeneity.

These unique features of rapidly alternating stratification-homogeneity cycle and the predominance of tidal prism volume over freshwater flow counteract effectively the nutrient pollution of the estuary, the former process resulting in a uniform vertical redistribution of nutrients and the latter, in their removal by dilution. This is seen from the fact that, in spite of an intensive NO_3 pollution, its concentrations at stations downstream of Dourduff are similar to or less than those recorded in the coastal waters at anytime of the year (Fig.7). The upper NO_3 limit for unpolluted rivers is about 40 ug-at N 1^{-1} (Ketchum, 1969) and such concentrations occur only upstream of stn 3, showing that eutrophication is not yet aserious threat to the estuary, a situation attributable to the large tidal prism volume and strong mixing.

What is of further interest in the Morlaix estuaryk is the rapid evolution of chemical and biological processes in spring summer despite strong mixing and tidal dominance. In many world estuaries, there is sufficient runoff to maintain a degree of physical stability throughout the year in the upper layers which in turn allows the spring bloom to be initiated earlier in them than in offshore waters (Sinclair *et al.*,). However, in Morlaix estuary, there was never sufficient stability, yet the consumption of nutrients and chl *a* increase in the estuary begins a month earlier than in coastal waters. Similarly, the nutrients also get exhausted a month earlier. There show that even a transient stability lasting for a few hours in each tidal cycle is enough to initiate and sustain phytoplankton development in the estuary earlier than in coastal waters and this also demonstrates a certain degree of adaptability of estuarine phytoplankton to its unstable environment.

The rapid growth of phytoplankton and removal by dilution of nitrate (flow ratios < 0.02) in spring-summer deplete nitrate in the estuary to a level where it becomes ultimately limiting to primary production. This is evident from the low nitrate concentrations (< 1 ug-at N 1^{-1}) and the N:P ratios (< 15) in June-July at the estuarine stations (Fig.7). This is consistent with what happens in most of the world estuaries (Boynton *et al.*, 1982) in that the spring pulse in primary production is frequently as a result of direct utilization of new nitrogen, and that nitrogen rather than phosphorus is more likely to limit production in coastal and estuarine systems (Ryther and Dunstan, 1971). Our results are also consistent with other findings (Ryther and Dunstan, 1971; Williams, 1972; Goldman *et al.*, 1973; Thayer, 1974) that nitrogen enrichment in estuarine areas often stimulates algal growth, indicating that despite relatively high ambient concentrations, nitrogen limitation of phytoplanktonic production can occur.

When nitrate becomes limiting, recycled nitrogen, as ammonium, sustains the summer increase in chl *a* (Fig. 8). The importance of NH_4 in sustaining summer production can be demonstrated in the following way: with the local intertidal volume for the different sections of the estuary and the river flow data, we calculated the high tide volume for an average tide, fraction of river water Qn in the estuary, and the residence time, by using the modified tidal prism method of Ketchum (1951). (Residence time was 7.2 tidal cycles in LRD period and 7.3 tidal cycles in HRD period). Following this, with the nitrate concentration for the seawater and freshwater ends of the estuary, and the Qn, we calculated the increase in nitrate content on mixing in the estuary for one residence time. Primary production measured at fortnightly intervals in the coastal waters of the Morlaix Bay were converted to ug-at N equivalent of assimation for one residence time, and were compared with the nitrate increase in the estuary.

The results (Fig.9) show clearly that accumulation of new nitrogen can sustain primary production only in winter-spring and that a substantial fraction of the summer production is necessarily sustained by recycled nitrogen. The importance of ammonium is also reinforced by the fact that peak production

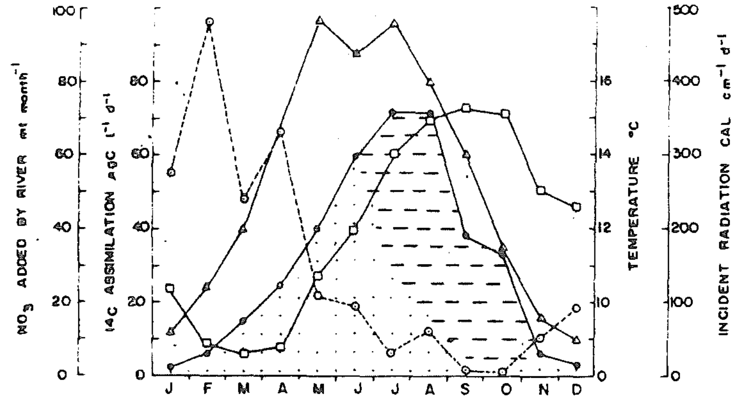

Fig.9 : Relative importance of nitrate and ammonium to primary production in the Morlaix estuary. Filled circles-primary production, open circles-nitrate added by river waters; squares-water temperature and triangles-incident radiation. Dotted portion-nitrate based production, lined portion - ammonium based production.

occurs in summer when temperature and incident radiation are at their maximum and the transport of nitrate is at its lowest (Fig.9).

Our conclusion that there is a seasonality of new nitrogen based spring production and regenerated nitrogen based summer production in Morlaix estuary can also be a characteristic feature of many temperate estuaries, since these receive maximum nutrient loading generally in winter-spring, whereas peak chl *a* and production, and inorganic N:P ratios much lower than 10 occur much later in summer (Nixon, 1981; Boynton *et al.*, 1982). Calculations similar to ours (Carpenter *et al.*,1969; Nixon 1981)also demonstrate that the accumulation of new nitrogen from freshwater in several temperate estuaries is sufficient to support primary production only in the order of a few days to few weeks.

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