

# Seasonal Variation of Phytoplankton Biomass in the Very Low Salinity Region of the James River Estuary, Virginia, U. S. A.

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Surface phytoplankton biomass was measured at approximately one month intervals from July 1986 to August 1987. There was a peak phytoplankton biomass in the very low salinity region during summer and autumn when river discharge was low. The peak biomass occurred independent of the tidal state, location of nutrient input, nutrient concentration and temperature. The peak biomass are probably caused by the hydrodynamic trapping, density-selective retention of particles by estuarine circulation.

## I. Introduction

The upward extension of an estuary is a place where chemical and biological processes actively occur (Morris et al., 1978) and many physical environmental factors such as the tidal state and circulation are involved in the complex processes. Phytoplankton study in the upper estuary is important for understanding the biogeochemical processes which occur in the estuary and for investigation the fate of freshwater phytoplankton. The variations of phytoplankton biomass in the upper estuary may regulate some geochemical processes and phytoplankton dynamics in the seaward portion of an estuary. From the standpoint of managing water quality, the area has an eutrophication problems because it is easily exposed to anthropogenic nutrient sources (Bennett et al., 1986). Phytoplankton in the upper estuary has received little attention to date, perhaps because this geographic area falls between the traditional realm of marine and freshwater ecologist.

In the James River estuary, high phytoplankton biomass in the very low salinity region (less than 0.5 ‰) was reported in summer and autumn by

Filardo and Dunstan (1985) who showed that the biomass was inversely related with the amount of river discharge. However, phytoplankton biomass in the more upper zone (freshwater region) was not investigated and their study was focused on the cause of rapid decrease in freshwater phytoplankton biomass when they met more saline estuarine water. Anderson (1986) observed a peak phytoplankton biomass in the upper reach of the Chesapeake Bay tributaries during the periods of low river discharge and proposed the mechanism responsible for the high plankton biomass to be the hydrodynamic trapping, density-selective retention of particles by estuarine circulation like the case of the San Francisco Bay reported by Cloern et al. (1983). However, he did not demonstrate whether or not temperature, location of nutrient input, tidal state might involved in the cause on the high biomass. Moreover, the possibility that the high biomass in the channel might be caused by the transport from lateral shallow shoals as in the case of the San Francisco Bay was not investigated. The objectives of this study were to observe the phytoplankton biomass distribution monthly along the axis of the James River estuary and to investigate

the most promising processes responsible for the biomass fluctuation in the very low salinity region of the James River estuary.

## II. Materials and Methods

The James River estuary (Fig. 1), the southernmost of the major rivers emptying into the western side of the Chesapeake Bay, extends the entire breadth of the state of Virginia, from its mouth at Newport News to its headwaters in the Appalachian Mountains near the Virginia-West Virginia State line.

Water samples were obtained at approximately one month intervals from July 1986 through August 1987. Stations were extended along the axial transect of the main channel from a fixed location off Newport News Shipyard (NNS) or from the 2 ‰ isohaline to a position off the city of Hopewell (Fig. 1). The locations of all stations were set based on the surface salinity during each cruise rather than geographic position. Surface water samples were collected from the pumped outflow of the fluorometer for the determination of extracted chlorophyll *a* dissolved silicate, phosphate and nitrate.

Chlorophyll *a* was determined by a continuous *in vivo* fluorescence method (Lorenzen, 1966) with a Turner Designs Model 10 fluorometer equipped with an infrared sensitive photomultiplier and the appropriate filters, calibrated with chlorophyll *a* concentrations determined fluorometrically on 90% acetone extracts of cells retained on a Gelman type A-E glass fiber filter (Yentsch and Menzel, 1963; Holm-Hansen et al., 1965). Relative *in vivo* fluorescence was converted to chlorophyll *a* by multiplying a calibration factor determined from samples taken every 10~15 kms. Calibration of extracted chlorophyll was done with 90% acetone solutions of pure chlorophyll *a* (Sigma Chemical Co.).

Water samples for nutrient analysis were filtered on shipboard through Gelman type A-E glass fiber filters, which were stored in polyethylene bottles and frozen until the analysis were performed. All nutrient concentrations were determined colorimetrically by the methods of Strickland and Parsons (1972), which were modified for the Rapid Flow

Analyzer (ALPKEM Corporation, 1986). The detection limit were  $\pm 0.05 \mu\text{mole/L}$  for nitrate and phosphate and  $\pm 1.0 \mu\text{mole/L}$  for silicate methods.

Salinity was measured with a Beckman RS-5 salinometer when the salinity was higher than 2 ‰, while Minisal Model 2100 salinometer was used for the salinity less than 2 ‰ after water samples were brought to the laboratory. Photosynthetic light intensities in the water column were measured at half meter intervals with a L1-185 Quantum/Radiometer/Photometer and light extinction coefficients were calculated by light attenuation with depth.

Daily mean values for river discharge were provided by the Virginia State Water Control Board. The discharge data were collected at station 0203 7500 (37°33'47"N, 77°32'50"W) in the James River near Richmond, Virginia.

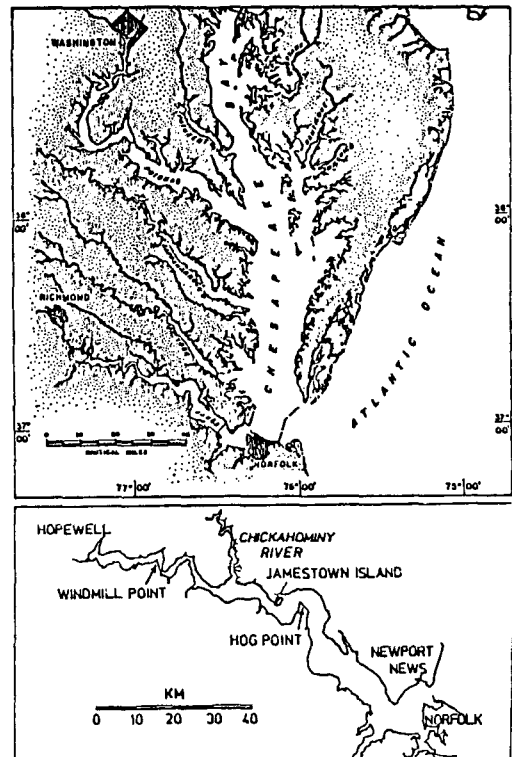


Fig. 1. The James River Estuary Study area

## III. Results

### Hydrographic Data

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River discharge varied, over the duration of the study, from a low of  $22.5m^3 \text{ sec}^{-1}$  on 11 October 1986 to a high of  $4109.9m^3 \text{ sec}^{-1}$  on 18 April 1987. The mean monthly discharge for July through November 1986 was relatively low compared with those of several previous years. The discharge in July was  $34.4m^3 \text{ sec}^{-1}$  and then increased to  $70.4m^3 \text{ sec}^{-1}$  in November. River discharge from December 1986 through March 1987 was representative of normal annual hydrography, ranging from 124.1 to  $407.3m^3 \text{ sec}^{-1}$ . The mean monthly discharge in April 1987 was a very high of  $1017.8m^3 \text{ sec}^{-1}$ , and then it declined to relatively constant lower flows until August 1987 when the mean monthly discharge was  $28.3m^3 \text{ sec}^{-1}$ (Table 1).

The surface salinity(Table 1) measured at the estuary mouth was dependent on freshwater input. It ranged from 15.3 to 25.0 ‰ except for on 21 April 1987 when the surface salinity was a very low of 2.30 ‰ as a result of abnormally high river discharge. Excepting April 1987, the location of the 1 ‰ isohaline extended over a distance of approximately 45km from Hog Point to just west of Windmill Point. The location is comparable to the 45km range for the very low salinity region designated by Filardo and Dunstan(1985). The water column in the very low salinity region was considered to be vertically homogeneous, the salinity varying less than 0.10 ‰. The depth within this zone ranged from 5 to 13 meters and was usually between 5 to 7 meters(the exception being April 1987). Water temperature varied in response to seasonal climate. Mean surface temperature measured along the axis of the main channel ranged from 4.78 °C in February 1987 to 29.57 °C in July 1987(Table 1).

Light extinction coefficient ranged from 1.19 at NNS on 12 August 1987 to 7.42 in the 0.78 ‰ isohaline on 27 February 1987(Table 2). Relatively higher values occurred each month in the upper portion of the estuary, and the values decreased in summer with decreasing river discharge. The compensation depth at which the photosynthesis of a cell is equal to its respiration was defined by the depth of 1% surface irradiance. The compensation depth at NNS was 2.5 meters in February and increased steadily to 3.9 meters in August. At the city of Hopewell, the compensation depth varied from 1.2 to 2.0 meters. The compensation depth in the upper portion of the estuary was shallowest in Fe-

bruary(less than 0.8 meter) and deepest in August (approximately 2 meter).

Table 1. Mean River Discharge(R,  $m^3 \text{ sec}^{-1}$ ), surface salinity at the mouth of the estuary(S, ‰), the location of the 1‰ isohaline(L, Km from the mouth) and mean surface water temperature(T).

Date	R	S(‰)	L(km)	T(°C)
Jul. 86	34.4	23.0	75.7	29.5
Oct. 86	50.5	23.6	79.8	19.5
Nov. 86	70.4	-	72.1	-
Dec. 86	124.1	17.8	52.1	7.4
Jan. 87	220.5	-	-	5.0
Feb. 87	301.6	15.3	35.9	4.8
Mar. 87	407.3	-	-	-
Apr. 87	1017.8	2.3	6.2	13.4
Jun. 87	147.5	-	60.0	29.4
Jul. 87	111.7	20.6	73.2	29.6
Aug. 87	28.3	25.0	78.0	28.8

Table 2. Light Extinction coefficient(k) in the main channel of the James River estuary from February through August 1987(D=distance from the mouth, S=surface water salinity)

Month	D(km)	S(‰)	k( $m^{-1}$ )
February	0.8	15.32	1.86
	13.8	7.70	2.66
	36.6	0.78	7.42
	49.6	0.02	6.15
	97.4	0	3.58
Jane	36.3	1.85	2.08
	66.1	0.09	2.50
	88.6	0	3.38
	105.4	0	3.14
July	0	20.58	1.30
	29.3	7.68	1.69
	49.7	2.36	2.06
	75.1	0.50	2.20
	98.8	0.06	5.99
August	6	25.00	1.19
	29.1	12.90	1.42
	61.3	3.05	2.15
	85.9	0.30	3.30
	102.9	0.06	3.99

## Phytoplankton Biomass

From July through December 1986 surface phytoplankton chlorophyll *a* ranged from 1.48  $\mu\text{g/l}$  on 20 December to 87.49  $\mu\text{g/l}$  on 25 July. There were chlorophyll *a* peaks in the very low salinity region from July through November. In July chlorophyll *a* was relatively constant and low from NNS to the 1.70 ‰ isohaline (69.0 km upstream). The concentration increased rapidly from the 1.70 ‰ isohaline and peaked in the 0.12 ‰ isohaline (102.5 km upstream) as 87.49  $\mu\text{g/l}$ . It decreased sharply in the freshwater zone. A similar pattern of chlorophyll *a* distribution occurred in October and November. The peak biomass disappeared in December, chlorophyll *a* ranging from 1.48 to 5.23  $\mu\text{g/l}$ .

A composite plot of chlorophyll *a* (July through December 1986) is shown in Figure 2. From July to November, maximum chlorophyll *a* decreased from 87.49  $\mu\text{g/l}$  to 40.65  $\mu\text{g/l}$  and the location of the peak moved 13.4 km downstream. The peak did not occur in December when chlorophyll *a* was low in the entire estuary including the freshwater zone.

By April 1987, chlorophyll *a* peak in the very low salinity region did not develop, chlorophyll *a* ranging from 1.50  $\mu\text{g/l}$  on 21 January to 11.69  $\mu\text{g/l}$  on 21 April. In February there was a phytoplankton bloom at the estuary mouth with 49.79  $\mu\text{g/l}$  chlorophyll *a*. The bloom disappeared by April and biomass at the mouth remained relatively low through the final sampling in August 1987. Chlorophyll *a* peak in the very low salinity region occurred in June with 61.35  $\mu\text{g/l}$  and the peak remained until August with increasing concentrations.

Surface phytoplankton chlorophyll *a* data over the tidal cycle were collected in three anchor stations and the results of the biomass fluctuation with the time of day are presented in Figure 3. Surface chlorophyll *a* concentration in October 1986, which was measured at Dancing Point, ranged from 9.67 to 23.49  $\mu\text{g/l}$ . In December 1986 (data collected at Dancing Point), maximum chlorophyll *a* was 4.66  $\mu\text{g/l}$  and minimum was 2.97  $\mu\text{g/l}$ . In August 1987, data were collected near the position where the peak biomass occurred (93.1 km upstream). Chlorophyll *a* concentration in the surface ranged from 86.58 to 101.97  $\mu\text{g/l}$ .

Figure 4. shows the surface chlorophyll *a* along the main channel during the periods of flood and ebb tides for one day. During each cruise, sampling began at the 2 ‰ isohaline at the time of ebb tide and proceeded upstream to the position off the city of Hopewell, and turned back at the time of flood tide and proceeded downstream to the 2 ‰ isohaline. Each tide was lasting for about 3 hours while sampling took 1 hour. Chlorophyll *a* data were continuously collected by *in vivo* fluorescence. In October 1986, maximum chlorophyll *a* during periods of flood tide was 78.61  $\mu\text{g/l}$  at the position off Hopewell Eity (100.6 km upstream) and the concentration at the same position decreased to 69.93  $\mu\text{g/l}$  during ebb tide. The difference of 8.98  $\mu\text{g/l}$  is comparable to 15.39  $\mu\text{g/l}$  of difference between maximum and minimum chlorophyll *a* concentration measured over one tidal cycle at the anchor station near the peak in August 1987. Maximum chlorophyll *a* concentration during periods of ebb tide was 74.23  $\mu\text{g/l}$  and occurred approximately 3 km downstream. The difference in chlorophyll *a* concentration between the two peaks was 4.38  $\mu\text{g/l}$  but the peak zones were almost equal in width. In December 1986, when the peak did not occur, there was little difference in chlorophyll concentration between the flood and ebb tides.

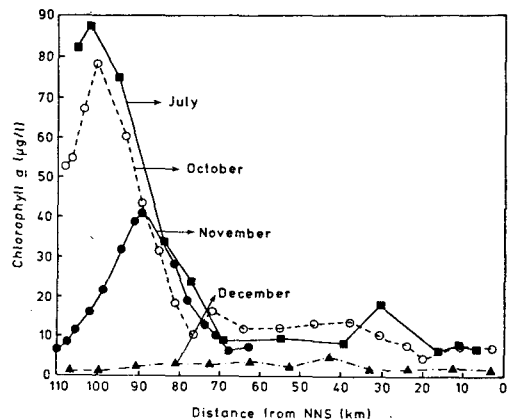


Fig. 2. Surface phytoplankton biomass along the axis from July through December 1986.

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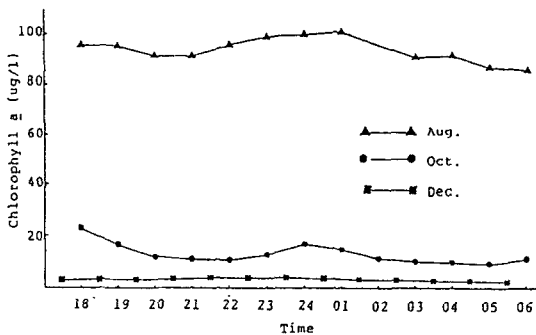


Fig. 3. Surface phytoplankton biomass over the tidal cycle at anchor station in October and December 1986, and August 1987 (Data in October and December were collected 61km upstream from NNS and data in August 93km upstream).

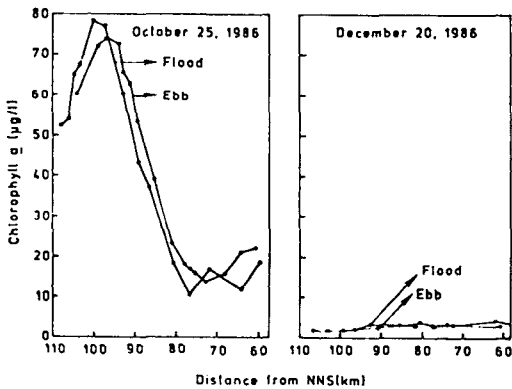


Fig. 4. Surface phytoplankton biomass during the periods of flood and ebb tide.

### Nutrients

The concentration of dissolved silicate ranged from undetectable levels on October 25, 1986 to 161.2  $\mu\text{mole/l}$  on January 21, 1987. Both maximum and minimum concentration occurred in the very low salinity region. A composite silicate plot from October 1986 through February 1987 is shown in Figure 5. During months characterized by high river discharge (December 1986 through February 1987), dissolved silicate concentration was relatively high along the axis of estuary, exhibiting a somewhat conservative mixing. However, when discharge decreased (October and November 1986),

there was almost complete removal of dissolved silicate in the very low salinity region, showing a non-conservative mixing. Another feature of dissolved silicate distribution during the periods of low river discharge was an increase in concentration at mid estuary. The increase in concentration in July and October 1986 occurred above the 10.45 ‰ and 11.11 ‰ isohaline, respectively. The positive relationship with salinity indicates that there is a source within the estuary resupplying the dissolved silicate to the water column. On the other hand, during months characterized by high river discharge, high concentration in the freshwater zone (more than 140  $\mu\text{mole/l}$ ) decreased steadily down-estuary until the lowest concentration (less than 27  $\mu\text{mole/l}$ ) was achieved at the mouth of estuary.

Phosphate was generally present in concentrations of less than 9  $\mu\text{mole/l}$ . The distribution pattern along the axis of the estuary is almost identical with that of dissolved silicate. During the periods of low river discharge the concentration in the freshwater zone was high (up to 8.70  $\mu\text{mole/l}$ ) and then decreased rapidly to undetectable levels in the very low salinity region where phytoplankton biomass peaked. Removal rate calculated in October and November 1986 was 100 and 90%, respectively. After removal within this zone, the concentration increased with salinity at mid estuary above the 15~50 ‰ isohaline. This is further downstream compared to the increase in dissolved silicate concentration which occurred until the 10~11 ‰ isohaline. During high river discharge, when the phytoplankton biomass was low within the entire estuary, the distribution exhibited a somewhat conservative mixing. The high concentration in the freshwater zone decreased steadily down-estuary.

Nitrate concentration ranged from undetectable levels in the 10.5 ‰ isohaline on 25 July 1986 to 136.2  $\mu\text{mole/l}$  in the 0.30 ‰ isohaline on 24 November 1986. The nitrate distribution pattern was different from that of dissolved silicate or phosphate (Fig. 6). The concentration in the freshwater was relatively low, usually less than 40  $\mu\text{mole/l}$  and it increased when freshwater mixed with seawater. During the summer and autumn months when the phytoplankton biomass peak occurred in the very low salinity region, nitrate concentration pea-

ked in the approximately 0.30 ‰ isohaline, while it peaked in the 3.0 ‰ isohaline when the peak biomass disappeared during winter and spring. Maximum concentration in summer and autumn (up to 135  $\mu\text{mole/l}$ ) was higher than that in winter and spring (up to 75  $\mu\text{mole/l}$ ). After the maximum concentration of nitrate, during summer and autumn, there was a rapid decrease in concentration within

the 0.3~6.0 ‰ mixing segment, and then the concentration decreased steadily. During winter and spring, the concentration decreased steadily down-estuary after the maximum concentration in the 3 ‰ isohaline. Consequently, nitrate mixed conservatively above the 6.0 ‰ isohaline regardless of the occurrence of phytoplankton biomass peak in the very low salinity region.

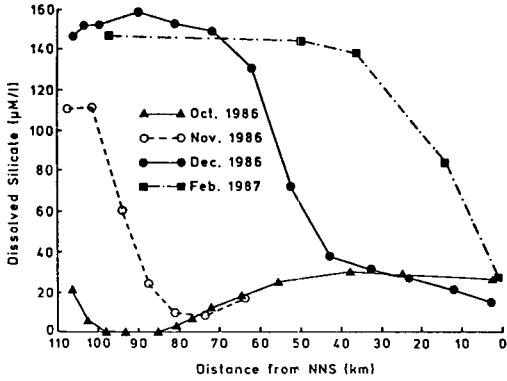


Fig. 5. A composite silicate plot from the surface water along the estuary axis from October 1986 through February 1987.

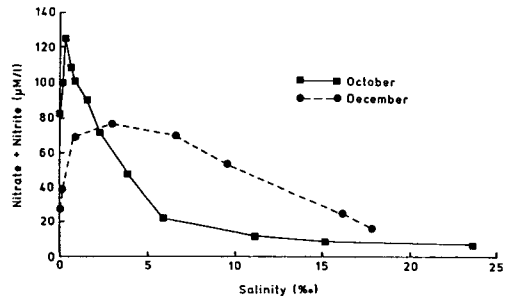


Fig. 6. The longitudinal distribution of nitrate plus nitrite on 25 October and on 20 December 1986.

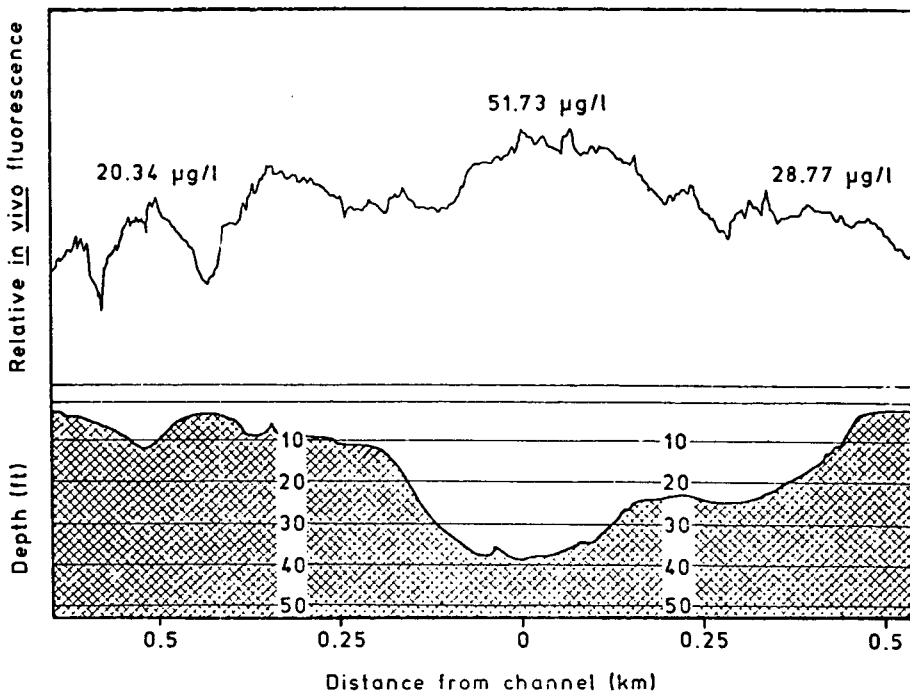


Fig. 7. Phytoplankton biomass between the lateral shoals and channel during the time of slack tide near the position where the peak biomass occurred on 19 June 1987.

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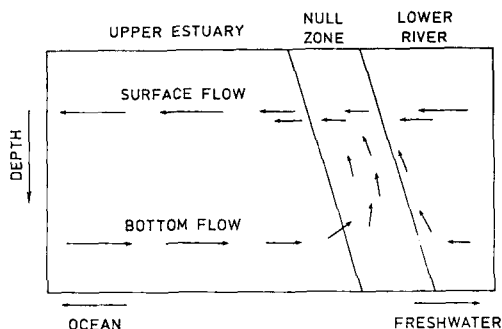


Fig. 8. A generalized diagram of the net circulation in a partially-mixed estuary(modified from Peterson et al., 1978).

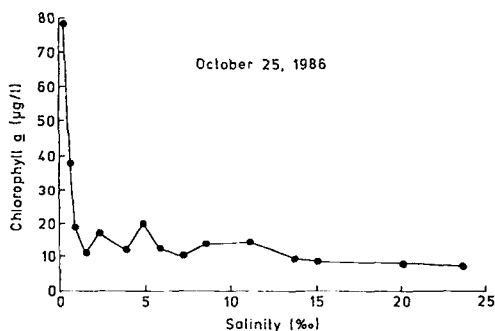


Fig. 9. Surface phytoplankton biomass versus salinity from the surface water along the estuary axis in October 1986.

#### IV. Discussion

The data show that there is a phytoplankton biomass peak in the very low salinity region of the James River estuary during summer and autumn. The peak region has five to ten times greater biomass than adjacent waters further up and downstream. High phytoplankton biomass in the very low salinity region of the mid-Atlantic rivers are considered as natural phenomena. Brehmer(1972) and Anderson(1986) reported the high biomass within this zone of the York, the Rappahannock and the James River estuaries, Simpson et al. (1977) in the Hudson River estuary, D'Elia et al. (1983) in the Patuxent River estuary, Woodward(1983) and Bennett et al. (1986) in the Potomac River estuary, Filardo and Dunstan(1985) in the James River es-

tuary, and Sharp et al. (1982) in the Delaware estuary.

Only a few studies have focused on the controlling processes responsible for the high phytoplankton biomass in the very low salinity region. Simpson(1972) and Bennett et al. (1986) assumed that the high biomass was due to the input of nutrients from anthropogenic sources in the upper estuary. The high phytoplankton biomass in the upper Hudson River estuary was attributed to nutrient enrichment from the New York city area which discharged runoff and waste water. In the Potomac River estuary, it was attributed to enrichment from the Washington, D. C. area.

In this study of the James River estuary, the location of nutrient inputs does not seem to be responsible for causing the observed phytoplankton biomass peak in the very low salinity region. High concentration of chlorophyll *a* (87.49 µg/l) in July 1986, which occurred 102.5km upstream (located off Hopewell city), decreased to very low biomass (16.06 µg/l) at the same position in November 1986 (Fig. 2), while the biomass occurred 13.4km further downstream. However, the peak always occurred in the region where salinity was less than 0.5 ‰.

From another view point, nutrient limitation could not be responsible for the low phytoplankton biomass during the months of winter and spring when the peak biomass disappeared. In spite of the fact that dissolved silicate concentration was more than 140 µmole/l, nitrate more than 30 µmole/l, and phosphate between 6 to 7 µmole/l in the very low salinity region, biomass was low, indicating that physical, not chemical, factors were controlling abundance within this zone.

Temperature also did not seem to be limiting factor which caused the disappearance of the peak biomass during winter and spring. At the time when spring bloom occurred at the estuary mouth in February 1987, the average surface temperature was lowest as 4.8 °C during study periods.

The effect of tidal state on the occurrence of the phytoplankton biomass peak has not been investigated before. There is evidence(Hass, 1977) that the James River estuary regularly oscillates between conditions of destratification and stratification

of water column according to the monthly spring-neap tidal cycle. When the water column becomes destratified during the spring tide, the distribution of nutrients and oxygen also become homogeneous (Webb and D'Elia, 1980). The diurnal cycles of tide are known to affect the vertical distribution of total suspended matter with varying current speed (Nichols, 1972). However, in this study of the James River estuary, chlorophyll *a* data collected in the peak biomass zone in August 1987 showed little variation over the tidal cycle (Fig. 3). The distance between the two locations of the peaks during the periods of flood and ebb tides in a day (October 1986) was approximately 3 km. The difference in chlorophyll *a* between the two peaks was less than 5  $\mu\text{g/l}$  (Fig. 4). In addition, the monthly spring-neap tidal cycle did not affect the occurrence of the peak biomass. Monthly sampling was done at spring and neap tide in an alternation pattern from July 1986 through February 1987. The peak biomass occurred in July through November 1986 independent of the tidal state.

Cloern et al. (1983) reported that the phytoplankton biomass in the northern San Francisco Bay was a result of transport from adjacent Suisan Bay, a very productive shallow area. However, the result in the James River estuary showed a pattern different from the above case. Phytoplankton biomass between the lateral shoals and channel was measured continuously during the time of slack tide on 19 June 1987 near the peak region. The biomass in the lateral shoals was much lower than in the channel (Fig. 7). Thus, the higher biomass in the channel does not appear to be transported from the lateral shoals.

Anderson (1986) proposed that the phytoplankton biomass peak in the very low salinity region of the Chesapeake Bay tributaries are caused by the same mechanism involved in the formation of the turbidity maximum in partially mixed estuary. The James River estuary is an example of a partially mixed estuary (Pritchard, 1952), which is often characterized by a non-tidal net circulation in which a surface layer of low-density water flows seaward over a landward flowing bottom layer of high-density water (Pritchard, 1967). A generalized diagram of the net circulation in the partially mixed estuary

is presented in Figure 8. The distribution of suspended particles is influenced by such a non-tidal net circulation. Dense particles sink into the bottom current, which converges with river current near the landward extent of salt intrusion where bottom current is zero and upward vertical velocity is greatest (Hansen and Rattray, 1965; 1967). Therefore, suspended particles accumulate to form a turbidity maximum near this convergence zone, or "null zone". Because particle concentration maxima result from a balance between sinking and vertical advection, only particles having appropriate densities accumulate (Postma, 1967). Light particles are advected seaward in the surface layer and dense particles are not resuspended. The density-selective accumulation of suspended sediments by estuarine circulation is documented in the northern Chesapeake Bay (Schubel, 1969), the Rappahannock River estuary (Nichols and Poor, 1967), the James River estuary (Nichols, 1972) and the northern San Francisco Bay (Conomos and Peterson, 1977).

In this study of the James River estuary, a sample selected from the peak biomass zone was used to make a qualitative assessment, using a microscope, to know the dominant species. The dominant species were freshwater forms of diatoms having heavily silicified frustules. The genera were *Melosira*, *Cyclotella*, *Synedra*, *Cocconeis*, *Gyrosigma*, *Navicula* and *Surirella*. Most of the dissolved silicate was removed in the very low salinity region when the peak biomass occurred (Fig. 5). Diatoms are probably selectively trapped because their relatively high sinking rates balance the net upward water velocity. Lighter forms of phytoplankton such as flagellates are advected out of the very low salinity region.

While it is hypothesized that the observed phytoplankton biomass peak in the very low salinity region of the James River estuary is caused by the same mechanism involved in the formation of the turbidity maximum in partially mixed estuary, the higher phytoplankton biomass did not seasonally correspond to the greater magnitude of the turbidity. The turbidity was stronger in winter and spring than in summer and autumn, but the peak biomass disappeared in winter and spring. As river discharge increases, the net non-tidal circulation in



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the San Francisco Bay is known to become stronger and the net upward vertical water velocity to become larger (Festa and Hansen, 1978; Peterson and Festa, 1984). Therefore, higher settling velocities are required to develop a turbidity maximum. Schubel (1969) showed that the mean diameter of particles in the turbidity maximum of the Chesapeake Bay is larger in winter than in summer. Meanwhile, sinking rate of a diatom during winter decreased due to the increased coefficient of dynamic viscosity at low temperature. Therefore, diatoms are probably not trapped in the turbidity maximum zone of the James River estuary during winter and spring due to both decreased sinking rate of diatoms and increased net-non tidal circulation.

Hydrodynamic trapping seems to be responsible for peak phytoplankton biomass in the James River estuary, but it is still an unanswered question why phytoplankton biomass does not accumulate further downstream, a region where other inorganic suspended particles are still accumulating? The distribution and abundance of phytoplankton in an estuary are determined by the biological processes in addition to the transport mechanism that affects the concentration of suspended particles. In addition to behaving like inorganic particles, phytoplankton cells also grow, divide, decompose or are consumed. Figure 9 shows that phytoplankton biomass in the very low salinity region decreases very rapidly before the approximately 1.5 ‰ isohaline. Several hypotheses have been suggested to account for the rapid decrease. They include limitation of light penetration (Sharp et al., 1982), increased flocculation (Avnimelech et al., 1982) and osmotic stresses placed on freshwater phytoplankton (Morris et al., 1978; 1982; Filardo and Dunstan, 1985). Evidence from the Tamar estuary (Morris et al., 1978; 1982) and the James River estuary (Filardo and Dunstan, 1985), which suggested that a mass mortality of freshwater hypophobic phytoplankton occurred in a narrow range of salinity, is most promising mechanism responsible for the initial decline of biomass in the very low salinity region.

## References

- Anderson, G.F., 1986. Silica, Diatom and Freshwater Productivity Maximum in Atlantic Coastal Plain Estuaries, Chesapeake Bay. *Estuaries, Coastal and Shelf Science*, 22:183~197.
- Avnimelech, Y., B.W. Troeger and L.W. Reed, 1982. Mutual Flocculation of Algae and Clay. Evidence and Implication. *Science*, 216:63~65.
- Bennett, J.P., J.W. Woodward and D.J. Schultz, 1986. Effect of Discharge on the Chlorophyll *a* Distribution in the Tidally-Influenced Potomac River. *Estuaries*, 9:250~260
- Brehmer, M.L., 1972. Biological and Chemical Study of Virginia Estuaries. Contribution No. 452, Virginia Institute of Marine Science, 69pp.
- Cloern, J.E., A.E. Alpine, B.E. Cole, R.L.J. Wong, J.W. Wong, J.F. Arthyr and M.D. Ball, 1983. River Discharge Controls Phytoplankton Dynamics in the Northern San Francisco Bay. *Estuarine, Coastal and Shelf Science*, 16:415~419.
- Conomos, T.J. and D.H. Peterson, 1977. Suspended Particle Transport and Circulation in San Francisco Bay: an overview. In *Estuarine Processes*, vol. 2 (Wiley, M. ed.). Academic Press, New York. pp 82~97.
- D'Elia, C.F. and D.M. Nelson and W.R. Boynton, 1983. Chesapeake Bay Nutrient and Plankton Dynamics: 111. The Annual Cycle of Dissolved Silica. *Geochimica et Cosmochimica Acta*, 47: 1945~1955.
- Festa, J.F. and D.V. Hansen, 1978. Turbidity Maximum in Partially Mixed Estuaries: A Two-Dimensional Numerical Model. *Estuarine and Coastal Marine Science*, 7:347~359.
- Filardo, M.J. and W.M. Dunstan, 1985. Hydrodynamic Control of Phytoplankton in Low Salinity Waters of the James River Estuary, Virginia, U.S.A. *Estuarine, Coastal and Shelf Science*, 21:653~667.
- Hansen, D.V. and M. Rattray, Jr., 1965. Gravitational Circulation in Straits and Estuaries. *Journal of Marine Research*, 23:104~122.
- Hansen, D.V. and M. Rattray, Jr., 1966. New Dimension in Estuary Classification. *Limnology and Oceanography*, 11:319~326.
- Hass, L.W., 1977. The Effects on the Spring-Neap Tidal Cycle on the Vertical Salinity Structure of the James, York and Rappahannock Rivers,

- Virginia, U.S.A. Estuarine and Coastal Marine Science, 5:458~496.
- Holm-Hansen, O., C.J. Lorenzen, R.W. Holms and J.D.H. Strickland, 1965. Fluorometric Determination of Chlorophyll. J. Cons. Perm. int. Explor. Mer, 30:3~15.
- Lorenzen, C.J. 1966. A Method for the Continuous Measurements of *in vivo* Chlorophyll Concentration. Deep Sea Research, 13:223~227.
- Morris, A.W., R.F.C. Montoura, A.J. Bale and R.J. M. Howland, 1978. Very Low Salinity Regions of Estuaries: important sites for chemical and biological reactions. Nature, 274:678~680.
- Nichols, M.M., 1972. Sediments of the James River Estuary, Virginia, p169~212. In. B. Nelson, ed., Environmental Framework of Coastal Plain Estuaries. The Geological Society of America, Inc. Boulder, Colorado.
- Nichols, M.M. and G. Poor, 1967. Sediment Transport in a Coastal Plain Estuaries. Proceedings of the American Socican Society of Civil Engineers, Waterways and Harbors, 4:83~94.
- Peterson, D.H. and J.E. Festa, 1984. Numerical Simulation of Phytoplankton Productivity in Partially Mixed Estuaries. Estuarine, Coastal and Shelf Science, 19:536~589.
- Postma, H., 1967. Sediment Transport and Sedimentation in the Estuarine Environments. In Estuaries(Lauff, G.H. ed.). American Association of Science, 83L37~44.
- Pritchard, D.W.,1952. Salinity Distribution and Circulation in the Chesapeake Bay Estuarine System. Journal of Marine Research, 11:106~123.
- Pritchard, D.W., 1967. Observations of Circulation in Coastal Plain Estuaries, p37~44. In. Estuaries, American Association for the Advancement of Science Publication 83.
- Schubel, J.R., 1969. Size Distribution of the Suspended Particles of the Chesapeake Bay Turbidity Maximum. Netherlands Journal of Sea Research, 4:283~309.
- Sharp, J.H., C.H. Culberson and T.M Church, 1982. The Chemistry of the Delaware Estuary. General Consideration. Limnology and Oceanography, 27:1015~1028.
- Simpson, H.J., S.C. Williams, C.R. Oslen and D.E. Hammond, 1977. Nutrient and Particulate Matter Budgets in Urban Estuaries. In Estuaries, Geophysics, and the Environment. Natural Academic of Science, Washington, D.C., pp94~103.
- Strickland, J.D.H. and T.R. Parson, 1972. A Practical Handbook of Seawater Anaysis, 2nd ed. Fisheries Research Board of Canada, Bulletin. 167.
- Webb, K.L. and C.F. D'Elia, 1980. Nutrient and Oxgen Redistribution during a Spring-Neap Tidal Cycle in a Temperate estuary. Science, 207:983~985.
- Woodward, J.C., 1983. Summer Phytoplankton Distribution in the Tidal Potomac River: Flow, Temperature, and Nutrients. Esturies, 6:229.
- Yench, C.S. and D.W. Menzel, 1963. A Method for the Determination of Phytoplankton Chlorophyll and Phaeophytin by Fluorescence. Deep Sea Research, 10:221~231.

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## James 강 하구 저염분 지역에서의 식물 부유생물 현존량의 계절적 변화

문 창 호

부산 수산대학 해양학과

James 강 하구에서 1986년 7월 부터 1987년 8월까지 약 1달 간격으로 식물 부유생물의 현존량에 대한 조사를 하였다. 강 유입량이 적은 여름과 가을에 담수와 해수가 만나는 저염분 지역에서 많은 양의 식물 부유생물이 출현하였다. 이 많은 양의 출현은 영양염, 조석 그리고 수온과는 관계없이 estuary의 순환에 의한 규조류의 축적에 기인한 것으로 사료된다.