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DISTRIBUTION OF SUSPENDED MATERIALS IN CHESAPEAKE BAY

BY

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ABSTRACT

The distribution of suspended materials in Chesapeake Bay and its tributaries, discussed in terms of light extinction, is characterized by marked variability. There are large local time changes, seasonal and tidal, as well as large horizontal gradients. Variability in the suspended load results from varying distribution in the amount of suspended inorganic materials caused by wind mixing, tidal scouring and river discharge. Direct positive correlation between the amount of suspended materials and the diatom population was not found, though occasionally the influence of large diatom populations appears in the optical examination of raw water samples.

INTRODUCTION

In the preceding paper, Burt (1955) has shown that the optical density (extinction) curves of natural water samples (measured with the Beckman Model DU Quartz Prism Spectrophotometer) are related to the size distribution and concentration of suspended materials. The suspended load in ppm by volume for the average particle size distribution with an estimated median radius of 0.3 µ was approximately 45 times the numerical value of the optical density measured at a wave length of 600 mµ over a 10 cm path length.

The optical density is designated by $E$ and a subscript to denote the wave length at which the measurements were made; the ratio $S_1 = (E_{400}/E_{600})$ serves as a criterion (Burt, 1955) of the coarseness of the suspended material. When $S_1$ is greater than the average value, the suspended material is finer than average; when less, it is coarser than average.

This paper discusses the optical density and its variability as a measure of the concentration and variability of concentration of
suspended materials. There is approximately a linear relationship between the optical density and the suspended load, but of course the exact concentration of suspended materials depends on the size distribution of the sample. It will be shown later that most of the samples appear to have little variability in the size distribution of suspended particles except in the case of the clearest samples, where the median radius of particles appears to decrease with increasing clarity of the water.

![Graph](image)

Figure 1. Plot of $E_{600}$ against chlorophyll concentration for surface samples taken in the St. Mary's River during June and July 1951. The correlation coefficient was -0.38.

**SEASONAL AND AREAL DISTRIBUTION**

Discharge from the principal rivers contributes most of the inorganic material that enters Chesapeake Bay. Thus the average optical density increases in the spring months during peak flow and tends to decrease in the fall when runoff is at a minimum. However, the flow of any given river may vary widely at any time from its normal or average values.

A second source of suspended particles arises from continual production and decay of living organisms. During spring and summer the chlorophyll concentration (the only available measure of the standing crop) usually increases from regions with low average $E_{600}$ to regions with high average $E_{600}$. However, there was no correlation between optical density and chlorophyll concentration for serial
Figure 2. Increase in $E_{600}$ with distance upstream in the main tributary rivers. Surface observations: October 1950 (left) and January 1951 (right).

observations made at a given station (see Fig. 1). Like results were obtained for similar data taken the year before in the James River. It has been suggested that the negative correlation should be expected since diatom growth is favored by clearer water.

The third source, wind mixing and tidal scouring, brings back into suspension the material which has settled to the bottom. Shallow depths, averaging approximately 20 feet, frequent cyclones, and summer thunderstorms combine to make wind mixing an important factor throughout the year except during the early fall months. On the other hand, tidal scouring is important at all times.

The annual cycle of optical density consists of high values during winter and early spring (wind mixing and runoff), relatively high but widely fluctuating values during late spring and early summer (thunderstorms, runoff, and biological production), lower but highly fluctuating values during middle and late summer (thunderstorms and biological production), and low consistent values during the early fall when all factors except tidal scouring are operating at a minimum.
Figure 3. The Chesapeake Bay Region.
Optical density normally increases upstream in the major rivers. Absolute values of $E_{600}$ range from extreme lows of 0.02 during the fall to more than 0.5 during spring periods with high runoff (see Fig. 2).

The optical density of surface waters in the lower part of the Bay, south of 38° 10' N (Fig. 3), was largely influenced by that of waters from inflowing rivers with $E_{600}$ ranging from 0.02 to 0.12. Fig. 4 gives a plot of surface $E_{600}$ against latitude for a series of stations located in a line up the center of the lower Bay; this shows that, during times of high river outflow (spring), tongues of highly turbid water were located in the Bay off the mouth of each river. The surface waters from stations located in the center channel of the Bay were usually slightly clearer than the surface waters near the shallower edges where tidal scouring, wind mixing and local runoff have a maximum effect.

Pritchard (1952) considered the area from the mouth of the Potomac River (38° 10' N) northward as an extension of the Susquehanna River, which provides 87 per cent of the fresh water that enters the northern half of the Bay. The deep natural channel in the center of the Bay ends abruptly at approximately 39° N (the location of the Chesapeake Bay Bridge). Above this point the Bay is shallow except for dredged navigational channels. Salinity shows an average
drop of 5% in ten miles centered at 39° N. The section of the Bay above 39° N, sometimes called the "mud flats" of the Susquehanna, acts in a number of ways as an integral part of that river. Here the optical density was uniformly high except during the fall season. It increased with increasing latitude toward the geographic mouth of the river at 39° 35' N. The normal range of $E_{600}$ was from 0.07 to 1.0, with occasional values as high as 1.3. $E_{600} = 1.3$ corresponds to an extinction coefficient per meter of approximately 30.0.

The part of the Bay between 38° 10' (mouth of the Potomac) and 39° N was unique in that it usually contained clearer water than the lower part of the Bay. The optical density values were relatively constant, with $E_{600}$ normally ranging from 0.01 to 0.1. During maximum flow of the Susquehanna, the northern boundary of this area with its large horizontal gradients of salinity and turbidity moved a few miles southward from 39° N in a manner somewhat analogous to the southward movement of an atmospheric cold front on the surface of the earth. Thus the average value of $E_{600}$ for this area was increased materially.

Fig. 5 shows the optical front between waters of the upper Bay and mid-Bay for four different cruises. Note the horizontal change in $E_{600}$ exceeding a factor of ten which was observed during one of the cruises.

Optical densities in the shallow sounds and wide river mouths along the eastern shore of the Bay had nearly the same values as those found in the Bay proper at the same latitude. The eastern shore rivers with their low runoff differed from the Susquehanna and the major rivers on the western shore in that the optical density values often decreased in an upstream direction.

DISTRIBUTION OF $E_{600}$ WITH DEPTH

Twenty-six depth series were made during two cruises (fall and winter). Samples were drawn at two-foot depth intervals from the surface to 20 feet, at five-foot intervals from 20 feet to bottom. Sharp layers of increased optical density (opacity) such as those found in other regions by Whitney (1938), Pettersson (1934) and Joseph (1949) were not observed. A hydrophotometer, similar to that designed by Pettersson, was constructed in order to determine if the pumping technique was missing highly opaque layers. Ten runs were made with this instrument on the following cruise (spring). At the same time samples were drawn at two-foot depth intervals. Two of the stations contained relatively opaque layers which were equally apparent on the data obtained from either technique. From
Figure 5. Optical density front observed near the site of the Chesapeake Bay bridge during four different cruises. Data were averaged when more than one station was taken at any given latitude. Interpolated values of $E_{600}$ are presented for the earlier cruises where $E_{600}$ and $E_{700}$ were read.

From this evidence and from the fact that the previous 26 serial observations showed no sharp discontinuities, one might assume that they do not occur normally in this region. For additional evidence, a series of more than 100 unpublished Clarke photometer observations taken by Dr. Alfred Armstrong, College of William and Mary, were examined for the presence of sharp breaks in slope. These readings were taken during all seasons over a period of four years in the lower Bay and in the James, York and Rappahannock Rivers. Only one observation indicated the presence of a thin, highly opaque layer.

The $E_{600}$ data from surface to 20 feet were analyzed statistically for 11 stations occupied during October and November 1950 (fall)
and for 13 stations occupied during January 1951 (winter). Data from one station for each period were not used because they showed obvious average increases or decreases in optical density with depth. The coefficients of variation for the various stations of the fall cruises ranged from 7 to 18\%, with a mean value of 12\% and a standard deviation of 4\%. The variability as obtained from data of the winter cruise increased slightly; coefficients of variation ranged from 2 to 32\%, with a mean value of 14\% and a standard deviation of 10\%.

Below a depth of 20 feet the optical density tended to remain nearly constant or to increase slowly with depth until the bottom was almost reached, at which point the optical density usually increased rapidly for the remaining depth. This latter phenomenon was more pronounced over soft muddy bottoms than over hard sandy ones. Fig. 6 shows a number of typical optical density-depth plots for stations ranging in location from the mouth to the head of the Bay.

The occasional increase in optical density with depth below 20 feet must be due to effects of settling from above and to continual tidal scouring and transport of suspended materials at these depths. The normally high turbidities just over the bottom indicated the presence of a continual stirring action.
In transition regions, the less saline surface water with high turbidity overruns the more saline water with less turbidity. This is shown in Fig. 6 for the observation taken at 38° 58' N.

**LOCAL TIME CHANGE IN OPTICAL DENSITY**

One of the most striking features in the optical density distribution was the magnitude of the local time change, which was measured by taking serial observations each half hour from an anchored vessel. The suspended material appeared to occur in clouds of varying density, much the same as water, dust or haze clouds in the atmosphere. Thirteen anchor stations, located in a line running up the center of the Bay and in three of the major rivers, were made during April and May 1951. Surface and ten-foot samples were drawn at five stations for one quarter of a tidal cycle (six hours) and at the other eight stations for one half of a tidal cycle (12 hours).

Individual mean values of $E_{600}$ averaged for all observations from each station varied from 0.017 to 0.598 and standard deviations from 0.003 to 0.165. No correlation was found between the values of the means and the coefficients of variation, which indicates that the percentage dispersion about the mean was independent of the average optical density at the station.

The values of the coefficients of variation for the different stations ranged from 5 to 38%, with an arithmetic average value of 20%. The standard deviation of the coefficients of variation was 9%. If the distributions are considered normal, this indicates that 68% of the coefficients of variation would have values between 11 and 29%, or that only 16% of the coefficients of variation are less than 11%.

The statistics on variation of $E_{600}$ with depth which were presented above under the heading of Distribution of $E_{600}$ with Depth were of the same order of magnitude as those presented here for the time variation within half a tidal cycle.

Except for values from one station, located in the boundary zone at 39° N, the means of the surface and ten-foot samples taken simultaneously had nearly the same numerical value; i.e., the individual values at surface and at ten feet varied about the same mean. However, the correlation between the individually paired samples taken at the same time was erratic; the correlation coefficients for the five stations were $+0.30$, $-0.30$, $+0.66$, $+0.21$ and $+0.51$. This is further evidence of the apparent randomness of the cloudlike distribution of suspended material in the Bay waters.

Current velocity and direction were observed at approximately hourly intervals at each anchor station (Figs. 7, 8) to ascertain whether or not certain relationships existed between observed currents (tidal
stage) and variations in optical density. If the average optical density increased in an upstream or up-Bay direction, then the highest optical density should occur at any station at low water, which corresponds to slack water between ebb and flood. Conversely, lowest optical densities should occur at high water, comparable to slack water between flood and ebb. The curve of the optical density should be 90° out of phase with the current velocity curve, with maximum flood occurring three hours later than maximum optical density. The curves for the data from the river stations show a slight tendency to follow the expected pattern.

Surface current and optical density data for four mid-Bay stations are plotted in Fig. 8. There is some tendency for the optical density curves to be periodic in shape, but they are almost completely out of phase with the current curves (station at 38° 48' N) or nearly in phase (station at 38° 18' N). These stations were located in the channel, nearly in the center of the Bay; therefore any cyclical variation in optical density due to changes in the effective tidal scouring velocities on bottom should be obscured by the time they effected the surface.
The variation in the estimated median particle radius, $\bar{r}$, from sample to sample will be discussed in terms of the parameters $S_1 = (E_{400}/E_{600})$ and $S_2 = (E_{800}/E_{600})$. Theoretically (Burt, 1955), $S_1$ should increase numerically with decreasing average radius of particles in suspension while $S_2$ should increase numerically with an increasing proportion of suspended particles that are large in comparison to the wave length of light.

Surface samples (101) from the October and November 1950 cruise and surface samples (62) from the January 1951 cruise were analyzed statistically for variation in $S_1$ and $S_2$. These two cruises represent seasonal periods when the water was clearest (fall) and most turbid (winter). The mean value of $E_{600}$ for the fall cruise was 0.054, which increased to 0.128 for the winter cruise. The average value of $S_1$ dropped from 2.05 ($\bar{r} = 0.2\mu$) for the fall to 1.71 ($\bar{r} = 0.3\mu$) for the winter. The average value of $S_2$ remained constant at 0.77 for both cruises.
The high average value of $S_1$ for the fall observations indicates the preponderance of fine suspended material in the water. This is to be expected since a minimum amount of material is being added to the water at this season from all sources except tidal scouring. Most of the larger particles have settled out, leaving a more or less permanent suspension of fine material. The numerical value of $S_1$ is closely related to the absolute value of $E_{600}$ (the total amount of suspended materials). In Fig. 9, $S_1$ is randomly distributed between 1.4 ($\bar{\tau} = 0.5\mu$) and 2.0 ($\bar{\tau} = 0.2\mu$) for values of $E_{600} > 0.04$. Below $E_{600} = 0.04$ (approximately 2 ppm by volume) the numerical values of $S_1$ increase rapidly such that all values of $S_1$ for $E_{600} < 0.02$ (less than 1 ppm by volume) have steep optical density curves with $S_1 > 2.7$ ($\bar{\tau} < 0.1\mu$).

The values of $S_1$ for the winter cruise were randomly distributed about the mean value of 1.71 independently of $E_{600}$. None of the winter values of $E_{600}$ was small enough to determine whether $S_1$ became large as the concentration of particles became small.

No reasonable explanation was found for the constant average value of $S_2 = 0.77$ for both fall and winter cruises. $S_2$ was plotted against $E_{600}$ for both cruises, but no correlation existed. The values of $S_2$ varied in random manner between 0.70 and 0.90 about the average, independent of the total particle concentration. A plausible explanation for this phenomenon may be that sufficiently large light particles of biological origin may have been present in enough of the fall samples to have maintained this average value of $S_2$. 

![Figure 9. Relation between $E_{600}$ and the ratio $E_{400}/E_{600}$ for all surface samples taken during October and November 1950.](image-url)
IRREGULAR FEATURES IN OPTICAL DENSITY CURVES (E vs λ)

In the case of high optical density, indicating a high concentration of suspended material, the curves were usually smooth and regular. Conversely, as the optical density decreased, the curves tended to become less regular, with humps and peaks. See Fig. 10. These irregularities may be explained on the basis of one or more of the following factors: instrumental errors whose effects tend to become important as the optical density decreases, the presence of a large proportion of particles with uniform radii between 0.5µ and 5µ, and
strong absorption in small wave bands by highly colored substances in suspension.

It is difficult to show quantitatively the irregularity in optical density curves due to a suspension that contains a relatively large fraction of particles of uniform radii between 0.5\( \mu \) and 5\( \mu \). According to theory, a spread of sizes in this uniform group as represented by a coefficient of variation of only 10\% would tend to smooth out the effect. Although some of the irregularities may be caused by this factor, no samples indicated its presence in a clear-cut manner.

Pigmented plants constitute the only highly colored material known to be in suspension in recognizable amounts. Chlorophyll A is the most abundant pigment in plankton of these waters. To determine the magnitude of this possible source of irregularity, a number of transmission readings were made at 667 m\( \mu \), the highest wave length absorption peak for Chlorophyll A in the visible part of the spectrum. At 667 m\( \mu \), absorption peaks were superimposed on the optical density curves quite regularly during the spring cruise (May and June 1951), with a maximum value for regular stations of less than 5\% of the expected reading; this was found by drawing a smooth curve through \( E_{600} \) and \( E_{700} \). One reading taken especially for this purpose in the inner harbor at Reedville, Virginia had an extreme value of 10\%. This long and narrow shallow harbor supports a high plankton bloom during this time of year due to continual fertilization from a large fleet of Menhaden fishing vessels and several Menhaden reduction plants.

Fig. 11 contains optical density plots for samples from Reedville Harbor, York River, two lower Bay locations, as well as a laboratory experiment. The experimental curve was run on the liquid from a laboratory culture of \textit{Chlorella} which had died. Most of the particulate matter had settled out before the sample was taken. This was measured to see if a purely "biological" curve would have the same shape as those from the Bay samples. Note that the water sample taken at 60 feet in the lower Bay showed optical evidence of a recognizable amount of chlorophyll particulate matter.

Chlorophyll A has a second broad absorption band centered between 400 and 450 m\( \mu \), which is wider and somewhat stronger in optical density units for a given concentration of chlorophyll than the narrow absorption peak centered at 667 m\( \mu \). The presence of this shorter peak is easily seen on all four of the upper curves in Fig. 11. Both the 667 and 400–450 m\( \mu \) peaks are absent from the York River curve taken at nearly the same time.

The above data show that, although the presence of green particulate or living organisms is easily detected by optical density measure-
Figure 11. Optical density curves illustrating the 667 mµ absorption peak due to absorption by particulate matter with a high concentration of Chlorophyll A. The solid curves are drawn to the scale of the left ordinate, while the broken and dotted curves are drawn to the expanded scale of the right ordinate.

ments at 450 or 667 mµ, it does not materially affect the over-all shape or magnitude of the optical density curves.

CONCLUSIONS

1. The distribution of suspended materials is highly variable both horizontally and vertically as well as with time.
2. Concentrations of suspended materials range from less than 1 to approximately 60 parts per million by volume.
3. Small particles occur in cloudlike distributions which may cause variations in extinction of as much as a factor of four at a given location during a single half tidal cycle.
4. Highly opaque layers did not normally occur.
5. The clearest samples contained the smallest average size particles; for the more turbid samples, no correlation was found between the average particle size and the concentration of particles.
6. No correlation was found between particle concentration and chlorophyll content for serial observations, although the presence of particles containing a high concentration of Chlorophyll A was indicated by an increased absorption at 667 m\(\mu\) on the optical density curves for unfiltered samples.

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