Turbidity and Suspended Solids Concentrations in Coastal Areas*

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Synopsis

The distributions of suspended solids in an estuary and in its coastal region were investigated by the gravimetric method and with the optical method using an *in situ* beam transmissometer under normal condition, during a rise of the river and during seasonal variation.

The turbidity values at the sea surface during a rise of river represent 3.5 to 4.0/*m* near the river mouth and 1.0/*m* at 3 km from the coast. Each value was 1.5 to 3.0 times as large as that of normal condition near the river mouth and was 5 to 7 times at 3 km from the coast. The turbidity values in summer and in autumn are higher than in winter because of the biological factors.

The turbidity and the concentrations of suspended solids show a high degree of covariance. It is possible to estimate the concentrations of suspended solids from the turbidity. There is a linear relation between the reciprocal secchi-depth and the mean values of the concentration between the surface and the secchi-depth.

1. Introduction

Recently, a large amount of suspended solids attendant upon dredging and public works in river has been discharged into coastal waters; unavoidably some coastal aquatic life has been adversely affected. The discharge of suspended solids into coastal areas is expected to increase in the future. If wastes are discharged or if consideration is given to their discharge, it is necessary to know about their diffusion in time and space. Beam transmissometers has been stimulated by the evolution of marine science toward direct investigation of processes.

In this paper, the distributions of suspended solids in an estuary and in its coastal region are investigated under normal conditions, during a rise of river, and during seasonal variations. Measurements were made in January, August and November, 1973; in October, 1974, and in January 1975. The concentrations of suspended solids were measured with the optical method using an *in situ* beam transmissometer. The sea water sampled from the surface and each layers was filtered and the concentrations of total suspended solids were determined.

2. Location

The distribution of suspended solids and of turbidity in the sea water off the coast of Uragami, on the east side of Kii Penisula were surveyed. The location of each station is shown in Fig. 1. More than three thouthand millimeters of rain fall here annualy. Consequently, a large amount of sand and mud are transported from upstream on the Ohota River and are discharged through the river into the coastal region. Tsuda, *et al.*[1] reported their measurements of the amount of particulate material discharged from the Ohota River which entered the inner side of Uragami Bay with sea water during ebb tide.

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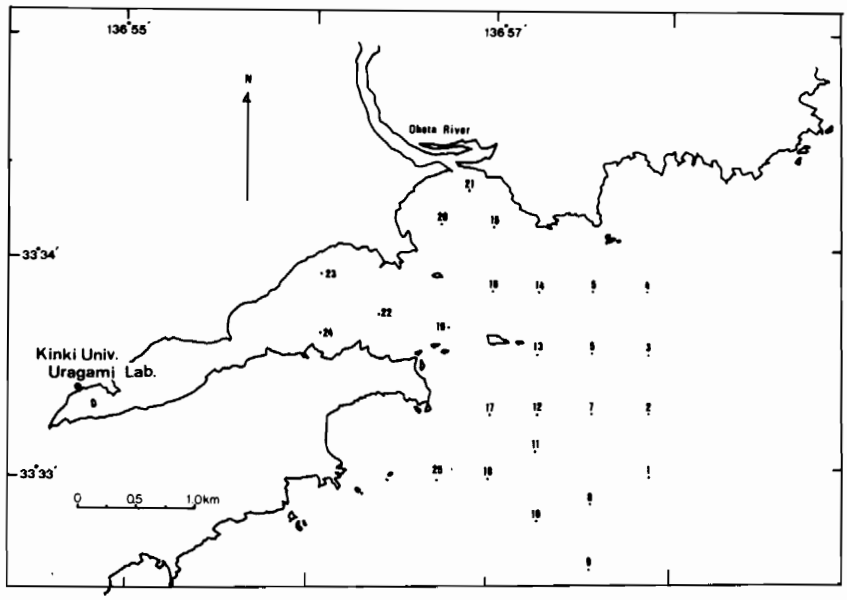


Fig. 1. The location of each station.

3. Methods

Measurement of turbidity of sea water

An *in situ* beam transmissometer of a 50 *cm* path length was used for measuring the turbidity of the sea water. A diagram of the optical system is shown in Fig. 2. The light source is a halogen lamp ($6V, 5A$) and a light flux from the lamp is converted to a parellel beam by a collimator lens. The lens-system of the receiver is designed to prevent, as far as possible ambient light and scattered light from reaching the photocell (Sharp SBC-111) with a pinhole (1.5 *mm* diameter) and a lens (f = 50 *cm*) so that the acceptance angle (2θ) is 1°49′.

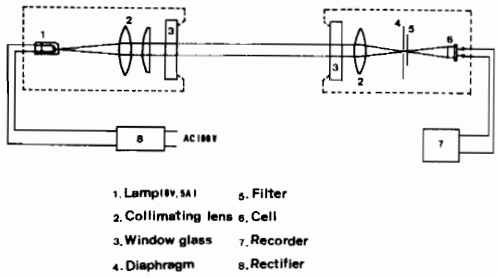


Fig. 2. Optical system and electrical circuit of *in situ* beam transmissometers.

The beam attenuation coefficient, α in the sea was obtained through the following equation.

$$\alpha = \frac{1}{r} \cdot \ln \frac{IA}{IW} - \frac{2}{r} \cdot \ln \left(\frac{1 - RW}{1 - RA} \right) \quad (m^{-1})$$

where IA and IW are readings of a recoder in the air and in the water, RA and RW are reflections of the collimated beam between the air and the glass and between the air and the water so that the calculated result of the second term is 0.149 and r is the path length.

The turbidity was defined by the light attenuation which is caused by suspended matter only in the sea, hence the absorption due to dissolved substances was minimized as much as possible. The filter was red interference filter (699 *nm* at the maximum transmittance). The calculated beam attenuation coefficient, α through the above equation, indicated the attenuation by water itself; therefore, its value must be deduced from the calculated values for discussing the turbidity in the sea. The attenuation coefficient of distilled water is 0.50/*m* at 699 *nm* from measurements by Hulbert[2].

Determination of suspended solids in the sea

Surface water was sampled with a plastic-bucket, and 2-10 *l* of sea water from each layer were sampled with the water-sampler. Sampled sea water was filtered through a *HA*-Millipore filter (diameter: 47 *mm*, pore size: 0.45μm) and the concentrations of total suspended solids were determined by the weight difference of filters before and after vacuum filtration.

4. Results

Horizontal distribution

Horizontal distributions of turbidity at the sea surface are shown in Fig. 3. Measurements were made in January, August and November, 1973; October, 1974 and January, 1975 during ebb tides. Especially, the horizontal distributions of January and November, 1973 are the results of measurements after a heavy rain and storms. The sea surface was more turbid because of the concequent increase of discharged suspended materials from the Ohota River. Turbidity values in January and November, 1973 represent 3.5 to 4.0/*m* near the river mouth and 1.0/*m* at 3 km from the coast. The turbidity values of January, 1973 were about 3 time as large as that of January in 1975 near the mouth and were 7 times as great at 3 km from the coast. Similarly, the turbidity values of November, 1973 were about 1.5 times as large as that of October, 1974 near the river mouth and 5 times as large at 3 km from the coast. Comparing the results of January with those of November, the latter indicated wider diffusion areas. The reason for this is related to the times and amounts discharged from the Ohota River.

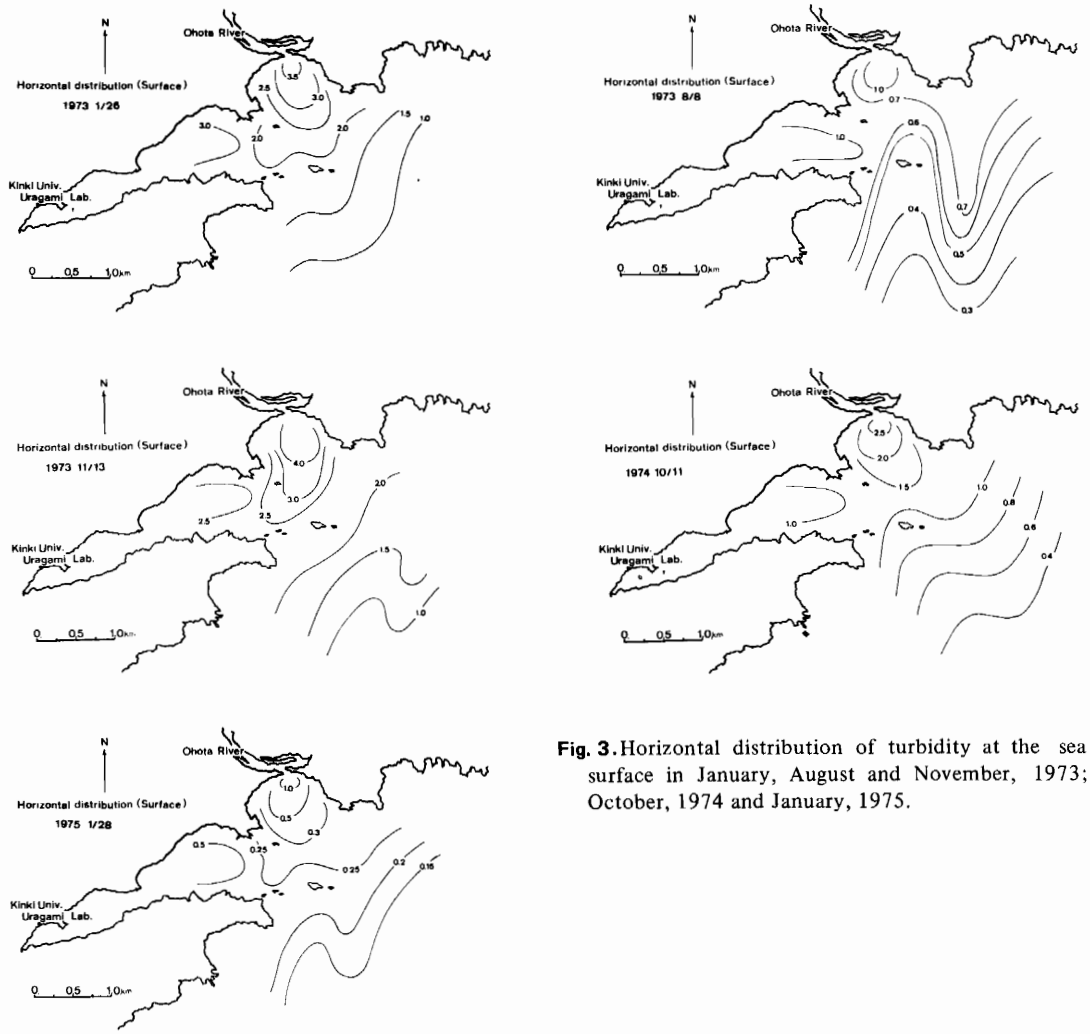


Fig. 3. Horizontal distribution of turbidity at the sea surface in January, August and November, 1973; October, 1974 and January, 1975.

Vertical distribution

Vertical distributions of the turbidity near the river mouth (St. 20), at 1.2 km (St. 14) and at 3 km (St. 11) from the coast are shown in Fig. 4. At each station, the turbidity in January and November, 1973 was high because measurements were taken after heavy rains.

Generally, the values of turbidity in the surface layer were high and gradually become lower with depth, but are again high near the bottom. The high value of the surface layer is due to particulate materials discharged from the Ohota River and that of the bottom is attributed to the fine sediment stirred up from the bottom by currents. As distance increases from the river mouth, there is not nearly as much difference in the amount of turbidity at the surface and at the bottom, so that the turbidity distribution seems to be constant. In winter, turbidity at the surface layer of St. 14 in 1973 and that of St. 11 in 1975 were nearly constant on account of violent turbulence. Generally, the profiles of vertical distribution are nearly the same except after heavy rains. If we accept that the profiles of turbidity

distribution of August, 1973, of October, 1974 and of January, 1975 are normal, these show that fresh water has no effect 3 km from the coast except at the sub-surface layer, and turbidity values in summer and in autumn are higher than in winter because of the biological factors. Venugopalan[3] reported that in an estuary, the values of particulate materials and chlorophyll-*a* in summer are larger than in winter.

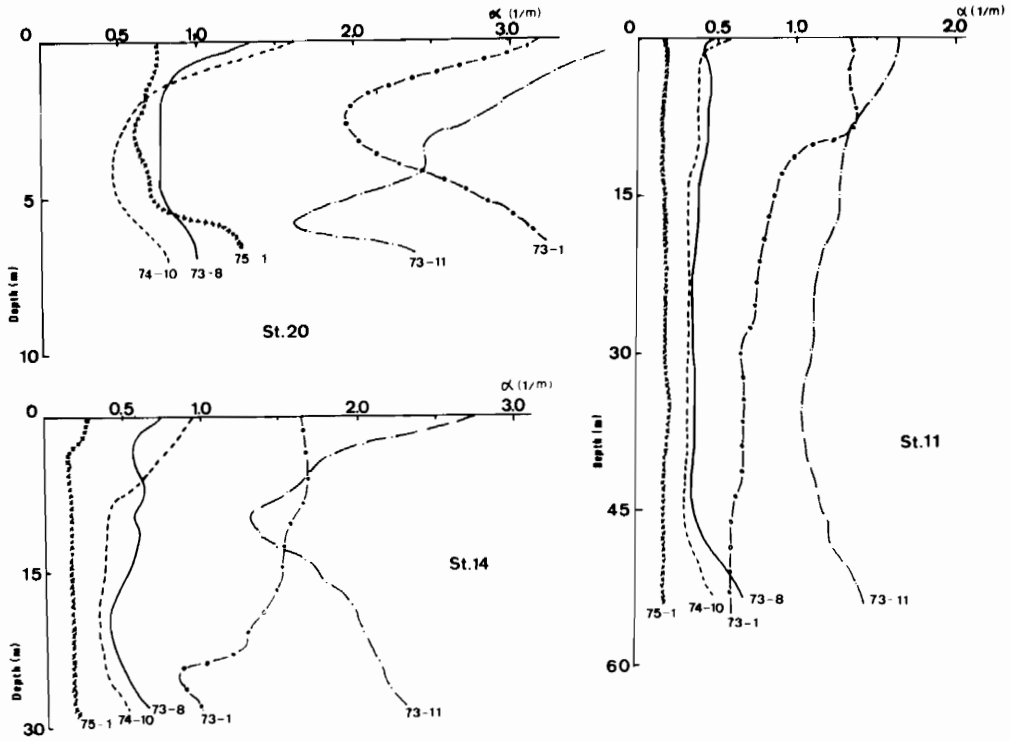
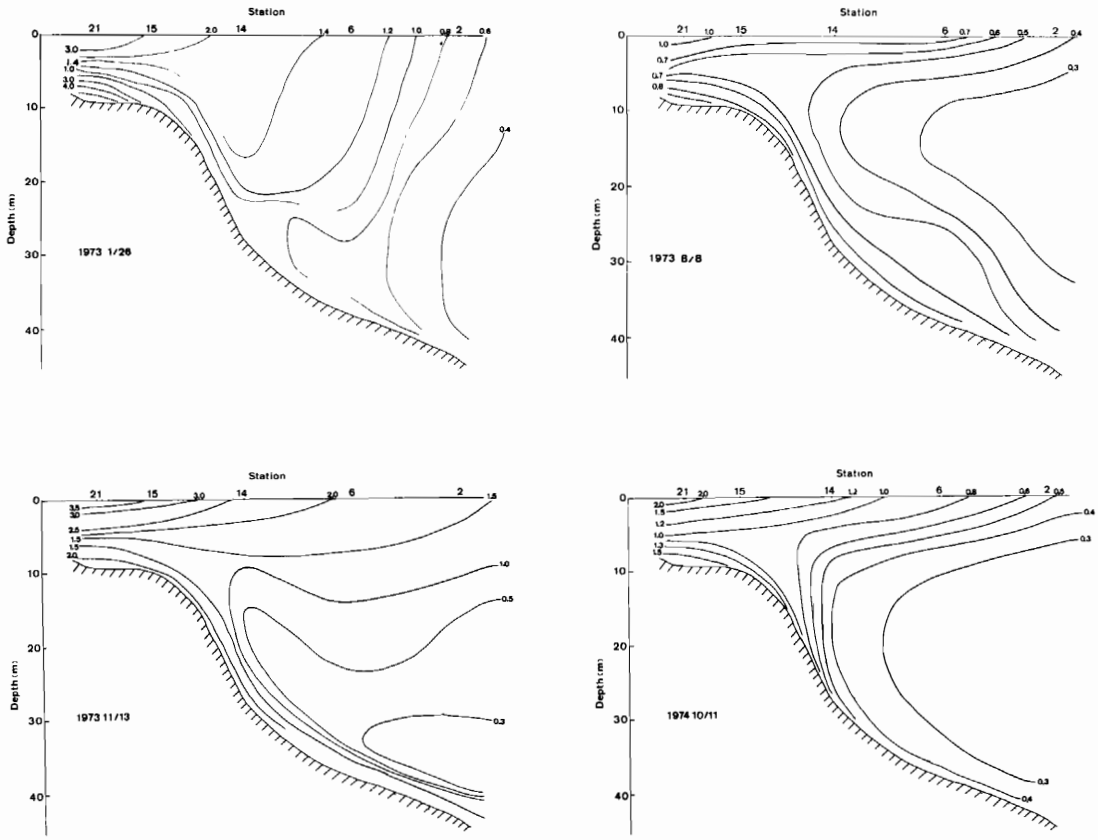


Fig. 4. Vertical distribution of turbidity of Sts. 11, 14, and 20.

Vertical sectional distribution

Fig. 5 shows the vertical sectional distribution of turbidity. In Fig. 5, the highly turbid waters in the surface layer from the river mouth to 3 km from the coast are due to the amount of suspended materials supplied by the Ohota River. The turbidity of the surface layer in January and in November, 1973 was very high because of a large amount of particulate materials discharged from the Ohota River which was raised by a heavy rainfall. The turbidity of the surface layer in January, 1973 was about five times that of January, 1975 and similarly, that of November, 1973 was about two times that of October, 1974 near the river mouth. At 3 km off the coast, the turbidity values of January and of November, 1973, were about two times that of January, 1975, and of October, 1974. Turbidity distribution near the river mouth is stratified, but each seasonal turbidity distribution has its own pattern at various distances from the river mouth. The vertical sectional distribution of turbidity are small at about 1.2 km off the coast, near St. 14, and highly turbid waters are found near the bottom layer; therefore, it may be assumed that the discharged particulate materials have been sedimented. The turbidity is nearly constant from the surface layer to the bottom layer on

account of violent turbulences in the water which increase with the distance from the shore. The vertical sectional distribution of turbidity in November, 1973, shows that highly turbid waters were noted to 3 km off the coast at the surface layer and were stratified and clear sea water the intermediate layer and penetrated to near the bottom layer, but the turbidity value was high near the bottom. The sedimentation phenomenon was less outstanding in November, 1973, that in January, 1973. Observations of January, 1973, were made three days after the Ohota River was in flood, but those of November, were made only two days after a flood so that it may be assumed that the sedimentation had not proceeded so much. The vertical sectional distributions of turbidity in August, 1973, in October, 1974 and in January, 1975, are simpler. The distribution of turbidity in summer and in autumn show that highly turbid waters have been in the surface layers near the river mouth, but clear sea waters have entered into the intermidiate layer and penetrated to the bottom layer. It may be assumed that on account of biological factors, the turbidity near the bottom is greater in summer than in autumn. The turbidity in winter is less than in other measured months and is nearly constant from the surface layer to the bottom layer seaward from the coast. Comparing the turbidity in summer and in winter, the former is grater than the latter. It seems to be a result of biological factors as before.



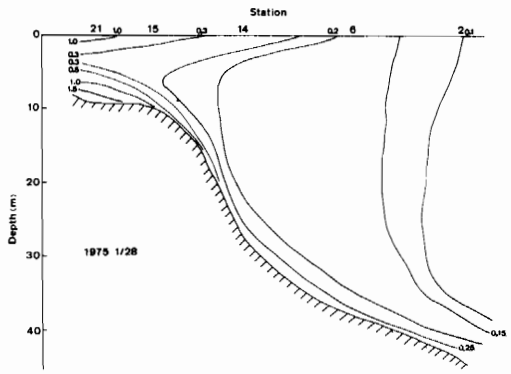


Fig. 5. Vertical sectional distribution of turbidity in January, August, and November, 1973; October, 1974 and January, 1975.

5. Discussions

Turbidity and precipitation

The increase of turbidity in the coastal region is due to a rise of the river, and flux from the river is closely related to precipitation (Fukuda, *et al.*[4]). Daily precipitation for five days before the observation day is shown in Fig. 6 and the total precipitation for five days, is shown in Table 1. The increase of turbidity in January and in November, 1973 is due to a rise of the Ohota River mentioned above. What is evident from Table 1 is the large amount of rainfall before the observation day. The heavy rainfall would logically increase the flux from the Ohota River.

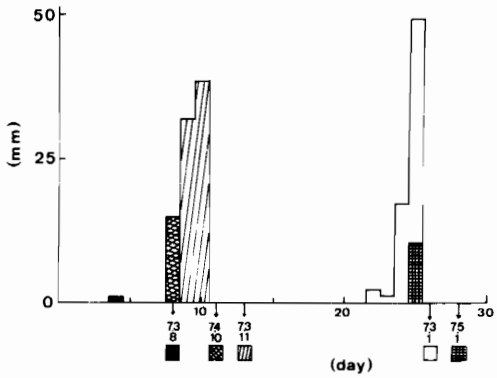


Fig. 6. Daily precipitation for five days before the observational day.

Table 1. Total precipitation for five days.

Day	Total precipitation
26/ 1/'73	70.0 mm
8/ 8/'73	1.1 mm
13/11/'73	70.2 mm
11/10/'74	15.1 mm
28/ 1/'75	10.5 mm

Fig. 7 shows the relation between the value of the surface turbidity and the distance from the river mouth. The turbidity values in January and in November, 1973, around the river mouth region were higher on account of a large amount of particulate materials discharged from river, but rapidly decreased with the distance from shore. Owing to continuous rainfall for a few days before the observation, the turbidity values around the river mouth was high in October, 1974, but were nearly constant at about 2 km off the coast. The turbidity

fluctuations of August, 1973, and of January, 1975, were smaller and become nearly constant about 1 km off the coast. From these results, it becomes clear that the turbidity distribution in coastal areas is closely related to flux from the river, namely precipitation.

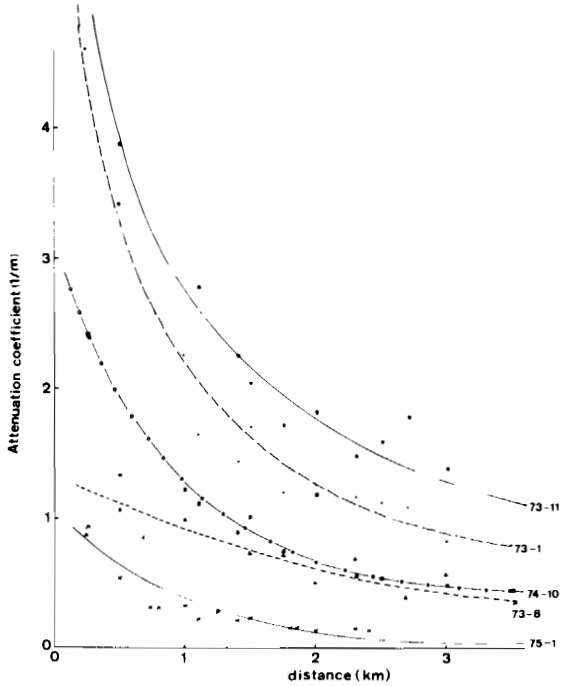


Fig. 7. The surface values of turbidity and the distance from the river mouth.

Turbidity and concentrations of suspended solids

What is evident from the measured values is that the turbidity of the Uragami coastal sea can be attributed to the particulate materials discharged from the Ohota River. It is an effective method to use an *in situ* beam transmissometer for estimating the concentrations of suspended solids in the sea. In this case, however, it is necessary to determine the relation between the concentrations of suspended solids and the turbidity, because the size and the composition of suspended solids are different in each area. Many researchers (Jones, *et al.*[5], Hanaoka, *et al.*[6], Otto[7], Takematsu, *et al.*.[8], Drake, *et al.*[9]) have reported that the relation between the concentrations of suspended solids and the attenuation coefficient is obtained by relating the attenuation coefficient to the rate of light attenuation caused by the concentrations of suspended solids.

The relation between the concentrations of suspended solids and the attenuation coefficient in the Uragami coastal sea obtained by the least squares method is shown in Table 2. Correlation coefficients for each these curves are about 0.9 demonstrating a high covariance of attenuation coefficient and particulate matter. Especially, the correlation of January and of November, 1973, has satisfactory value and the correlation coefficients are 0.99 and 0.97. This is because the particulate materials discharged from river conprised a greater part of the suspended matter around the coastal sea and these materials appear to be composed of the same size distribution and costitution. The correlations of August, 1973, and that of January,

1975, are satisfactory, too. The gradients in August, 1973, and in January, 1975, are 0.31 and 0.41. These are very close to the results of January and of November, 1973. This is because the concentrations of suspended solids around the Uragami coastal sea is due to particulate materials supplied from the Ohota River. Therefore, the correlation between the suspended living and decaying organic matter in the sea and the suspended inorganic matter seems to be unsatisfactory. When the concentrations of suspended solids is zero, the attenuation coefficient is $0.29/m$, $0.23/m$, $0.18/m$ and $0.10/m$ in each equation. It may be assumed that these values are contributed to the scattering of particles below $0.45\mu m$.

Table 2. Relation between the concentrations of suspended solids, C and the attenuation coefficient, α.

Day	Nr. of observ.	Relation between α and C	Correl. coeff.
26/ 1/'73	29	$\alpha = 0.40 \cdot C + 0.29$	0.99
8/ 8/'73	70	$\alpha = 0.31 \cdot C + 0.23$	0.88
13/11/'73	16	$\alpha = 0.41 \cdot C + 0.18$	0.97
28/ 1/'75	11	$\alpha = 0.40 \cdot C + 0.10$	0.95

Using the measurements obtained around the Uragami coastal sea, the relation between the concentrations of suspended solids and the turbidity was extracted as follow:

$$\alpha = 0.42 \cdot C + 0.13 \qquad (r = 0.98) \tag{1}$$

α is the attenuation coefficient and C is the concentrations of suspended solids.

Fig. 8 shows the relation between the concentrations of suspended solids and the attenuation coefficient.

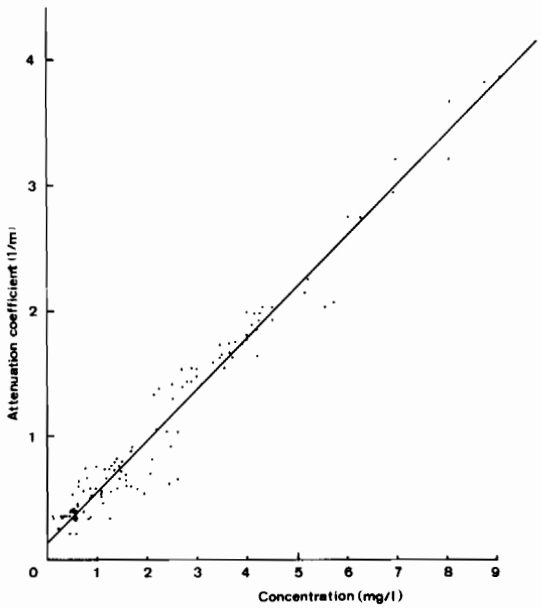


Fig. 8. Relation between the concentrations of suspended solids and the attenuation coefficient.

Secchi depth around the coastal seas of high turbidity seems to be closely related to the concentrations of suspended solids. For the mean value $\overline{C}$ of C between the surface and the secchi-depth Z_{SD}, a relation $\overline{C} \cdot Z_{SD} = 16$ has been established by Jones, *et al.*[5] for observations in the English Channel near Plymouth. Postma[10] has pointed out that the relation between the concentrations of suspended solids and the reciprocal secchi-depth is linear for observations made in the Wadden Sea. The mean value $\overline{C}$ of C between the surface and the secchi-depth Z_{SD} in the Uragami coastal seas is given in Table 3. The correlations for the observations of January and of November, 1973, are not so satisfactory. As seen from the vertical distribution of turbidity, a large amount of particulate materials are discharged from the Ohota River after a heavy rainfall. As result, more turbid water is distributed at the sub-surface layer and the optical properties of the water masses are inhomogenous so that when a large amount of particulate material is discharge through the river after its rise, it is difficult to estimate the mean concentrations of suspended solids from the observations of the secchi-depth. The relation between the mean value of the concentration between the surface

Table 3. Relation between the mean value, $\overline{C}$ and the secchi-depth, Z_{SD}

Day	Nr. of observ.	Relation between C and Z_{SD}	Correl. coeff.
26/ 1/'73	22	$1/Z_{SD} = 6.0 \cdot \overline{C} \times 10^{-3} + 0.18$	0.24
8/ 8/'73	24	$1/Z_{SD} = 4.9 \cdot \overline{C} \times 10^{-2} + 0.03$	0.86
13/11/'73	15	$1/Z_{SD} = 2.5 \cdot \overline{C} \times 10^{-2} + 0.08$	0.66
28/ 1/'75	11	$1/Z_{SD} = 4.0 \cdot \overline{C} \times 10^{-2} + 0.06$	0.93

and the secci-depth and the reciprocal secchi-depth for the observations of August, 1973, and of January, 1975, obtained by the least squares method is as follows:

$$\frac{1}{Z_{SD}} = 0.044 \cdot \overline{C} + 0.042 \quad (r = 0.88) \tag{2}$$

Fig. 9 shows the means value $\overline{C}$ of the concentration between the surface and the secchi-depth and the reciprocal secchi-depth Z_{SD}. The slope given by this equation is similar to that of Menai Strain in England in the results of Buchen, *et al.*[11].

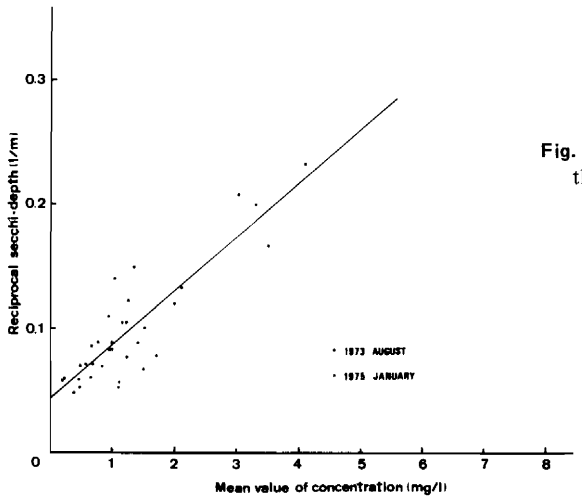


Fig. 9. Relation between the reciprocal secchi-depth and the mean value of concentration.

Using the equation (1) and (2) from the secchi-depth obtained for the observations in October, 1974, the mean values, α of attenuation coefficient between the surface and the secchi-depth were estimated. For example, the secchi-depths of Stns. 11, 14 and 20 are 17.0 m, 12.5 m and 7.5 m, respectively. The values of α calculated from each are $0.37/m$, $0.50/m$ and $0.87/m$. The mean values, α obtained from the observations are $0.46/m$, $0.50/m$ and $0.90/m$. The measured values agree with the calculation results so that using the equations (1) and (2), it is possible to estimate C and α from the values of the secchi-depth in Uragami coastal seas. The distribution of the mean concentrations of suspended solids in this sea after a rise of the river were estimated from the values of the secchi-depth using the equation (2). The results of the calculation are presented in Fig. 10. In January, the mean concentrations

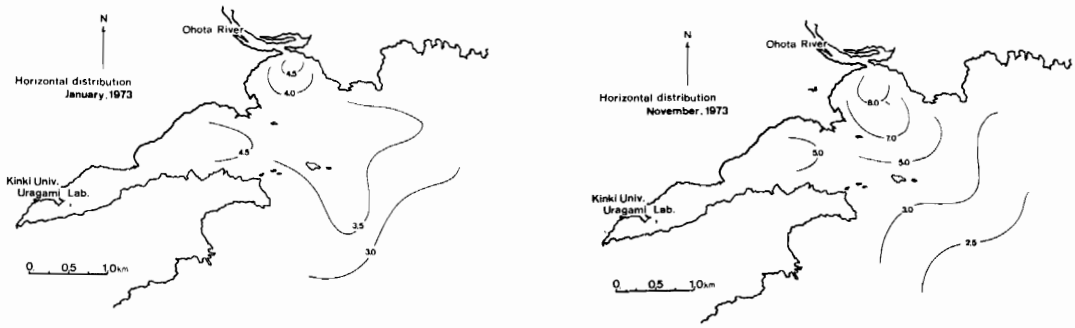


Fig. 10. The calculated values of suspended solids in January and November, 1973.

of suspended solids were about 4.0 – 4.5 mg/l near the river mouth and were about 3.0 mg/l at 3 km off the coast, and in November, these were about 8.0 mg/l near the river mouth and about 2.5 mg/l at 3 km off the coast. At the river mouth, the mean concentrations of suspended solids in November were about two times as large as that in January. As before, this may be attributed to the discharge time and to the flux of the Ohota River.

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沿岸域における濁度と懸濁物濃度

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要 約

沿岸域における濁度と懸濁物濃度 河川流入域とその沿岸域における懸濁物分布を河川水の平水時と増水時に分けて調べると共に，その季節変化も調べた。懸濁物の水平，鉛直分布は現場用濁度計を用いて測定した。その結果，増水時における表面の濁度は河口域で3.5~4.0 m^{-1}で平水時の約1.5倍~3倍であった。また，沖合い3*km*付近における値は1.0 m^{-1}と平水時の約5倍~7倍であった。一般に夏季，秋季における濁度は冬季よりも大きいが、これは生物的な原因によるものと思われる。

濁度と懸濁物濃度の間には高い相関が見られ、また透明度と透明度深までの平均懸濁物濃度の間には直線関係が示された。

（昭和53年10月16日受理）