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OPTICAL MODELS AND DATABASES

Estimation of the Total Concentration of Suspended Matter and Its Organic and Mineral Fractions in Lake Baikal by the Secchi Disk

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Abstract—Based on the measurements of light scattering functions in different regions of Lake Baikal in summer 1979, the characteristics of suspended matter in surface waters are calculated, including the mass and number concentrations of particles of suspended matter and its different fractions. From this data, the relationships with Secchi Disk are derived. The formula for the relationship between the mass concentration of suspended matter and the Secchi Disk for Lake Baikal is compared with similar formulas for marine waters.

Keywords: Lake Baikal, scattering phase function, Secchi Disk, Secchi depth, suspended matter, organic particles, mineral particles, mass concentration of suspended particles, number concentration of suspended particles

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INTRODUCTION

All natural water basins contain particles of different origin suspended in water, named “suspended matter”. The suspended matter plays an important role in numerous biological, physical, and chemical processes occurring in the water medium. Therefore, acquisition of the information on the concentration and composition of suspended matter in natural waters is an urgent task.

There are different methods for determining the suspended matter concentration: direct and indirect. The widely used gravimetric method is direct. It requires significant time for preparation of filters, sampling, filtration, washing filters with filtrate from marine salt, drying filters with filtrate, weighing of filters, etc. Therefore, in practice, indirect (faster) methods are used, where the suspended matter concentration is calculated by empiric formulas of relationships with certain optical characteristics, in particular, with the Secchi depth Z_w.

The suspended matter influences the character of light scattering in water. There are methods for inversion of the light scattering phase function $\sigma(\theta)$, which allows the determination of the number and mass concentrations of organic and mineral particles, as well as their total concentration from the measured values of the scattering phase function. This method was used in [1] and in this work for finding the concentration of suspended matter in the Lake Baikal waters.

The aim of this work is derivation of the relationship between the Secchi depth and total concentration of suspended matter and concentrations of its organic and mineral fractions in surface waters of Lake Baikal.

MEASUREMENT REGIONS AND EQUIPMENT

The measurements were conducted by the Limnology Institute, Siberian Branch, Russian Academy of Sciences, in June 1979 during the expedition of the G. Yu. Vereshchagin research vessel. During the expedition, the limnologic section was made along the axis of Lake Baikal from its south end to the north end. Simultaneous measurements of the scattering phase function and Secchi depth were made at 13 stations in different regions of the lake.

The scattering phase function was measured with the nephelometer [2] at a depth of 5 m. The nephelometer specifications are given in Table 1. The Secchi depth was determined in the standard way.

The minimal angle, for which the scattering phase function can be determined with the nephelometer, is 2°. The scattering phase functions, necessary for suspended matter calculation at the angles $\theta < 2°$, were determined through extrapolation of the measured scattering phase function into this region by the formula $\log\sigma(\theta) = A + B\theta + C\theta^2$. To find the coefficients A, B, and C, the scattering phase functions $\sigma(\theta)$ measured at angles $\theta = 2; 7.5; 12.5°$ were used.

Table 1. Specifications of the nephelometer

Parameter	Value
Angles of measurements $\sigma(\theta)$, deg.	2; 7.5...(5)...162.5
Spectral range of measurements, nm	520 (±40)
Measurement error $\sigma(\theta)$, %	10
Maximal immersion depth, m	150

Table 2. Regression coefficients *m* and *n* and relative root mean square errors δ in determination of suspended matter parameters

r, μm	θ, deg.	N, mil/L			C, mg/L		
		m	n	δN	m	n	δC
0.2–0.5	45.0	3×10^4	–1.0	0.29	8.9×10^3	–3.0	0.16
0.5–1.0	6.0	9.5	0.2	0.14	24.0	0.5	0.14
>1.0	1.0	0.2	0.3	0.35	12.0	16.0	0.20

FORMULAS FOR SUSPENDED MATTER CALCULATIONS

To calculate suspended matter characteristics from the scattering phase functions, formulas from [3] were used. In this work, formulas are presented for calculation of the number and mass concentrations for three particle fractions: 1) $r = 0.2$–0.5; 2) 0.5–1.0, and 3) $r > 1.0$ μm (r is the particle radius) from light scattering indices ($\lambda = 546$ nm). Particles of the first and second fractions compose the mineral fraction of the suspended matter, and of the third fraction, organic. In calculations of the mass concentration, the density of mineral particles is taken as 2 g cm^{-3}, and of organic particles, to 1 g cm^{-3}.

For particles of the third fraction, the scattering phase function $\sigma(\theta)$ at $\theta = 1°$ is used; for particles of the first and second fractions, at $\theta = 45$ and 6°. Table 2 presents coefficients for calculation of the number of particles N and their mass concentrations C by the formula

$$N(C) = m\sigma(\theta) + n \quad (1)$$

(m and n are the regression coefficients).

The suspended matter concentration was determined by the gravimetric method in a series of samples. The total concentrations calculated by formulas from [3] were compared with the values calculated by the gravimetric method. The ratio $C_{grav}/C_{calc} = 1.058$ was obtained over 25 measurements in the range of suspended matter concentrations in the gravimetric method $C_{grav} = 0.40$–1.25 mg/L. Since the difference between the results obtained by both methods was insignificant, the magnitude C_{calc} was used without correction.

Table 3. Ranges of variations in the mass *C* and number concentrations *N* of suspended matter

Parameter	Range
Mass concentration, mg/L	
C_{tot}	0.35–1.36
C_{org}	0.21–0.78
C_{miner}	0.14–0.58
C_{miner}/C_{tot}	0.24–0.51
Number concentration, mil/L	
N_{tot}	463–1540
N_{org}	3.6–13.6
N_{miner}	459–1531
N_{miner}/N_{tot}	0.980–0.994

RESULTS

Table 3 presents the ranges of the suspended matter parameters calculated from measurements of the scattering phase function at a depth of 5 m. The range of variation in the Secchi depth is 5–19 m.

Figures 1 and 2 show the correlations between Z_w and the mass and number concentrations of the suspended matter and its organic and mineral fractions.

Table 4 presents parameters of the correlations between Z_w and concentrations of all fractions of the suspended matter.

DISCUSSION

Mass Concentration of Suspended Matter

Strong correlations are observed between Z_w and the mass concentrations of the suspended matter and its organic and mineral fractions, particularly, the mineral fraction.

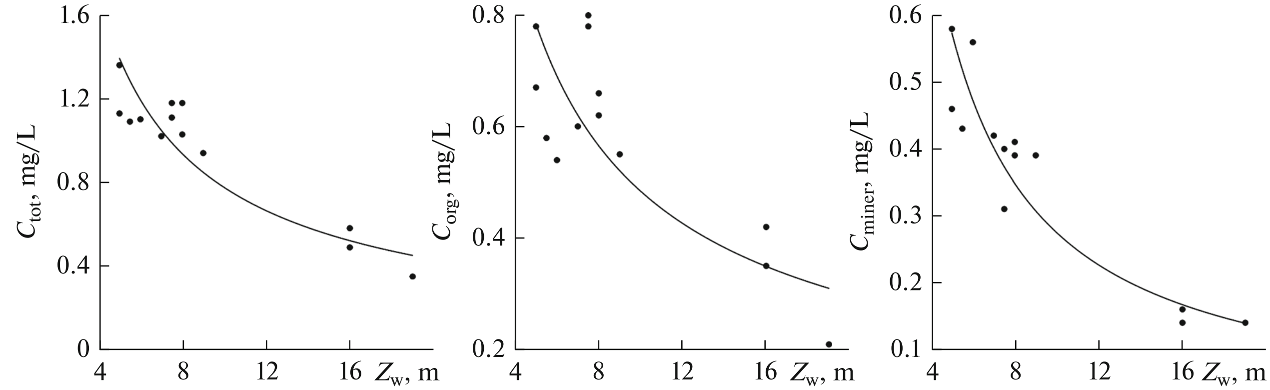

Fig. 1. Correlations of the mass concentration of (a) suspended matter and (b) its organic and (c) mineral fractions with the Secchi depth in Lake Baikal.

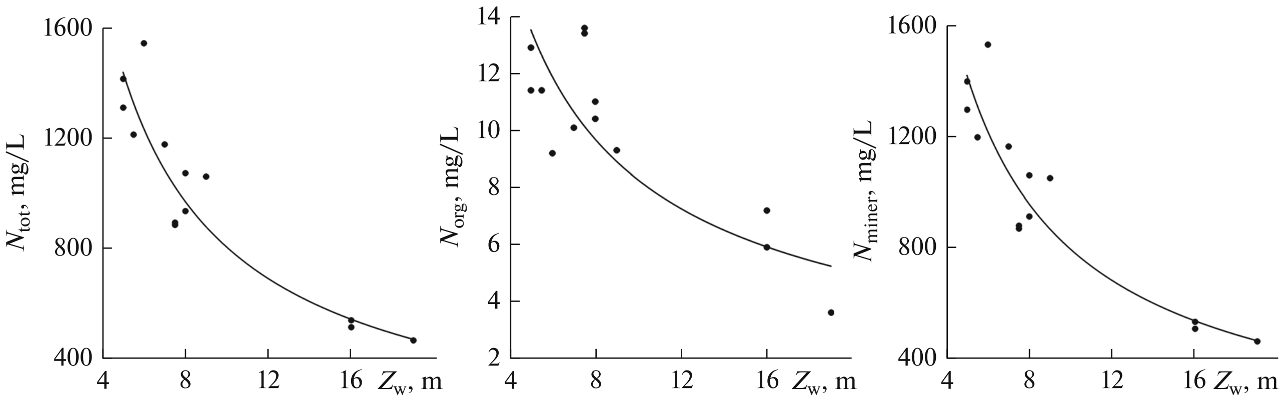

Fig. 2. Correlations of the number concentration of (a) suspended matter and (b) its organic and (c) mineral fractions with the Secchi depth in Lake Baikal.

Let us compare values of the total mass concentration of the suspended matter calculated by regression equations (Table 4) C_{tot} and $C_{org} + C_{miner}$ (Fig. 3). The results differ insignificantly: $C_{tot}/(C_{org} + C_{miner}) = 1.002$ for $Z_w = 19$ m and 1.023 for $Z_w = 5$ m, i.e., calculations from all formulas of suspended matter concentration show good agreement.

In works [4, 5], the correlation between the total concentration of suspended matter and the Secchi depth in sea water was studied. In [4], the following formula was derived ($R = 0.74$) from observation data in the Mediterranean and Black Seas, the Atlantic and Indian Oceans for the Z_w range 1.5–29.0 m:

$$C_{tot} = 4.59 Z_w^{-0.85}. \quad (2)$$

In [5], results of observations in the Mediterranean, Caspian, and Black Seas and at Guinean Shelf in the Atlantic Ocean were used. For the Z_w range 0.05–29.0 m, the formula

$$C_{tot} = 14.79 Z_w^{-1.29} \quad (3)$$

was derived ($R = 0.97$).

Figure 4 shows curves $C_{tot} = f(Z_w)$ plotted by our data for Lake Baikal and by equations from [4, 5]. The curves for Lake Baikal and from [4] have equal slopes. In the equations [4], the exponent of Z_w (–0.85)

Table 4. Parameters of correlation between Z_w and concentrations of all suspended matter fractions (13 measurements; R is the correlation coefficient; S is the standard error of regression)

Correlation equation	R	S
Mass concentration, mg/L		
$C_{tot} = 5.41 Z_w^{-0.844}$	0.927 ± 0.040	0.110
$C_{org} = 2.40 Z_w^{-0.695}$	0.828 ± 0.091	0.097
$C_{miner} = 3.16 Z_w^{-1.06}$	0.951 ± 0.014	0.045
Number concentration, mil/L		
$N_{tot} = 5552 Z_w^{-0.841}$	0.954 ± 0.026	102
$N_{org} = 42.48 Z_w^{-0.711}$	0.847 ± 0.081	1.5
$N_{miner} = 5508 Z_w^{-0.842}$	0.953 ± 0.025	103

almost coincides with our formula ($Z_w^{-0.844}$). These expressions differ by factors outside Z_w: 4.59 in [4] and 5.41 for the Lake Baikal. The higher suspended matter concentrations (by 1.2 times) from the formula for the lake at equal values of Z_w can be explained by a high relative content of mineral particles in the suspended matter: C_{miner}/C_{tot} = 0.24–0.51 (see Table 3). Because of the lower concentration of organic particles, which are primary light absorbers in suspended matter, the Secchi depth in Lake Baikal is higher in the layer 0–Z_w at the same total suspension concentration, which is shown in Fig. 4.

For comparison, let us present information on the relative content of mineral suspended particles in surface waters of the Black and Mediterranean Seas. Measurements in these seas composed the main data array on the relationship $C_{tot}=f(Z_w)$ in [4]. Results on the scattering phase function are given in [6, 7]. In the deep-water region of the Black Sea, C_{miner}/C_{tot} = 0.15–0.20, and C_{miner}/C_{tot} = 0.25–0.35 at the northwestern shelf of the sea [6]. In the Mediterranean Sea (from Alboran to Aegean Sea), the relative content of the mineral fraction of suspended matter C_{miner}/C_{tot} = 0.08–0.18 [7]. These data agree with the above idea which explains the difference between the formulae $C_{tot}=f(Z_w)$ in work [4] and for Lake Baikal.

As for the relationship $C_{tot}=f(Z_w)$ from [5], its strong divergence (Fig. 4) from other curves at low values of Z_w (<7 m) should be noted. For Z_w = 5 m, $C_{[7]}$ = 1.87 mg/L, C_{Baikal} = 1.39 mg/L, and $C_{[1]}$ = 1.17 mg/L.

The strong divergence of the curve [5] from curves [4] and for Lake Baikal at low values of Z_w is evidently due to the fact that the total data array in [5] includes the results obtained at Guinea Shelf (59% of the total quantity), where the suspended matter concentration reaches 1390 mg/L. Such high concentrations are caused there by tides which raise sediments from the bottom in coastal waters; they are not characteristic for off-lying ocean waters, where tides do not affect the suspended matter concentration. The same refers to the data included in the total array in [5] of measurements in the Caspian Sea in the mouth of Kura river, where the suspended matter concentration reaches 866 mg/L (7% of the total quantity).

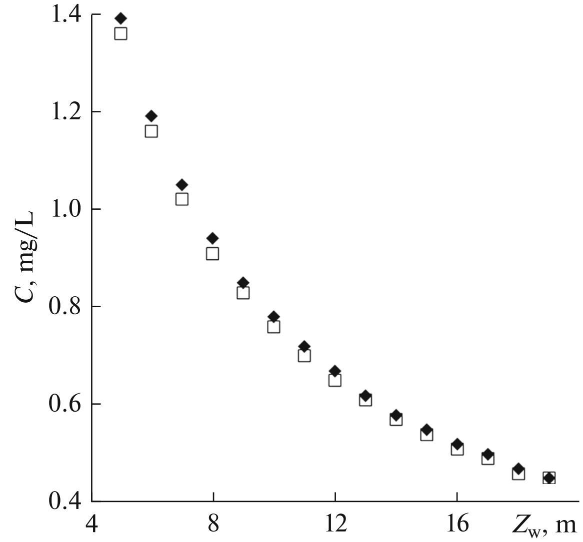

Fig. 3. Comparison of the total concentration of suspended matter C_{tot} calculated by regression equations from Table 4 (◆) with the sum of concentrations of suspended matter fractions C_{org} + C_{miner} (×).

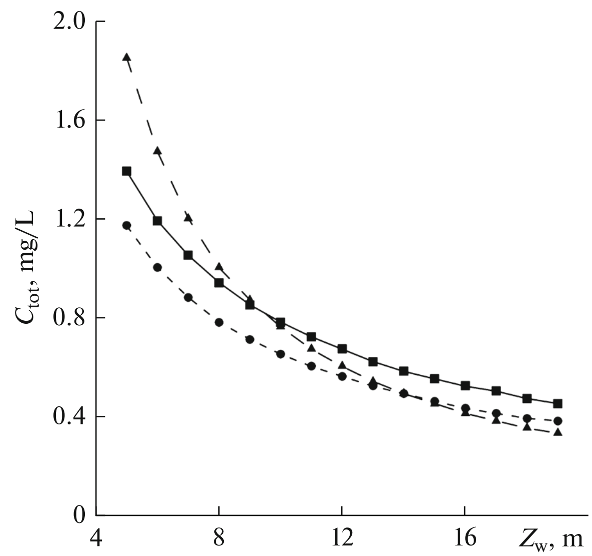

Fig. 4. Regression lines $C_{tot}=f(Z_w)$ for Lake Baikal (■) and from [4] (●) and [5] (T).

Number Concentration of Suspension

Correlation coefficients for the number concentration of suspended matter with the Secchi depth are as high as for the mass concentration for all fractions (see Table 4).

Note that mineral particles compose the overwhelming part (98–99%) of the total number of suspended particles; in this fraction, 90–96% are particles with radii of 0.2–0.5 μm.

The comparison of the total number of particles N_{tot} with the sum of numbers of particles of the organic and mineral fractions N_{org} + N_{miner} shows the agreement of all the coupling equations. Calculations by formulas for N_{tot} and N_{org} + N_{miner} give the following results: $N_{tot}/(N_{org} + N_{miner})]$ = 1.01 for Z_w = 19 m and 1.008 for Z_w = 5 m.

The comparison of the relationships between the number of particles and the Secchi depth in Lake Baikal with similar formulas for other water basins is impossible, because of the lack of such information in the literature.

CONCLUSIONS

The mass and number concentrations of suspended matter and its organic and mineral fractions are estimated for surface waters of different regions of Lake Baikal in summer from measurements of light scattering phase functions. The correlations between these parameters and the Secchi depth are found for the Z_w range 5–19 m. All correlations are characterized by high correlation coefficients.

The correlation formula $C_{tot} = f(Z_w)$ for the total mass concentrations of suspended matter in Lake Baikal are compared with similar formulas from [4, 5] for sea waters. The slopes of the curves $C_{tot} = f(Z_w)$ for Lake Baikal and in [4] are equal, but they are parallel shifted so that the suspended matter concentration for Lake Baikal is 1.2 times higher at the same Z_w. This difference is explained by a high relative content of suspended mineral particles in the waters of the lake. The equation $C_{tot} = f(Z_w)$ in [5] at low values of Z_w (<7 m) gives much higher concentration than formulas in [4] and for Baikal. This fact can be explained by the fact that the total data array in [5] includes data of measurements conducted at the Guinea Shelf and in the Caspian Sea in the mouth of Kura river, where suspended matter concentrations are very high (~1000 mg/L and more), which is not characteristic for open sea and ocean waters.

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