

*A Model Experiment Referring to the Cause of the Formation of the Turbid Layer in the Lake**

Toshiji TAKEMURA

(Department of Physics, Faculty of Liberal Arts and Science)

§ 1. Introduction

Small but deep lakes usually become thermally stratified during the summer showing the stable vertical distribution of the temperature of the water. A layer, called thermocline, is formed and the circulation of the water ceases for the time being.

Fig. 1 indicates the vertical distributions of the temperature of the water in Lake Nojiri in 1955: curves A, B, C represent those observed on the 22nd June, the 4th August and the 23rd of the same month, respectively. There had been developed a thermocline in the depth of between 6 and 15 meters. The upper portion to the thermocline is named epilimnion and the lower hypolimnion. Since the beginning of the autumn the surface of the water becomes gradually cooled down and the partial circulation occurs thereby destroying the thermocline from the upside.

Prof. Mukai has been performing the observations concerning with the transparency of the water of lakes for these years, and found out a conspicuous turbid layer developed in the thermocline with the Lakes Aoki, Kizaki and Nojiri.⁽¹⁾ The broken line in Fig. 1 gives an example of the turbid layer observed on the 23rd of August. The extinction coefficient K in Lambert-Beer's law, measured per unit centimeter, is plotted along the depth and should be regarded to be proportional to the concentration, C , of the suspending particles in the lake water, approximately.

Judging from the precedent, the turbid layer would have been in the most marked development, if the observation had been performed timely, as shown by a dotted line in the same figure.

Suspending materials in the lake water are known generally as sestons.

Most sestons forming a turbid layer are usually of the size from one to scores of microns and supposed to be the dead remains of plankton.

* Received November 12, 1955.

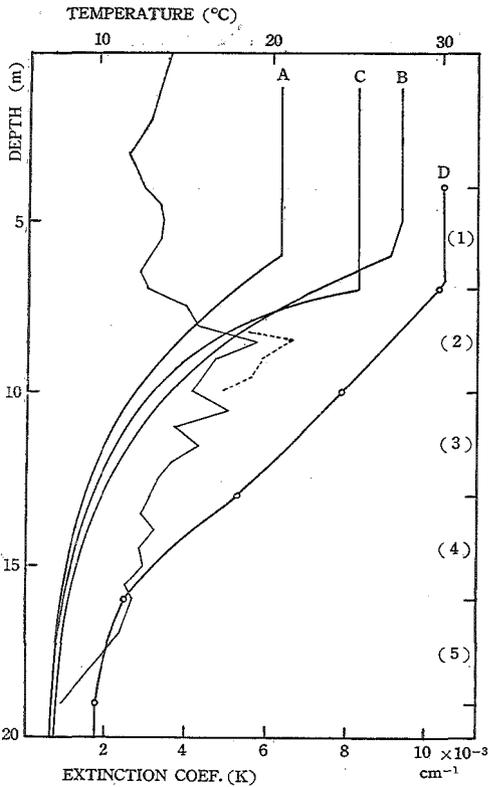


Fig. 1. Thermocline and Turbid Layer in Lake Nojiri (1955)

As the causes of the development of the turbid layer, the following may be given:

- (1) The growth of nanoplankton or bacteria in proportion to the distribution of turbidity;
- (2) Inflows from the rivers or from the coast extending over the thermocline;
- (3) Accumulation of the materials from the upper portion.

The author has once discussed these assumptions in his former publication, and proposed that the third might be the principal factor, taking into consideration of the various facts in this phenomenon.

Previously, Stokes proposed the following formula to express the velocity of a spherical particle falling through a liquid:

$$u = \frac{g(\rho - \rho')d^2}{18\mu}$$

where, u = velocity of the falling particle.

ρ = density of the body. ρ' = density of the liquid.

g = acceleration due to gravity (980 cm/sec²).

d = diameter of the body. μ = coefficient of viscosity of the liquid.

Owing to the fact that Stokes' law, as mentioned above, involves several fundamental assumptions, it can safely be used only when the Reynolds' number, $R = \rho'ud/\mu$, is less than one. To express the velocity of the sinking plankton organisms, Ostwald proposed the following simplified formula: $u = \frac{\rho - \rho'}{\mu \cdot f}$, where f is the form resistance. In either case, when a particle is in the slow motion, its velocity increases or decreases inversely as viscosity μ .

Now it is supposed that the propagation of phytoplankton is the most active in the epilimnion and also in the upper thermocline judging from

the facts of the increase of PH there, etc., so the distribution of the concentration at the state of equilibrium will be calculated approximately, assuming, for the sake of simplification, that the production of suspending materials is equally frequent from the surface to the upper part of the thermocline but scarce in the lower part of it.

The dotted line $C_0-C_1-C_2-C$ in Fig. 2 indicates the result obtained in such a condition. But in the process of reaching equilibrium, the result must be expressed either by curve C_1-B or C_1-A . If the production in the lower part of the thermocline is taken into consideration, the peak of the curve corresponding to the turbid layer would be lowered.

Thus, the formation of the turbid layer in the upper thermocline can be explained at once. But if one compares C_1-A , for example, with a curve practically observed, some differences will be noticed. Firstly, the turbidity by calculation is not so conspicuous as the actual one.

In the second place, the increase of the concentration with the depth, as shown in the calculated curve, has never appeared really in the epilimnion. Here, in order to solve these problems, the author has performed a model experiment of the thermocline in a laboratory scale, the principle of which is to drop some amount of test particles in a bath filled with water and to measure the concentrations of the particles, at several places and at various times. Thus, it is possible to explain the above mentioned disagreements to some extent.

§ 2. Apparatus and Procedure of the Measurement

(a) Operation

Fig. 3 shows a section of the apparatus. A indicates a copper cylindrical vessel of 38 cm. in height and 6 cm. in diameter, fitted with five small side-tubes for the drain-pipes at intervals of 6 cm. from the bottom.

B and D are thermostat baths of 30°C. and 10°C., respectively. They

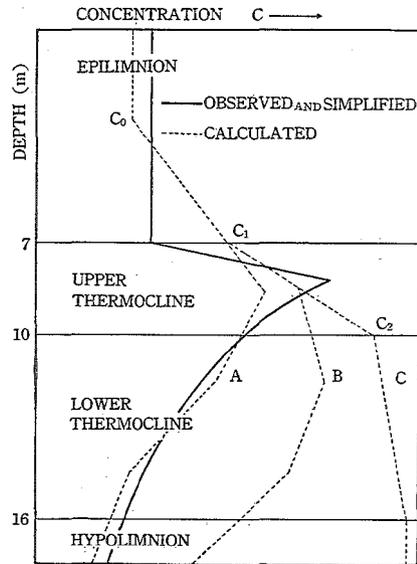


Fig. 2.

are separated from each other by an insulating chamber, C, which naturally encloses the vessel. In the first place, put a thermometer in each tube, and then fill the vessel with water to the height of 36 cm.

By leaving the apparatus for 50 minutes, a state of thermal equilibrium, as shown by the curve D in Fig.1, can be obtained. Thereafter, plug up all tubes instead of inserting thermometers, and 50 minutes after pouring pure water, drop 5 cc. of the test suspension, heated previously to 30°C., through the entrance E. Then, after the appropriate time, t minutes, pick up a certain amount of waters out of each tube into five beakers separately and number them in order as (1)~(5) from up to down. Lastly, draw up the remaining suspension and number it (6). Every one has the same volume of 170 cc., and so, their total volume amounts to 1020 cc. Therefore, the mean value of the concentration of these six suspensions must be 0.49 % of the test suspension.

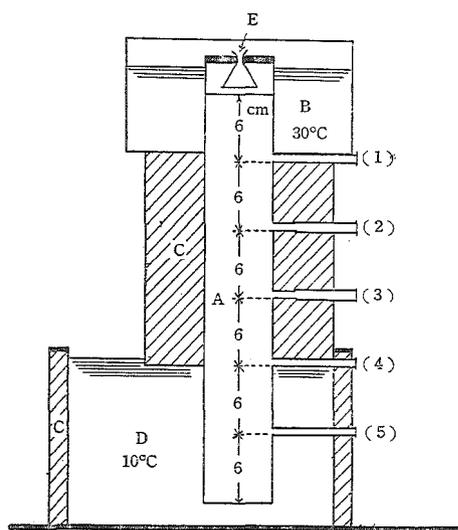


Fig. 3. Section of the Apparatus

Firstly, put some amount of lycopodium in pure water, followed by shaking, and then leave as they are for two or three days. Then, their air-bladders being all broken, they precipitate to the bottom. Now separate them from the liquid by use of a separating funnel, wash them thoroughly with water, and then make one percent solution as the test suspension. The density of this suspension is 1.00055 at 24°C. The diameters of the particles are $20\mu\sim 40\mu$, the average being 35μ , and the mean density is 1.05.

(b) Test Suspensions

Naturally, it must be better to use the suspending particles involved in lake waters as the test substances, but to adjust the concentration of lake water which contains the particles of the primary state is very difficult, so the following two kinds of suspensions, representing bioeston and abioeston, have been used. In this case, the word "model experiment" means the model of the thermocline and not of the particle.

(1) Lycopodium Suspension

(2) **Silt Suspension**

Take ordinarily silt, choose what can be filtered by the glass filter No.2 but not by No.3, wash them several times with water and make one percent solution as the test suspension. The density of this suspension is 1.0050 at 30°C. The diameters of the particles are $4\mu\sim 11\mu$, the average being 8μ , and the mean density is 2.9.

(c) **An Example of the Measurement**

Table 1 shows the procedure to obtain the concentrations of six suspensions which are picked out from the vessel after 20 minutes of putting 5 cc. of silt suspension to the vessel.

A Shimadzu photoelectric spectrophotometer has been used in this experiment to measure the concentration. The length of absorbing tube is 10 cm. and the wavelength of monochromatic light is $400m\mu$.

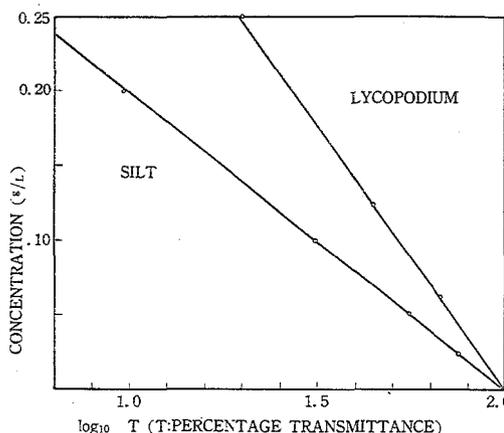


Fig. 4. Calibration Curves

Table 1.

No.	T	log ₁₀ T	log ₁₀ T'	C ₀ × 10	C × 10
(1)	45	1.653	1.662	0.68	0.67
(2)	34.5	1.538	1.547	0.91	0.93
(3)	49	1.690	1.699	0.60	0.62
(4)	64	1.806	1.815	0.37	0.37
(5)	82	1.914	1.923	0.15	0.16
(6)	79	1.898	1.907	0.19	0.19
mean				0.48	0.49

T : percentage transmittance(%)
 log₁₀ T' - log₁₀ T : correction to the absorbing tube.

C₀ : concentration obtained from calibration curve (g/L).

C : concentration obtained from C-t diagram (g/L).

(d) **Errors of Measurement**

The relative errors of the measurement are as follows:-

- Errors in reading photometer 3% or less
- Errors of mean value 5% //
- Errors of C₀ to C (t: 0-20 min.) 6% //
- (t: 20 min.-) 4% //

§ 3. Experimental Data

(a) Distributions of the Concentration in Thermocline

The concentrations of lycopodium measured at intervals of 10 or 20 minutes are shown in Table 2 and Fig. 5, and those of silt in Table 4.

(b) Distributions of the Concentration at Constant Temperature

For comparison, the author has also measured the concentration at a constant temperature following the same procedure. But in the perfectly uniform equilibrium of the temperature, the turbulence of water was unavoidable thereby interrupting the observation. So, some change was made to the apparatus shown in Fig. 3: the thermostat, D, of 10°C. was replaced by another one of 28°C. This means that the gradient of the temperature in the bath has been reduced to 2°C. Table 3 and Fig. 6 show the results with the lycopodium, and Table 5 shows that with the silt.

Table 2. Concentration $C \times 10$ (g/L) (Lycopodium, Thermocline)

t(min.) No.	10	20	30	40	50	60	70	80	90	100	120	140	160	180	200	240	280
(1)	1.80	1.31	0.96	0.77	0.63	0.57	0.51	0.48	0.45	0.43	0.40	0.37	0.34	0.31	0.28	0.25	0.23
(2)	0.91	1.23	1.39	1.38	1.31	1.16	1.02	0.85	0.75	0.65	0.55	0.48	0.43	0.39	0.34	0.30	0.26
(3)	0.12	0.24	0.37	0.49	0.64	0.77	0.85	0.92	0.92	0.91	0.75	0.62	0.50	0.44	0.38	0.32	0.28
(4)	0.05	0.09	0.13	0.19	0.23	0.27	0.34	0.42	0.48	0.52	0.55	0.54	0.50	0.45	0.39	0.34	0.30
(5)	0.03	0.04	0.05	0.06	0.07	0.09	0.12	0.15	0.19	0.21	0.27	0.32	0.37	0.36	0.34	0.31	0.28
(6)	0.03	0.03	0.04	0.05	0.06	0.08	0.10	0.12	0.15	0.22	0.42	0.61	0.80	0.99	1.21	1.42	1.61

Table 3. Concentration $C \times 10$ (g/L) (Lycopodium, Const. Temp.)

t(min.) No.	0	10	20	30	40	50	60	70	80	90	100	120	140	160
(1)	2.94	1.20	0.87	0.70	0.59	0.50	0.44	0.39	0.35	0.31	0.28	0.25	0.23	0.20
(2)	0	1.03	1.04	0.90	0.77	0.66	0.57	0.50	0.45	0.40	0.37	0.31	0.25	0.21
(3)	0	0.54	0.70	0.75	0.76	0.71	0.65	0.60	0.55	0.50	0.45	0.37	0.30	0.25
(4)	0	0.13	0.25	0.35	0.42	0.50	0.53	0.52	0.50	0.45	0.43	0.36	0.32	0.30
(5)	0	0.04	0.10	0.15	0.21	0.27	0.32	0.36	0.37	0.37	0.35	0.32	0.30	0.28
(6)	0	0.00	0.00	0.09	0.19	0.30	0.43	0.57	0.72	0.91	1.06	1.33	1.54	1.70

Table 4. Concentration $C \times 10$ (g/L) (Silt, Thermocline)

t(min.) No.	0	5	10	20	30	40	50	60	70	80	90	100	120	140	160
(1)	2.94	1.32	0.98	0.67	0.52	0.45	0.40	0.37	0.34	0.32	0.30	0.28	0.25	0.22	0.20
(2)	0	1.12	1.18	0.93	0.78	0.65	0.58	0.50	0.43	0.38	0.35	0.33	0.30	0.28	0.26
(3)	0	0.34	0.47	0.62	0.61	0.58	0.54	0.50	0.45	0.41	0.38	0.36	0.31	0.30	0.28
(4)	0	0.12	0.21	0.37	0.44	0.47	0.45	0.43	0.40	0.38	0.37	0.36	0.34	0.32	0.30
(5)	0	0.04	0.07	0.16	0.22	0.26	0.29	0.28	0.27	0.26	0.25	0.24	0.22	0.21	0.20
(6)	0	0.00	0.03	0.19	0.37	0.53	0.68	0.86	1.05	1.19	1.29	1.37	1.52	1.61	1.70

Table 5. Concentration $C \times 10$ (g/L) (Silt, Const. Temp.)

t(min.)	0	5	10	15	20	30	40	50	60	70
(1)	2.94	1.14	0.80	0.54	0.43	0.34	0.27	0.23	0.22	0.21
(2)	0	1.01	0.92	0.80	0.69	0.51	0.41	0.33	0.29	0.25
(3)	0	0.54	0.66	0.69	0.66	0.57	0.45	0.35	0.33	0.31
(4)	0	0.24	0.34	0.42	0.44	0.45	0.35	0.31	0.30	0.29
(5)	0	0.08	0.15	0.24	0.29	0.31	0.28	0.26	0.24	0.23
(6)	0	0.00	0.07	0.25	0.43	0.76	1.18	1.46	1.56	1.65

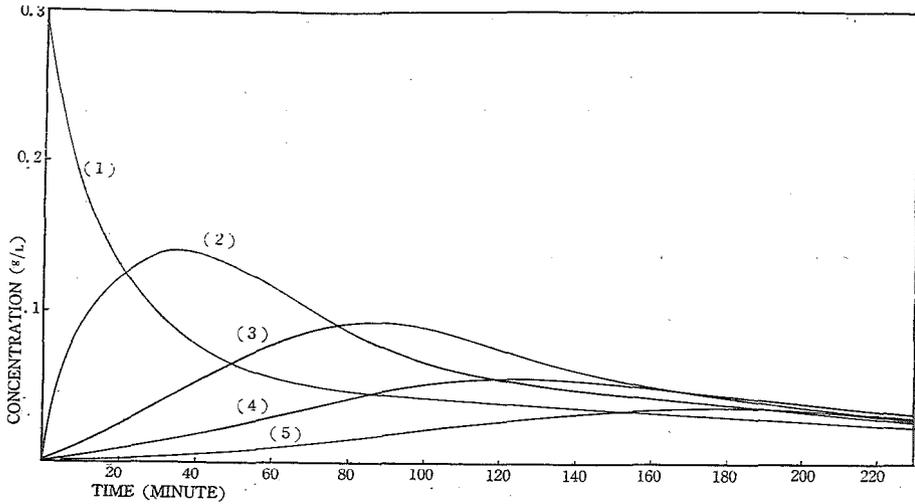


Fig. 5. C-t Diagrams (Lycopodium, Thermocline)

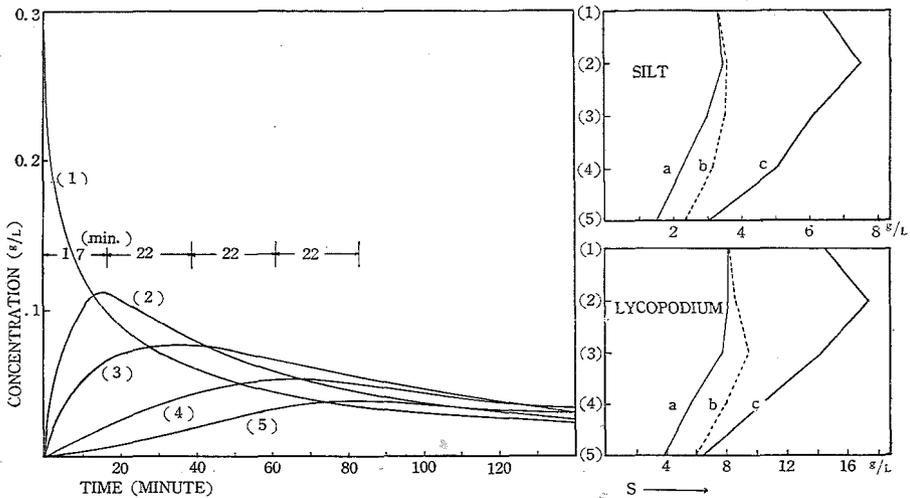


Fig. 6. C-t Diagrams (Lycopodium, Const. Temp.)

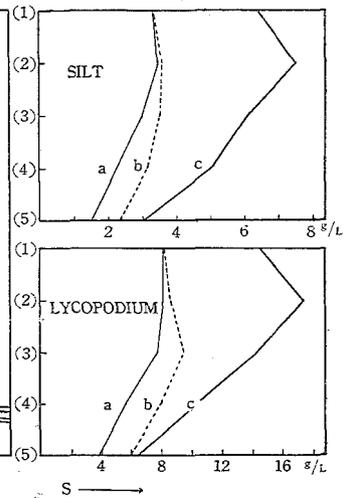


Fig. 7. Accumulative Concentration S
 a : Observed (Const. Temp.)
 b : Calculated (Thermocline)
 c : Observed (Thermocline)

§ 4. Discussions

(a) Falling Velocity of the Particle

The approximate velocities of particles are obtained from the C-t diagrams at constant temperature. The times corresponding to the peaks of each curve are almost in regular intervals, i. e., the falling time of 6 cm. (Fig. 6) They are also calculated from Stokes' formula by substituting the values shown in § 2 (b). (Table 6) In the next place, the time, t, corresponding to the concentration, $C=1.61 \times 10^{-1}$ (g/L), of No. (6) are given in Table 7.

Table 6.

	Time requisite to fall 6 cm.	Velocity obtained from diagram	Velocity obtained from Stokes'	Reynolds' number
Lycopodium	22 (min.)	0.27 (cm/min)	0.25 (cm/min)	$1.9 \sim 1.8 \times 10^{-3}$
Silt	8.5 (")	0.71 (")	0.48 (")	$1.2 \sim 0.78 \times 10^{-3}$

Table 7. (* interpolated value)

		t(min.)	S(1)	S(2)	S(3)	S(4)	S(5)	S(6)
Lycopodium	Const. temp.	150*	8.10	8.12	7.81	5.65	3.95	10.55
	Thermocline	(194)	(8.10)	(8.61)	(9.43)	(7.87)	(6.05)	(—)
Silt	Const. temp.	65*	3.34	3.47	3.02	2.26	1.54	5.47
	Thermocline	(84)	(3.34)	(3.56)	(3.65)	(3.15)	(2.36)	(—)
		140	6.46	7.55	6.11	5.06	3.07	12.99

From this table, it can be seen that the velocities at constant temperature are greater by 2.1 or 1.9 times than those in the thermocline, and yet the ratio of the coefficients of viscosity to the average temperature of the water, 29°C. and 18°C, in both distributions, is 1:1.3.

The author considers that the partial turbulences of the water will probably accelerate the apparent falling velocity of particles at constant temperature, and retard it in the upper thermocline.

It may also be from the same reason that the maximum of the curve, No. (2), in Fig. 6, appears a little earlier than the average, owing to the unstability in the upper part where the temperature is perfectly uniform.

(b) Accumulative Concentration (S)

Accumulative concentration S defined by $S = \int_{t=0}^t C dt$ (g/L) may be considered to denote the concentration of No. (1)~No. (5) after t minutes of being supplied with 5 cc. of test suspension or 0.05 g. of test particle to the surface every minute. The values of S obtained from C-t diagrams are given in Table 7 in the case where the concentration of No. (6) is 1.61×10^{-1} (g/L).

The relation $\sum_{i=1}^6 S_i \times 0.17 = 0.05 \times t$ (g), has been used for the check.

(1) **Distribution of the Concentration at Constant Temperature**

S(2) is slightly greater than S(1) owing to the facts that the distribution of the temperature forms a thermocline to some extent and that the first velocity exceeds the terminal one. In the case where the temperature is exactly uniform, S(2) will be slightly smaller than S(1). The values corresponding to those in the thermocline will be obtained by dividing the results at constant temperature with the ratio of the coefficient of viscosity determined to each temperature of the water. The values calculated in this way are written in parentheses.

(2) **Distribution of the Concentration in Thermocline**

Measured values are exceedingly different, both in distribution and in magnitude, from the calculated. (Fig. 7)

Generally speaking, S(2) is greater than S(3) in the actual observation, but smaller when they are calculated. These differences may be explained from the same reason as stated in (a) of this paragraph.

In a real lake water, the above effect must be much more remarkable because the thickness of the epilimnion corresponds to the twice of that, and the temperature gradient in the upper thermocline is steeper than that in the model.

(c) **Summary**

In the epilimnion, where the temperature of the water is almost uniform, the partial disturbances of water apt to occur, and, if the velocity of particles there be accelerated and then retarded at the upside of the thermocline as a result, the particles will be accumulated at the upper part of the thermocline instead of making a gradually denser distribution towards the bottom. And, if such a effect may be added to the curve C₁-A in Fig. 2, it will be possible to get a curve which indicates the existence of the turbid layer as seen in the lake.

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References

- (1) M. Mukai, : Jour. Shinshu Univ., 1952, 1~42.
- (2) T. Takemura, : Jour. Limnology Japan, Vol.17, No.2, 1955.
- (3) B. Fujimoto, : Applied Fluid Mechanics.
- (4) Paul S. Welch, : Limnology, 1952.

Shinshu University,
Matsumoto,
Japan.