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O minimum i maksimum tlenowym w metalimnionie Jezior Rajgrodzkich — On oxygen minimum and maximum in the metalimnion of Rajgród Lakes

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The seasonal yearly changes have an influence on the differentiation of the environment in relation to temperature and oxygen. As a result of the warming of the upper strata of water during summer months there arises in deeper lakes a thermal stratification which is not disturbed by winds, generally weaker in that season. We can perceive three different strata: the epilimnion, metalimnion and hypolimnion. The epilimnion is characterized by the highest temperature — in the metalimnion we observe a great change of temperature in the water, which is at its lowest in the hypolimnion.

The changes in the oxygen content of the different strata of water do not depend solely on temperature. In both oligotrophic and eutrophic lakes the epilimnion usually contains large amounts of oxygen that reach 80 — 120% of saturation. The differences that exist between various types of lakes appear in the metalimnion. In lakes of the alpine type the amount of oxygen is high, but in those of the Baltic type the oxygen content in this stratum falls sharply, and the differences in the hypolimnion are even greater.

We can often observe differences in oxygen content in the metalimnion. In some lakes the highest oxygen content (amounting to 381% of saturation) accumulates in the metalimnion (the Otter Lake, Birge and Juday, 1911); in others, the oxygen content of the metalimnion is subject to significant reduction. There arises then the so-called oxygen minimum in the metalimnion. The phenomenon of the appearance of the minimum or maximum of oxygen in the metalimnion was first observed by Birge nad Juday. According to them and to Voronkov (1913) the minimum coincides with the gathering in this stratum of dead plankton. Minder (1922) and Antonescu (1931) consider the breathing of the zooplankton, concentrated in the metalimnion, as the cause of the oxygen minimum. Alsterberg (1927, 1928) is of the opinion that the principal cause of the smallest amount of oxygen is the morphometry of the lake and a lack of circulation of the water owing to light winds. Thienemann (1928) explains those phenomena by the fact that the waters do not intermingle during summer stratification. Riikoja (1929) and Järnefelt (1932) also mention the existence of an oxygen minimum in the metalimnion of lakes. Kusnetzov and Karsinkin (1931) and Kusnetzov (1939, 1952) explain the oxygen minimum in this stratum by the breathing of large quantities of bacteria concentrated in it. None of those assertions can be confirmed by facts.

The oxygen maximum, according to the above-mentioned authors, is the result of the domination of assimilation over breathing. This happens in all transparent lakes. Yoshimura (1938) demonstrated an important conformity of the disposition of the oxygen maximum stratum with the transparency and the limits of the bottom macrophytes in a number of Japanese lakes.

Koźmiński (1932) reports on the oxygen maximum on the lower limit of the thermocline in the Hańcza Lake. Ruttner (1933) indicates the dependence of oxygen content in the metalimnion on the thermic leap. He supposes that in the deep localization of the thermocline in the metalimnion an oxygen minimum ought to appear — and, when the metalimnion is situated at an insignificant depth, a maximum is found. He assumes that the diagram of the penetration of atmospheric oxygen into water that is being intermingled in conditions of a different thickness of the epilimnion is not subject to changes.

Vinberg (1934 a) ascribes great importance to the transparency of water in a lake, on which depends the depth of the compensation point. An important factor influencing the oxygen content in the metalimnion, is the thickness of the epilimnion. The third factor, according to Vinberg, is the intensity of the oxygen consumption in water, which again is dependent on the amount of organic substance contained in the living and dead plankton. Vinberg executed a series of observations in the lake Glubokoye, employing the method of small darkened and undarkened bottles, to explain the intensity of the production of oxygen in the process of assimilation, in the consumption of oxygen in 24 hours by plankton and bacteria and in the oxidation of organic matter.

Without taking into consideration the work of Ruttner (1933) and Vinberg (1934 a) which sufficiently explained the existence of the minimum and maximum of oxygen, Lepneva (1950) referring to the work of Kusnetzov (1939) considers that the oxygen minimum in the lake Glubokoye is the result of a considerable accumulation of bacteria in the metalimnion.

Grim (1955) comparing the curve of the vertical distribution of oxygen in the lake Bodensee — Obersee in the years 1923, 1935 and 1953 emphasizes that the eutrophisation of those lakes caused the formation of a distinct minimum of oxygen in the metalimnion. The increase of the amount of phytoplankton increased, according to Grim, the oxygen minimum in the metalimnion.

I shall further mention here the interpretation of this problem by Hutchinson (1957). The author, examinig the oxygen maximum and minimum, considers them as two separate phenomena. He believes that an oxygen maximum appears in lakes with a large quantity of phytoplankton. As to the oxygen minimum, Hutchinson inclines towards the theory of Birge and Juday („falling seston", 1911) more than to the morphometric one of Alsterberg (1927).

As results from the interpretation of this problem, the opinions are even now divided. In 1957 I commenced research work on the factors influencing the oxygen content in the metalimnion of certain Rajgród Lakes, (north-eastern part of Poland, district of Białystok). I chose out of them the Rajgród lake, demonstrating a distinct minimum of oxygen in the thermocline, and the lake Białe, in whose thermocline a maximum of oxygen appears during summer months.

Methods

In the above-mentioned lakes temperature was measured and the amount of dissolved oxygen, and capacity for oxidation were determined. Simultaneously, samples were taken at the same place and at the same time, beginning with the surface and ending with layers near the bottom, to determine the chlorophyll content, which enabled an estimation of the dynamic of phytoplankton in the different strata of the lake. Zooplankton samples were also taken. Small bottles, darkened and undarkened, were placed at the dephts from which samples were taken to determine chlorophyll and zooplankton, to ascertain the intensity of assimilation, the amount of oxygen consumed by living and dead organisms and the depth at which the compensation point is found, in which oxygen exhaled in the process of assimilation is wholly consumed in the process of breathing of the plankton and the oxidation of organic matter.

The temperature was noted with accuracy to 0,1°. Oxygen was definded by the Winkler method. The samples of water were collected with the aid of Ruttner's water sampler. They were then transferred by means of a siphon into two bottles of 200 ml each. The oxidation and its determination was carried out by Winkler's metod. The degree of oxidation was determined by the method of Kubl using potassium permanganate in an acid environment.

Water for determining the amount of chlorophyll in phytoplankton was collected by means of Ruttner's water sampler and strained through a membrane filter No O. The amount of chlorophyll in the phytoplankton which remained on the filter was determined by the method of Vinberg and Sivko (1953), applying the photoelectric colourmeter Lumentron Mod — 400 A with a red filter with 650 mu wavelength.

Samples of zooplankton were collected with the 5-litre water sampler of Bernatowicz, calculation of the amount was carried out by Hansen's method on a small slab.

The amount of oxygen produced as a result of the assimilation process and consumed by breathing was determined according to Vinberg (1934 b) at different depths.

Besides, the so-called BOD_2 (biochemical oxygen demand) was determined at different depths by means of bottles darkened with rubber. The transparency of the water was measured by lowering of Secchi disc.

Results of researches

Of the whole group of Rajgród Lakes, lake Białe is characterized by a slight maximum of oxygen in the metalimnion, and lake Rajgród -- by an oxygen minimum.

Data concerning the morphometry of these lakes are presented in table I. As can be seen on Fig. 1, the oxygen minimum in the Rajgród lake in the first fortnight of August, 1957 was at the depth of 10 m, where the quantity of oxygen amounted to 4,2 mg per liter. On the surface it amounted to 11,5, at the depth of 40 m to 6,5 mg per liter.

I observed a similar vertical distribution of exygen in the month of August, 1958.

The percentage of organic matter in the surface stratum of the bottom sediment at different depths is presented in the following table:

depth in m	% of organic matter for 1 g of dry bottom sediment
0,1	2,60
0,5	5,45
4,0	13,60
12,0	13,00
15,0	12,00
17,0	23,30

Table I

Morphometric data of investigated lakes

lake	area in ha	depth in m		thickness of bottom sediment in m	% of org. substance in a 20 cm stratum of bottom surface		colour of bottom sediment	remarks
		max.	mean		min.	max.		
Rajgród	1919,15	51	14	1	16,70	20,80	blue	anal. of bot. sed. depth 6 m
Białe	146,37	38	15	1,7	5,66	19,70	blueish-brown	anal. of bot. sed. depth 4,5 m

According to analyses of Czeczuga (1958 b).

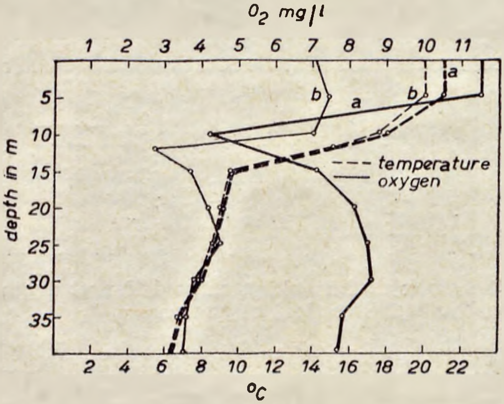

Fig. 1. Amount of oxygen in the water of Lake Rajgród at different depths (a — 1957, b — 1958)

As can be seen, in the surface stratum of the bottom sediment at the depth where the oxygen minimum begins (12—15 m), approximately the same percentage of organic matter can be found.

Fig. 2 illustrates the degree of oxidation of organic substance at different depths of lake Rajgród in the period of summer thermal and oxygenic stratification. From this diagram it appears that the demand for oxygen consumed in the oxidation of organic substance found at different depths of lake Rajgród is more or less the same and fluctuates between 5,4 — 6,8 mg O_2 per liter and rises to 8,9 mg O_2 per liter at the depth of 40 m.

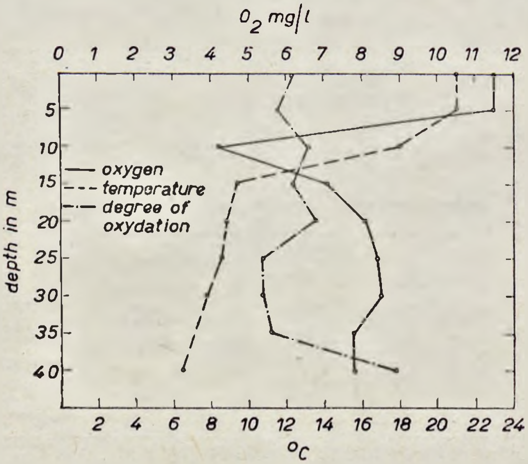

Fig. 2. The oxidation of water of Lake Rajgród ot different depths (August 1957)

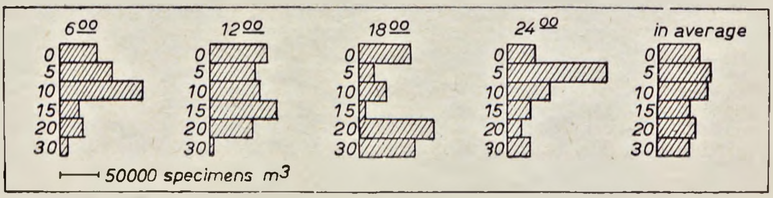

Fig. 3. Relation of the amount of zooplankton at different depths in Lake Rajgród, taking into account the vertical migration

Fig. 3 shows the quantities of zooplankton at different depths of the lake Rajgród. For crustaceans their daily (24 hours) vertical migrations are considered. As illustrated in Fig. 3, the maximum amount of crustaceans pass twice in 24 hours trough the stratum of oxygen minimum. At 6 o'clock in the morning the maximum of crustaceans is seen at a depth of 10 m, at 12 o'clock — at 15 m, at 18^{00} — at 20 m and at 24^{00} — at 5 m.

On an average, the largest amount of crustaceans in 24 hours resides at a depht of 5 m, a slightly smaller quantity at a depth of 10 m, and the smallest amount — at a depth of 15 and 30 m.

The mean amount of rotatoria at different depths of the Rajgród Lake on he basis of samples taken at 6 o'clock, 12^{00}, 18^{00}, and 24^{00}, on August 7, 1957 amounted to:

depth in m	number of individuals
0	10.400
5	10.700
10	3.200
15	5.050
20	6.800
30	950

Therefore, in the stratum of oxygen minimum a relatively small mean quantity of rotatoria is seen in relation to the higher and lower strata. The largest amount of rotatoria remains during 24 hours in the surface strata of the lake.

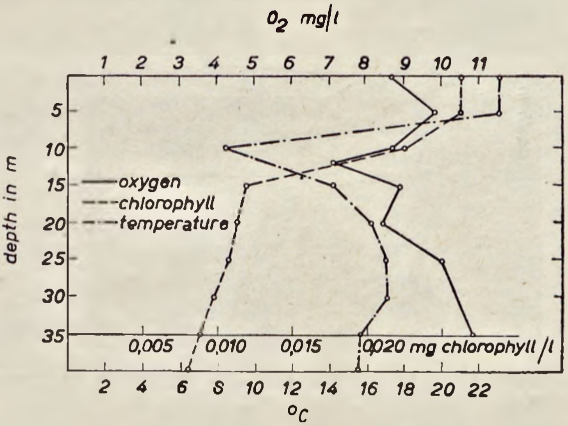

Fig. 4. Amount of chlorophyll in the phytoplankton of Lake Rajgród at different depths (August 1957)

The amount of chlorophyll noted at different depths of the Rajgród Lake was the lowest in the thermocline (Fig. 4) (Czeczuga 1958 a).

This was also confirmed by samples collected in 1958 during summer stratification (Fig. 5).

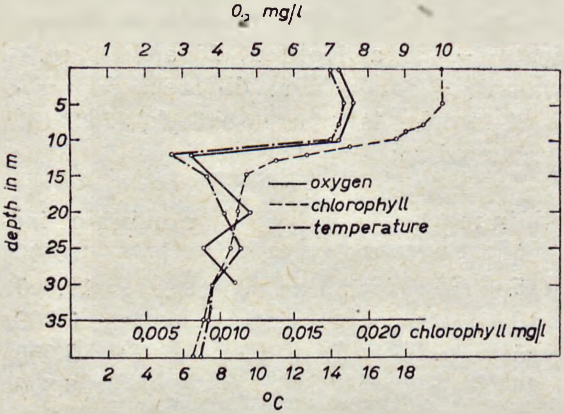

Fig. 5. Amount of chlorophyll in the phytoplankton of Lake Rajgród at different depths (August 1958)

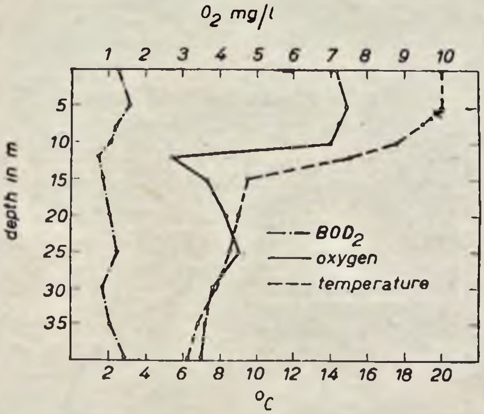

Fig. 6. Biochemical oxygen demand for 48 hours (BOD_2) in the water of Lake Rajgród at different depths (August 1958, t = 20 °C).

The biochemical oxygen demand in the course of 48 hours (BOD_2) also indicated a minimum of this factor at the depth of the minimum limit (Fig. 6). At the depth of 12 m, during two days, 0,75 mg O_2 per liter is consumed, but at the depth of 5 m — 1,56 mg O_2 per liter and at 40 m — 1,39 mg O_2 per liter.

Conclusions

The results of analyses of the amount of organic matter in the sublittoral do not permit the conclusion that the oxygen minimum is caused by an intensive process of oxidation in the thermocline.

The diagram of the capacity for oxidation of water in lake Rajgród at different depths (Fig. 2) does not confirm the suppositon of Birge and Juday (1911) and Voronkov (1913), that the oxygen minimum is caused by the accumulation of organic matter (especially of dead plankton) in the metalimnion due to the increasing density of the water. The oxidation of organic matter diminishes to minimum limits the amount of dissolved oxygen of this stratum.

Neither did quantitative analyses of the zooplankton confirm the inference of Minder (1922) and Antonescu (1931) that the largest amount of zooplankton accumulates in the thermocline. This might influence the diminution of oxygen content through breathing. The vertical distribution of chlorophyll (Fig. 4 and 5) indicates a maximum of phytoplankton in the thermocline.

The biochemical oxygen demand gives no foundation for the conclusions of Kusnetzov and Karsinkin (1931) and Kusnetzov (1939, 1952) that the mass acumulation of bacteria consumes enormous quantities of oxygen, causing its minimum in the thermocline. On the contrary — this factor is the smallest in the thermocline, which means that the least amount of oxygen is consumed there.

Ruttner (1933) considers the most important cause to be the dependence of the rapidity of oxidation in temperature. Ruttner is of the opinion that in the occurrence of a thick stratum of epilimnion an oxygen minimum ought to appear — and a maximum when the stratum is thin. Vinberg (1934 a) and Yoshimura (1938) indicate that in very transparent lakes an oxygen maximum appears, that is that oxygen maximum and minimum depend on the depth in which the compensation point is situated. When it is found in the epilimnion, we can expect the oxygen minimum to be in the thermocline and reversely, when this point lies in the thermocline — the oxygen maximum should be in the metalimnion. The above was confirmed by the result of my researches in the Rajgród Lakes.

Fig. 7 presents the amount of oxygen consumed in 24 hours at various depths. The average consumption of oxygen in a small darkened bottle in the epilimnion, at a temperature of 20°, amounts to 0,72 mg O_2 per liter per 24 hours. If we admit, according to Ruttner (1933) that the coefficient of temperature $Q_{10} = 2$, that is that the course of the reaction is twice as quick (at every rise of 10 °C in

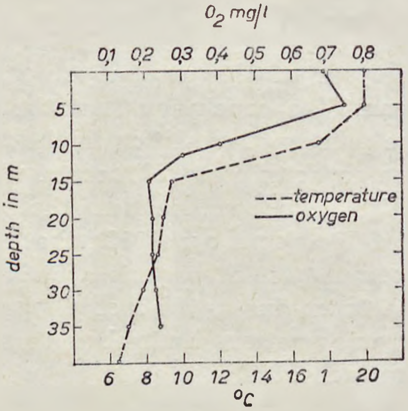

Fig. 7. Oxygen consumption in Lake Rajgród in 24 hours at different depths (August 1958)

the temperature). At the depth where the temperature amounts to 10° the consumption of oxygen is only 0,36 mg O_2 per liter, that is half as much as that consumed at a temperature of 20°. Having the data concerning the consumption of oxygen at various depths at a temperature of 20° we can calculate its consumption at the lake depths in relation to the temperature. As we can see in Fig. 7, the largest amount of oxygen is consumed in the epilimnion, the smallest in the hypolimnion and an average amount in the metalimnion (without taking into consideration the bottom strata where, as a result of a large amount of organic matter, more oxygen is being consumed than in the higher strata of the hypolimnion). Such a large amount of consumed oxygen in the epilimnion is compensated by the assimilation process of phytoplankton and underwater vegetation. As a result of the mixing of waters in the epilimnion an adequate concentration of oxygen is obtained. In the thermocline the oxygen consumption for oxidation and breathing is in general large, and compensation does not arise in the same degree as in the epilimnion, the compensation point being situated in the epilimnion there is no assimilation in the metalimnion. The water of the epilimnion strata does not mix with that of the metalimnion. Though a compensation of the consumed oxygen does not arise in the hypolimnion either, its quantity per unit of water-volome is greater, because less is being consumed by processes of oxidation and breathing. The general balance of oxygen per unit of water-volume is much smaller in the metalimnion than in the hypolimnion, not to mention the epilimnion. The above, as it seems, is the decisive factor which

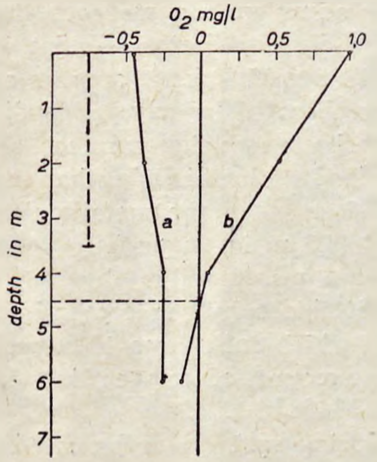

Fig. 8. Assimilation of phytoplankton, destruction, compensation point and transparency of Lake Rajgród (maximum quantity). The vertical line indicates the depth in m — the horizontal one, the differences between the amount of oxygen in small darkened bottles (a) and in non-darkened ones (b), in relation to the initial amount of oxygen (0). The initial amount of oxygen (vertical line 0) for every depth is marked 0. The vertical broken line indicates the transparency of Secchi's disc in m, — the horizontal broken line, the depth of the compensation point (August 1958)

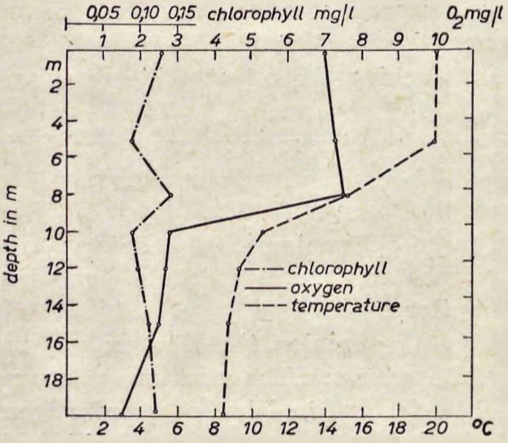

Fig. 9. Temperature, content of oxygen and chlorophyll in Lake Białe at different depths (August 1958)

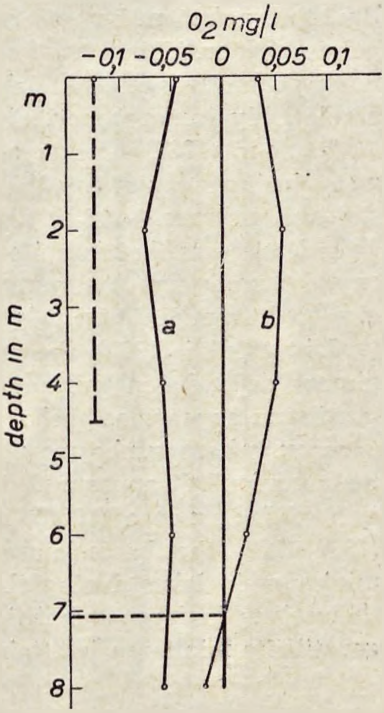

Fig. 10. Assimilation of phytoplankton, destruction, compensation point and transparency of Lake Białe (maximum amounts). Explanation as in Fig. 8 (August 1958)

occasions an oxygen minimum in the metalimnion. As we see, the thickness of the trophogenic stratum is the decisive factor — that is the depth of the compensation point. In the Rajgród Lake it appears at a depth of 4,5 m (Fig. 8). The above is corroborated by oxygen conditions in the lake Białe, in which we can observe during summer an oxygen maximum in the metalimnion (Fig. 9). It is in this lake that the compensation point is found at a depth of 7 m — in the metalimnion (Fig. 10). It is a lake of great transparency (4,5 m in August).

In Lake Białe at the depth of the oxygen maximum in the metalimnion we can observe a greater amount of chlorophyll in comparison with the higher and lower strata (Fig. 9), which influences to a certain measure the partial increase of the amount of oxygen in the metalimnion.

In certain lakes an oxygen maximum during spring months can be observed, and in summer an oxygen minimum appears in the same lake (Minder, 1922 — Ruttner, 1933). The above phenomenon does not depend on the thickness of the epilimnion, as is the opinion of Ruttner, but rather on the transparency of which the compensation point depends. This can be confirmed by the fact that an oxygen maximum generally apears in lakes approaching the oligotrophic type, with a relatively transparency.

Strom (1931) reports an oxygen maximum appearing in Feforwatn during summer months. The thickness of the epilimnion was 13 m, the transparency — 18 m (the analyses were made at a depth of 50 m). Thus it appears that in spite of a large epilimnion in lake Feforwatn an oxygen maximum, and not an oxygen minimum, as could have been expected from Ruttner's assumptions.

Lityński (1952) also expresses the opinion that the oxygen maximum depends on transparency. He writes: „The stratum of oxygen maximum appears as a characteristic feature in lakes of greater transparency, where sunbeams penetrate deep into the water, reaching the metalimnion". It appears that there exists no foundation for the assumption of Lepneva (1950), referring to the opinion of Kusnetzov (1939, 1952), that bacteria are a decisive factor in the origin of an oxygen minimum in lakes during the sumer stagnation period when, grouping themselves in large quantities in the metalimnion, they consume oxygen till its minimum is attained.

STRESZCZENIE

Autor badał przyczyny wywołujące minimum i maksimum tlenowe w metalimnionie na przykładzie niektórych Jezior Rajgrodzkich (północno-wschodnia część Polski).

Minimum tlenowe występuje w Jeziorze Rajgrodzkim (Fig. 1) należącym do typu jezior mezotroficznych, maksimum — w Jeziorze Białym (Fig. 9) zbliżonym do jezior oligotroficznych.

Utlenialność wody Jeziora Rajgrodzkiego (Fig. 2), stosunki ilościowe zooplanktonu (Fig. 3), zawartość chlorofilu w fitoplanktonie (Fig. 4 i 5) oraz dwudobowe zapotrzebowanie tlenu (Fig. 6) na różnych głębokościach Jeziora Rajgrodzkiego nie potwierdziły teorii, że minimum tlenowe powstaje w wyniku gromadzenia się dużej ilości żywego i martwego planktonu lub mikroorganizmów w metalimnionie. Mało prawdopodobne jest to, że minimum tlenowe jest wywołane morfometrycznym kształtem jeziora.

Autor uważa, że decydującym czynnikiem powodującym minimum lub maksimum tlenowe w metalimnionie jest głębokość zalegania punktu kompensacyjnego, co zależy od przezroczystości wody. Jeżeli punkt kompensacyjny znajduje się w epilimnionie, to możemy spodziewać się w metalimnionie minimum tlenowego, natomiast gdy punkt kompensacyjny znajduje się w metalimnionie, wówczas występuje tam równocześnie maksimum tlenowe (Fig. 8 i 10).

Na ilość tlenu w poszczególnych warstwach wody wpływa zużywanie go na oddychanie i procesy utleniania rozkładającej się materii organicznej. Szybkość przebiegu tych procesów zależy od temperatury, w myśl prawa Van' t Hoffa zwiększenie się temperatury o 10 °C podwaja szybkość procesów utleniania. Stosownie do tego ze spadkiem temperatury w głąb jeziora zmniejsza się zużycie tlenu (Fig. 7). Jest ono największe w ciepłym epilimnionie, jednakże fotosynteza glonów planktonowych uzupełnia zapasy zużywającego się tlenu. Ponieważ intensywność fotosyntezy uzależniona jest od światła, zatem natlenianie wody z tej przyczyny wiąże się ściśle z punktem kompensacyjnym.

Ostatecznie więc położenie minimów i maksimów tlenowych zależy przede wszystkim od przezroczystości wód w jeziorach.

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