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Original Article
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# Long-term dynamics of spectral water transparency in the surface layer of Lake Teletskoye in summer

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**ABSTRACT.** The article presents the long-term experimental data on spectral water transparency in the surface layer of Lake Teletskoye (21 sampling stations) obtained in summer of 2017–2022. During the study period, values of the light attenuation index calculated at the natural logarithmic base at four wavelengths (430, 450, 550 and 670 nm) ranged within 0.2–4.0 $m^{-1}$. The index of light absorption by yellow substance varied from 0.1 to 3.2 $m^{-1}$. Relative transparency measured with the use of a white Secchi disk made up 0.8–11.7 m at its average of 6.3 m. Over a 6-year study period, the content of chlorophyll-*a* in the surface layer was 0.1–4.1 $mg/m^3$ that corresponded to the oligotrophic type of lakes. The concentration of yellow substance in the lake, optically determined through measuring light absorption by yellow substance at a wavelength of $\lambda = 450$ nm, ranged from 0.9 to 15.0 $g/m^3$. Calculations of the spectral contribution of the main optically active components of lake water to light attenuation in the surface layer of Lake Teletskoye in various sampling sites indicated that yellow substance and suspension had the greatest optical effect on the total attenuation. It is shown that the optic structure of the study reservoir (dynamics of major primary hydro-optical properties) depends on spatial-temporal variability of concentrations of different optically active components influenced by the in-water processes closely related with those occurred in the lake catchment.

***Keywords:*** spectral transparency of water, light attenuation index, index of light absorption by yellow substance, physical model, yellow substance, chlorophyll-*a*, suspension, pure water, Lake Teletskoye

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## 1. Introduction

Water transparency was long thought to be just a qualitative visually defined characteristics. Traditionally, relative transparency of various natural waters (oceans, seas, lakes, reservoirs, rivers, etc.) is determined by a semi-instrumental method, i.e. maximum visibility depth of a standard Secchi disk (SD) in the water column until its complete disappearance from view (measured in meters). Close to waters of oceans and seas, water transparency of Lake Baikal is one of the highest among freshwater water bodies due to few dissolved and suspended substances. For instance, SD in Baikal water is visible to a depth of 40 m (Sherstyankin, 1993), while in Lake Teletskoye – up to 15.5 m (Selegey et al., 2001). This method, widely used by hydrobiologists because of its simplicity and practicality, is still considered subjective. It has significant measurement errors (20% or more) and limitations in application during a winter under-ice period. Being universal and more precise, electronic spectrophotometric methods and devices (spectrophotometers, turbidimeters, transparency meters, etc.) can measure spectral water transparency at any depth day and night with the provision of its data records.

According to (Erlov, 1980; Kopelevich and Shifrin, 1981; Shifrin, 1983; Kopelevich, 1983; Mankovsky et al., 2009; Dera, 1992; Mobley, 1994; Mankovsky, 2011; Levin, 2014), spectral transparency of water (measured in reverse meters) refers to the primary (or internal, intrinsic) hydro-optical features. It is a physical quantity characterizing optical properties of natural waters. Spectral water transparency defines the conditions for light propagation in water and contains the information about suspended organic-mineral particles and organic matter dissolved there.

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The relevance of our study is dictated by the need to expand and improve the understanding of spectral transparency of Lake Teletskoye waters greatly depending on its periodically varying main optically active components, i.e. yellow substance (YS), suspension (S), chlorophyll (Chl) and pure water (PW). Currently, special attention is worldwide paid to studying the spectral contribution of each optically active components of natural waters to the total light attenuation and dynamics of their concentrations in time and space.

The purpose of our study is to experimentally estimate the longstanding variations in spectral water transparency in the 5–7 cm surface layer of Lake Teletskoye in summer of 2017–2022 and the influence of its main optically active components on the total light attenuation.

## 2. Material and methods

*Object of study*

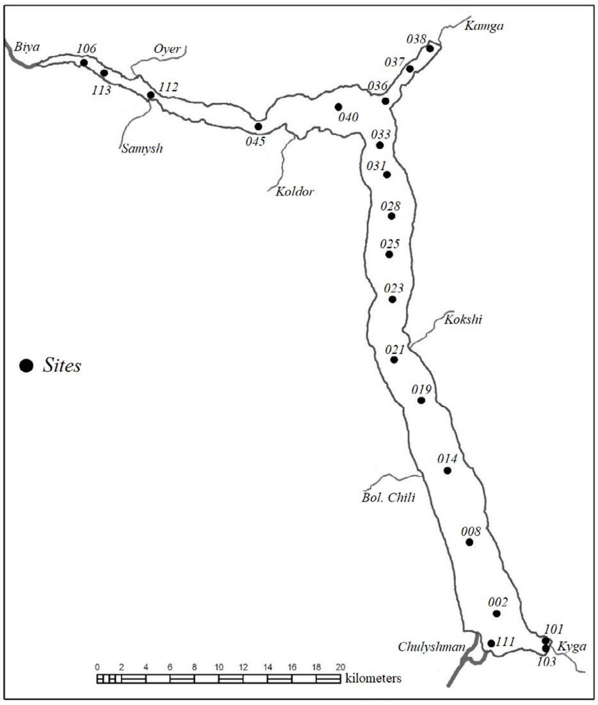
Lake Teletskoye (coordinates: 51°21′46″ – 51°48′36″N, 87°14′40″ – 87°50′54″E) is a deep-water reservoir of tectonic origin located at an altitude of 434 m asl in the northeastern part of the Altai Mountains (south of Western Siberia). Its water area is 227.3 km$^2$, drainage basin area – 20400 km$^2$, length – 77.8 km, average width – 2.9 km, maximum depth – 323.0 m, and volume – 41.1 km$^3$ (Selegey and Selegey, 1978). The lake consists of two parts, i.e. the 50 km southern elongated along the meridian and the northern latitudinal one of 28 km long. As compared to the deep-water (pelagic) zone, the shallow (littoral) part of the lake is distinguished by a considerable hydrodynamic impact caused by intensive wind-wave processes (maximum wave height up to 2.5 m) and significant (up to 6 m) annual fluctuations in water levels. The lake's coastline is weakly rugged. There are few bays here, but the largest are Kamginsky and Kyginsky with an area of 6.5 km$^2$ and 3.1 km$^2$, respectively. Kamginsky Bay is the shallowest and well-protected from waves. In terms of thermal regime and soil type, it is the most favorable among all bays of Lake Teletskoye. By its hydrochemical regime, the lake is a weakly mineralized, oxygen-rich mountain water body with low temperatures and a little content of organic and biogenic substances in the water (Selegey et al., 2001).

In recent years, the anthropogenic load on the lake (especially in its northern part) has increased due to intensive development of tourism in the Altai Mountains. Ecosystems of cold-water oligotrophic lakes are the most vulnerable to external impacts. Poor development of aquatic organisms in such reservoirs is responsible for the low potential of biological self-purification of coming from the catchment suspended, dissolved and slightly soluble substances able to affect water quality and intensity of intra-reservoir processes significantly.

*Research methods*

Studies of the main hydro-optical characteristics (indicators of light attenuation by water, light absorption by yellow substance and relative transparency measured using a white Secchi disk) in the water area of Lake Teletskoye were carried out by IWEP SB RAS in summer of 2017–2022 (July 7–11, 2017; June 19–23, 2018; July 1–5, 2019; June 24–29, 2020; July 29–August 1, 2021; August 1–5, 2022).

Every year, 21 samples were taken from the surface layer of Lake Teletskoye using a bathometer installed a board of a research vessel (Fig. 1). During the 6-year period of the lake study, a total of 126 water samplings were implemented and 1008 separate measurements of spectral water transparency (transmission factor) at four wavelengths (430, 450, 550 and 670 nm) on the stationary single-beam spectrophotometer PE-5400UF before and after sample filtration were examined in the laboratory.




| Sites | Toponymic name |
|---|---|
| 002 | riv. Chulyshman (pelagial) |
| 008 | sett. Bele (pelagial) |
| 014 | riv. Chulyush (pelagial) |
| 019 | cape Syraktu (pelagial) |
| 021 | riv. Kokshi (pelagial) |
| 023 | cape Vakty (pelagial) |
| 025 | riv. Adamysh (pelagial) |
| 028 | riv. Taldu-kool (pelagial) |
| 031 | riv. B. Korbu (pelagial) |
| 033 | m. Otyk-Tash (pelagial) |
| 036 | riv. Kamga (pelagial) |
| 037 | riv. Kamga (pelagial) |
| 038 | riv. Kamga (littoral) |
| 040 | sett. Yailyu (pelagial) |
| 045 | cape Azhu (pelagial) |
| 101 | riv. Kyga (pelagial) |
| 103 | riv. Kyga (littoral) |
| 106 | sett. Artybash (pelagial) |
| 111 | riv. Chulyshman (littoral) |
| 112 | riv. Samysh (pelagial) |
| 113 | Kamenny Bay (pelagial) |

**Fig.1.** Sampling sites in the water area of Lake Teletskoye

The spectral light attenuation index $c(\lambda)$ was calculated using the formula derived from the Bouguer's law

$$c(\lambda)=\left(\frac{1}{L}\right)\cdot\ln\left(\frac{1}{T(\lambda)}\right), \quad (1)$$

where $L$ is the length of a measuring glass cuvette of 50 mm long, $T(\lambda)=I(\lambda)/I_0(\lambda)$ – the spectral transparency of water in relative units; $I(\lambda)$, $I_0(\lambda)$ – the intensity of transmitted and incident light on the cuvette, respectively, $\lambda$ – the wavelength of light. The indicator of light absorption by yellow substance $a_{ys}(\lambda)$ was determined after measuring spectral transparency of the water purified from suspension by filtration through «Vladipor» membranes of MFAS-OS- 1 type with a pore diameter of 0.22 μm. The maximum absolute error in measuring $c(\lambda)$ and $a_{ys}(\lambda)$ within the studied spectral range made up 0.1 $m^{-1}$.

The spectral dependence of light absorption by YS was approximated by the exponential law

$$a_{ys}(\lambda)\sim e^{-\mu\cdot\lambda}, \quad (2)$$

where $\mu$ – the coefficient of spectral variability, characterizing the qualitative composition of dissolved organic matter (DOM). Following (Mankovsky, 2015), we measured $a_{ys}(450)$ (at $\lambda = 450$ nm) and estimated the content of YS in water samples by the formula

$$C_{ys}=a_{ys}(450)/a_{sp.ys}(450). \quad (3)$$

Here, $C_{ys}$ is the concentration of YS, in g/m$^3$, $a_{sp.ys}(450)$ is the specific indicator of light absorption by YS (m$^2$/g). Taking into account the approach proposed in (Mankovsky, 2015), we calculated $C_{ys}$ using the value $a_{sp.ys}(450)$ from (Nyquist, 1979).

In addition, to compare our data on spectral water transparency with the results of similar optical studies previously performed in aquatic ecosystems by other researchers, we measured relative transparency by *SD*.

The concentrations of chlorophyll $C_{Chl}$ were determined by a standard spectrophotometric method according to (GOST, 2003).

The relative spectral contribution of major optically active components of lake water (S,YS, Chl-***a*** and PW) to $c(\lambda)$ in the surface layer of the studied reservoir was calculated using the modified semi-empirical light attenuation model (Akulova, 2015) first proposed by O.V. Kopelevich (Kopelevich, 1983) and having the form

$$c(\lambda)=a_{Chl}(\lambda)+a_{ys}(\lambda)+b_{mol}(\lambda)+b_s(\lambda)+a_{pw}, \quad (4)$$

where $a_{Chl}(\lambda)$ and $a_{ys}(\lambda)$ are indicators of spectral absorption by Chl-*a* and YS, respectively, $b_{mol}(\lambda)$ – spectral molecular scattering by PW, $b_s(\lambda)$ – spectral scattering by S, $a_{pw}(\lambda)$ – spectral absorption by PW. As can be seen from this expression, spectral attenuation of light is described by a three-parameter model. Since the parameter $a_{ys}(\lambda)$ is identified experimentally, the spectral index for PW scattering $b_s(\lambda)$ can be derived from the formula

$$b_s(\lambda)=c(\lambda)-\left[a_{Chl}(\lambda)+a_{ys}(\lambda)+b_{mol}(\lambda)+a_{pw}(\lambda)\right]. \quad (5)$$

The trophic status was assessed using the Carlson Trophic State Index (Carlson, 1977) and the international trophic classification of water bodies (Environment Canada, 2004). We also applied the spectral index of light attenuation $c(\lambda)$. The oligotrophic type of reservoirs corresponds to a range of values $c(\lambda)$ from 0 to 2 $m^{-1}$, mesotrophic – from 2 to 3 $m^{-1}$, eutrophic – from 3 to 23 $m^{-1}$, and hypereuthrophic – from 23 $m^{-1}$ or more (Sutorikhin et al., 2017).

## 3. Results and discussion

Summer field works (2017–2022) in Lake Teletskoye allowed to estimate the primary hydro-optical characteristics, i.e. indicators of light attenuation $c(\lambda)$, light absorption by yellow substance $a_{ys}(\lambda)$, relative transparency according to *SD* at heterogeneous spatial distribution. Values of $c(\lambda)$ at four wavelengths ($\lambda = 430$, 450, 550 and 670 nm) in water samples taken in the surface layer of the reservoir varied from 0.2 to 4.0 $m^{-1}$. In summer of 2017 and 2021, this indicator changed slightly (1.0–1.6 $m^{-1}$). Reduced spectral transparency was noted in 2022 (0.2 $m^{-1}$). At the confluence of rivers Chulyshman, Chulyush and Kyga, including Cape Syraktu, $c(\lambda)$ exceeded 3.0 $m^{-1}$. Its peak was registered in the littoral zone of the Kyga River in 2018–2020. This is due to intensive removal of suspension (mainly mineral) by river waters and shoreline destruction. Here, in shallow waters, induced by wind-and-waves currents lifted bottom sediments and mixed them throughout the water column. In the pelagic zone, from Cape Vakty (site 023) to Cape Azhu (site 045), including Kamenny Bay (site 113), $c(\lambda)$ did not exceed 2.1 $m^{-1}$. This is in good agreement with YS content (close to its average in summer).

Over a 6-year period of optical investigations, indicators of light absorption by yellow substance $a_{ys}(\lambda)$ at wavelengths $\lambda =$ 430, 450, 550 and 670 nm in the surface layer showed minor fluctuations (0.1–3.2 $m^{-1}$) Maximum values (above 2.0 $m^{-1}$) were recorded in 2018–2020 on rivers Chulyshman, Chulyush and Kyga, including Cape Syraktu. As an example, Fig. 2 and 3 represent the dynamics of $c(430)$ and $a_{ys}(450)$, respectively.

During the study period, *SD*-measured relative transparency widely ranged as 0.8–11.7 m with its average of 6.3 m. Transparency of 11.0 m was observed in 2019 in the pelagic zone of the Adamysh and Taldukool (sites 025 and 028, respectively). The highest SD value (11.7 m) was marked at the village of Yailyu in 2018.

It is known from (Mankovsky et al., 1996; Kukushkin, 2011; Voskresenskaya et al., 2011; Korchemkina and Latushkin, 2016; Churilova et al., 2018; 2022; Matyushenko et al., 2001; Betancur-Turizo et al., 2018; Shi et al., 2017; Slade and Boss, 2015; Korosov et al., 2017; Woźniak and Stramski, 2004; Reinart et al., 2004) that spectral transparency of water largely depends on the content of suspension (organic, mineral). Therefore, to explain inter-annual variations of $c(\lambda)$, the data on chlorophyll-*a* concentrations $C_{Chl}$-*a* are required.

In the course of our 6-year study, the content of Chl-*a* the main photosynthetic pigment of phytoplankton

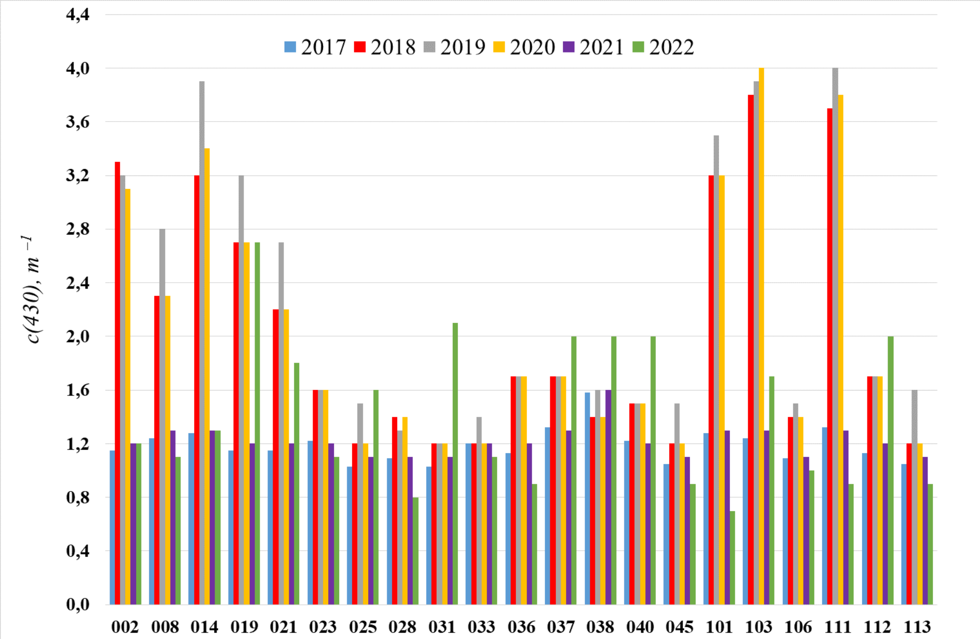



**Fig.2.** Long-term dynamics of light attenuation at a wavelength of λ = 430 nm in different sites of Lake Teletskoye

algae, varied as 0.1–4.1 mg/m$^3$ (average: 2.1 mg/m$^3$), thereby corresponding to the oligotrophic type of lakes (Fig. 4). Its maximum was recorded in 2021 in all sampling sites of the lake (1.1–4.1 mg/m$^3$), while its minimum – in 2019 (0.1–1.8 mg/m$^3$).). In general, the lake is characterized by poor development of algae phytoplankton because of low concentrations of nutrients and instability of the water column most of the year. In Lake Teletskoye waters, the specialists of the Chemical Analytical Center of IWEP SB RAS headed by Dr. Sc. Papina detected a low content (0.7–1.9 mg/dm$^3$ that is typical for oligotrophic lakes) of biogenic elements of the nitrogen group dominated by nitrate ions as a mineral nitrogen form. The concentrations of phosphate ions in the lake were insignificant (within micrograms), while silicon was one or two orders of magnitude higher than the content of other biogenic elements and averaged 2.2–2.9 mg/dm$^3$.

In 2017–2022, concentrations of yellow substance $C_{ys}$ in the surface layer of the lake varied greatly, i.e. from 0.9 to 15.0 g/m$^3$ (average: 8.0 g/m$^3$) (Fig. 5). For the last two years of our investigations, it decreased (0.9–7.1 g/m$^3$) and reached the indicators of 2017 (2.9–5.1 g/m$^3$).

Calculations of the spectral contribution of optically active components of the lake water in the surface layer of Lake Teletskoye in various sampling sites are evidence of the greatest optical influence of YS and S on the total attenuation.

**In 2017**, the maximum contribution (89.2%) to light attenuation by YS at λ = 430 nm was noted in the littoral zone of the river Kamga (site 038). At a wavelength of 550 nm, this indicator varied from 60.0% to 83.3% in sites 111 and 038 of the Chulyshman River littoral. Suspension made its maximum contribution (17.1%) at λ = 430 nm in site 103 of the Kyga River.

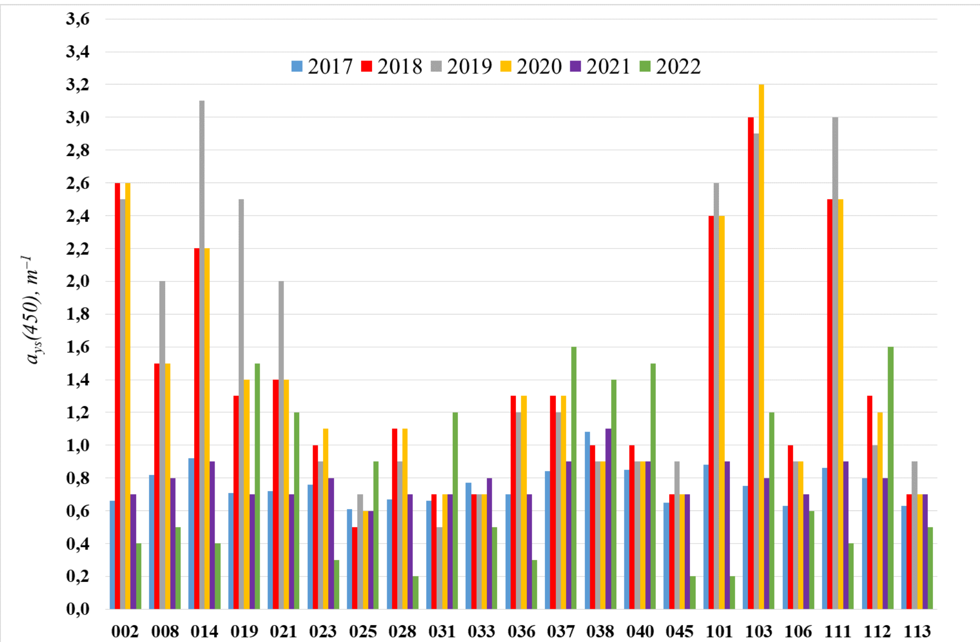



**Fig.3.** Long-term dynamics of light absorption by YS at a wavelength of λ = 450 nm in different sites of Lake Teletskoye

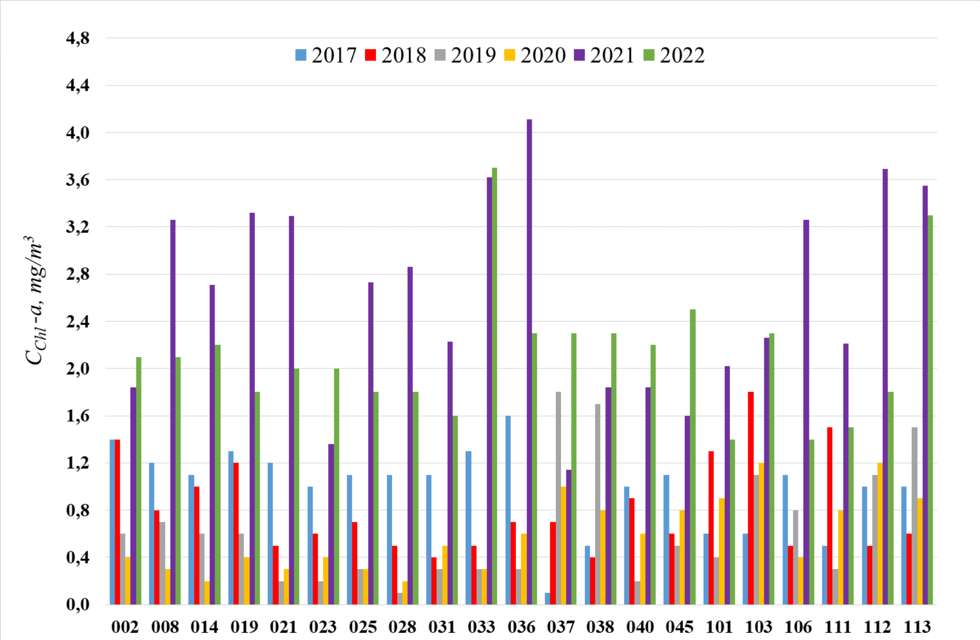



**Fig.4.** Long-term dynamics of chlorophyll-*a* concentrations in different sites of Lake Teletskoye

It increased to 28.1% at λ = 550 nm in site 111. The contribution of PW was insignificant at λ = 430 nm in all sampling stations (less than 0.4%). However, it drastically increased in the long-wave region (up to 18.8%) at λ = 550 nm. The contribution of chlorophyll at λ = 430 nm was 0.6% – 11.3% (sites 037 and 036 of the pelagic zone of the Kamga River), whereas at λ = 550 nm – from 0.1% (site 037) to 2.6% (site 002 – the pelagic zone of the Chulyshman River).

**In 2018**, the largest contribution of YS to *c(λ)* at λ = 430 nm occurred in the pelagic zone of rivers Kamga (site 036) and Chulyshman (site 002), i.e. 94.1 and 90.9%, respectively. At a wavelength of 550 nm, its contribution varied from 40.0% (site 025 – the pelagic zone of the Adamysh River) to 91.3% (site 103 – the littoral of the Kyga River). Suspension made the maximum contribution (33.4%) at λ = 430 nm in site 119 of the pelagic zone of Cape Syraktu, which increased to 47.8% in site 025 of the pelagic zone of the Adamysh River at λ = 550 nm. Contribution of PW was inessential (0.4%) at λ = 430 nm. However, it greatly increased up to 14.1% in the long-wave region at λ = 550 nm. The contribution of Chl-*a* at λ = 430 nm ranged as 1.8% (site 021 – the pelagic zone of the Kokshi River) and 4.8% (site 040 – the pelagic zone of Yailyu village), at λ = 550 nm – from 0.3% to 1.2% (sites (021 and 040 of the pelagic zone of Yailyu village).

**In 2019**, the largest contribution of YS at λ = 430 nm was noted in the pelagic zone of rivers Chulyush, Kyga and Kokshi (87.1, 85.7 and 85.1%, respectively). At a wavelength of 550 nm, the contribution of YS changed from 50.0% (the pelagic zone of the B. Korbu River and Kamenny Bay, respectively) to 95.4% (the pelagic zone of the Chulyush River). Suspension made its maximum contribution (31.5%) to light attenuation at λ = 430 nm in site 025 of the pelagic part of the Adamysh River, increasing to 41.9% at λ = 550 nm in site 113 of the pelagic zone of

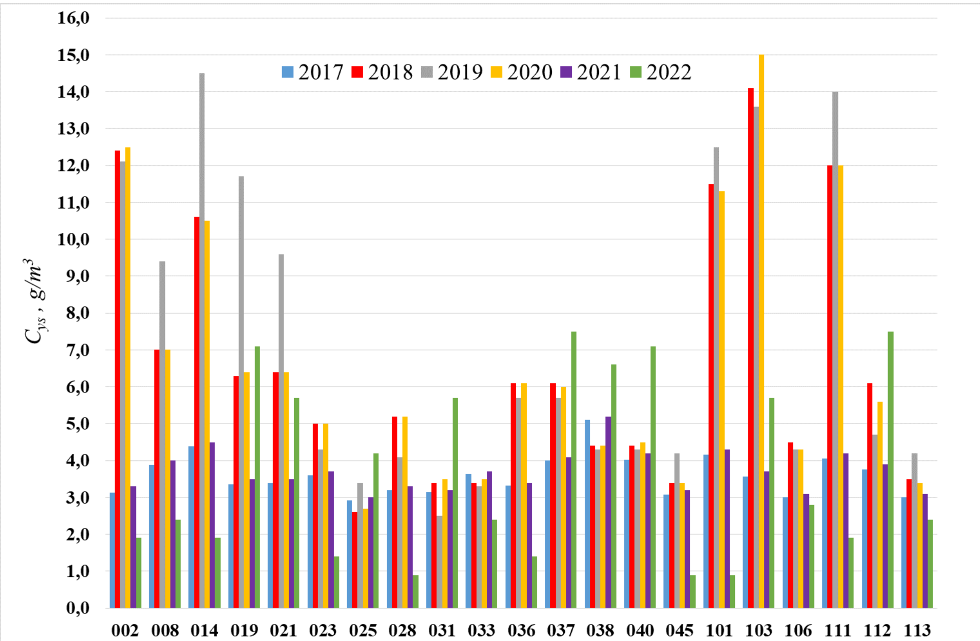



**Fig.5.** Long-term dynamics of YS concentrations in different sites of Lake Teletskoye

Kamenny Bay. The contribution of PW to light attenuation was insignificant (up to 14.1%) at $\lambda = 430$ nm (less than 0.4%), but at $\lambda = 550$ nm it increased sharply in the green region of the spectrum. The contribution of chlorophyll at $\lambda = 430$ nm ranged from 0.6 to 8.5% and at $\lambda = 550$ nm – from 0.1% to 1.8%.

**In 2020**, the largest contribution of YS at $\lambda = 430$ nm was recorded in the pelagic part of rivers Kamga and Chulyshman (94.1 and 93.5%, respectively). At a wavelength of 550 nm, YS contribution varied from 40.0% (the pelagial area of the Adamysh River) to 91.3% (the littoral of the Kyga River). Suspension made its maximum contribution (32.1%) at $\lambda = 430$ nm in site 019 (the pelagic zone of Cape Syraktu), which increased to 46.4% (site 014 – the pelagic part of Chulyush River) at $\lambda = 550$ nm. At $\lambda = 430$ nm, PW demonstrated minor contribution in all sites (less than 0.1%), but it abruptly increased in the green region of the spectrum (up to 14.1%). The contribution of chlorophyll at $\lambda = 430$ nm ranged from 0.5 to 6.0%, while at $\lambda = 550$ nm – from 0.1% to 1.4%.

**In 2021**, the largest contribution of YS at $\lambda = 430$ nm was detected in the pelagic and littoral parts of the Kamga River (85.8 and 75.0%, respectively). At a wavelength of 550 nm, the contribution of YS varied from 29.6% (the pelagic part of Kamenny Bay) to 67.0% (the pelagic part of the Kamga River). Suspension made the greatest contribution (21.4%) at $\lambda = 430$ nm in site 103 (the littoral of the Kyga River) and was growing up to 43.8% at $\lambda = 550$ nm in site 113 of the pelagic part of Kamenny Bay. The contribution of chlorophyll at $\lambda = 430$ nm ranged as 6.8–27.3% and at $\lambda = 550$ nm – from 1.4% to 7.8%. PW made an insignificant contribution to light attenuation at $\lambda = 430$ nm (less than 0.1%), but sharply increased up to 18.8% in the green region of the spectrum at $\lambda = 550$ nm.

**In 2022**, the largest contribution of YS at $\lambda = 430$ nm was noted in the pelagic part of rivers Kamga and Saimysh (90.0%). At a wavelength of 550 nm, this indicator varied from 33.3% (the pelagic part of the Kamga River) to 88.8% (the pelagic part of Yailyu village). Suspension showed its maximum contribution (40.3%) at $\lambda = 430$ nm in site 014 of the pelagic zone of the Chulyush River) and increased to 46.1% at $\lambda = 550$ nm in site 002 of the pelagic part of the Chulyshman River. A share of PW was negligible (less than 0.1%) at $\lambda = 430$ nm, but abruptly increased up to 28.2% at $\lambda = 550$ nm. The contribution of chlorophyll at $\lambda = 430$ nm ranged from 3.2 to 29.3% and at $\lambda = 550$ nm – from 0.8% to 10.5%. The least indicators (about 0.1%) of molecular light scattering by PW were observed in the study spectral range.

Thus, YS and S turned out to be the most significant optically active components affecting the total light attenuation in Lake Teletskoye waters.

The analyzed literature data confirm our pioneer calculations of spectral contributions of the main optically active components of Lake Teletskoye waters to the spectral index of light attenuation $c(\lambda)$ (2017–2022).

The trophic status of the lake is determined by limnoclimate, a type of a catchment area and its altitude. Prolonged periods of mixing of water masses and short periods of stratification, oxygenated water supply by mountain streams, low water temperature throughout almost the whole year – all this contributes to oxygen saturation of the entire water column. Note that at the bottom saturation may be even higher than at the surface.

Our findings suggest that the trophic status of Lake Teletskoye can be characterized mainly as oligotrophic with the elements of mesotrophy in sites of the large rivers' confluence.

From general and specific indicators (i.e. tropho-saprobity, mineralization and hardness of water, the hydrogen index and the presence of harmful substances (GOST, 1977), including quantitative characteristics of aquatic organisms (abundance, biomass and species number) it follows that waters of Lake Teletskoye belong to the class of "clean waters", as well as "very clean" and "quite clean" according to the unified ecological classification of the surface waters of the land (Oksiyuk et al., 1993).

## 4. Conclusions

During Lake Teletskoye investigations (2017–2022), we collected new field data on spatiotemporal variability of light attenuation, light absorption by YS, SD-measured relative transparency, Chl and YS concentrations for various sampling sites. The modified semi-empirical model was applied to describe the spectral contribution of the main optically active components of natural waters to light attenuation with due regard for light absorption by terrigenous and biogenic particles. Summer studies of Lake Teletskoye demonstrated insignificant changes in the long-term dynamics of hydro-optical characteristics thus indicating good oligotrophic ecosystem conservation and high water quality of Lake Teletskoye under growing economic loads on the reservoir and its drainage basin. The obtained results suggest that hydro-optical characteristics can be widely used in studying large lakes, reservoirs and rivers to monitor the heterogeneity of water pollution level, qualitative assessment of the content of suspended and dissolved substances and, consequently, the ecological state of different-type waters.

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## Conflict of interest

The authors declare no conflicts of interest.

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