

RESEARCH ARTICLE

Isotope stratification of meromictic Lake Trekhtzvetnoe at the White Sea coast (Russia)

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Abstract – Postglacial isostatic uplift of the coastal zone resulted in the formation of isolated lakes along the shores of White Sea developed into permanently stratified (meromictic) lakes. On the basis of monitoring the vertical distribution of selected water quality parameters including temperature, salinity, concentration of major ions, microbial activity, dissolved oxygen and hydrogen sulfide, seasonal changes in the structure of the stratified water column are explored and governing factors identified. Lake Trekhtzvetnoe has a strong vertical stratification with seasonal mixing being confined to the upper part of the water column (mixolimnion). Chemical water composition in the mixolimnion reflects the influence of precipitation with the underlying chemocline being defined by sharp gradients of salinity, dissolved oxygen and hydrogen sulphide levels. We found strong stable isotope stratification of water column in winter-early spring seasons of 2013, 2015 and 2016 and in the early autumn of 2015. The lowest isotope values were obtained near the surface in the mixolimnion. There was a gradual increase of isotope values towards the chemocline reaching the maximum in the bottom layer (monimolimnion). It was found that water in the mixolimnion was isotopically depleted in winter as a result of ice formation and isotopically enriched in the early autumn due to evaporation. Obvious desalination of mixolimnion and upper chemocline from 2012 to 2016 was possibly caused by the increase of precipitation and freshwater inflow in lake supply. Monimolimnion is a stable layer of high salinity, and it has enriched isotope composition that corresponds with meromictic structure of water column.

Keywords: White Sea / separating lakes / meromixis / stratification / stable isotopes

1 Introduction

Most of the White Sea coast still rises isostatically after the last glacial period gradually leading to the separation of numerous small gulfs and coastal channels from the sea and the subsequent formation of small lakes. In the vicinity of the White Sea Biological Station of MSU (WSBS), the rate of the uplift is about 40 cm per century (Romanenko and Shilova, 2012). This, together with meandering shoreline and abundance of islands and cross-country terrain provides favourable conditions for separating the bays from the sea and forms many water bodies. Some lakes present different stages

of isolation from the sea beginning with the lagoon with tidal fluctuations to the meromictic reservoirs with a fresh upper layer and strong stratification (Krasnova *et al.*, 2014). The influx of salt water stimulates the process of bacterial sulfate reduction resulting in hydrogen sulfide in the lower water layer and proliferation of anaerobic phototrophic microorganisms, including green sulfur bacteria in the redox zone. Colored microbial water layers in the redox zone are indicators of the stage of lake evolution. Red beds with cryptophyte algae bloom indicate early stages of the reservoir development, green layers with green sulfur bacteria indicating advanced stages. The development of microbial color layers influences the vertical hydrological structure by depriving light of most of the water column (Pantuyulin and Krasnova, 2011; Krasnova *et al.*, 2013, 2014). These newly formed lakes provide the

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opportunity to study the formation of anaerobic conditions in the hydrosphere and the subsequent interactions between marine and fresh-water based fauna as well as a variety of associated biogeochemical processes in water and sediments. The lake separated from the sea is forcing the stratification of water column and transformation to typically meromictic structure. This is accompanied by development of stagnation in the bottom layer which sharply impairs ecological conditions of the lake.

The typical hydrological structure of stratified lakes consists of an upper layer mixolimnion 1–1.5 m thick and a monimolimnion divided into two layers: the upper photic aerobic and lower aphotic anaerobic layers. Between the main layers there is narrow transition zone with sharp gradients of physical and chemical parameters: a pycnocline on the border of freshened and salt layers, and a redox zone between aerobic and anaerobic layers. Oxygen and hydrogen isotope composition of water column of stratified lakes often shows three-layered structure as following: the mixolimnion layer which has an isotopic signal coherent with the values for local precipitation, the chemocline having the $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values increasing towards the monimolimnion where they reach their maximum.

As ^{18}O is a minor constituent of the water molecule, it imparts conservative properties of meteoric waters through the hydrological cycle. In conjunction with salinity, the isotopic ratios may be used to detect any dilution resulting from mixing of isotopically distinctive components, for example sea-water with continental waters. The isotopic composition may also provide some insight into any physicochemical process which can modify the isotopic ratio. For example, water in isolated lakes is exposed to evaporation, which leads to isotopic enrichment and to an offset of the $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values below the meteoric water line (GMWL) defined by the equation: $\delta^2\text{H} = 8\delta^{18}\text{O} + 10\%$ (Craig, 1961).

Case studies show that isotope stratification of water may be caused by different factors. For the Black Sea, enrichment in deuterium and ^{18}O isotopes for the deep waters (depth over 500 m) compared with the surface layer is explained by mixing of surface water with the Lower Bosphorus Current inflow (Dubinin *et al.*, 2014). For seasonally isolated marine basin in the Canadian High Arctic, the stable oxygen and hydrogen isotope data coupled with hydrochemical data showed the brine rejection during ice formation as a mechanism for the generation of hypersalinity (Dugan and Lamoureux, 2011).

In meromictic lakes Sophia and Garrow studied on the Little Cornwall Island, Canadian Arctic, mixolimnion zone is characterized by low chloride concentration and $\delta^{18}\text{O}$ values close to that of precipitation. In the monimolimnion zone (20–47 m depth) $\delta^{18}\text{O}$ values reach a maximum at a salinity which is 2–2.5 times higher than in the adjacent ocean (45–50 g/L). The hyper-saline water enriched with isotopes could have been formed in the monimolimnion of both lakes as a result of crenogenic salinization that started when both lakes became isolated from the sea following gradual uplift of the land over 4000 years ago. Stable isotope and salinity stratification in Lake Sophia caused by infiltrating brines from the ocean subterraneously through the unfrozen zone into the lake also (Page *et al.*, 1984; Ouellet *et al.*, 1989).

Studies of shallow stratified permafrost-thaw lakes (depth 2.7–4 m) in the Canadian Subarctic showed that density

stratification of water is especially developed during winter when the lakes are covered with ice. The concentration of dissolved oxygen in these lakes then decreases to zero across the entire stratified water column because of reducing conditions, and lack atmospheric oxygen. At high concentrations of organic matter this results in methane production during winter (Deshpande *et al.*, 2015).

This study investigates stable isotope stratification of meromictic Lake Trekhtzvetnoe. In the study area it is one of the deepest coastal lakes separated from the White Sea. Long-term detailed studies of hydrological parameters of Lake Trekhtzvetnoe revealed that it is characterized by stable stratification of water column, and anomalously high hydrogen sulfide concentration that makes it unique among known meromictic reservoirs. The objective is to elucidate the mechanisms that result in the formation of observed isotope composition of mixolimnion, chemocline and monimolimnion. These data provide a new addition to the modern isotope dataset of meromictic lakes.

2 Materials and methods

2.1 Study site and sampling

Trekhtzvetnoe Lake is located in the Rugozerskaya Bay of the White Sea (66°35,53'N, 32°59,97'E), near WSBS of Moscow State University (Fig. 1). The size of the lake is 340 m × 150 m, the maximum depth is 8 m. It is separated from the White Sea by an isthmus that only allows for minimal drainage of lake water into the sea during summer (max. 1 l/s) with no flow occurring during winter. Consequently, no tidal fluctuations of the water level in the lake are observed.

The bottom of the lake has a funnel form (Fig. 2) that together with a lack of lake-sea water exchange resulted in stable stratification of water column and formation of a typical meromictic structure with upper freshwater layer and salty monimolimnion separated by chemocline (Fig. 2).

For the isotopic analysis 50 ml water samples were collected at every 0.5 m from surface to bottom in March 2012, 2013 and 2016, in January and September 2015, using the Whale Premium Submersible Pump GP1352 (USA). Samples were sealed and stored at a temperature of about 2 °C.

2.2 Meromictic structure of Trekhtzvetnoe Lake observed in 2011–2016

The Russian name “Trekhtzvetnoe” means “three-color” because of the impressive differences in color of its three layers determined by sampling of water: the upper, fresh mixolimnion from the surface to 1–1.5 m depth is brownish due to humic substances entering the lake from the surrounding swamp. From 1–1.5 to 2.5–3 m there is chemocline with a steep salinity gradient. Underneath the water is salty. The middle water layer from 1.5 to 1.75–1.9 m is aerobic; the border between aerobic and anaerobic layers can be observed at a depth of 1.75–1.9 m depending on the seasonal water level fluctuations. At the same time, this boundary is a chemocline or redox zone, yet all through the year, its color remains bright green as a result of the growth of green sulfur bacteria (Kharcheva *et al.*, 2013;

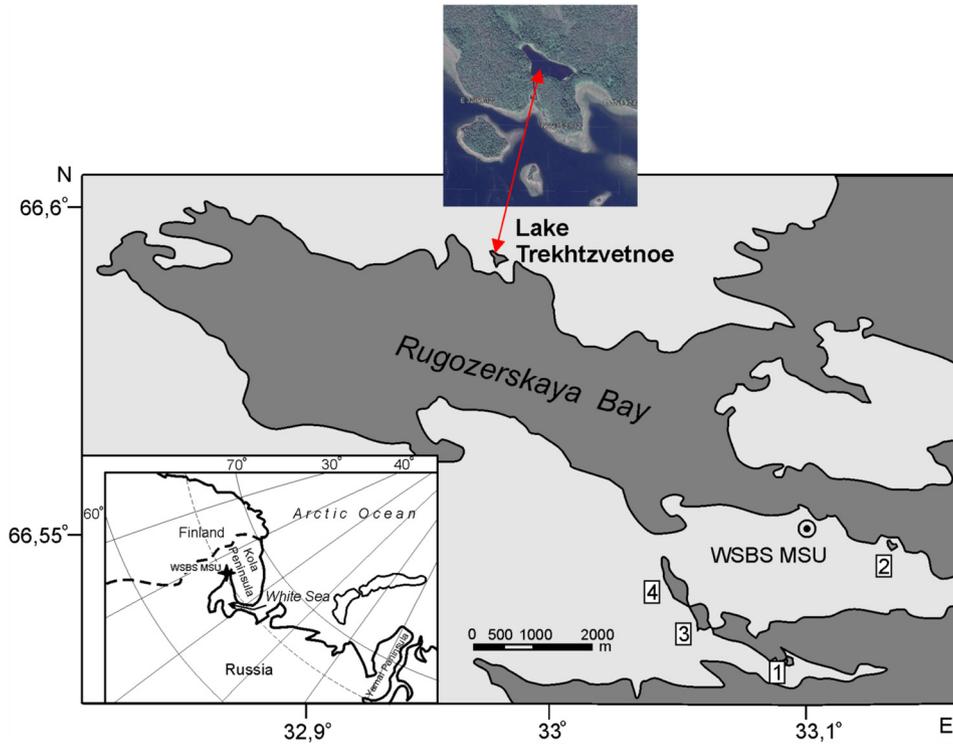


Fig. 1. Location of Trekhtzvetnoe Lake in the vicinity of WSBS.

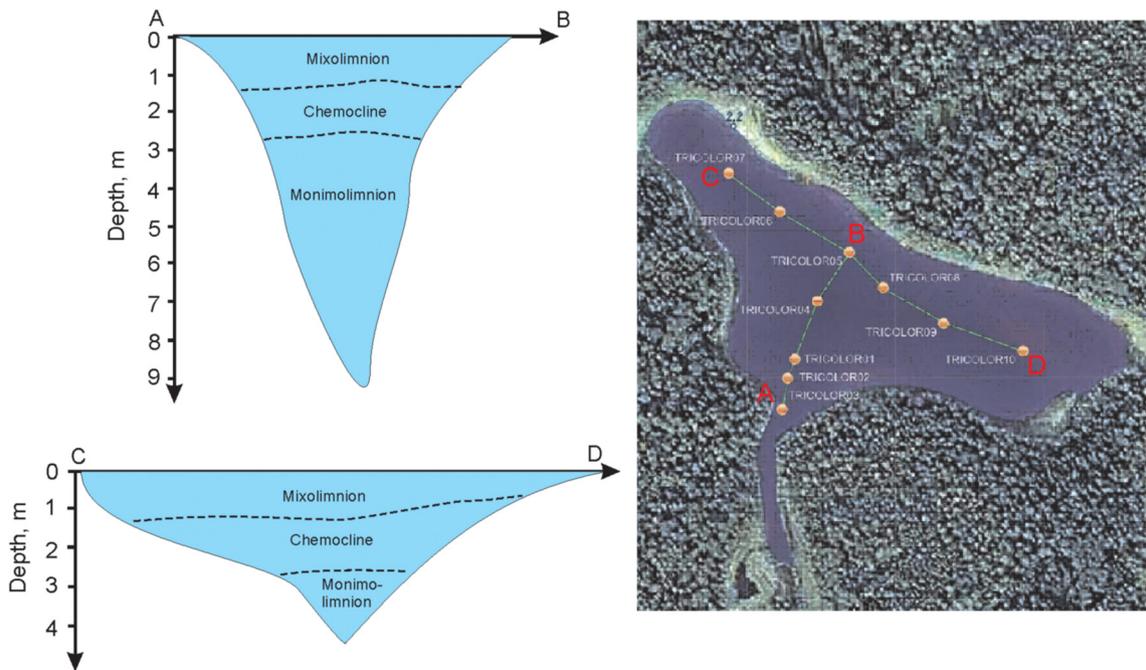


Fig. 2. Average position of mixolimnion, chemocline and a monimolimnion borders in the Trekhtzvetnoe Lake during 5 years of studies (2012–2016) based on salinity distribution along the cross (AB) and longitudinal (CD) profiles.

Krasnova *et al.*, 2015). Below the redox zone, there is a hydrosulfide water layer colored in lemon yellow, turbid due to sulfur crystals. When lifting to the air gas bubbles appear in the water samples (presumably methane). Among the known

lakes separated from the White Sea the Lake Trekhtzvetnoe best meets the meromictic concept (Vasil'chuk *et al.*, 2016). The vertical stratification was constant throughout the year and over the six years (2011–2016) of observation.

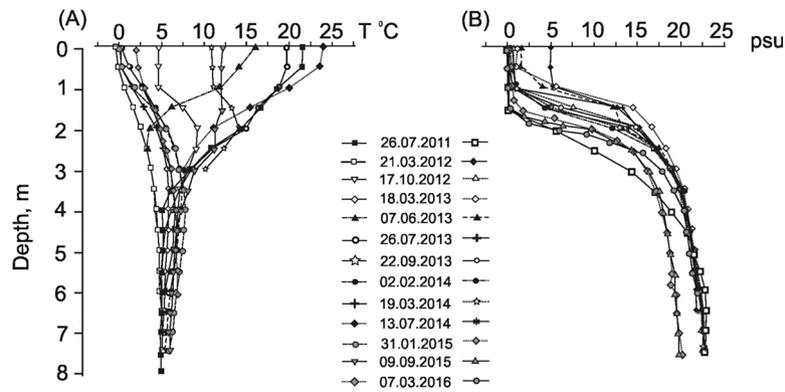


Fig. 3. Annual variability of temperature (A) and salinity (B) in the Lake Trekhtzvetnoe in 2011–2016.

2.2.1 Temperature and salinity

Vertical temperature profiles of the lake suggest the existence of three layers across all seasons. These include the following: (1) a surface layer affected by wind-related mixing, (2) a subjacent layer of temperature transition layer (thermocline) and (3) a lower layer where density-driven convection is absent. Generally, in winter the water temperature below the ice is about 0 °C. In winter 2012, the temperature of lake water under the ice cover was –0.4 °C due to higher salinity caused by preceding intrusion of sea water in autumn 2011.

After ice melting, the temperature of the upper water layer gradually increases to summer maxima of about 14–16 °C, some 2 m above the thermocline. In early September, the bottom boundary of the thermocline drops to 3–4 m depth below surface. The surface water layer gradually cools down to 10–16 °C depending on weather conditions in late August to September. During this time a specific temperature depth profile is formed in the thermocline: it is warmer than the upper and the lower layers with temperature reaching up to 18 °C. In early spring, an inverse temperature profile develops. The temperature of the bottom water layer remains constant at 5.5–6.0 °C throughout the year (Fig. 3A).

The salinity of mixolimnion during a year does not exceed 0.8–1.8 psu, except for 2012 when it reached 5 psu (Fig. 3B). The salinity in the chemocline does not exceed 16 psu and in the monimolimnion it gradually declines from 14 to 16‰ at the upper boundary to 20–23 psu at the bottom. In November 2011, a high tide coinciding with a wind surge pushed seawater into all coastal lakes, including the Trekhtzvetnoe Lake. This event was unique for a lake that was separated from the sea for many years. As a result, in winter 2012, the thickness of mixolimnion decreased to 1 m and the water turned brackish. In the next winter seasons, salinity of the surface layer decreased to 0.8–0.6 psu and in winter of 2015 it did not exceed 0.4 psu. The water salinity in the monimolimnion (from 4 m depth to the bottom at 8 m), was about 20–23 psu, during both summer and winter.

Chemical composition of the lake water is characterized by chlorine and sodium dominance (Tabs. S1, S2). The sum of ions increases from 13 g/L (at a depth of 2 m) to 23 g/L at the bottom, but concentration of all major ions remains nearly constant throughout the year. The distribution of main ions and dissolved elements correlates with chloride concentration and is typical for water with intermediate salinity (Savenko *et al.*,

2015). Vertical distribution of sulfates shows maxima at the depth of 2–4 m, and below this level, it decreases with depth, which is different from the vertical profile of all other ions and caused by bacterial oxidation of sulfides to elemental sulfur.

The penetration of dissolved oxygen into the lake is limited by the chemocline level at 1.75–1.9 m. During winter seasons ice cover prevents input of atmospheric oxygen into the lake and while the decomposition of organic matter consumes the available remainder of DO, anoxic conditions gradually develop which allow for the subsequent accumulation of hydrogen sulfide up to 630 mg/l in monimolimnion (Kokryatskaya *et al.*, 2013; Losyuk *et al.*, 2015) that is about 2–3 times higher than in the Norwegian Framvaren Fjord where one of the highest level of H₂S was measured (Millero, 1991; Behnke *et al.*, 2006).

Light penetration in this lake is limited by the upper 1.5 m. The middle green layer is muddy because of the huge number of bacteria, and it completely absorbs light; so most of the water column in this lake stays in the aphotic zone. Our studies showed oxygen isotope stratification of Lake Trekhtzvetnoe water column in March 2012 (Lisitzin *et al.*, 2013). Surface layer from 0 to 1 m was characterized by the lowest $\delta^{18}\text{O}$ values from –10.8 to –10.2‰; at 1.5 a shift to $\delta^{18}\text{O}$ value of –7.1‰ was observed with gradual increase to +2.1‰ to the bottom. In the vicinity of WSBS some lakes on the initial stage of separation from the sea were characterized by rather uniform vertical distribution of $\delta^{18}\text{O}$ and salinity close to that of the sea. Uniform $\delta^{18}\text{O}$ profiles were also typical for the shallow lakes completely separated from the sea and turned to fresh (Lisitzin *et al.*, 2013). It is found that applying the stable isotope data together with temperature and salinity distribution in water column may appear as an effective method in defining the water sources feeding lakes isolated from the sea.

2.3 Analytical measurements

Isotope measurements were made in the Stable Isotope Laboratory of the Faculty of Geography at the Lomonosov Moscow State University by isotope equilibrium method on CF-IRMS (Finnigan Delta-V). Equilibration for CO₂ took place during 24 h in 24 °C temperature tray, for ²H during 40 min with Pt-catalizator. For calibration international standards (V-SMOW, GISP, SLAP) were used.

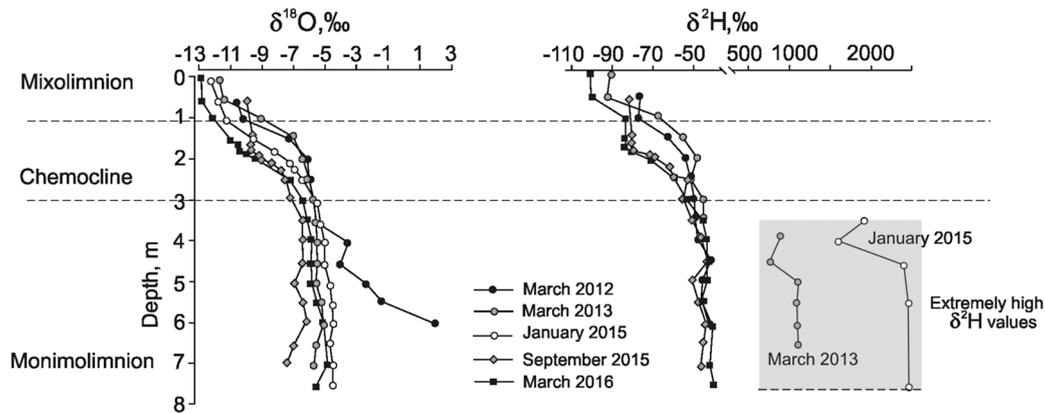


Fig. 4. The $\delta^{18}\text{O}$ and $\delta^2\text{H}$ profiles in the water of Lake Trekhtzvetnoe, 2012–2016.

All $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values were expressed relative to Vienna Standard Mean Ocean Water (VSMOW) in parts per thousand (‰),

$$\delta^{18}\text{O} \text{ or } \delta^2\text{H} = [(R_{\text{sample}}/R_{\text{standard}}) - 1] \times 10^3,$$

where R is the ratio of ^2H to ^1H atoms or ^{18}O to ^{16}O atoms in the sample and the standard VSMOW.

Anomalous high values of $\delta^2\text{H}$ in the monimolimnion of Lake Trekhtzvetnoe were obtained for several sampling dates (March 2013 and January 2015). Repeated measurements carried out 3 weeks later showed no anomalously high ^2H levels and a much reduced smell of hydrogen sulfide. Perhaps, high $\delta^2\text{H}$ values obtained in the monimolimnion are explained by instrumental errors (mass spectrometer Delta V) that occur if isotope ratios are measured as in water as in the dissolved H_2S found at high concentrations in the monimolimnion that could disrupt the chromatogram.

To compare values obtained on different isotope analyzers some samples (March 2016 and September 2015) were also measured at the Saint Petersburg State University Resource Center for Geo-Environmental Research and Modeling (GEOMODEL) on the Isotopic Water Analyzer Picarro L-2120i (Picarro INC., USA). Picarro analyzers use the method of Wavelength Scanned Ring Down Spectroscopy (WS-CRDS) providing precise, quantitative measurements even in samples with trace gas concentration. Measurement precision was $\pm 0.1\text{‰}$ for $\delta^{18}\text{O}$ and $\pm 1\text{‰}$ for $\delta^2\text{H}$.

3 Results and discussion

3.1 Oxygen and hydrogen isotopes

The contrasting distribution of oxygen and hydrogen isotope values observed in 2012–2016 corresponds with meromictic structure of Trekhtzvetnoe Lake (Tabs. S1 and S2, Fig. 4), except for March, 2012 when water column stratification was slowly indistinct that most likely caused by the input of a large volume of seawater in November 2011. The $\delta^{18}\text{O}$ – $\delta^2\text{H}$ ratio slope was 5.54 with $R^2 = 0.97$ (Fig. 5, Tab. S3) for whole water column that was close to the sea water. In March 2013, in the mixolimnion $\delta^{18}\text{O}$ values varied from -9 to -11.8‰ and $\delta^2\text{H}$ values – from -68.9 to -91.5‰ (Tab. S1). In the chemocline (1.5–3 m depth) $\delta^{18}\text{O}$ values increased

to -5.8‰ , $\delta^2\text{H}$ values to -49.3‰ . In the monimolimnion layer the $\delta^{18}\text{O}$ values varied from -5.4 to -5.7‰ .

In January 2015, the isotope stratification of water slightly changed. According to $\delta^{18}\text{O}$ values distribution, the layer of mixolimnion had a thickness of about 1 m ($\delta^{18}\text{O}$ varied from -12.1 to -11.1‰), in the chemocline to the depth of 3 m $\delta^{18}\text{O}$ values raised to -5.5‰ , in monimolimnion they varied in the narrow range between -4.7 and -5.2‰ (see Tab. S1). In 2013 and 2015, anomalously high values of $\delta^2\text{H}$ were determined in monimolimnion (see Tab. S1, Fig. 4). In 2013, the $\delta^2\text{H}$ values were 780–1100‰ (4–6.5 m depth) and in 2015 $\delta^2\text{H}$ values ranged from 1600 to 2400‰ (3.5–7.6 m depth). In March 2016, the isotope composition of water in the mixolimnion (0–1 m) was quite depleted: $\delta^{18}\text{O}$ values varied from -12.6 to -13.6‰ , $\delta^2\text{H}$ values – from -102 to -94‰ . In the chemocline (1–3 m), the isotope values increase to -6.9‰ for $\delta^{18}\text{O}$ and to -53‰ for $\delta^2\text{H}$. In the monimolimnion $\delta^{18}\text{O}$ values varied in the range from -5.6 to -6.4‰ , $\delta^2\text{H}$ values – from -40 to -47‰ . In September 2015, the meromictic isotope structure of the lake was less distinct – the range of oxygen isotope values between mixolimnion and monimolimnion was 4.8‰ while in winter months the range was 6.7–12.9‰ (see Tab. S2). Nevertheless, the mixolimnion to the depth of 1.8 m had $\delta^{18}\text{O}$ values from -10.7 to -10.9‰ , whereas the $\delta^2\text{H}$ values ranged from -82 to -80‰ . In the chemocline, the increase of isotope values was noted: to -7.1‰ for $\delta^{18}\text{O}$, to -54‰ for $\delta^2\text{H}$ to the depth of 1.9–3.0 m. In the monimolimnion $\delta^{18}\text{O}$ values varied from -6.1 to -7.3‰ , $\delta^2\text{H}$ values from -45 to -51‰ .

It is revealed that in 2013, 2015 and 2016, the water of mixolimnion and chemocline had values of $\delta^{18}\text{O}$ – $\delta^2\text{H}$ ratio from 6.7 to 7.6 that is close to those for meteoric water. The water of monimolimnion in 2012, 2016 and 2015 (September) was characterized by values of $\delta^{18}\text{O}$ – $\delta^2\text{H}$ ratio from 2.5 to 5.6 with R^2 from 0.31 to 0.58 that would indicate the lack of mixing between monimolimnion and upper layers of chemocline and mixolimnion (see Fig. 5, Tab. S3).

The d -excess values of the lake water in 2012–2016 varied from -59.2 to 10.4‰ , the most values were in the range from -5 to 7‰ (see Tabs. S1 and S2, Fig. S1). These data are comparable with those obtained for lakes in Western Siberia (between 62 and 67°30'N) (Ala-aho *et al.*, 2018) in winter-spring and indicates that even in high latitudes the lake water has a noticeable signal of evaporation.

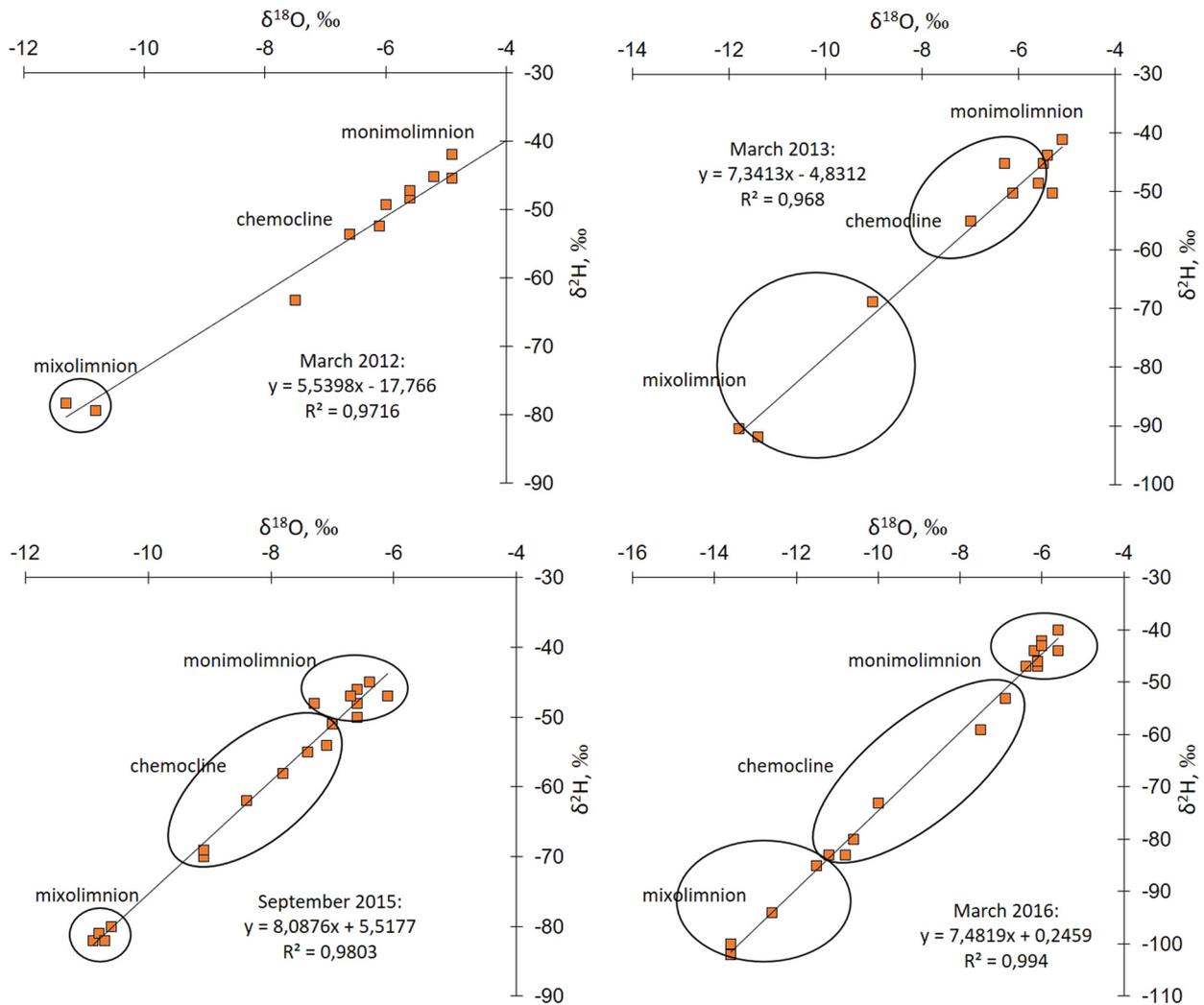


Fig. 5. The $\delta^{18}\text{O}$ – $\delta^2\text{H}$ plots for water column of the Trekhtzvetnoe Lake.

The $\delta^{18}\text{O}$ – $\delta^2\text{H}$ diagrams show the large range of isotope values in the mixolimnion in March 2013 and 2016 (see Fig. 5), that is possibly caused by ice formation. The difference in isotope values between upper and lower layers in mixolimnion was about 2–3‰ for $\delta^{18}\text{O}$ and about 20‰ for $\delta^2\text{H}$ that indicates isotope fractionation factor for water-ice separation. Obviously, surface water is a source of ice formation and it is well known that the ice is always isotopically enriched compared to the original water. The difference between $\delta^{18}\text{O}$ values of ice and water is usually between 2 and 2.6‰ (O’Neil, 1968; Lehmann and Siegenthaler, 1991; Macdonald *et al.*, 1995). A difference of 4‰ was observed between ice and initial water during the experimental ice formation in closed system (Vasil’chuk, 2011). In 2013, the ice was characterized by the values of $\delta^{18}\text{O} = -10.2\text{‰}$, and $\delta^2\text{H} = -74.4\text{‰}$ that allows us to suppose, that surface water layer was the source for lake ice formation. Therefore, due to the ice formation the isotope stratification of water column in winter is more pronounced.

3.2 The dynamics of $\delta^{18}\text{O}$ –S ratio in 2012–2016

The additional approach for isotope stratification analysis of the lake water is $\delta^{18}\text{O}$ – salinity ratio which is usually applied for the studies of sea water masses and their mixture. As salty water in Trekhtzvetnoe Lake originated from the White Sea and fresh water of mixolimnion – from precipitation and runoff, it is possible to use a theoretical mixing line of White Sea water and local fresh water (Fig. 6, line AB). The point A represents the White Sea water (mean salinity value is 30 eps, mean $\delta^{18}\text{O}$ value is –2‰, according to (Pavlov *et al.*, 2016)). In the study area the salinity of White Sea water is about 27–29 psu in winter and 24–25 psu in summer. The point B represents the average value of mean annual precipitation on Kandalaksha weather station (GNIP data) together with runoff of large rivers flowing into the White Sea (mean salinity value is 0 eps, mean $\delta^{18}\text{O}$ value is –14‰).

However, for Trekhtzvetnoe Lake the best linear approximation of the figurative points is the line connecting water of the White Sea and a fresh water with $\delta^{18}\text{O}$ value of –12‰

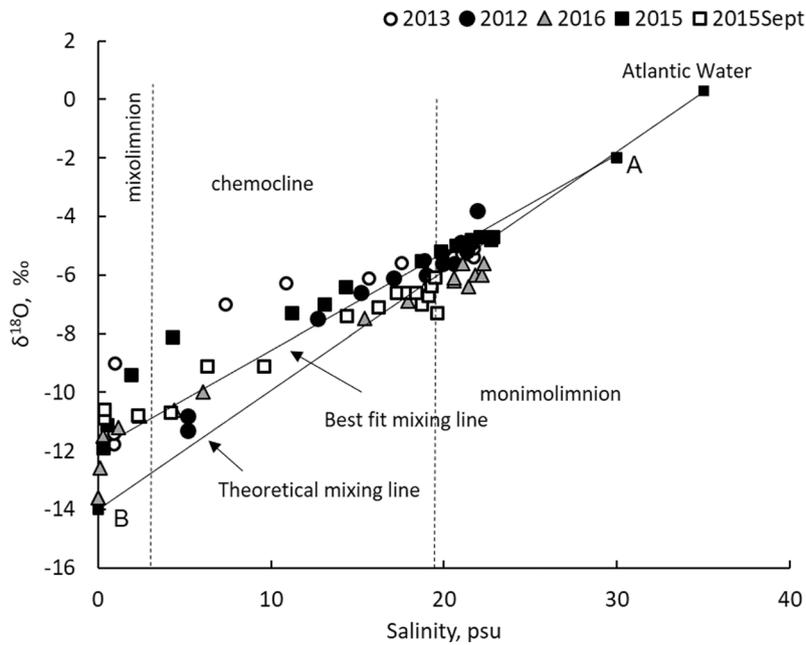


Fig. 6. $\delta^{18}\text{O}$ -S ratio in Trekhtzvetnoe Lake in 2012–2016. AB – mixing line of White Sea water and continental fresh water (local precipitation and runoff).

(“best fit mixing line” on the Fig. 6). The difference of 2‰ may be explained by evaporation from the lake surface. In 2012–2016, the obvious variations of $\delta^{18}\text{O}$ -S ratio are noted in mixolimnion and chemocline and less noticeable – in monimolimnion. The deviation from the mixing line is expressed by a value of $\Delta\delta^{18}\text{O}$ (Tab. S3): the negative $\Delta\delta^{18}\text{O}$ values indicate the lower oxygen isotope values of water than at proportional dual-component mixture (mixing line AB). The positive $\Delta\delta^{18}\text{O}$ values indicate the higher oxygen isotope values of water relative to the dual-component mixture.

3.2.1 Mixolimnion (0–1–1.5 m)

In winter of 2012, the lake water was brackish and salinity of upper 0.5–1 m layer was 5.2 psu. At the same time the $\delta^{18}\text{O}$ values were 1‰ lower relative to dual-component mixture. The negative $\Delta\delta^{18}\text{O}$ values indicate cryogenic isotopic transformation of water due to ice formation. Approximate balance calculation for the upper 1.5 m water layer (considering brine squeezing and isotope depletion of water as well as equilibrium fractionating at slow ice formation) showed that initial salinity and $\delta^{18}\text{O}$ of surface lake water would be equal to 3.7 psu and -10.5‰ , respectively. The calculated $\delta^{18}\text{O}$ value for ice would be -8.5‰ (Fig. S2a).

In winter of 2013, the $\delta^{18}\text{O}$ value of lower layer of lake ice was -10.2‰ and the water under ice had a $\delta^{18}\text{O}$ value of -11.8‰ (see Fig. S2b). These data may indicate fast ice formation as the isotope shift between ice and initial water (ε) was 1.6‰ that is lower than obtained for slow ice formation (O’Neil, 1968; Vasil’chuk, 2011). From 0 to 1 m depth, the $\delta^{18}\text{O}$ values increased by 2.8‰ while the salinity increased only by 0.09 psu that also shows isotope depletion due to ice formation. The similar $\delta^{18}\text{O}$ -S ratio in the mixolimnion was observed in winter 2015: $\delta^{18}\text{O}$ values increased by 1‰, the

salinity increased by 0.2 psu (Fig. S2c, Tab. S3). In 2016 the upper 1 m layer of water was fresh, the values $\delta^{18}\text{O}$ increased downward by 1‰ (Fig. S2e), whereas the negative $\Delta\delta^{18}\text{O}$ values indicate isotope depletion due to ice formation (see Tab. S3).

Thus, it is possible to assume that the upper layer of mixolimnion was isotopically depleted as a result of ice formation, and its desalination from 2012 to 2016 occurred due to precipitation and freshwater inflow from the catchment. In September 2015, the mixolimnion was characterized by $\delta^{18}\text{O}$ values = -10.9 and -10.6‰ at salinity 0.4 eps, so the water was almost fresh and isotopically enriched compared to winter seasons, that possibly reflects the prevailing influence of summer precipitation.

3.2.2 Chemocline (1–1.5–2.5–3 m)

In the chemocline (2012), the $\delta^{18}\text{O}$ values (from -7.5 to -6.1‰) and salinity (from 5.2 to 17.1 psu) were close to the $\delta^{18}\text{O}$ -S line (see Fig. S2a). In 2013, the $\delta^{18}\text{O}$ values increased from -9 to -6.1‰ , and salinity increased from 1 to 15.65 psu. Within 1.5–2 m, the $\delta^{18}\text{O}$ -S points lie above the mixing line (see Fig. S2b); $\Delta\delta^{18}\text{O}$ values at the depth 1–2 m exceeds 2 (see Tab. S3), which indicates stronger enrichment in isotopic composition relative to salinity. The same tendency was observed in winter 2015: $\delta^{18}\text{O}$ values increased from -11.1 to -6.4‰ , whereas the salinity increased from 1.9 to 14.3 psu. $\delta^{18}\text{O}$ values were 1–2.5‰ higher than it is expected from dual-component mixture equation (see Fig. S2c, Tab. S3). This effect is often observed in sea water after melting of sea ice which is a source of rather fresh and isotopically enriched water (Bauch *et al.*, 2016).

As it was mentioned above, the calculated value $\delta^{18}\text{O}$ for lake ice in 2012 was -8.5‰ and in 2013 $\delta^{18}\text{O}$ value of lower layer of ice was of -10.2‰ . Therefore, the melting of lake ice

could not cause the isotope enrichment of water in the chemocline. The possible reason of this effect would be isotope fractionation during photo- and chemosynthesis which is active in the upper layer of chemocline characterized by high bacterial density on the border of aerobic and anaerobic zones.

In September 2015 and March 2016, the effect of isotope enrichment in the chemocline was not observed: in the layer between 1.5 and 2.5–3 m depth, the $\delta^{18}\text{O}$ and salinity values were close to mixing line (see Fig. S2d and e). Comparison of $\Delta\delta^{18}\text{O}$ variations in the chemocline in 2012–2016 shows considerable variability of values within the upper layer on the border of mixolimnion (depth 1–2 m) and lower variability within 2–2.5 m. In 2016, the upper part of chemocline was fresh as well as that of the mixolimnion due to precipitation and freshwater inflow from the catchment.

3.2.3 Monimolimnion (below 3 m)

The water in the monimolimnion is characterized by the highest values of salinity and $\delta^{18}\text{O}$. In 2012, 2013 and 2015, the salinity values varied from 17.5 to 22.9, the $\delta^{18}\text{O}$ values varied from -6.9 to -3.8‰ , and the figurative points of $\delta^{18}\text{O}$ and S clustered close to the mixing line (see Fig. 5 and S2a–c). In September 2015 and March 2016, a shift from the mixing line was observed (see Fig. S2d and e): at the same salinity values (from 20.6 to 22.3 psu), the $\delta^{18}\text{O}$ values became lower (from -6.2 to -5.6‰), the $\Delta\delta^{18}\text{O}$ values in 2016 were the lowest (see Tab. S3). Comparison of $\Delta\delta^{18}\text{O}$ variations in the monimolimnion in 2012–2016 shows the relative stability of values within the same depths. In 2012–2015 below 3 m $\Delta\delta^{18}\text{O}$ values varied between 0.2 and -0.6 , in 2016 $\Delta\delta^{18}\text{O}$ values became much more negative (from -0.6 to -1.4‰) due to a decrease in $\delta^{18}\text{O}$ values. In general, the monimolimnion is characterized by a high stability of physical and chemical parameters, including oxygen isotope composition. In contrast, the layer can be spatially non-uniform with slight variations of salinity and isotope values.

4 Conclusion

Overall, it can be concluded that the stable meromictic stratification in Lake Trekhtzvetnoe is caused by distinct differences in salinity and ion concentration, isotopic composition as well as dissolved oxygen and hydrogen sulfide concentrations. The water column of Lake Trekhtzvetnoe is characterized by stable isotope (^{18}O and ^2H) stratification. The lowest isotope values were obtained in the upper mixolimnion gradually increasing to the chemocline and reaching the maximum in the bottom layer (monimolimnion).

In winter seasons the oxygen isotope composition of water in the upper 0.5 m layer of mixolimnion was depleted due to ice formation. In winter seasons of 2013 and 2015, the water in the chemocline was isotopically enriched possibly due to isotope fractionation during photo- and chemosynthesis in the upper layer of chemocline where high bacterial density was reported. In September 2015 and March 2016, the $\delta^{18}\text{O}$ –S ratio was close to mixing line of White Sea water - local fresh water that was possibly caused by influence of precipitation and freshwater inflow as well as a decrease in bacterial activity.

The monimolimnion is a layer of stable high salinity, it exhibits enriched isotope composition; however, from 2012 for 2016, a slight decrease in isotope values was observed.

The obtained data contribute to the modern isotope dataset of polar meromictic lakes separated from the sea. Stable isotope composition of water column together with standard hydrological parameters provides valuable information for understanding the formation and evolution of these lakes. It is important for forecasting future changes in lake processes such as sea-level rise and coastal inundation.

Supplementary material

Supplementary tables.

The Supplementary Material is available at <https://www.limnology-journal.org/10.1051/limn/2018012/olm>

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