

# Estimation of Gaseous Interchange in the Irkutsk Reservoir

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**Abstract.** In the article the problem of analysis of the water-dissolved greenhouse gases interchange ( $\text{CO}_2$  and  $\text{CH}_4$ ) through the water surface with atmosphere is considered. We assess the seasonal variation of the gaseous interchange in the Irkutsk water reservoir. We propose an original approach to solving this problem, in which modern GIS and data analysis technologies are used.

**Keywords:** greenhouse gases, gas interchange, reservoir, cluster analysis, methane, carbon dioxide.

## 1 Introduction

Increasing global energy demand and concerns about environmental changes have led to the desire to estimate the impact of hydropower plants and the other artificial reservoirs on the emission of greenhouse gases into the atmosphere of Earth. The desire has led to the need for quantitative assessment of the exchange of greenhouse gases ( $\text{CO}_2$  and  $\text{CH}_4$ ) in the system “water-atmosphere” of reservoirs of the hydropower plants. The first scientific papers in the field [1-2] has focused on the reservoirs located in Canada, South America, and later in Finland, Sweden, and Switzerland. In the first global review [4] it has been observed, that such factors as: age, water temperature, and the amount of flooded organic carbon regulate the greenhouse gas emission by the reservoirs. Due to the greater influence of  $\text{CH}_4$  on global warming in comparison with  $\text{CO}_2$ , the negative effect of the flow of methane to the atmosphere can exceed the positive effect of the carbon dioxide fixation by algae.

Studies conducted since the beginning of 2000 have shown that the rate of the flow of  $\text{CO}_2$  and  $\text{CH}_4$  from the reservoirs depends on the age of the reservoir and its geographic latitude [5]. Increased greenhouse gas emissions are observed in young (less than 10 years) reservoirs [6–10]. They are caused by the rapid decomposing of the most labile ground surface organic matter, and with the course of time most reservoirs will have the same gas emissions as natural lakes, but some of the reservoirs may still reveal the increased greenhouse gas emissions, at least for the first 20 years after flooding [11].

In accordance with the decree No. 670-r dated April 14, 2016, the Russian Federation has signed the Paris Agreement of the 21st Conference of the Parties of the United Nations Framework Convention on Climate Change and recommendations for the application of the Greenhouse Gas Measurement Guidelines for Freshwater Reservoirs developed under the auspices of UNESCO, which is a standard procedure for calculating the major greenhouse gas emissions due to the creation of reservoirs in river basins. In connection with the planned amendments to the current legislation of the Russian Federation regarding the development of a reporting procedure for the volume of greenhouse gas emissions, there is an urgent need to understand the processes of greenhouse gas emission and absorption and study their volume in the climatic conditions of Eastern Siberia.

All the climatic scenarios and studies of the global carbon balance consider Siberia as one of the most significant regulators of the carbon-containing gases in the Northern Hemisphere [1-3]. Meanwhile, a number of researchers have a theory, that emissions from these reservoirs are significantly higher than it is commonly believed [12-15]. Since currently there is no consensus on the amount of greenhouse gas emissions from freshwater reservoirs and, accordingly, on the carbon neutrality of the reservoirs of large hydropower plants as well as on the estimates of their gas absorption capacity, measurements of greenhouse gas emissions and the absorption capacity of freshwater reservoirs are of great current interest.

In this paper we consider the approach we have developed to process measurements made at the reservoir of the Irkutsk Hydroelectric Power Station in order to obtain a quantitative estimate of greenhouse gas flows and the results of the use of this approach.

## 2 Input data

Several expeditions to the Irkutsk reservoir were conducted and we have received the results of measurements of gas concentrations and other environmental parameters at various points. An example of the reservoir coverage by measurements is shown in Figure 1.

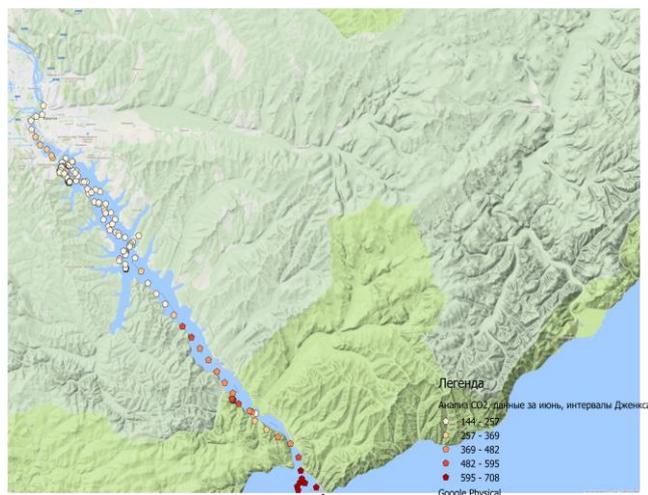


Figure 1. June 2017 sampling points.

### 2.1 Cluster analysis of the measurements

To estimate the total volume of gas exchange, it is necessary to perform spatial and temporal interpolation of the measurements. It should be taken into account that measurements at a single sampling point can be determined by various factors. Therefore, first of all, we have analyzed the relationships between the obtained point attributes. To analyze the dependencies between the attributes at different sampling points we use cluster analysis, which allows us to group the points that have similar properties.

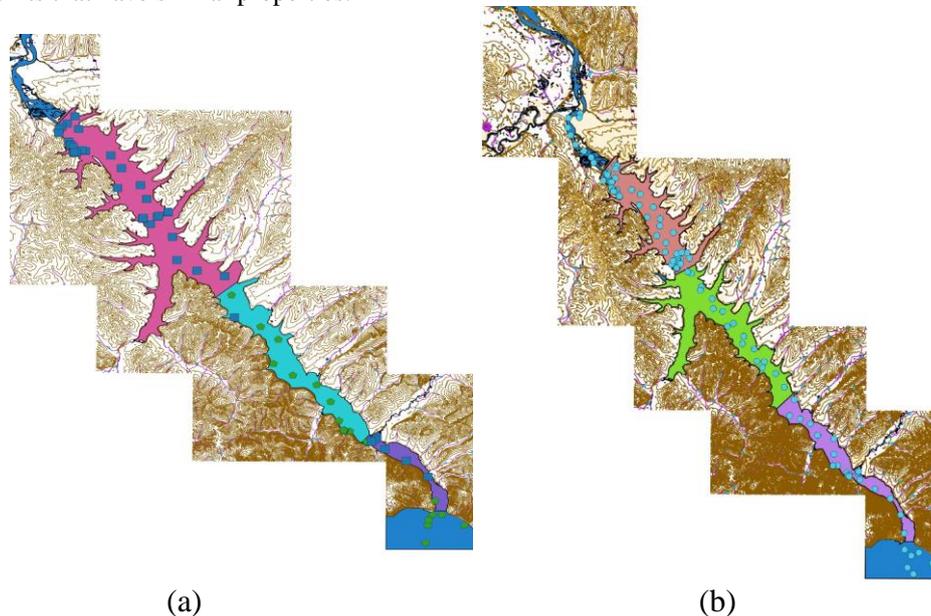


Figure 2. The result of subdividing the Irkutsk reservoir into zones (a) by absorption of  $\text{CO}_2$  and (b) by emission of  $\text{CH}_4$ . From northwest to southeast: 1 - dam influence zone, 2 – intermediate zone и 3 - zone of active influence of Lake Baikal.

For the cluster analysis of the samples we used the following set of attributes: latitude, longitude, time, partial pressure of  $\text{CO}_2$  in air ( $\mu\text{atm}$ ), partial pressure of  $\text{CO}_2$  in water ( $\mu\text{atm}$ ), partial pressure of  $\text{CH}_4$  in air ( $\mu\text{atm}$ ), partial pressure of  $\text{CH}_4$  in water ( $\mu\text{atm}$ ), concentration of  $\text{CO}_2$  in water (mg/l), concentration of  $\text{CH}_4$  in water (mg/l), atmospheric pressure (mmHg), wind speed (m/s), air temperature ( $^\circ\text{C}$ ), solar radiation (r.u.), air humidity (%), water temperature ( $^\circ\text{C}$ ). In the space of these coordinates we have performed a cluster analysis using the K-means method for the results of each of the expeditions. By generalization of the boundaries of the clusters found we have obtained a spatial partition of the reservoir surface into zones (Figure 2). The sampling points assigned to each of the zones have

similar characteristics (they belong to the same cluster and they are compactly located in the space of the point attributes).

## 2.2 Spatial interpolation

Using the measurements obtained in the sampling points at the time of expeditions it is required to estimate the gas exchange over the entire area of the reservoir for the entire summer period. For just the spatial interpolation it was possible to use the various well-known methods such as: the method of natural neighbors, kriging, etc. However, it should be taken into account that the measurements at the sample points were also performed at different times, so it is also necessary to average the results over time. In addition, sometimes the methods of spatial interpolation can extend the features of a single sampling point (which may also be an outlier) to an excessively large fragment of the water area.

As a result, we have decided to use the averaging of the measurements over the reservoir zones, which is simpler and more robust. Note that the choice of partitioning of the reservoir area into zones will affect the final result of the averaging, since the weight of the point depends on the area of the zone to which it is assigned and on the number of sampling points in the zone. The main point attributes we use in the further calculations are the partial pressure differences of the gases considered in this work (CO<sub>2</sub> and CH<sub>4</sub>). Water temperature and wind speed are also taken into account, since these attributes also affect the gas exchange rate.

## 2.3 Estimation of gas exchange volumes

The flow  $F$  of free CO<sub>2</sub> through a unit area of the lake surface is proportional to the difference in partial pressures in air  $p_{CO_2a}$  and in water  $p_{CO_2w}$  at the contact between them [1]:

$$F = \alpha(P_{CO_2w}^{CO_2} - P_{CO_2a}^{CO_2}) \quad (1)$$

where  $\alpha$  is the coefficient of dissolution rate of CO<sub>2</sub>, which depends on several factors: temperature, wind speed, salinity of water, etc. When the partial pressure is measured in atmospheres,  $\alpha$  is measured in  $mg \cdot m^{-2} \cdot atm^{-1} \cdot day^{-1}$ . In [16] the positive flow is directed into the water, but, following [17], [18], we will use the opposite direction (the negative flow is directed into the water).

In [17], [18] it is stated that the dependence on temperature of the dissolution rate coefficient of CO<sub>2</sub> is very weak. For example, in the temperature range 5° - 25° it changes only by 7%. Thus, if we neglect the temperature dependence, the accuracy of the result obtained will change very little.

In [16], using the calculation of the carbon balance, the authors derive an estimate of the average value of the coefficient of dissolution rate of CO<sub>2</sub> for Lake Baikal:

$$\alpha = 6.3 \times 10^5 \text{ mg} / (\text{m}^2 \cdot \text{atm} \cdot \text{day}) = 630 \text{ g} / (\text{m}^2 \cdot \text{atm} \cdot \text{day}) \quad (2)$$

The difference in partial pressures is traditionally measured in parts per million of the atmosphere  $\mu atm = 10^{-6} atm$ . When measuring the surface area in  $km^2 = 10^6 m^2$ , these coefficients ( $10^{-6}$  and  $10^6$ ) cancel each other, so, we can also rewrite the coefficient in the more convenient units of the input data:

$$\alpha = 630 \text{ g} / (\text{km}^2 \cdot \mu atm \cdot \text{day}) \quad (3)$$

## 2.4 Computation of the dissolution rate coefficient

To obtain more accurate estimates, as well as to determine the methane dissolution rate coefficient, we use the formulas from [17], [18]. Next, we present some information from the article [18] to the extent that will help the reader save some time spent on its understanding.

The gas flow  $F$  from water is determined by the difference in the gas concentrations in water  $C_w$  and in air  $C_a$ .

$$F = k(C_w - C_a) \quad (4)$$

The gas flow  $F$  is measured in  $(\text{mass area}^{-1} \cdot \text{time}^{-1})$ , the gas transition rate  $k$  is measured in  $(\text{length time}^{-1})$ , and the concentrations  $C_w$  and  $C_a$  of gas in water (more precisely, in the top water layer in direct contact with the atmosphere) and in the atmosphere are measured in  $(\text{mass volume}^{-1})$ . The gas transition rate depends on temperature, wind speed and water salinity.

The flow  $F$  of gas  $G$  can also be expressed in terms of the partial pressure difference:

$$F = \alpha(P_w^G - P_a^G) = kK_0(P_w^G - P_a^G) \quad (5)$$

where  $K_0$  is the gas solubility in water ( $\text{mass volume}^{-1} \cdot \text{pressure}^{-1}$ ),  $P_w^G$  and  $P_a^G$  are the partial pressures of the gas in equilibrium with the water surface and in the near-surface air layer respectively (pressure). It is this formula we need, since all the summer sample points contain partial pressures, but there are many points among them without concentrations measured.

In [17], [18], it was proposed to approximate the dependence of the gas transition rate on the wind speed by a quadratic function. This approximation is valid for the range of wind speeds of 3 - 15 m/s. It is also noted that winds of more than 15 m/s blow only 3-5% of the time, and winds less than 3m/s are similarly rare. The global average wind speed is 7.4 m/s.

The dependence of the gas transition rate on the wind speed is described by the formula

$$k = 0.251 \frac{U^2}{\sqrt{Sc/660}} \quad (6)$$

It is customary to measure  $k$  in cm/h.  $U$  is the average wind speed at 10m above the water (m/s),  $Sc$  is the dimensionless Schmidt number. So the units of measure for the coefficient 0.251 are cm / (h (m/s)<sup>2</sup>).

Thus

$$\alpha = 0.251 \frac{U^2}{\sqrt{Sc/660}} K_0 \quad (7)$$

Because the ratio  $\frac{K_0}{\sqrt{Sc/660}}$  is almost constant for CO<sub>2</sub>, the expression (7) in this case can be simplified for seawater to

$$\alpha_{\text{sea}}^{\text{CO}_2} = 7.7 \cdot 10^{-4} U^2 \quad (8)$$

where  $\alpha^{\text{CO}_2}$  is measured in mol / (m<sup>2</sup> year  $\mu\text{atm}$ )

Let us denote by  $\gamma$  the coefficient in the formula (7)

$$\gamma = \frac{\alpha}{U^2} = 0.251 \frac{K_0}{\sqrt{Sc/660}} \quad (9)$$

To compute  $\gamma$  the Schmidt number is calculated using the tables and formulas from [18] (the value of  $Sc$  depends on temperature and salinity). Table 1 presents some quantities used during the computation at different values of temperature and salinity of the water.

**Table 1.** Calculation of  $\alpha_{\text{CO}_2}$

Quantity	Fresh water			Seawater			
	t, °C	0	5	10	0	5	10
<b>Sc</b>		1923.6	1397.5	1032.1	2116.8	1542.9	1143.1
<b><math>\beta</math></b>		1.738	1.436	1.202	1.448	1.201	1.010
<b>K0</b>		0.0775	0.0641	0.0536	0.0646	0.0536	0.0451
<b><math>\gamma</math></b>		$9.99 \cdot 10^{-4}$	$9.68 \cdot 10^{-4}$	$9.43 \cdot 10^{-4}$	$7.93 \cdot 10^{-4}$	$7.70 \cdot 10^{-4}$	$7.53 \cdot 10^{-4}$

In a similar way to seawater, we take the value  $9.68 \cdot 10^{-4}$  at 5°C as the coefficient  $\gamma$  for fresh water. Let us compare the obtained coefficient with the estimate (3). The molar mass  $M_{\text{CO}_2} = 44.01$  g/mol.

$$K_{\alpha, 5^\circ\text{C}, \text{CO}_2} = \frac{\alpha}{U^2} \cdot M_{\text{CO}_2} = 9.68 \cdot 10^{-4} \left( \frac{\text{mol}}{\text{m}^2 \mu\text{atm year (m/c)}^2} \right) \cdot 44.01 \text{g/mol} =$$

$$9.68 \cdot 10^2 \cdot 44.01 / 365 \left( \frac{\text{g}}{\text{km}^2 \mu\text{atm day (m/c)}^2} \right) = 116.717 \left( \frac{\text{g}}{\text{km}^2 \mu\text{atm day (m/c)}^2} \right) \quad (10)$$

Hence, using the global average wind speed of 7.4 m/s, we get the estimate

$$\alpha_{\text{CO}_2}^1 = 6391 \text{ g}/(\text{km}^2 \cdot \mu\text{atm} \cdot \text{day}) \quad (11)$$

which is 10 times higher than the estimate (3).

On the other hand, if we take into account that for Irkutsk the average wind speed in summer and autumn is 2.0 m/s [19], then we obtain the estimate

$$\alpha_{\text{CO}_2}^2 = 467 \text{ g}/(\text{km}^2 \cdot \mu\text{atm} \cdot \text{day}) \quad (12)$$

which is much closer to the previous one. Later on we will use the same average wind speed for methane.

Note that at the average wind speed of 2.0 m/s, we use the formulas from [18] outside the range of wind speeds of 3–15 m/s, for which the approximation was suggested. In particular, at windless calm we get the value  $\alpha_{\text{CO}_2} = 0$ , which is clearly wrong. The true graph of the function describing this dependence should be a monotonic function, which takes at  $U = 0$  some positive value corresponding to the coefficient of dissolution rate in calm. Thus, the true graph should gradually shift higher than that used by us when the wind speed changes from 3 to 0 m/s. Therefore, we can assume that as a result we get a lower estimate for the dissolution rate coefficient, which is in good agreement with the objectives of this project.

**Table 2.** Calculation of  $\alpha_{\text{CH}_4}$

t, °C	0	5	10	15
<b>Sc</b>	1909.4	1399.7	1043.1	794.0
<b><math>\beta</math></b>	0.0574	0.0495	0.0434	0.0385
<b>K0</b>	0.00256	0.00221	0.00194	0.00172
<b><math>\gamma</math></b>	$3.31 \cdot 10^{-5}$	$3.34 \cdot 10^{-5}$	$3.39 \cdot 10^{-5}$	$3.45 \cdot 10^{-5}$

Now in the same way let us calculate  $\alpha_{CH_4}^2$  immediately for fresh water. Note that the rate of change of the value  $\gamma$  for methane does not differ too much from the rate of change of the similar value for  $CO_2$ , Therefore, as a first approximation its temperature dependence can also be neglected.

The molar mass of methane  $M_{CH_4} = 16.04$  g/mol.

$$K_{\alpha,5^\circ C,CH_4} = \frac{\alpha}{U^2} \cdot M_{CH_4} = 3.34 \cdot 10^{-5} \left( \frac{\text{mol}}{\text{m}^2 \mu\text{atm year (m/c)}^2} \right) \cdot 16.04 \text{g/mol} =$$

$$33.4 \cdot 16.04 / 365 \left( \frac{\text{g}}{\text{km}^2 \mu\text{atm day (m/c)}^2} \right) = 1.468 \left( \frac{\text{g}}{\text{km}^2 \mu\text{atm day (m/c)}^2} \right) \tag{13}$$

For the average wind speed of 2.0 m/s we get the estimate

$$\alpha_{CH_4}^2 = 5.87 \text{ g}/(\text{km}^2 \cdot \mu\text{atm} \cdot \text{day}) \tag{14}$$

## 2.4 Time interpolation

Further, between the moments of the expeditions we perform the linear interpolation in time of the calculated values for each of the zones. As a result we obtain the estimates that characterize the values of the greenhouse gas flows at each of the time points. Figure 3 and Figure 4 show the resulting graphs for the summer of 2017.

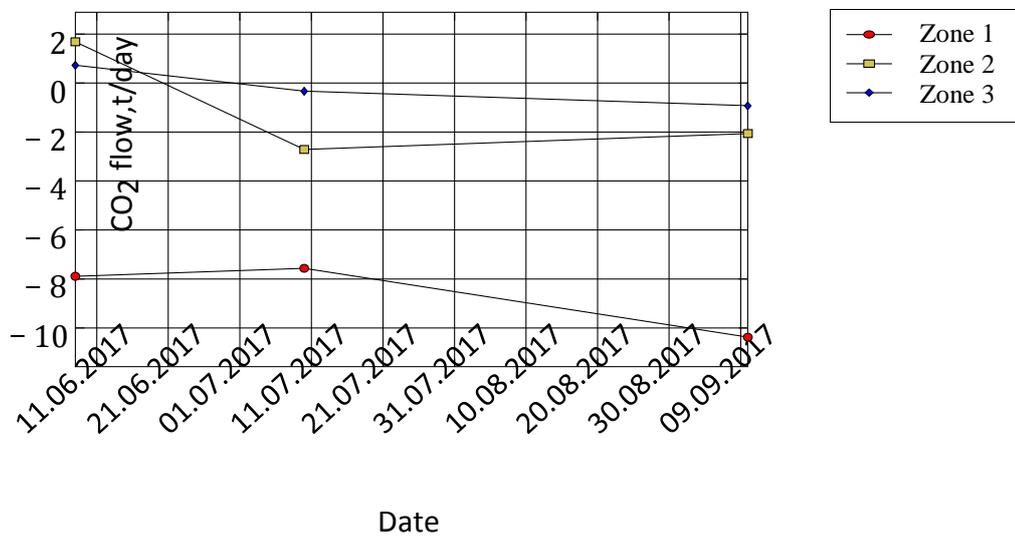


Figure 3: The graph of CO<sub>2</sub> absorption by the Irkutsk reservoir

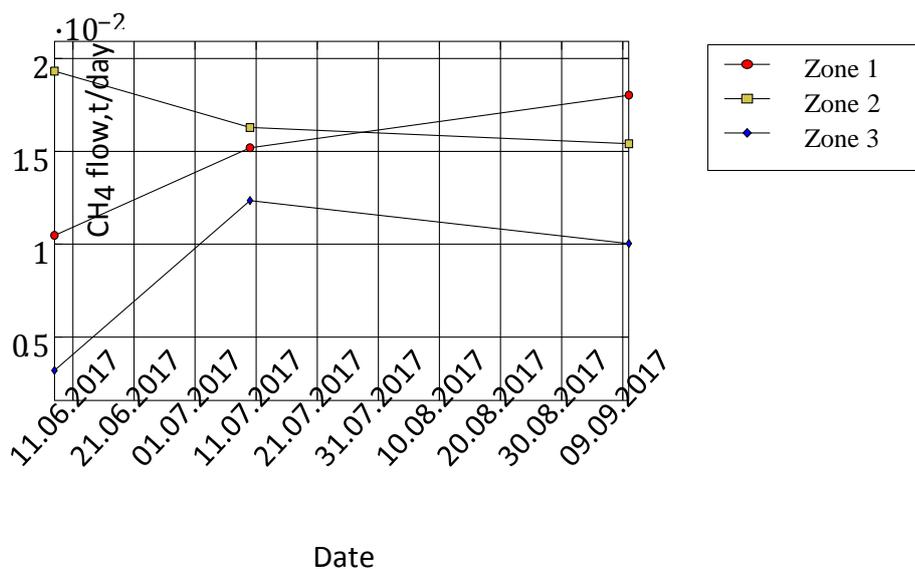


Figure 4: The graph of CH<sub>4</sub> emission by the Irkutsk reservoir

As a result of integration of the obtained interpolated estimates, we obtain summarized estimates of the gas exchange volumes for the whole observation period. At first, we have computed coarser estimates using just the

average wind speeds for the area in question. Then, using meteorological data of the weather stations closest to the Irkutsk reservoir, we have attempted to refine these estimates. Unfortunately, the available weather data refer to the weather stations located in the city of Irkutsk, which are rather far from the reservoir. Therefore, it is not necessarily the case that the improved results are closer to reality. Fortunately, both estimates are not too much different. Also note that the estimates obtained using specific meteorological data more closely reflect the situation for a particular season, and the estimates obtained using long-term average indicators for the territory should be somewhat closer to the average gas exchange estimates, although, of course, to obtain more accurate average estimates, it is necessary to regularly perform similar measurements.

### 3 Conclusion

As a result of the measurements performed at the Irkutsk reservoir and their analysis, the following estimates were obtained.

Using the average wind speed in the area we have computed that during the observation period, which was 94 days long, 1002 tons of CO<sub>2</sub> were absorbed through the surface of the Irkutsk reservoir and 3.116 tons of CH<sub>4</sub> were emitted.

And using the wind speed information from the Irkutsk weather station these estimates slightly change to the absorption of 936 tons of CO<sub>2</sub> (-7%) and the emission of 3.679 tons of CH<sub>4</sub> (+ 18%).

However, if we'll use the information about the average square of wind speed over the Irkutsk reservoir of the actual observations obtained during the expeditions, then the initial estimates will go up one-and-a-half times to absorption of 1,500 tons of CO<sub>2</sub> and emission of 4.674 tons of CH<sub>4</sub>.

Thus, the proposed method for processing measurements allowed us to estimate the actual volumes of gas exchange through the surface of the Irkutsk reservoir. Despite the relatively large area of the reservoir, these volumes turn out to be quite small. They are by several orders of magnitude less than the volumes of the dissolved in the water gases entering the reservoir from Baikal and leaving the reservoir into the lower pool of the Irkutsk Hydroelectric Power Station.

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