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Remote Estimation of Water Body Depth Based on the Date of the Beginning of Ice Formation Using a Hydrophysical Model

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Abstract

The aim of the study is to develop a methodology for estimating the average lake depth based on remote sensing data of ice conditions using methods of modelling thermohydrodynamic processes in a freezing water body. The primary tool for accomplishing this goal is the FLake — lake hydrophysical model. Using meteorological data from the ERA5 reanalysis for the coordinates of the selected water body, the model calculates the time of ice formation on the water body at different values of its average depth. Based on remote sensing data, the date or time interval of water body freezing estimated. If data for several years are available, the depth of the water body specified by averaging the values for each year. At discreteness of satellite images with an interval of several days, the range of average lake depths corresponding to the time interval between satellite passes over the water body is determined. Information on the onset of ice phenomena was obtained based on the results of thematic interpretation of Sentinel-2, Landsat-7, 8, 9 satellite images for the period from 2016 to 2023. The methodology tested on four groups of morphometrically- studied lakes located in permafrost zone of Eastern Siberia in the Republic of Buryatia and Transbaikal Territory. The results of approbation showed a satisfactory correspondence between the calculated and measured values of the average depth of the lakes under consideration. The quality and quantity of satellite images in the study region limited the accuracy of the proposed methodology. The prospects of the methodology lie in the possibility of fully remote assessment of water resources of poorly studied regions of the country.

Keywords: lake hydrophysical model, satellite imagery, reanalysis, mean depth, ice formation

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Дистанционная оценка глубины водоемов по дате начала ледостава с использованием гидрофизической модели

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Аннотация

Цель исследования — разработка методики оценки средней глубины озера на основе дистанционной информации о ледовых условиях с использованием методов моделирования термогидродинамических процессов в замерзающем водоеме. Основным инструментом достижения поставленной цели является гидрофизиче-

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ская модель озера FLake. С использованием модели и метеоданных реанализа семейства ERA5 для координат выбранной точки расположения объекта рассчитывается время ледостава на водоеме при различных значениях его средней глубины. По данным дистанционного зондирования Земли оценивается дата или интервал времени замерзания акватории водоема. При наличии данных за несколько лет, глубина водоема уточняется осреднением значений для каждого года. При дискретности спутниковых снимков с интервалом в несколько суток определяется диапазон средних глубин озера, соответствующий промежутку времени между пролетами спутника над водоемом. Информация о начале ледовых явлений — результаты тематического дешифрирования спутниковых снимков Sentinel-2, Landsat-7, 8, 9 за период с 2016 по 2023 годы. Методика апробирована на четырех группах морфометрически исследованных озер на многолетнемерзлых почвах Восточной Сибири в Республике Бурятия и Забайкальском крае. Результаты апробации показали удовлетворительное соответствие рассчитанных и измеренных значений средней глубины рассматриваемых озер. Точность предложенной методики ограничена качеством и количеством спутниковых снимков в регионе исследований. Перспективы методики заключаются в возможности полностью дистанционной оценки водных ресурсов малоизученных регионов страны.

Ключевые слова: гидрофизическая модель озера, спутниковая съемка, реанализ, средняя глубина, ледостав

1. Introduction

Modern satellite imagery reveals approximately 3.8 million natural water bodies across the Russian Federation, of which around 3.3 million (~88 % of the total number in the country) are located in regions underlain by permafrost [1]. Water bodies of these territories belong to the category of poorly studied due to their inaccessibility and impossibility to perform regular contact measurements of morphometric, thermohydrodynamic and other characteristics.

Average lake depth is an important morphometric parameter of a water body. Determination of average lake depths is necessary for calculation of water level and its fluctuations during the year, which is important for forecasting floods, high waters, droughts and other natural phenomena affecting water management. Although water body measurements works are important for determining the shape of a water body bed, the volume of water it contains, and other hydrologic studies, they do not allow for rapid estimation of average depths for many water bodies.

The choice of method for determining the average depth of a lake depends on the available data, the objectives of the study, and the characteristics of the lake itself. Bathymetric methods are preferred for precise calculations, while empirical formulas or approximation relationships can be used for preliminary estimates.

Geostatistical methods, methods of approximation of the lake basin shape, satellite methods and hydrodynamic modeling are the most frequently used methods for determining the depths of water bodies. The choice of depth determination methods depends on the objectives, available data and technological capabilities.

To determine the average depths of groups of identical lakes, geostatistical methods are mainly used, the essence of which is to reveal statistical dependencies between the average depth and other morphometric parameters of the lake basin [2–5]. This method is reasonable to apply if there is a sufficient sample of morphometrically studied lakes. Such samples are formed on the basis of various assumptions about geographical location of lakes, their belonging to different natural zones and common genetic origin.

The methods of approximation of the lake basin shape consists in determining the linear dimensions of the lake (usually length and width) with the subsequent assumption that the basin can be approximated by a paraboloid, ellipse, cone, and other figures [6, 7]. It is clear that such a method is of little use for irregularly shaped lakes with strongly indented shorelines.

Satellite-based methods for depth determination include various approaches, among which we can distinguish methods based on obtaining data on the bottom topography and water level measured with an altimeter (e. g., ERS-2, EnviSat, TOPEX, Jason-1 and Jason-2), as well as combined methods using optical sensors such as Landsat or Sentinel, which are used to estimate water transparency and color, which are indirectly related to depth [8, 9].

Hydrodynamic modeling methods for determining the depths of water bodies can use various relationships of water body depth with thermodynamic characteristics, wind waves, relocation of bottom sediments, etc. [10]. Various combinations of the above-described methods are also used. The combination of such methods as satellite data and hydrodynamic modeling expands the possibilities for studying lake morphometry.

In order to overcome difficulties in studying numerous hard-to-reach lakes in the northern territories of our country, the Institute of Limnology of the Russian Academy of Sciences is developing methods of remote assessment of characteristics of unstudied lakes in the northern territories of the Russian Federation using satellite information and mathematical modeling.

2. Study Region

The objects of the study are four groups of morphometrically studied lakes located in permafrost zone in the taiga natural zone of Eastern Siberia in the Republic of Buryatia and the Transbaikal Territory. These include: 1) Eravninsk Lakes [11, 12], 2) lakes of the Amut Basin [12–14], 3) Ivan-Arakhley Lakes [15], 4) Kuando-Chara Lakes [16], 5) as well as the separately located Lake Baunt, which was used to work out the methodology. (Fig. 1, Table 1).

The lakes are located in the zone of continental and sharply (harsh) continental climate and are characterized by a significant number of clear days, which facilitates thematic interpretation of satellite images.

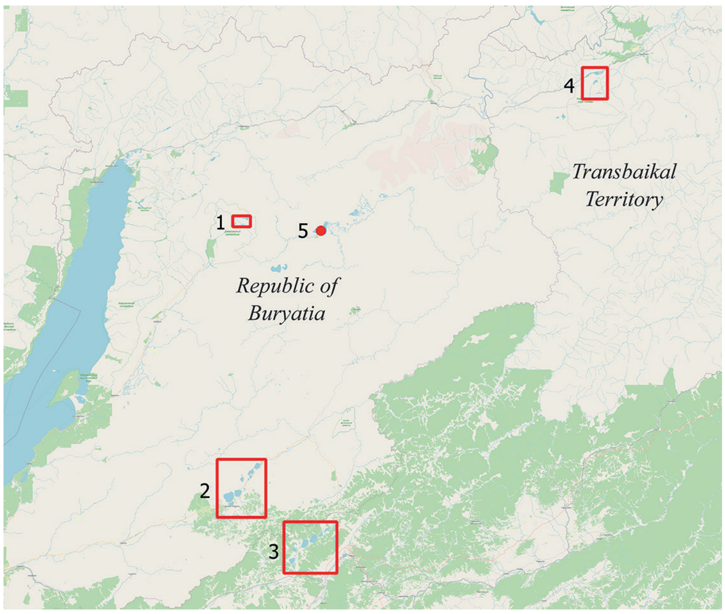

Fig. 1. Study lake groups: 1 — lakes of the Amut basin; 2 — Eravninsk lakes; 3 — Ivano-Arakhleysk lakes; 4 — Kuando-Char lakes; 5 — Lake Baunt

Table 1

Main morphometric characteristics of the studied lakes. Surface area (S, km²); maximum depth (H_{max}, m); average depth (H_{avg}, m); maximum length (L, km); maximum width (B, km)

Lake	S, km^2	H_{max}, m	H_{avg}, m	L, km	B, km
Lake Baunt	111	33	17	16.3	9
Eravna Lakes (Eravna-Khorga system)					
Sosnovoe	22.7	5.10	2.8	7.8	4.5
Bolshoye Eravnoe	104	5.7	3.5	14	13
Maloye Eravnoe	56.2	2.5–3.5	1.8	9.7	8.4
Arshan (Angirta)	1.24	–	1.5	1.4	1
Gunda	16.8	5	3.5	4.5	3
Malaya Khorga	7.4	2.4	1.4	3	3
Bolshaya Khorga	29.5	2	1.5	8.5	4.5

Fin table 1

Lake	S, km^2	H_{max}, m	H_{avg}, m	L, km	B, km
Isinga	32.98	4.6	2.7	7.2	5.9
Shchuchye	3.1	9	5.3	2.37	1.97
Lakes of the Amut Basin (Upper Barguzin River, Dzherginsky Nature Reserve)					
Amut	10.7	70	10–15	6.8	3.5
Yakondykon	1.16	21	5–10	1.2	0.7
Balan-Tamur	0.95	16	2	2.3	1.1
Malan-Zurkhen	2.62	15	5–7	3	1.2
Churikto	0.56	14	2	0.3	0.25
Ivano-Arakhley Lakes (Beklemishev or Chita Lake Group)					
Irgen’	33.2	3.1	1.8	8	4.2
Bolshoy Undugun	11.6	2.2	2.1	5	2.3
Shakshinskoye	51.8	4.5	4.4	11	4.8
Arakhley	58.2	17	10.4	11	5.3
Ivan	15.2	4.4	3.1	7.1	2.1
Tasey	14.5	3.1	2.1	8.1	1.8
Kuanda-Chara Lakes					
Bolshoye Leprindo	18.15	65	25	11.5	2.8
Maloye Leprindo	6.05	67	30	7	1.5
Leprindokan	12.1	32	8.6	7	3.3
Dovochan	4.9	48.5	33.3	5.5	1.2

The lakes of the Amut Depression (55°11′10.7″N, 113°00′54.7″E) are located in the upper part of the Barguzin basin in the zone of the Ikat and Barguzin ridges junction at an absolute altitude of 1200 to 1400 m. The sharply continental climatic conditions of Transbaikalia in the Amut Depression become even more severe due to the altitude difference. The average air temperature of the coldest month (January) is –26 °C, while the warmest summer month (July) is +11 °C. Such climatic conditions lead to widespread permafrost [17]. The lakes of the Amut Basin are covered with ice for 8 to 9 months a year — the ice breaks up in mid-June [13]. The beginning of freeze-up for this group of lakes occurs in mid- to late October [18]. The climatic conditions in the area of Lake Baunt (55°11′32.2″N, 113°00′24.3″E) are similar.

The Eravninsky Lakes (Eravno-Khargins Lake System) (52°46′20.8″N, 111°42′43.9″E) are located on the watersheds of the Vitim River (Lena River basin) and the Uda River (Lake Baikal basin) in the Eravninsky Depression, located between the spurs of the Zusy Ridge. The climate of the region is sharply continental. January temperatures are 35 to –40 °C, July temperatures rise to 25–28 °C, permafrost is widespread, the lower boundary of which is at a depth of 100–250 m, with an average thickness of the active layer of about 2 m [19]. Lakes freeze over mainly in the second half of October, and ice breaks up in the first half of May [20].

The lakes of the Ivano-Arakhley group (52°09′36.0″N, 112°43′22.0″E) are located in the intermountain Beklemishevskaya Depression at an absolute altitude of about 950 m at the junction of the drainage basins of the Lena and Yenisei rivers. Due to the mountainous relief, the climate of the depression is moderately humid, with an average annual air temperature of –3.2 °C [21, 22]. The first ice phenomena on the lakes of the Ivano-Arakhley group begin in October, with ice forming first on Lake Shakshinskoye and last on Lake Arakhley. The average freeze-up duration on this lake system is 185 to 226 days [23].

The Kuanda-Chara Lakes (Bolshoye and Maloye Leprindo, Leprindokan, Dovochan lakes) (56°33′10.1″N, 117°28′50.3″E) are located on the watershed of the Kuanda and Chara rivers in the Verkhnecharskaya Basin in the foothills of the Kodar Ridge at an absolute altitude of about 1000 m [24]. The average annual air temperature of the Verkhnecharskaya Depression fluctuates between 3.4 to –8.0 °C. The coldest month is January (from –25.8 to –33.8 °C), the warmest is July (from 14.7 to 16.3 °C). Negative temperatures are observed for 7–8 months of the year. Autumn comes quickly, frosts begin at relatively high average daily temperatures in early September. The stable transition of temperature through 0 °C is observed in spring at the beginning of May, and in autumn — in the twenties of September. The ice regime of the Kuanda-Chara Lakes is formed in conditions of a sharply continental climate with a protracted cold winter. Due to the features of the relief, the diversity of climatic, soil-geological and permafrost conditions, with vertical zonality, such features of the ice regime as ice floes, polynyas and freezing are often observed on the rivers. The formation of ice on the lakes begins in early October. Stable ice cover is usually established in the second or third decade of October. The freeze-up duration is approximately 215 to 250 days. The ice-break on reservoirs occurs in April, and the complete melting of ice occurs in May or June [16].

3. Description of the One-Dimensional Hydrophysical Model

The basis of the developed methodology for finding the average depth of a water body is the hydrophysical model of lake FLake, developed jointly by the Institute of Limnology of the Russian Academy of Sciences, the Northern Water Problems Institute of the Russian Academy of Sciences, the Institute of Freshwater Ecology and Inland Fisheries (IGB, Germany)) and the German Weather Service (DWD) [25–27]. FLake[1] is a universal parameterized one-dimensional mathematical model of thermodynamics (THD) processes in the lake, which implements the results of research obtained during many years of field and laboratory studies carried out at the Limnological Station of the Institute of Limnology RAS, as well as the latest world achievements in the field of physical limnology.

Currently, FLake serves as a basic tool for developing models of aquatic ecosystems functioning and water quality formation in natural and artificial reservoirs, and is used as a training manual in environment and hydrometeorological education. As an accounting technique of the influence of lakes on the formation of local climatic conditions, it is widely implemented in the practice of numerical weather forecasting in meteorological organizations of different countries and the International European Centre for Medium-Range Weather Forecasts (ECMWF) [28].

In addition, the COSMO[2] forecasting system, which is widespread in the world (also used for making weather forecasts throughout the Russian Federation), includes FLake as a means of assessing the impact of freshwater lakes on local climate around the world. It follows that the model *a priori* can be applied for unexplored small and medium-sized reservoirs of lake regions considered in this work.

The model reproduces seasonal dynamics of the vertical temperature distribution in the snow — ice — water column — bottom sediments system (Fig. 2).

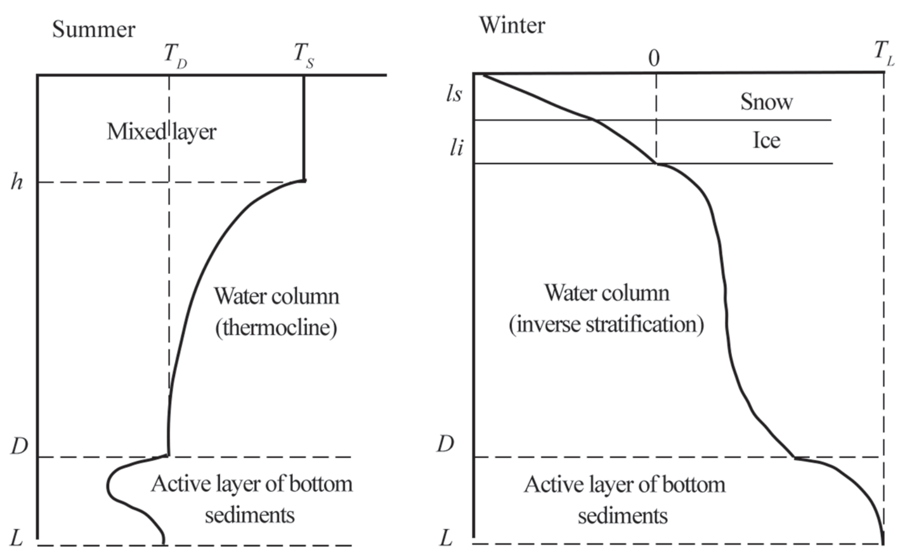

Fig. 2. Scheme of the vertical profile of temperature (T) in the system snow — ice — water mass — bottom sediments, realised in the FLake model

[1] FLake one-dimensional thermodynamic lake model. URL: https://www.lakemodel.net (accessed 15 March 2024).
[2] COSMO weather forecasting system, Roshydromet. Available at: https://www.meteorf.gov.ru/product/cosmo/ (accessed 15 March 2024).

According to Fig. 2, the lake in the model has a three-layer structure. During the open water period ("Summer"), the upper mixed layer (UML) with thickness h is on top. Due to the constantly present wind/convective mixing, the mixed layer has the same temperature T_s throughout the depth. Below the UML there is a thermocline zone of thickness $D\text{-}h$. In the thermocline, the water temperature decreases to T_D — the water temperature at the water-bottom interface. At the same time, the water mass of the lake has stable density stratification, which prevents the penetration of mixing and, correspondingly, heat into the bottom zone.

The water mass of the lake borders the thermally active layer of bottom sediments, the thickness of which $L{-}D$ is determined by the presence of seasonal temperature fluctuations in it. Usually, the lower boundary of the active layer of bottom sediments is taken as the depth at which the intra-annual temperature fluctuations do not exceed 10 % of the variability of the- near bottom temperature T_D. Since seasonal temperature fluctuations at this depth are considered negligible, the temperature at the lower boundary of the active layer T_L is assumed to be constant. The thickness of the layer itself in lakes of temperate latitudes varies in the range of 3–5 m.

From the moment of ice formation ("Winter"), the model calculates the temporal dynamics of ice thickness *li* and snow cover *ls* on it, as well as the vertical profile of temperature in both snow and ice. During the winter period, the temperature at the ice-water boundary is equal to the water freezing point — 0 °C. The water mass of the lake in winter, unlike in summer, has inverse temperature stratification, i. e., the water temperature increases with depth. Due to the fact that cooling of the lake occurs due to its interaction with the atmosphere, i. e., from above, the bottom sediments are warmer than the overlying water mass in winter. This causes the so-called "under ice warming" effect, when the redistribution of heat between warm bottom sediments and the cold-water mass takes place. This results in a constant slow increase in the temperature of the water mass throughout the winter period.

The model is based on the solution of the one-dimensional non-stationary heat conduction equation in both water mass and bottom sediments. At the same time, vertical profiles are described by self-similar representations in both media, which allows avoiding the calculation/setting of turbulent/molecular exchange coefficients and reducing the system of equations to ordinary differential equations. The latter makes the model highly efficient in terms of computational time.

The main peculiarity of the model application to lakes located in permafrost zones is that the thermally active layer of bottom sediments is the so-called seasonal thawing layer (STL), which is not a constant value and experiences pronounced seasonal fluctuations. In the period of summer warming, it increases due to heat input from the atmosphere through the water mass, while in winter the STL degrades due to heat transfer to the water. Thus, the value of L (Fig. 2) becomes an additional variable of the model. In the course of this work, the FLake model was supplemented with an equation for calculating the thickness of the thermally active layer of bottom sediments, in this case the thickness of the STL [29].

Despite the model's extensive capabilities and versatility, the water bodies to which the model is applied must meet the following conditions:

– the extent should not be so large as to generate significant climatic differences between separate parts of the water area (a consequence of the one-dimensional nature of the model) and not so small that secondary wind effects, such as friction of moving water against the shoreline or seiches, play a very significant role in the vertical mixing of the bulk of the water body;

– the bottom should be more or less flat and horizontal so that it can be approximated by a horizontal plane. This limitation of the model applicability is caused by the necessity to exclude from consideration the presence of slope baroclinic currents that can lead to the formation of bottom boundary layers, which the model is unable to reproduce due to the self-similar representation of the temperature profile;

– advective processes should not contribute significantly to turbulent mixing. In other words, there should be no constant currents in the water body that can make a significant contribution to wind mixing.

4. Model Forcing and Input Data

To represent atmospheric forcing in the simulation of thermohydrodynamic (THD) processes in lakes, we used data from the ERA5 family of meteorological reanalyses. ERA5 provides reconstructed time series of meteorological parameters globally, updated daily with a latency of approximately five days. As the fifth-generation global climate and weather reanalysis product, ERA5 offers hourly estimates of numerous atmospheric, ocean wave, and land-surface parameters dating back to 1940. The temporal resolution of the data used in this study is 6 hours, with a spatial resolution of 0.25° in both latitude and longitude. Data are extracted by geographic coordinates of the target location. To facilitate a range of climate applications, ERA5 also provides monthly means of key hydro-meteorological parameters.

To determine the onset of ice phenomena for the lake groups under study, we employed satellite imagery from Sentinel-2, Landsat-7 (ETM+), Landsat-8 (OLI), and Landsat-9 (OLI-2) for the period 2016–2023. A script was written on the Google Earth Engine (GEE) geospatial data processing platform [30] to automatically determine the presence of ice on the studied objects for a multi-year period. The script execution algorithm is summarized in the following steps:

– inputs are the coordinates of the analyzed area and the time interval under study;

– the Dynamic World V1 dataset [31] is filtered by time interval and coordinates;

– a band is selected from the data set, which is responsible for a certain class of the underlying surface. For the objectives of the present study, these are snow and ice;

– a time series is generated, showing the change in the probability of the underlying surface class for a given coordinates and time period.

This time series analysis allowed us to identify time intervals in different years of the beginning of ice phenomena on the lake water surface area. Expert analysis of satellite images was performed on the basis of snow and ice detection by Normalized Difference Snow Index (NDSI) [32], as well as in different combinations of satellite image channels. For the most reliable recognition of snow and ice on the water surface of lakes, combinations of channels in the near and middle infrared and in one of the visible parts of the spectrum (blue and red) were used [33, 34].

5. Method for Estimating Mean Lake Depths

The proposed methodology for determining the average depth of a lake using remote information on ice formation dynamics is based on the assertion that the freezing rate of a lake is an objective indicator of the volume of water mass in a water body, i. e., actually its average depth at a fixed water area. The main stages of average depth calculations are as follows:

1. Geographical coordinates of the water body location point are determined.

2. Using the FLake model and reanalysis meteorological data for the coordinates of the selected object, a series of calculations of the freeze up date of the water body at different values of its average depth are performed. A functional dependence of the average depth (H) on the date of ice freezes up start (t) defines as $H = f(t)$ for each year.

3. Using remote sensing data or some other method, the date or time interval of freezing of start of the water body is estimated.

4. If the date of ice formation on the lake can be determined with the accuracy up to a day, then according to the dependence $H = f(t)$ for a particular year, the value of its average depth (H_{FLake}) is calculated (Fig. 3). If data for several years are available, the depth of the reservoir is specified by averaging the values for each year.

5. At discreteness of satellite images with an interval of several days, it is possible to determine only the range of average lake depths corresponding to the time interval between satellite passes over the water body where the ice cover appeared. To truncate this interval, data for several years can be used. The final interval of possible dates of ice cover onset is the truncation of all intervals obtained for several years. In this case, the average lake depth is determined by the middle of the truncated interval.

6. The applicability of the methodology is limited not only by the horizontal dimensions of the water body (see above), but also depends on the depth of the water body. The results of additional calculations for depths up to 1000 m (the average depth of Lake Baikal is ~750 m) showed that approximately from a depth of 200 m the freezing date ceases to depend on the water body depth — after monotonic growth in the depth range 0–200 m the curve of dependence tends to asymptotic (Fig. 3).

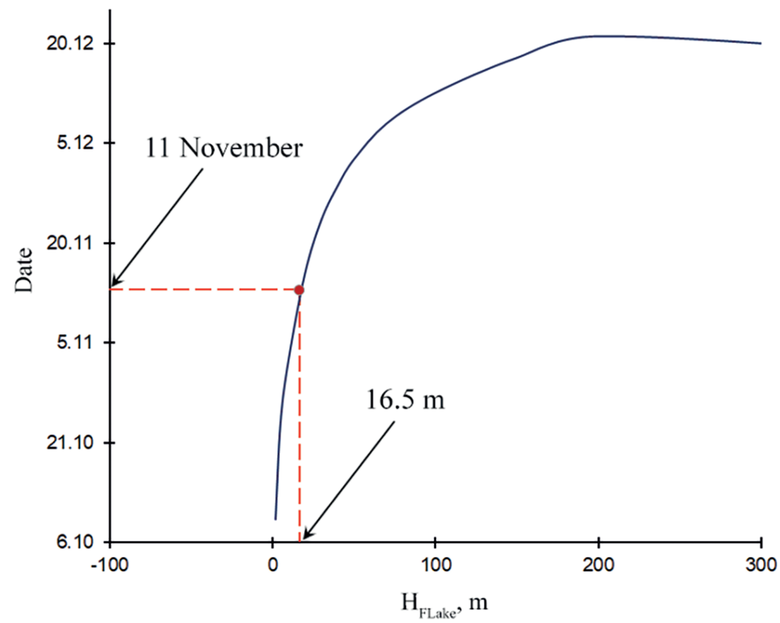

Fig. 3. Determination of average lake depth by established date of ice cover formation using Lake Baunt as an example in 2018

6. Results and Discussion

It is obvious that the accuracy of the average depth estimation using the above methodology increases with more frequent satellite imagery of the lake water area and, accordingly, the moment of ice formation onset is estimated more accurately. Hence, there is a limitation on the frequency of satellite images — during the time interval between two consecutive satellite overflights over a water body, ice formation should start.

Fig. 4 illustrates the performance of the methodology when combining the calculated intervals of the average depth estimation of Lake Arakhley (52°12′25.2″ N, 112°52′50.7″ E) from satellite images for 2018 and 2020.

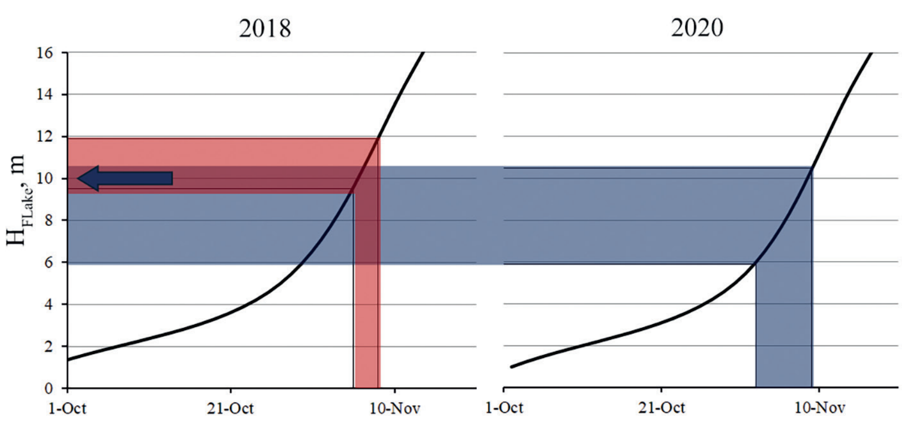

Fig. 4. Graphical representation of the determination of the intervals of values of the average depth of Lake Arakhlei by the interval of freezing dates in 2018 and 2020 determined from satellite images

In 2018, two consecutive satellite images of Lake Arakhley, one of which showed the water surface and the other of which showed the ice formation, took place on November 5 and 8. Thus, we can say that ice formation on the reservoir began in the specified date interval. In this case, in accordance with the curve $H = f(t)$ calculated by the FLake model, the lake depth value is in the interval from 9.5 to 11.9 m (Fig. 3). Similarly, in 2020 we can determine the time interval of ice cover formation from November 2 to 9, which corresponds to the depth range of 5.9–10.9 m. The truncated range of the average depth of Lake Arakhley is found as the intersection of the ranges obtained for all years, and it is 9.5–10.9 m. Accordingly, the calculated depth of the lake is determined as an average and is equal to 10.2 m. At the same time, the measured value of the average lake depth is 10.4 m. Table 2 and Fig. 5 presents the results of comparing the depths of the studied lakes calculated by the FLake model and bathymetric surveys.

Table 2

Comparison of average lake depths derived from the FLake model (H_{FLake}, m) and from in situ bathymetric measurements (H_{avg}, m) for the studied lakes

Lake	H_{avg}, m	H_{FLake}, m	Δ, m	δ,%
Baunt	17.0	16.5	0.5	2.9
Ivano-Arakhley Lakes				
Irgen’	1.8	2.0	–0.2	–11.1
Bolshoy Undugun	2.1	2.0	0.1	4.8
Shakshinskoye	4.4	5.0	–0.6	–13.6
Arakhley	10.4	10	0.4	3.8
Ivan	3.1	3.5	–0.4	–12.9
Tasey	2.1	2.0	0.1	4.8
Kuanda-Chara Lakes				
Bolshoye Leprind	25.0	23.0	2.0	8.0
Maloye Leprindo	30.0	28.0	2.0	6.7
Leprindokan	8.6	8.0	0.6	7.0
Dovochan	33.0	30.0	3.0	9.1
Eravna Lakes				
Sosnovo	2.8	3.0	–0.2	–7.1
Bolshoye Yeravnoe	3.5	4.0	–0.5	–14.3
Maloye Yeravnoe	1.8	2.0	–0.2	–11.1
Arshan (Angirta)	1.5	1.5	0.0	0.0
Gunda	3.5	4.0	–0.5	–14.3
Malaya Khorga	1.4	1.0	0.4	28.6
Bolshaya Khorga	1.5	1.5	0.0	0.0
Isinga	2.7	3.0	–0.3	–11.1
Shchuchye	5.3	6.0	–0.7	–13.2
Lakes of the Amut Basin				
Amut	12	14.0	–2.0	–16.7
Yakondykon	7.0	6.5	0.5	7.1
Balan-Tamur	2.0	2.0	0.0	0.0
Zurkhen	6.0	5.5	0.5	8.3
Churikto	2.0	2.0	0.0	0.0

Note: Δ denotes the absolute error; δ denotes the relative error.

Based on the results obtained, it can be concluded that there is a satisfactory correspondence between the data on the average depth obtained during depth measurements of the reservoir and those calculated by the FLake model. Average absolute error of calculations is 0.65 m, average relative error is 9.0 %. Small discrepancies between calculated and measured values of average depth (up to 5 %) are explained by the fact that freezing of some water areas may occur unevenly during several days. Thus, the conditions of applicability of the one-dimensional model for the whole lake are violated.

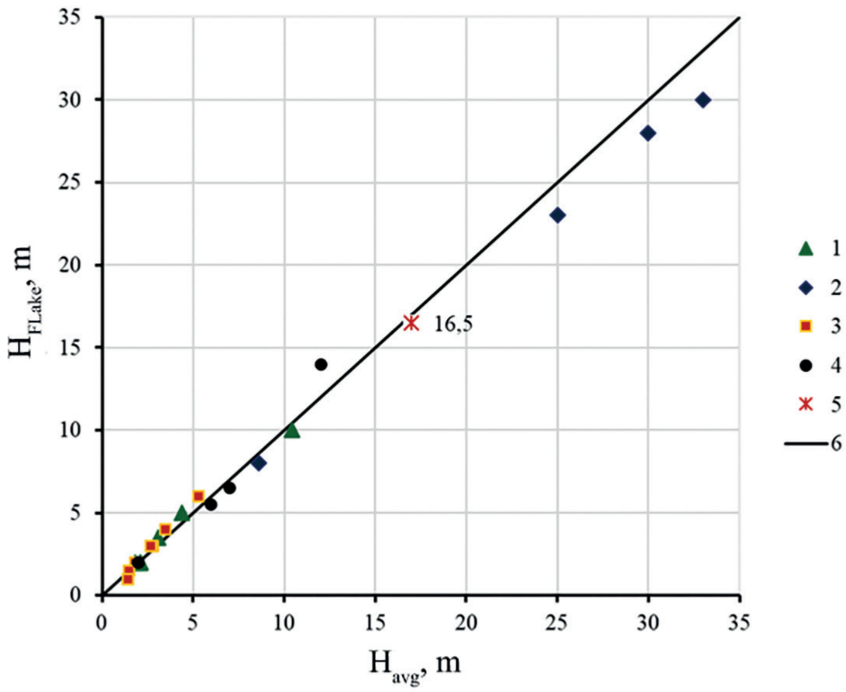

Fig. 5. Comparison of mean lake depths calculated using the FLake model (H_{FLake}, m) and obtained from in situ measurements (H_{avg}, m).Lake groups are indicated by different symbols: 1 — Ivano-Arakhley group, 2 — Kuanda-Chara group, 3 — Yeravna group, 4 — Amut Basin, 5 — Lake Baunt; line 6 represents the 1:1 reference (ideal agreement) line

7. Conclusion

The study confirmed the prospects for further development of the methodology for estimating the average lake depth based on remote information on the dynamics of ice formation using methods of modeling THD processes in a freezing water body. One of the promising directions of using the developed methodology is a fully remote assessment of water resources and their temporal dynamics for hard–to–reach or vast territories. The present methodology can be improved by including other thermal characteristics of water bodies that can be determined from satellite data, for example, surface temperature. This will allow using the developed methodology for determining average depths not only for northern freezing lakes, but also for regions with positive mean annual temperatures.

The accuracy of the proposed methodology is limited by the quality and quantity of satellite images. In particular, in case of high cloudiness in the study region, it is impossible to separate ice and clouds with sufficient accuracy during image processing. Also, breakdowns of satellite sensors often occur. Obviously, such satellite images are unsuitable for determining ice phenomena on water bodies. In order to improve the accuracy of determining the date of ice formation start, it is necessary to increase the frequency of imaging of the study region on the approximate dates of ice formation, as well as to extend the period of all observations.

Application of the methodology has a number of other limitations both in terms of applicability of the one-dimensional model and in terms of the depth of the water bodies under consideration. In particular, the FLake model, due to its one-dimensional nature, cannot be applied to water bodies within which spatial climatic variability of hydrophysical characteristics may exist. In addition, as it was shown in the course of this work, from a certain depth (~ 200 m; see Fig. 3), the freezing date of a water body ceases to depend on its depth, and the application of the methodology loses its meaning.

The prospects for practical use of the developed methodology are in the possibility of fully remote assessment of slowly renewable water resources in various natural zones of our country with a large number of unexplored and understudied water bodies. Also, the undoubted advantage of the developed method of determining the average depths of small and medium-sized lakes is its low cost compared to modern equipment for bathymetric survey.

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