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A CANOPUS-V IMAGERY-BASED STUDY OF THE SIZE-DISTRIBUTION OF SMALL LAKES IN THE DISCONTINUOUS PERMAFROST ZONE OF WESTERN SIBERIA

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The paper presents the results of the remote sensing studies of size- distribution of small thermokarst lakes using Canopus-V satellite images with high spatial resolution (2 m) obtained during the summer months of 2013–2014. In this research, a total of 18 test sites have been investigated within the area of discontinuous permafrost in Western Siberia. Results of the interpretation of satellite images allowed to determine the number of lakes, their areas, and limnicity of the surface area for each test site. It has been determined that the size-distribution of small thermokarst lakes within the study area corresponds to a power law.

Permafrost, satellite imagery, climate changes, emission of methane, small thermokarst lakes, Western Siberia

INTRODUCTION

Current climate warming in northern latitudes of our planet promotes the deepening of the seasonal thaw of surface soil, which compromises the underlying permafrost strength and causes damages to infrastructure. Moreover, permafrost, serving as a carbon sink in the vast frozen peat bogs of Northern Eurasia and in some parts of North America, is capable to give an additional impetus to climate warming, once emissions of greenhouse gases take off [*Zimov et al., 1997*].

Carbon dioxide and methane are the main components of greenhouse gases. The former is commonly known to contribute a greater half to the overall greenhouse phenomenon, while methane despite its concentration in the atmosphere being much lower, inherently bears higher potential to amplify global warming, due to its multiplying effect on carbon dioxide [*Karol, 1996*].

Bogs and wetland landscapes, thermokarst lake plains, deepwater methane hydrate deposits occurring on the shallow continental shelves and in large bodies of water in the permafrost zone are considered to be major natural sources of carbon dioxide and methane emissions in northern regions [*Walter et al., 2007; Bastviken et al., 2008; Juutinen et al., 2009; Sabrekov et al., 2014*]. According to [*Zhiliba et al., 2011*], a quarter of the world's natural methane is stored in Western Siberia whose area abounds in numerous lakes of different size and age, which form these unique thaw lakes- and bogs-dominated landscapes. Despite the fact that lakes make up only a small fraction of the earth's surface, lake ecosystems represent areas of intense biogeochemical activity and act therefore as a potent source of methane emissions into the atmosphere.

After [*Pokrovsky et al., 2011; Shirokova et al., 2013*], small thermokarst lakes with an area of less than 0.05–0.1 ha appear the most active sources of methane emissions in the permafrost-affected areas. However, because of their small size such lakes are generally disregarded in the predictive estimates of methane contribution to the total greenhouse gas emissions. In the context of changing climate, obtaining well-grounded forecasts for dynamics of methane emissions from small thermokarst lakes in the permafrost zone is a topical issue, and its solution should be based on the analysis of experimental data on size distribution of thermokarst lakes. Given that much of northern West Siberia is a difficult-to-access area represented for the most part by permafrost-affected swampy and tundra landscapes, obtaining such data would be problematic, but for remote sensing approaches (aerial photography and current satellite data).

Among recent remote surveys of areas dotted with thermokarst lakes in the permafrost zones, the applications of predominantly medium resolution Landsat images are most common. However, they do not allow decoding and reliably assessing areas of lakes with areas less than 0.5–1 ha. Accordingly, this work focuses on the study the small-size distribution of thermokarst lakes in the areas of discontinuous permafrost of Western Siberia, using high-resolution Canopus-V imagery.

ANALYSIS OF REMOTE SENSING STUDIES OF LAKE SIZE DISTRIBUTION

Numerous attempts have thus far been made to study the number and spatial distribution of lakes at the global and regional levels. The data resulted from these studies are necessary in assessing the amount of methane emissions. Quite many research works [*Lehner and Doll, 2004; Downing and Prairie, 2006; Seekell and Pace, 2011; Verpoorter et al., 2014*] are dedicated to the problems of quantification and size distribution of lakes on the global scale.

The widely used database of lakes and other water bodies for estimating methane emissions [*Lehner and Doll, 2004*] is based on cartographic materials and does not include lakes with an area >10 km^2. The considerations of water reservoirs of smaller size in statistical extrapolation of a power-law distribution of lakes revealed by this study, as shown in [*Downing and Prairie, 2006; Seekell and Pace, 2011*], may overestimate the number of lakes and, therefore, the amount of methane emissions. In recent years, different studies of the abundance and size-distribution of lakes have increasingly involved satellite imagery. The research by [*Verpoorter et al., 2014*] presents the results of studies of lake distribution performed with the use of medium resolution Landsat-7 satellite images obtained over the period of 1997–2003, suggesting that lake size distribution obeys a power law. These studies allowed the creation of a global database of water reservoirs of the Earth's surface that comprises all lakes with an area larger than 2000 m^2 (0.2 ha).

The total number of such lakes was estimated at 117 million, with a total water surface area of about $5{\cdot}10^6$ km^2, which accounts for 3.7 % of non-glaciated land area. Large and medium-sized lakes tend to dominate in terms of their total surface coverage. The number of relatively small lakes with an area of 0.2–1 ha makes up more than 80 % of their total number in the database, while their total coverage area reaches 0.25 million km^2, which is only 0.27 % of the overall lake surface coverage. However, the number of small lakes with areas less than 0.2 hectares, their total area and size-distribution have not yet been studied in great detail.

Earlier regional studies of thermokarst lakes in the permafrost-affected areas (in Alaska, Scandinavia and Siberia) aimed primarily at studying variations in their size [*Smith et al., 2005; Kirpotin et al., 2009; Kravtsova and Bystrova, 2009; Polishchuk et al., 2014*]. While remote sensing studies of the number and size-distribution of lakes on regional scale using medium resolution Landsat, Resource-O and other imagery are associated with the territory of Siberia [*Polishchuk V.Yu. and Polishchuk Y.M., 2013; Karlsson et al., 2014; Polishchuk V. and Polishchuk Y., 2014; Bryksina and Polishchuk, 2015*].

Only few research works have actually addressed the role and characteristics of small size lakes (<0.2–0.5 ha) on a regional scale, e.g. [*Grosse et al., 2008; Polishchuk et al., 2015a,b*]. Thus, [*Grosse et al., 2008*] analyzes research results from three sites in the continuous permafrost zone of Eastern Siberia using high (Spot-5) and ultra high spatial resolution (Ikonos-2) space images that allowed to identify small lakes with very small areas of 30 m^2 at two sites and one of 100 m^2 at the third site. Despite relatively small areas of the investigated sites (about 54 thousand hectares), these were found to count a fairly large number, a total of 29,361 lakes, most of which are small size lakes (0.02–0.05 ha).

The diagrams for lake number and size distribution for the three investigated test sites are presented in [*Grosse et al., 2008*]. In the authors' opinion, the lakes size-distribution diagrams can be described by a power-law distribution. However, the authors' inferences about the power-law distribution of lakes should be taken as tentative, given that these were derived from visual analysis of a few diagrams. Moreover, the test sites examined in [*Grosse et al., 2008*] were situated in the proximity to the coastal boundary of the Arctic Ocean, and therefore the results of these studies cannot fully comprehend patterns of lakes distribution in the vastly expanding permafrost-underlain area of Siberia.

A more consistent study of distributions of small lakes in the permafrost zone of Western Siberia using ultra-high resolution images was conducted by [*Polishchuk et al., 2015a*] for eight test sites (TS) located in different permafrost zones of this region (one test site in the zone of sporadic permafrost zone, two – in the zone of discontinuous permafrost, and five – in the area with continuous permafrost). The areas of lakes were determined from ultra-high resolution satellite images collected by the QuickBird satellite sensor (0.61 m pixel resolution degree of detail).

Analysis of experimental data on the abundance and size of thermokarst lakes has shown that histograms of lake size-distribution across TS areas allow their approximation by both power and exponential functions with fairly high determination coefficients 0.95 and 0.90, respectively; the approximating function of power dependence, however, provides higher confidence. Noteworthy is that the test sites being few in number and geographically spaced out in different permafrost zones, the results can hardly be considered well-substantiated and require additional research.

Other researchers [*Karlsson et al., 2014; Polishchuk V. and Polishchuk Yu., 2014*] have provided results of the study (underpinned by medium resolution Landsat imagery) on lake number and area distribution across the territory of Western Siberia over the period of 1973–2014. The studies conducted on 29 test sites in zones of continuous, discontinuous and sporadic permafrost [*Polishchuk V. and Polishchuk Y., 2014*] have shown that, according to Pearson criterion, lake distribution in this area obeys the exponential law.

Whereas in [*Karlsson et al., 2014*], who applied remote sensing methods to studying the changes in thermokarst lakes area and their number in the discontinuous permafrost zone of Western Siberia, the authors conclude that thermokarst lakes areas distribution is fitted by a power law. It should be noted that the lognormal lake size-distribution on thermokarst plains has been theoretically discussed and proved by [*Victorov et al., 2015*].

In our opinion, inconsistency of inferences about the laws of lake distribution is stemming from the lack of knowledge on regional distribution thermokarst lakes size, which is particularly true for the poorly studied small size lakes. The remote sensing approaches to the study of small to very small thermokarst lakes distribution in the discontinuous permafrost zone requires application of space imagery with high spatial resolution.

ISSUES OF RESEARCH MEODOLOGY FOR SMALL LAKES SIZE DISTRIBUTION

The investigations were carried out in the discontinuous permafrost zone of Western Siberia using high-resolution space images from Canopus-V (2 m resolution) whose collection included 13 images. The Canopus-V images for test sites were obtained within the boundaries of space imagery scenes, in zones of active thermokarst [*Victorov, 2006*], determined by the greatest concentration of lakes. Table 1 provides general characteristics of the selected test sites, and their layout scheme is shown in Fig. 1.

Table 1. **Test sites parameters and shooting date**

TS No.	Latitude, deg	Longitude, deg	Image date	TS area, ha
1	64.04	70.56	29.06.2014	3233
2	64.31	70.93	17.07.2013	3187
3	64.85	74.05	23.06.2013	3321
4	64.21	74.54	23.06.2013	3050
5	63.50	76.18	09.07.2013	2816
6	64.05	78.16	30.06.2014	2986
7	64.60	79.36	29.07.2013	2807
8	65.15	82.38	05.07.2013	2981
9	65.96	83.18	14.08.2013	3270
10	65.56	80.00	20.06.2014	3311
11	65.44	79.05	03.08.2014	3421
12	65.96	76.73	30.06.2014	3294
13	65.69	72.93	18.07.2013	3100
14	64.84	69.37	22.07.2013	2969
15	65.58	68.63	22.07.2013	3174
16	65.42	66.87	07.06.2013	3155
17	65.69	67.31	03.08.2014	2882
18	66.25	72.46	18.07.2013	3167

According to [*Victorov, 2006*], among major controls of the formation of thermokarst lakes, predominant are the presence of very ice-rich permafrost and the terrain flatness. That is why most researchers studying thermokarst lake plains are assuming that, given the impact from thermokarst processes is essential, lakes of thermokarst or mixed origin will prevail in the areas of very ice-rich permafrost distribution.

Thus, relying on the climatic geomorphological data analysis, in [*Kravtsova and Bystrova, 2009*] the entire permafrost zone of Western Siberia is classified as a region with ubiquitous distribution of thermokarst lakes. Therefore, all the lakes investigated by this remote sensing study are classified as thermokarst lakes.

Verification of the uniformity of distribution of the selected test sites across the study area was carried out by correlation of the TS layout schemes with the maps of geocryological and landscape zoning of the area of Western Siberia [*Sidorenkova, 1984; Gudilin, 1987*]. Fig. 1 shows a schematic map of the permafrost subzones of Western Siberia, with an evidence of the test sites being distributed fairly evenly throughout the research area.

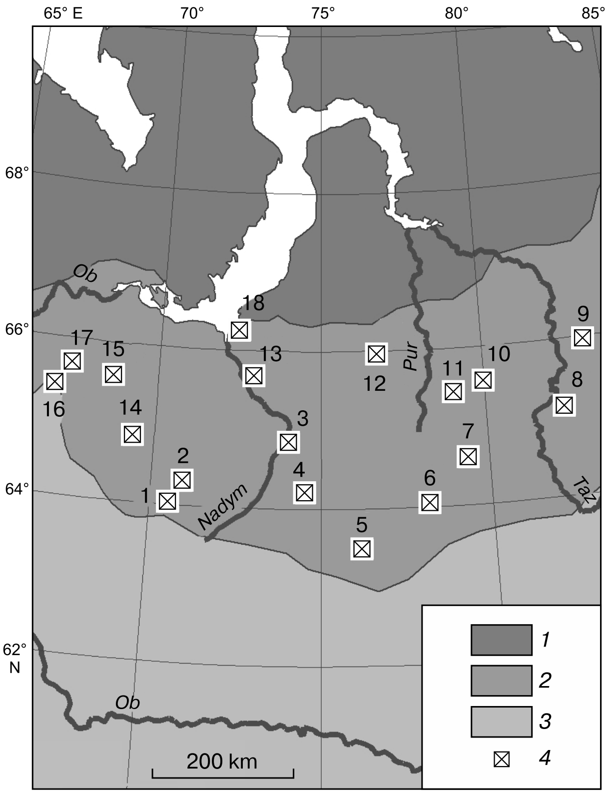

Fig. 1. Layout of test sites in the discontinuous permafrost zone of Western Siberia.

Permafrost: *1* – continuous, *2* – discontinuous, *3* – sporadic; *4* – test site.

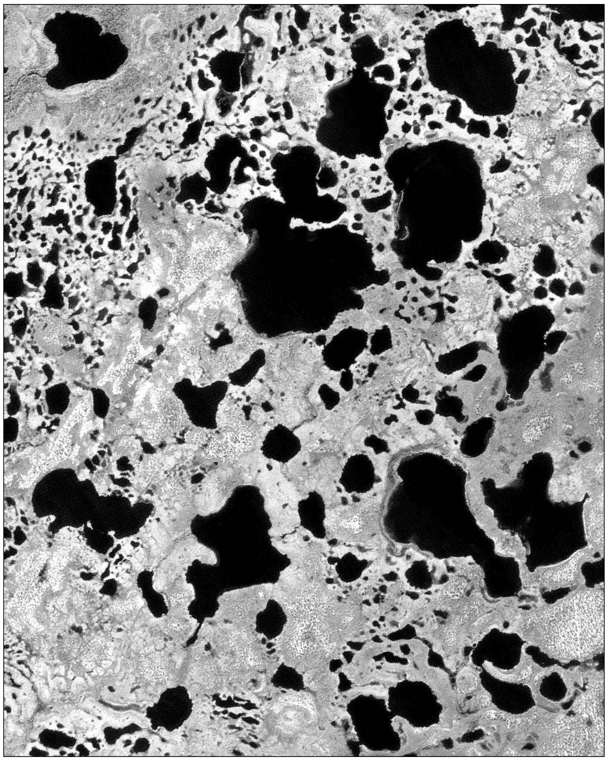

Fig. 2. Type representation of thermokarst lakes in the discontinuous permafrost zone on Canopus-V satellite image (29.07.2013) for Test Site 7.

All the 13 cloudless Canopus-V space images selected for conducting the remote sensing studies were obtained in 2013–2014, within a relatively short time period spanning less than two months beginning late in June through early August, when lakes are completely free from the ice cover, which would otherwise make it difficult to discern lakes when deciphering the images. The picture showing a fragment of TS-7 area (Fig. 2) illustrates diversity of fields with lakes differing in sizes and coast outlines.

The space images were interpreted using standard tools of the ArcGIS 10.3 geographic information system. To ensure acceptable accuracy in the lakes areas determinations, the smallest size of the registered lakes was taken to be a polygon with 10 pixels within its bounds. Therefore, having a 2 m resolution and the pixel size of 4 m^2, the analysis yielded a minimal lake size of 40 m^2.

RESULTS OF RESEARCH OF SIZE-DISTRIBUTION OF SMALL LAKES

The results of the remote determinations of lakes number and their surface areas at different test sites using high-resolution Canopus-V images allowed to generate characteristics of the thermokarst lakes fields in the study area (Table 2). The overall area of lakes listed in Table 2 was defined as cumulative totals of lakes areas from each TS. Lakes density was calculated as the ratio of lakes number in the test site to its area. Limnicity factor of the territory was defined as the ratio of the total area of lakes to the TS area. General characteristics of the fields of lakes established within the study area were derived from Table 2 that provides average values of the indicators, determined for all TS.

Table 2. **Characteristics of the thermokarst lakes fields on different test sites based on Canopus-V images**

TS No.	Number of lakes	Maximum lake area, ha	Total area of lakes, ha	Density of lakes, ha^{-1}	Limnicity, %
1	1470	170.0	810.13	0.45	25.1
2	1739	71.8	780.99	0.55	24.5
3	2547	44.5	1038.10	0.77	31.3
4	2082	100.8	1163.80	0.68	38.2
5	1120	49.4	658.79	0.40	23.4
6	1965	62.5	1197.46	0.66	40.1
7	988	33.9	413.84	0.35	14.7
8	970	96.2	626.55	0.33	21.0
9	1200	209.0	1044.11	0.37	31.9
10	616	80.0	533.88	0.19	16.1
11	663	58.1	730.62	0.19	21.4
12	1553	143.6	758.63	0.47	23.0
13	1522	128.6	876.62	0.49	28.3
14	221	32.0	222.84	0.07	7.5
15	178	26.2	386.27	0.06	12.2
16	1200	70.6	484.81	0.38	15.4
17	450	23.1	381.54	0.16	13.2
18	750	36.3	376.19	0.24	11.9
Average	1179.6	79.8	693.6	0.38	22.2

As follows from Table 2, the sizes of lakes in different test areas vary greatly, from 40 m^2 to several hundred hectares. Abundance of lakes on TSs varies from several hundreds to tens of thousands of different size lakes. Limnicity of land surface in TS areas varies from 7.5 to 40.1 %, averaging 22.2 %. Lake density is subject to even greater variability, ranging in some test sites about 2 times greater than the range of limnicity coefficient (Table 2).

Establishing a law of statistical distribution of lakes areas is critical for estimating the contribution of small thermokarst lakes to methane and carbon dioxide budget in the permafrost zone. According to the data on measurements of lake areas using remote sensing, the thermokarst lakes distribution histograms were plotted for all the investigated TS. Fig. 3 shows histograms for distribution of lakes areas for two test sites (TS-1 and TS-7) presented on a double logarithmic scale.

Relative numbers in Fig. 3 falling into each i-th interval of the histogram are defined as n_i/N, where n_i is the number of lakes in each interval of the histo-

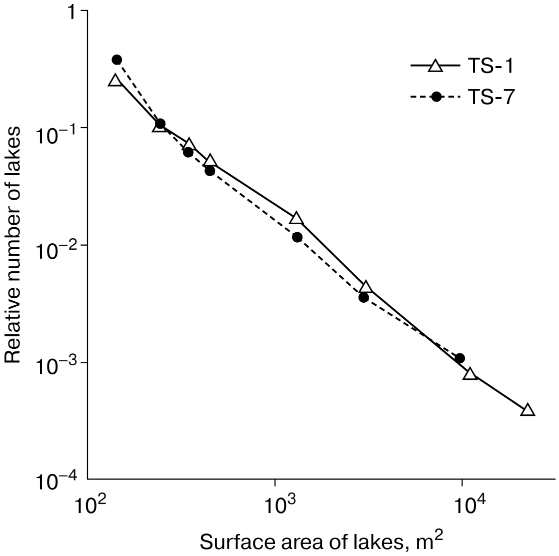

Fig. 3. Examples of histograms of lake size-distribution on two test sites.

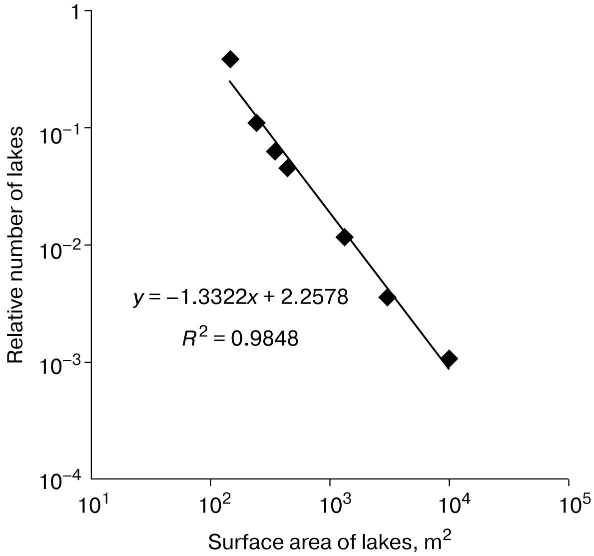

Fig. 4. Approximation of histograms of lake size-distribution at Test Site 7, represented on double-logarithm scale.

gram; i is interval number; N is total number of lakes on the investigated test site. As is seen from Fig. 3, diagrams for different TSs exhibit similarity, thus bearing evidence of an increase in lakes number as their coverage area decreases.

Histograms plots for distribution of lakes area in Fig. 3 are presented on a double logarithmic scale in order to verify whether empirical distributions fit a power-law

$$k = AS^B, \quad (1)$$

where k is relative number of lakes in the histogram intervals; S is the area of water surface of lakes; A, B are power function coefficients.

It is revealing that in case of a power-law distribution of lakes areas, the histogram plots for the empirical distribution of lakes on a double logarithmic scale will be represented by linear functions.

After taking the logarithm both in the right and left parts of the equation (1), we obtain the relation:

$$\lg k = \lg A + B \lg S,$$

which is modified by introducing substitutions $\lg k = y$ and $\lg S = x$ into:

$$y = \lg A + Bx. \quad (2)$$

Equation (2) illustrates linear interdependence of the logarithms of relative number of lakes and of their areas on the histogram curves presented on a double logarithmic scale. Indeed, the histogram plots for distribution of lakes presented on such scale in Fig. 3 have approximately linear form.

To confirm this linear dependence, we approximate the histograms by the equation of a straight line. The points in Fig. 4 represent values of relative number of lakes in the histogram intervals with lakes size-distribution for TS-7, while the straight line represents the approximating dependence obtained with a high level of confidence (determination coefficient: 0.98) in the form (2), which corroborates a power-law distribution of lakes area as given in (1).

The coefficients for a power-law distribution of lakes areas for TS-7 were derived from the approximation equation shown in Fig. 3:

$$A = 181, B = -1.3322.$$

A similar approximation was made for empirical histograms with distribution of lakes across all the TSs. The calculated coefficients for a power law lake-size distribution for different TSs are listed in Table 3, showing that coefficient B establishing power dependence, varies at different TSs within rather small interval from −1.62 to −0.95 (averaging −1.26), which is indicative of relative constancy in lakes areas distribution at different TSs.

Therefore, despite fluctuations in density of lakes and limnicity factor for the surface areas are considerable at different TSs (Table 2), we can assume a relatively low variability in lakes distribution across them. A composite plot for a family of histograms of lakes distribution at different TSs (Fig. 5) also demonstrates proximity of histograms for each of the TS to a straight line representing the result of approximation of the averaged histogram of small lakes areas distribution across all the investigated TSs in the discontinuous permafrost zone of Western Siberia.

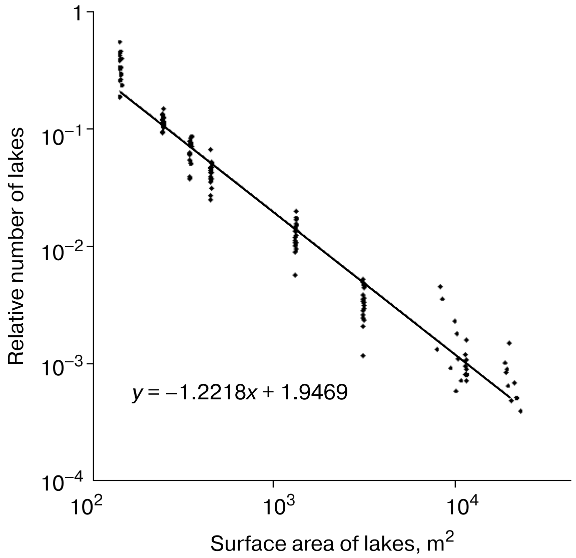

Fig. 5. Approximation of the averaged histograms of small lakes size-distribution in the discontinuous permafrost zone of Western Siberia.

The determination coefficients R^2 listed in Table 3 show high level of confidence of linear approximation of the histograms for distribution of lakes represented on a double logarithmic scale, which is indicative of small lakes areas distribution fitting a power law.

Verification of the assumed good agreement between empirical distributions and theoretical (power-law) law of lake distribution over areas on the basis of the Pearson criterion showed that the hypothesis is confirmed at a significance level of 0.99 by all the test sites. We would like to point out that the inferences on small thermokarst lakes distribution obeying a power law ascertained in our research, are valid for lakes whose areas vary between 40 m^2 and 1 ha.

It should be noted that the distribution of lakes on a global scale can be fitted by a power-law distribution [*Downing and Prairie, 2006; Verpoorter et al., 2014*], as discussed above. The results of remote sensing studies of fields with thermokarst lakes on the basis of high-resolution satellite imagery have shown that the size-distribution of lakes can be assumed to fit a power law on a regional scale rather than for the entire permafrost zone of Western Siberia.

CONCLUSIONS

The presented results of remote sensing analysis of small thermokarst lakes distribution in the discontinuous permafrost zone of Western Siberia using high-resolution satellite images Canopus-V allowed to decipher small to very small size lakes. The 13 cloudless images applied thereto were obtained during the summer seasons (late June through early August) of 2013 and 2014. We studied a total of 18 test sites, spaced out fairly evenly across the research area.

Based on the results of the interpretation of satellite images, the number of lakes, their coverage and the level of limnicity of the surface area were determined for each of the test sites. Lakes sizes varies greatly – from 40 m^2 to several hundreds of hectares – at different TSs, and so does the number of lakes – from several hundreds to tens of thousands of lakes of different sizes. Limnicity factor in different test areas varies from 7.5 to 40.1 %, averaging 22.2 %.

The histograms of lake size-distribution were plotted for each of the test sites. In order to verify whether the empirical distributions can be fitted by a power-law distribution and for the convenience of their graphic representation, they are presented on a double logarithmic scale.

Statistical analysis of the experimental histograms of lakes distribution showed that for all the test sites studied within the discontinuous permafrost zone of Western Siberia, the empirical histograms of lakes areas distribution can be approximated by a power function. The approximation function degree defining a power-law distribution, varies in different test areas within a small range, from −1.62 to −0.95 on average −1.26, which is indicative of a relative constancy (low variability) of the lake area distribution law at different TS, regardless of the significant oscillations of limnicity in different areas.

Table 3. **Coefficients of power law distribution of lakes on different test sites**

TS No.	Coefficients of a power-law approximation model		R^2
	B	*A*	
1	−1.23	98.02	0.98
2	−1.62	1056.33	0.97
3	−1.28	137.28	1.00
4	−1.34	200.49	0.99
5	−1.16	62.60	0.99
6	−1.26	126.15	1.00
7	−1.33	181.05	0.98
8	−1.16	62.23	0.98
9	−1.25	84.51	0.92
10	−1.23	88.47	0.94
11	−1.08	32.88	0.94
12	−1.46	419.76	0.99
13	−1.30	152.16	0.98
14	−0.95	14.01	0.93
15	−1.03	23.53	0.94
16	−1.45	388.06	0.99
17	−1.15	53.13	0.96
18	−1.44	357.27	0.98

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