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Application of remote sensing and mathematical morphology of landscape for studying thermokarst processes

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Abstract: The purpose of this work is to study the development and regularity of morphological structures associated with thermokarst processes. An attempt is made to solve two problems, by analyzing the spatial regularity of morphological structures associated with thermokarst, and that of their dynamics. We use the method of landscape mathematical morphology – a branch of landscape science, investigating quantitative laws of landscape mosaics using methods of mathematical analysis of these mosaics. Investigation was carried out for five parcels in Siberia and Alaska. The analysis shows that a number of deductions from the proposed mathematical model for thermokarst lake plains are generally corroborated by empirical data.

Keywords: remote sensing, landscape pattern analysis, mathematical morphology, landscape

Introduction

More than 60% of Russia is within a permafrost zone. Accordingly problems of permafrost and related exogenous geological processes are very important, especially in Siberia, which includes most of the permafrost area and contains most of mineral deposits of Russia. As a rule, frozen ground processes including those in a stage of stabilization or attenuation become more active under technogenic intervention and climatic changes, receiving a new impulse. And even more, they can reach higher degrees of intensity in their development. Besides other processes arise, which were not developed earlier at this territory.

Thermokarst is a geocryological processes especially sensitive to anthropogenic intervention and climatic changes. Thermokarst is a process of formation of closed negative landforms as a result of degradation of soils containing ice. Thermokarst originates when the following conditions are satisfied:

- Soils contain ice in the form of beds or schlieres (ice lenses);
- Depth of seasonal thawing exceeds the depth of occurrence of underground ice or soils containing schlieres of ice;
- The water formed after ice thawing is drained away so that a sinking of soil occurs.

Thermokarst depressions depend greatly on the types of underground ice and ground that thaw, as well as on water flow conditions. The presence of close water-bearing horizons promotes thermokarst processes, therefore many thermokarst forms are associated with alluvial sediments of ancient and actual river systems (Kachurin 1961).

Rates of thermokarst processes depend on the ice content of sediments: the higher it is, the faster ground is destroyed. Rate of destruction of walls of an exposure depends on climate, composition of deposits overlaying ice, ice thickness, exposure of slopes and depth of erosion base level. Persistent thermokarst destruction and self-development of this process is possible at a water body depth of 1.5 m and more. The water regime of a thermokarst lake is stable provided that thawing stocks of ice comprise more than 35% of total volume of ground of an underground ice complex. On thawing there is a self-development of thermokarst lake irrespective of weather conditions of the year. In this case further evolution is limited by the underground ice amount and the drainage conditions of the locality. When a drainage channel forms, along which water from a thermokarst lake outflows, the water level drops sharply leading to temporary stabilization of the lake shores. Growth of thermokarst lakes then slows down sharply (Are et al. 1974).

One of the important problems is to find principles of distribution and dynamics of thermokarst development with the purpose of forecasting environmental changes. Many researchers have been devoted to studying thermokarst processes (e.g. Zolotarev 1983, Burn & Smith 1990, and others), but inadequate attention has been given to statistical methods. In particular, little consideration has been given to quantitative analysis of the morphological structures produced by thermokarst processes. Although many researchers offered new quantitative characteristics of landscape mosaics (Ivashutina & Nikolaev 1969, Simonov 1972, Viktorov 1998, 2007, 2008), attempts to compare different methods of quantitative analysis, and to give estimated engineering forecasts based on landscape morphological structure, have not led to any significant result as there were not enough basic mathematical dependencies.

The purpose of the present work is to study regularity of structure, and development of morphological structures, associated with thermokarst processes. Within the framework of this work an attempt has been made to solve two problems:

- analyze the spatial pattern of the morphological structures associated with thermokarst;
- analyze dynamics of the morphological structures associated with thermokarst.

Study methods

In my work I use mathematical morphology of a landscape – a branch of landscape science, investigating quantitative laws of construction of mosaics which are formed on an earth surface by natural units, and methods of mathematical analysis of these mosaics (landscape patterns) (Viktorov 1998, 2008). The theoretical basis of mathematical morphology of a landscape is formed by mathematical models of morphological structures – the quantitative dependences describing the basic properties of morphological structures. Canonical initial mathematical models play a special role in the mathematical morphology of a landscape. They deal with the patterns developed in uniform conditions, that is, at a constancy of major factors of landscape differentiation. Mathematical models of morphological structures of a certain genetic type are referred to as canonical if they are formed under the action of the same process in homogeneous natural conditions, i.e. of simple landscape pattern.

The further combination of such models, in view of the interaction of processes, allows us to describe the variety of morphological patterns developed under diverse combinations of natural conditions. The possibility of constructing a model capable of describing the complete variety of geometrical features of morphological patterns of a given genetic type with several equations is quite real, though it is not obvious at first sight. Researches demonstrate that basic equations do not depend on a lot of particular conditions, for example, the material structure of surface sediments, annual sum of precipitation, etc. Thus, the model allows us to examine the problems in general, i.e., obtaining a solution applicable to a broad spectrum of natural geographical conditions.

We can imagine an appearance that may present a *perfect* area with thermokarst lakes in conformity with postulates of canonical initial models. It will be a territory uniform in landscape with round lakes, almost without any erosion. In real conditions I can find it in plane watersheds.

Mathematical models of thermokarst lakes are based on the following assumptions:

- The process of origination of new depressions is probabilistic and proceeds independently on disjoint areas.
- The probability of origination of one depression on a sample area depends only on area size and on time interval. Also, this probability is much greater than the probability of origination of several depressions.
- Growth rate of depressions due to thermal abrasion occurs independently from each other, it is directly proportional to the heat stocks in a lake and inversely proportional to the area of a lateral surface of the lake basin under water level.

The first two assumptions follow from the uniformity of territory under consideration and reflect a comparative rarity of initiation of thermokarst depressions. The third assumption proceeds from the fact that thermal influence is proportional to the magnitude of the thermal flux passing through a unit of surface area. This assumption is fair, even if growth of lakes does not occur every year (in a case when a water table is reduced and does not reach a lake basin border and thermal abrasion does not develop).

After data analysis, the probabilistic mathematical dependences reflecting the most essential geometrical properties of a pattern for territories with thermokarst processes have been developed by Viktorov (1998, 2006, 2007, 2008). The obtained expressions include:

- Probabilistic distribution of the number of thermokarst lakes which have appeared within a specified site during a given time interval (Poisson process).

$$P(\kappa, t) \frac{(\gamma ts)^k}{k!} e^{-\gamma ts}$$

where γ is an average of the depressions appearing per unit area in unit time; s is the size of test site; t is time.

- Probabilistic distribution of changes of thermokarst lake areas (Weiner random process relative to logarithms of areas)

$$F_r(x) = \frac{1}{\sqrt{2\pi}\sigma x\sqrt{t}} e^{-\frac{(\ln x - \alpha t)^2}{2\sigma^2 t}}$$

where α, σ are distribution parameters, t is lake age.

Results and discussion

The first task of my work was to analyze the spatial regularity of the morphological structures associated with thermokarst. It follows from the model that, if the spread in sizes of primary depressions is considered small and given that lakes originated over a comparatively short period of time, then at any time lake diameters should follow a lognormal distribution. This deduction has been verified over a series of reference parcels. Satellite imagery has been used as the source of information on morphological structure.

In selecting parcels I was guided by their internal morphological uniformity and the availability of remote sensing data for the given area. Parcels should be uniform in microstructure, in background phototone, and in the location and form of lakes.

The researches were carried out for five parcels, located:

- in Khanty-Mansy autonomous region in the River Valoktayagun valley of the Middle Ob lowland (Fig. 1)
- in Alaska in an intermountain valley which reaches a gulf deeply indented in the western part of Seward Island (Fig. 2),

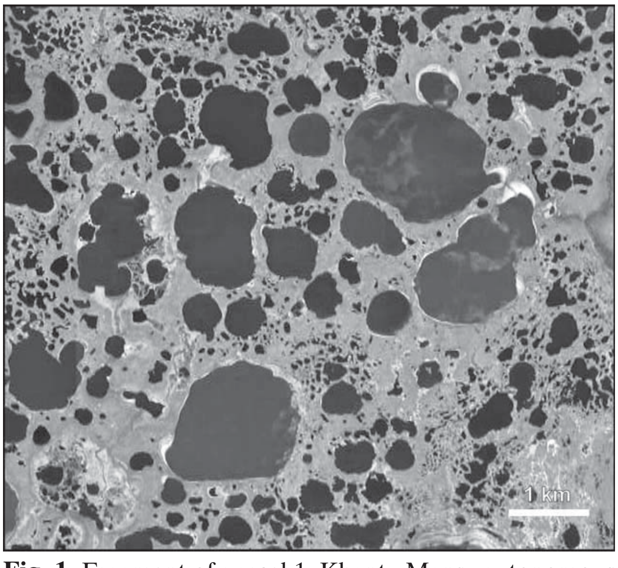


Fig. 1. Fragment of parcel 1, Khanty-Mansy autonomous region in Middle Ob lowland

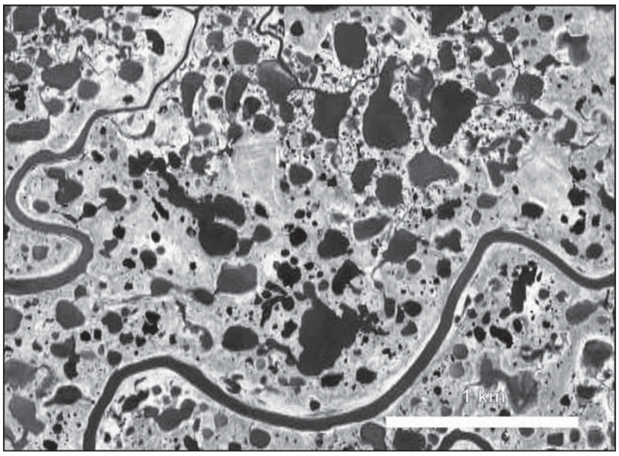


Fig. 2. Fragment of parcel 2, Seward Island, Alaska

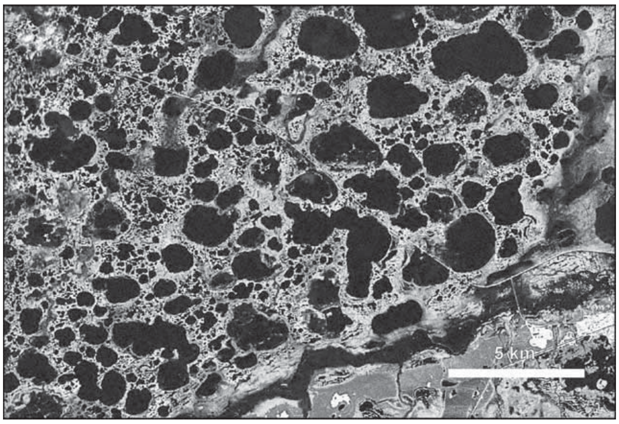


Fig. 3. Fragment of parcel 3, the Pjakupur River, West Siberia

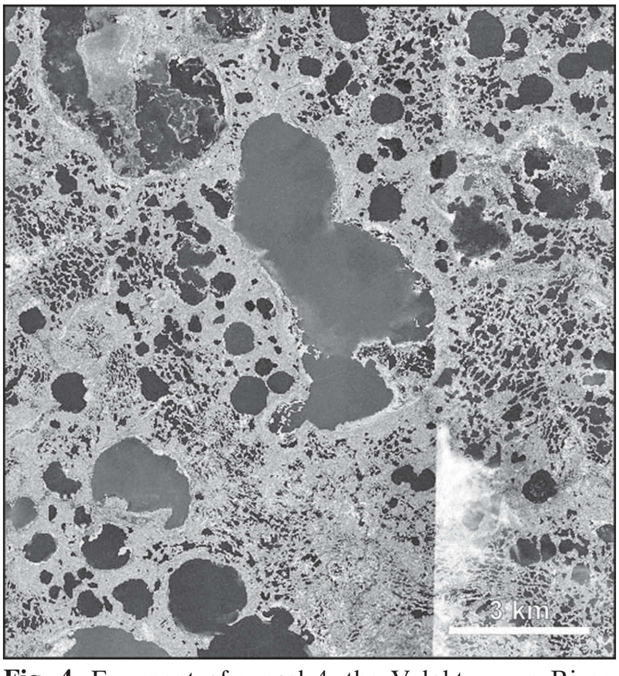


Fig. 4. Fragment of parcel 4, the Valoktayagun River, West Siberia

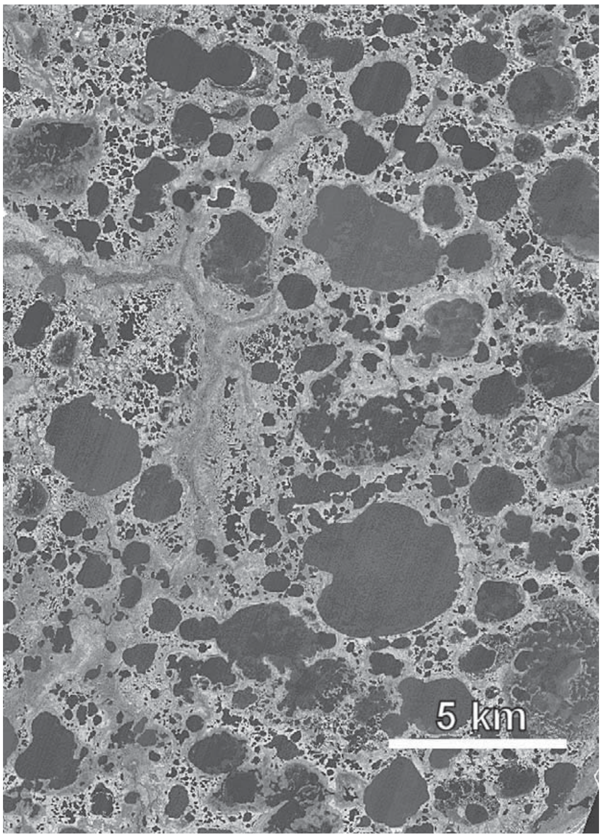


Fig. 5. Fragment of parcel 5, the Pjakupur River, West Siberia

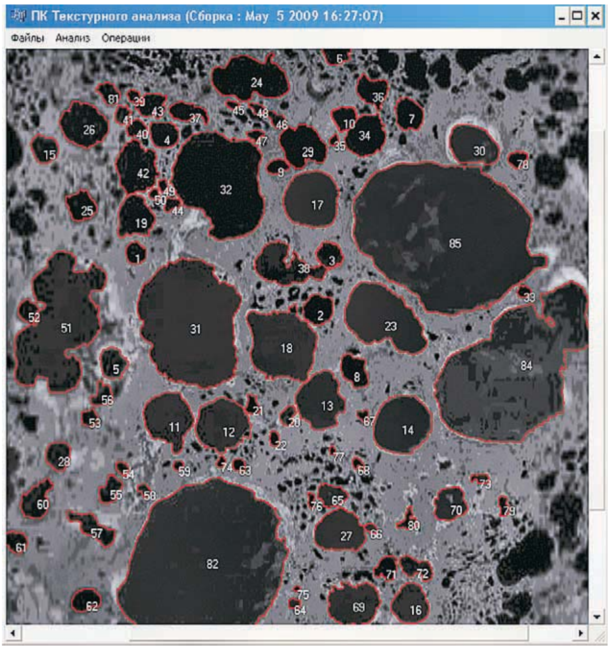


Fig. 6. Screen shot of operating window of Vektorizator program

– in the West Siberian plain, on the Pjakupur River (Fig. 3, 5) and on the Valoktayagun River (Fig. 4).

These are undulating tundra surfaces with numerous round thermokarst lakes within Mid-Quaternary deposits.

The studied parcels were analyzed using the specially developed program Vektorizator (by A.A. Viktorov). The water surface of lakes contrasts with their surroundings and is clearly identifiable visually. So the Vektorizator reduces it to binary form without losing lake geometry data. After that, on an enlarged section of the image, the operator can outline the lake border in semi-automatic mode. Then the program will automatically calculate with a high degree of accuracy the diameter, area, perimeter, centre of gravity and other parameters of the lake outline (Fig. 6).

The program was applied to digitized repeated spatial images for the same areas. We selected lakes that do not coalesce. After that, in the program *Statistica*, values of the theoretical function of distribution were determined. Each sample was compared, first of all, with a lognormal distribution; comparison with other theoretical distributions including Raleigh distributions, normal and exponential, was sometimes carried out. Graphs were plotted showing the relationship of empirical and theoretical distributions of lake areas (Fig. 7 for parcels 1). The conformity of theoretical and empirical distributions was determined by Pearson's criterion (Table 1).

We found good conformity between theoretical and experimental data. This implies that for the selected parcels a lognormal distribution of lake areas is acceptable. Modelling shows also that at a specific moment of time the location of lakes should follow a Poisson distribution. This deduction does not depend on assumptions about uniform or non-uniform generation of lakes over time. On the same reference parcels the distribution of centres of thermokarst lakes was analyzed. For this purpose a region with la-

Table 1. Parameters of distribution graphs and their conformity to log-normal distribution

Parcels	χ^2	Degrees of freedom	Critical value χ^2 on the level 0,95 (0,99)	$\alpha_0(t)$	$\sigma_0(t)$
Parcel 1 (Khanty-Mansy autonomous region)	13.80	5	11.07 (15.09)	5.41	1.29
Parcel 2 (Alaska)	5.60	5	11.07 (15.09)	5.91	2.01
Parcel 3 (West Siberian plain river Pjakupur, 2000)	4.02	4	9.49 (13.28)	0.40	0.13
Parcel 4 (River Vatiegan, 2006)	10.72	4	9.49 (13.28)	4.69	1.03
Parcel 5 (West Siberian plain, river Pjakupur, 2007)	3.91	5	11.07 (15.09)	11.98	1.29

kes was outlined, and the number of lake centres in a randomly-placed field (in this case – a circle) of a constant size was calculated in the program Vektorizator. The position of fields was defined with the help of 100 runs of a random-number generator (Fig. 8). The statistical distributions of lake centres were obtained. For each parcel several experiments were made with circles of different area. Distribution graphs were plotted, their parameters were obtained and conformity to a Poisson distribution (Table 2) was determined. Here too, I found good conformity between theoretical and experimental data.

The second task was to analyze the regularity of dynamics of the morphological structures associated with thermokarst. From the model of Viktorov (2006), the increments of logarithms of lake areas for any specific period should follow a normal distribution. This study was carried out on parcel No. 5 on the West Siberian Plain, in the region of the Pjakupur River. Materials from different satellites (Landsat, IRS) and different periods were used for research: 1987 (with space resolution 28.5 m), 2001 (with space resolution 14.5 m) and 2007 (with space resolution 5.8 m). For this task I also used the program Vektorizator. We select lakes within a special polygon using remote sensing data of each year. Then I extract data about lake areas and compare it.

To detect possible misinterpretation error, repeated independent measurements of lakes of different area were carried out: as a limiting misinterpretation error a double root-mean-square deviation was taken. After the analysis of misinterpretation values for various lakes, for limiting misinterpretation estimation while measuring lakes of the different area, a linear dependence (Fig. 9) was used:

$$y = 0.025x + 3.3.$$

Table 2. Parameters of distribution graphs and their conformity to Poisson distribution

Parcels	Field size (pixel)	Circle size (pixel)	λ	χ^2	Degrees of freedom	Critical value χ^2 on the level 0.95 (0.99)
Parcel 1	521×580	70	1.28	1.12	2	5.99 (9.21)
		90	1.76	0.41	3	7.82 (11.34)
		119	3.25	6.35	4	9.49 (13.28)
Parcel 2	562×470	61	1.55	0.72	3	7.815 (11.34)
		79	2.3	10.03	4	9.49 (13.28)
		128	7.21	10.25	8	15.51 (20.09)
		52	1.14	6.39	2	5.99 (9.21)
		128	7.21	7.40	8	15.51 (20.09)
Parcel 3 (1973)	541×77	114	19.87	12.35	11	19.68 (24.73)
		87	10.83	4.89	4	9.49 (13.28)
		68	9.15	8.25	9	16.92 (21.67)
		52	6.71	3.97	7	14.07 (18.48)
		42	3.28	10.87	4	9.49 (13.28)
		31	1.52	2.25	3	7.82 (11.34)
Parcel 4 (1988)	213×96	50	5.54	16.78	6	12.59 (16.81)
		37	2.86	2.90	5	11.07 (15.09)
		28	1.64	5.73	3	7.82 (11.34)
		16	0.54	0.11	1	3.84 (6.64)
Parcel 5 (2007)	1022×1595	337	2.58	0.91	4	9.49 (13.28)
		316	1.99	9.73	4	9.49 (13.28)
		269	1.26	0.27	2	5.99 (9.21)
		232	0.96	1.78	2	5.99 (9.21)
		199	0.89	1.54	2	5.99 (9.21)
		173	0.54	0.92	1	3.84 (6.64)

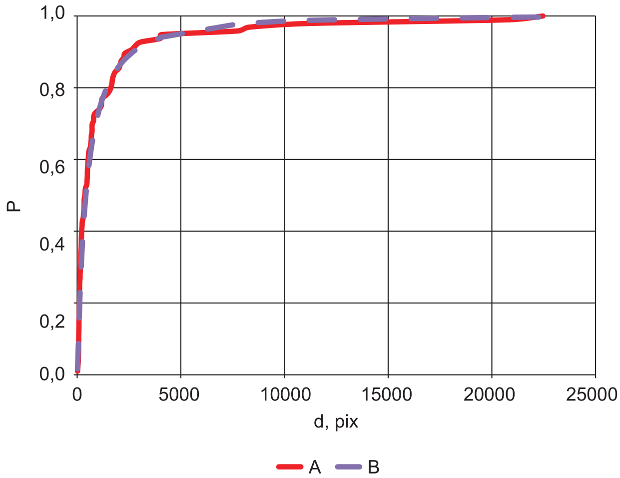


Fig. 7. Relationship of empirical (A) and theoretical (B) distributions of areas of thermokarst lakes in parcel 1

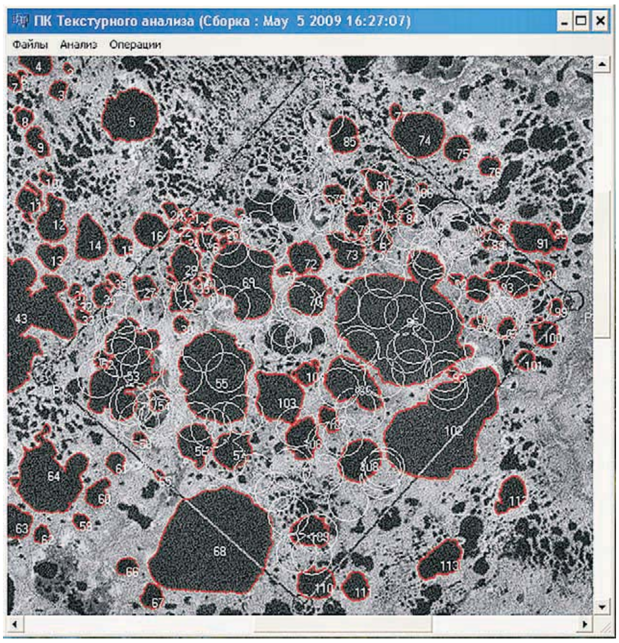


Fig. 8. Random-number generator in the Vektorizator program

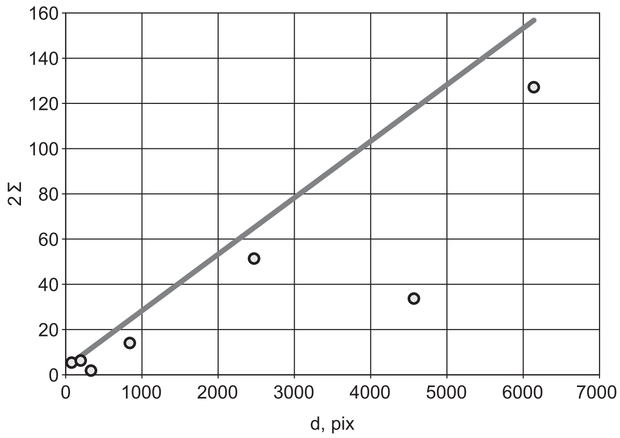


Fig. 9. Misinterpretation diagram for the image of 1987

On the graph points show empirically obtained misinterpretations, a continuous line – dependence according to which values of misinterpretation for lakes of different area were calculated. The analysis has shown that a significant part of the obtained data on area changes is beyond misinterpretation error, even at such overestimation.

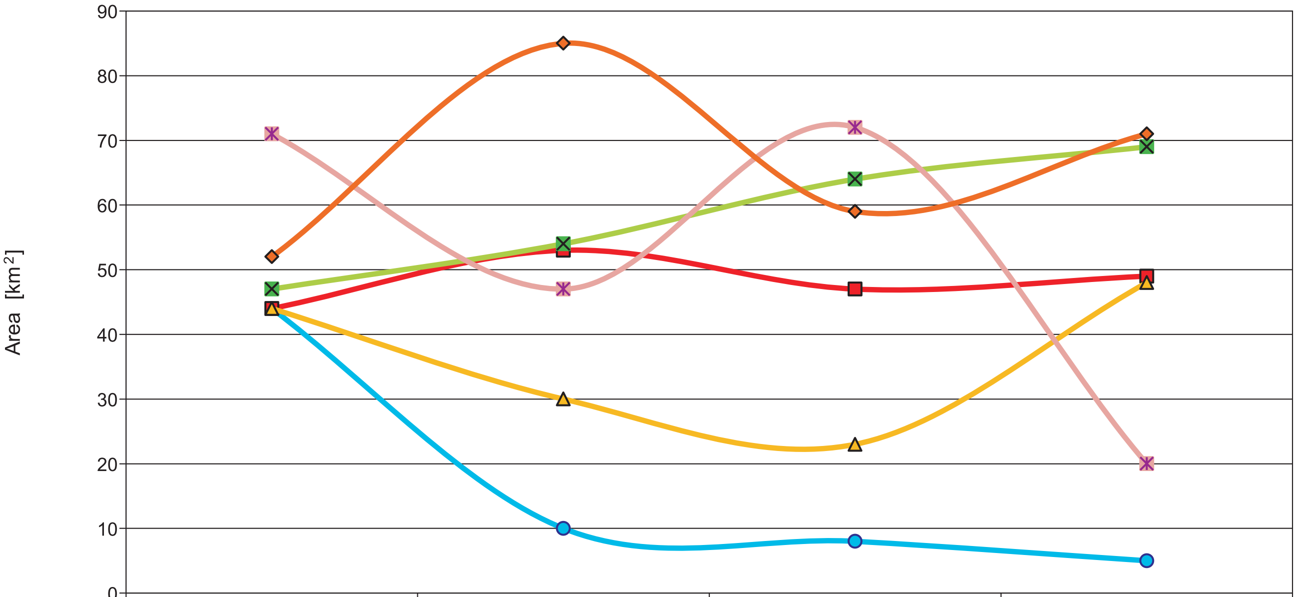
After calculating the lake areas (in the program *Statistica*) values of a theoretical distribution function and conformity of theoretical and empirical distributions were determined by Pearson's criterion (Table 3). Graphs of the distribution of increments of logarithms of lake areas for different periods are similar to lognormal ones, however, the chi-square criterion indicates considerable deviations for the shorter time interval (6 years) and agreement with the model for longer intervals (14 and 20 years). This may be accounted for the fact that at small time intervals I may speak about changes of a water table instead of a lake basin, for which other model will work. Thus, I cannot speak with confidence about lognormality of distributions. It does not contradict the suggested model as it is based on a situation when the water table directly adjoins the border of a lake depression and the area of a depression coincides with the area of a water table. At the same time the observed situation differs from that described above.

Comparison of the dynamics of various lakes during the research period gave us additional data. We studied lakes of the same territory in 4 years: 1973, 1987, 2001, 2007. We may see from the plots (Fig. 10) different dynamics of various lakes of the same territory, that is, asynchronous change. Analysis of the data permits the following conclusions:

- While it is obvious that the dimensions of active thermokarst lake depressions can only increase, the water table area of lakes can either decrease or increase.
- The different behaviour of lakes on one parcel permits exclusion of the influence of meteorological conditions during a specific year.
- Adequate description of development of thermokarst lake plains is provided by a synthesis of two models: the first one, describing dynamics of depressions under degradation of frozen ground and the basic tendencies of long-term change of the water table area, and the second one, descri-

Table 3. Table of empirical-to-theoretical log-normal distribution correspondence for parcel No. 5

Period	χ^2	Degrees of freedom	Critical value χ^2 at the level 0.95 (0.99)
2001–1987	3.66	1	3.84 (6.64)
2007–2001	16.57	1	3.84 (6.64)
2007–1987	4.79	1	3.84 (6.64)



	1973	1987	2001	2007
Lake 1	44	10	8	5
Lake 2	44	53	47	49
Lake 3	44	30	23	48
Lake 4	47	54	64	69
Lake 5	71	47	72	20
Lake 6	52	85	59	71

Fig. 10. Dynamics of lake's water table

bing dynamics of water table area over short time intervals, related to a different set of factors.

Conclusions

Thus a number of deductions from the proposed mathematical model for thermokarst lake plains are in general corroborated by empirical data. Deviations are probably due to some non-uniformity of terrain. The adequate description of development of thermokarst lake plains is a synthesis of two models: the first describing lake basin dynamics under the influence of permafrost degradation and the basic tendencies of long-term change of water table area, and the second – describing the table area dynamics for short time span (other set of factors). The model of lake dynamics was directly verified from repeated data for a specified territory. These conclusions have essential practical value. The researches broadly confirm the validity of the model, which in turn permits forecasting of risks for linear, areal, and point objects (Viktorov, 2006).

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