Genetic, Morphological, and Statistical Characterization of Lakes in the Permafrost-Dominated Lena Delta

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Abstract

This study provides a detailed inventory of lakes in the Lena Delta, northern Siberia. The inventory is based on Landsat-7 ETM+ image data and spatial analysis in a Geographical Information System (GIS). Several morphometric lake attributes were determined from the resulting dataset and statistically analyzed with respect to the lakes' association with one of the three geomorphological main terraces of the Lena Delta. Significant differences in the morphometric lake characteristics allowed the distinction of a mean lake type for each main terrace. The lake types reflect the special lithological and cryolithological conditions and geomorphological processes prevailing on each terrace. Special focus was laid on the investigation of lake orientation and the discussion of possible mechanisms for the evolution of the second terrace's oriented lakes.

Keywords: GIS; lake morphometry; Lena Delta; oriented lakes; remote sensing; thermokarst lakes.

Introduction

Numerous lakes occur as characteristic landforms throughout the Lena Delta. They are of importance to the contemporary ecology and geomorphology in this sensitive Arctic environment as well as for the reconstruction of the delta's environmental history. So far, only general descriptions of the lake population were available (e.g., Grigoriev 1993). They suggest that several lake types of different genesis can be distinguished and that the western delta is characterized by oriented lakes. However, a detailed inventory of the Lena Delta lakes did not exist. Such an inventory potentially provides a base dataset essential to a variety of research conducted in this region. This study was aimed to create a lake dataset of the Lena Delta including morphometric and spatial characteristics using remote sensing and GIS techniques to analyze the dataset regarding a morphometric lake classification, and to investigate possible hypotheses of the morphogenesis of the lakes in this periglacial delta environment.

Regional Setting

The Lena Delta in northern Siberia is the largest Arctic river delta (Walker 1998). It is situated in the zone of continuous permafrost and is widely affected by thermokarst. It is characterized not only by alluvial sediments and active fluvial processes, but also by large non-deltaic units. Three main terraces can be distinguished by their geomorphology (e.g., Are & Reimnitz 2000, Schwamborn et al. 2002) (Fig. 1). The first main terrace, which represents the modern active delta, is comprised of the lower and upper floodplains and the first terrace above the floodplain. It forms most of the eastern Lena Delta and is characterized by alluvial Holocene sands with silts and peat. The second terrace captures broad parts of the western Lena Delta. It consists of Late Pleistocene to Early Holocene sands of fluvial genesis, but is hardly influenced by modern fluvial processes. The third main terrace is the relic of a Late Pleistocene accumulation plain with fine-grained and ice-rich deposits.

Materials and Methods

Remote sensing

A mosaic of three Landsat-7 ETM+ scenes taken in the summers 2000 and 2001 covering 98 % of the Lena delta (Schneider et al., in prep.) was used as a basis for lake extraction using the software ENVI™ 4.1. First, we conducted a gray-level thresholding on the mid-IR band 5 to separate open water from land, as water bodies are strong absorbers in these wavelengths and easily distinguishable from other land cover classes. Second, the water class was subjected to a segmentation algorithm to differentiate standing water from rivers and the sea. This method creates separate classes for coherent pixels with the same value. As rivers and estuaries are connected with the sea, they form one single class and were deleted. Some lakes along the coastline that have broad (in the range of several pixels) connections to the sea were thereby also removed from the dataset. They experience a strong marine influence; for example, during storm floods, which can lead to major changes in lake morphometry and lagoon formation. Thus, these lakes were not considered for morphometric and further analysis.

GIS and morphometric analysis

The resulting raster dataset of all remaining lakes was imported into ArcGIS™ 9.0 and converted into vector format

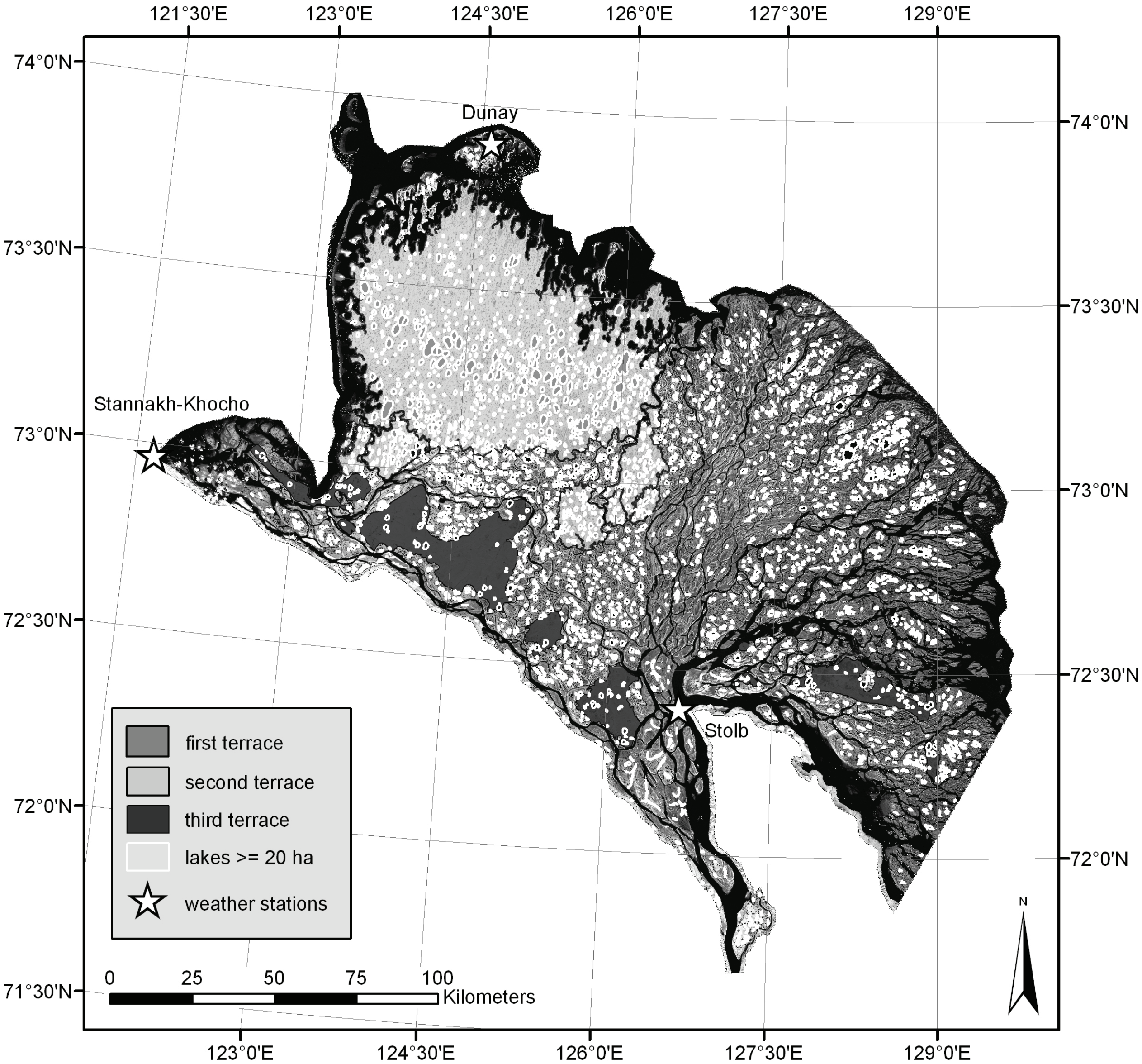

Figure 1. Landsat-7 ETM+ mosaic of the Lena Delta (Band 2) with analyzed lakes and main terraces, and meteorological stations.

where each lake is represented by a polygon. Shape metrics like *area*, *perimeter*, *circularity index* ($4\times\pi\times area/perimeter^2$), *elongation index* (main axis/minor axis), *orientation of main axis* (reference axis is E-W, value range is [0.1;180]°), and *degree of deviation from mean orientation* were calculated. The *circularity index* (values between 0 and 1, with 1 being a perfect circle) is not simply a counterpart to the *elongation index*, but also reflects the smoothness of the shoreline.

As the spatial resolution of the Landsat imagery is 30 m, minimum lake size for analyses was set to 20 ha to ensure reasonable results for reckoning the shapes of the lakes. The lake dataset was manually checked for errors due to misclassification caused by light cloud cover in some places.

On the second terrace in the western Lena Delta, several coalesced lakes occur, which is obvious in the red spectrum from deep basins divided by flat underwater ridges, some of them cut by deeper channels beneath the present lake water level. As our analyses were aimed on lake genesis, we manually divided the coalesced lakes (n=51) along the middle line of the ridges into their single basins and treated each basin as an individual lake (n=120 of which n=17 < 20 ha were excluded from further analysis). The final lake dataset contained 2669 lakes.

Another vector layer was created for the second and third geomorphological main terraces of the Lena Delta by manually digitizing their boundaries based on the Landsat image data, where they are visually easily distinguished. At places of uncertainty, results of field observations were used to determine terrace affiliation. The lake dataset was then divided into three subgroups according to the lakes' association with one of the geomorphological main terraces. The subgroup for the first terrace lakes was created by subtraction of the second and third terrace lakes from the whole lake population.

The variables described above were statistically analyzed for these subgroups using the software SPSS™ 12.0. Several statistics were calculated for the variables within an explorative data analysis (EDA). Variables were tested for normal distribution using the *Kolmogorov-Smirnov test* and for homogeneity of variance using the *Levene test*. In case of non-normal distribution skewness was minimized by data transformation and subsequent tests were performed with the transformed data. To test significant differences in the means of the variables between the three terraces analysis of variance (ANOVA) was performed. Non-parametric *Median test* and *Kruskal-Wallis test* (rank-based) were used with the non-transformed data for validation. Furthermore, multiple comparative tests (*Games-Howell*) were applied to identify terraces between which significant differences in the mean values occur at the 5% level. Bivariate correlations were calculated for the variables *area*, *circularity*, *elongation*, and *degree of deviation from mean orientation* using the rank-based *Spearman's Rho* correlation coefficient.

Results

The total area of lakes ≥ 20 ha is 1861.8 km², which corresponds to 6.4 % of the delta area, as the delta area within the extent of the mosaic was calculated to be 29,000 km² (Schneider et al., in prep.). Table 1 shows the area calculations for the three geomorphological main terraces. The results show great differences in lake occurrence, density, and area. The first terrace shows the highest number of lakes in total, but lake density and the ratio of lake area to the area of the corresponding terrace are highest on the second terrace. For the third terrace, all calculated values are the lowest.

Major results of the EDA are the following (see also table 2). Means, medians and percentiles for *area* show that comparatively larger lakes occur on the second terrace and rather smaller lakes on the first. The frequency distributions are strongly skewed towards lower values on all terraces, so smaller lakes are in general much more abundant than larger ones. Maximum values for the *circularity index* are well below 1 (< 0.7), i. e. throughout the delta no nearly circular lakes occur. Lakes with values of nearly 1 for the *elongation index* (which means almost equal major and minor axes) therefore have complex shorelines at the image resolution. Values for *circularity index* and *elongation index* show generally the largest deviation from perfect circularity for the first terrace and the smallest for the third terrace. Mean *orientation* of all lakes is 90.0°, the median is 80.2°. Means (medians) are 94.9° (95.9°) on the first main terrace, 78.6° (75.9°) on the second terrace, and 90.7° (82.0°) on the third terrace, respectively. Figure 2 shows the frequency distributions of *orientation*. The percentage of lakes with a deviation from the *orientation* mean (median) of ≤ 10° of the according terrace are 9.6 % (9.5 %) for the first terrace, 63.0 % (66.2 %) for the second, and 24.7 % (35.8 %) for the third terrace, respectively. Also the means and medians of *degree of deviation from mean orientation* show that lakes on the second terrace deviate the least and lakes on the first terrace the most from the according mean orientation.

The results of the ANOVA as well as of the non-parametric tests show significant differences in the parameter values between the three main terraces for all variables. Multiple comparative tests revealed the following results at the 5% level. The lakes of the first terrace significantly differ from the second terrace lakes in all variables. No significant differences were found between the first and the third terraces regarding *orientation*, and between the second and the third regarding *orientation* and *area*. On the first terrace, lakes are smaller on average than on the second and third terraces. Nearly circular lakes are more abundant on the third than on the other terraces.

In the context of our analyses we defined oriented lakes as lakes with little deviation from mean orientation and with a deviation from circularity. Deviation from mean orientation is significantly smaller on the second terrace than on the other two terraces, it is highest on the first terrace. Thus, lakes on the second terrace can be statistically characterized as oriented lakes with their main axes tending in NNE-SSW directions.

Of the 18 tests for correlations ten were significant at the 5% level. These include medium negative correlations (r = -.444 to -.465) between *circularity* and *elongation* on all terraces as expected from the design of the variables. All other significant correlations are very small ($|r| \leq .186$) except for the correlation between *area* and *degree of deviation from mean orientation* on the third terrace (r = -.415, p = .01).

Discussion

For all analyzed morphometric lake variables we found significant differences between the three geomorphological main terraces of the Lena Delta. From these differences we deduce one mean lake type for each terrace:

1. Lakes on the first terrace are on average small and elongated, with irregular shapes and strong deviations from mean orientation.

2. On the second main terrace, large elongated lakes with a NNE-SSW orientation of their major axes prevail. Lake density is highest here.

3. The third terrace lakes are mainly characterized by regular shorelines and little deviation from circularity.

These results imply that the forming of a lake's shape towards one of these mean lake types is linked to the according delta main terrace, i. e. lake morphometry is influenced differently on the different main terraces. Different lake morphometries can be caused primarily by diverse lake genesis or by secondary processes subsequently altering the lake's primary shape. The different conditions and processes prevailing on each terrace of the Lena Delta are used to explain the development of the mean lake types found.

The first main terrace is the only one with widespread recent and Holocene fluvial and deltaic activity. The genetic lake type

Table 1. Area calculations for the three geomorphological main terraces of the Lena Delta.

		First terrace	Second terrace	Third terrace
Terraces	Area in km²	15,840.1	6098.6	1711.6
	Percentage of delta area	54.6	21.0	5.9
Lakes ≥ 20 ha	Number	1796	792	81
	Number per 1000 km²	113.4	129.9	47.3
	Percentage of total lake number	67.3	29.7	3.0
	Total area in km²	997.0	808.1	56.7
	Percentage of terrace area	6.3	13.3	3.3
	Percentage of delta area	3.4	2.8	0.2

* Differences from 29,000 km² and 100% total delta area arise from the percentage of sea and river area, respectively, in the mosaic.

Table 2. Descriptive statistics for the analyzed morphometric lake variables.

		Delta	First terrace	Second terrace	Third terrace
Area (in m²)	Mean	697,579	555,124	1,020,382	699,922
	Median	409,500	372,600	557,100	442,800
	Standard deviation	956,500	634,463	1,410,506	566,554
	Interquartile range	452,700	339,075	757,800	598,500
Circularity	Mean	0.31	0.28	0.36	0.46
	Median	0.31	0.27	0.36	0.48
	Standard deviation	0.14	0.14	0.12	0.11
	Interquartile range	0.22	0.22	0.15	0.18
Elongation	Mean	2.11	2.26	1.83	1.49
	Median	1.75	1.85	1.66	1.37
	Standard deviation	1.20	1.37	0.64	0.45
	Interquartile range	0.92	1.12	0.55	0.36
Orientation (in °)	Mean	90.0	94.9	78.6	90.8
	Median	80.2	95.9	75.9	82.0
	Standard deviation	47.1	54.3	21.4	38.2
	Interquartile range	65.94	94.8	12.3	44.4
Degree of deviation from mean orientation (in °)	Mean	38.6	47.5	12.9	29.1
	Median	31.5	48.3	6.8	21.4
	Standard deviation	27.0	26.3	17.0	24.5
	Interquartile range	48.1	45.3	11.7	33.5

typical for such environments is abandoned lakes. Walker (1983) differentiates between abandoned-channel lakes resulting from channel braiding and abandoned meanders or oxbow lakes resulting from meandering. They are predominantly small, often elongated and/or crescent-shaped because they occupy former river branches or meanders, and do not show any particular orientation as the fluvial system shows no clear directional pattern itself at a small scale. Thus, the morphometric characteristics for these lakes are consistent with the mean lake type deduced for the first terrace of the Lena Delta. Further lake types described for the first terrace are polygon ponds and small circular thermokarst lakes (e.g., Grigoriev 1993). Polygon ponds were generally not considered in this study because of their small size. As for the circular thermokarst lakes no area range is reported in the literature, but we assume that they mostly have areas below 20 ha and were therefore not treated in our analyses. Their characteristics, such as smooth shorelines and approximate circularity, are not reflected in the mean lake type of the first terrace.

The morphometry of the lakes on the second terrace and their formation will be discussed in the following section on lake orientation.

Characteristics of the lake shapes on the third main terrace are typical for thermokarst lakes in ice-rich permafrost. The results are therefore consistent with landscape descriptions given in the literature (e.g., Grigoriev 1993). The shape of the lakes is controlled by their thermokarst genesis and is not significantly changed by other factors during further evolution.

In comparing morphometric lake characteristics in the Lena Delta with other arctic deltas like the Colville or the Mackenzie River deltas, only the first geomorphological main terrace should be considered, as it represents an actual deltaic environment. Lake types described for the Colville Delta are abandoned lakes, point-bar lakes, and thermokarst lakes (e.g., Fürbringer 1977, Walker 1983). In the Colville Delta, remnants of oriented lakes also occur, but these were not a part of the delta originally until a river branch cut through an area with oriented lakes (Walker 1983). For the Mackenzie Delta, typical lakes are described as irregular in outline with indented shorelines, and genetic lake types are primarily abandoned channel lakes, point-bar lakes,

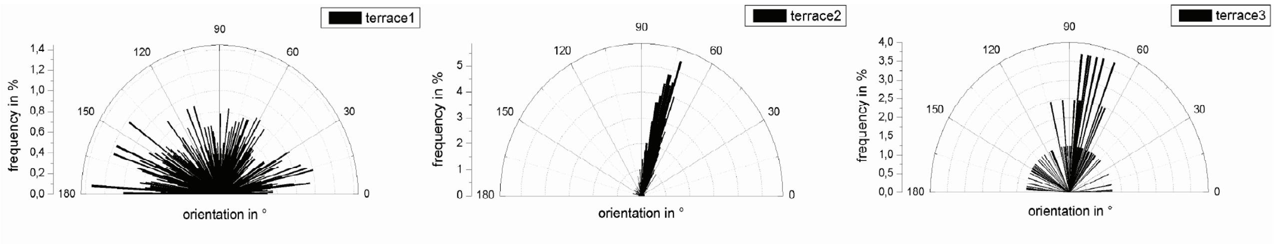

Figure 2. Frequency distribution of *orientation* of the Lena Delta lakes (intervals = 1°).

floodplain lakes, and thermokarst lakes (Mackay 1963). Lake types described for these deltas are thus comparable to the first terrace lakes of the Lena Delta.

Lake orientation

The character of lake orientation as expressed by the variables *degree of deviation from mean orientation* and *circularity* differs significantly between the three main terraces as described above. The process of lake orientation is long term and requires stability of exogenous orienting factors. Active fluvial processes prevailing on the first terrace may overlay tendencies of lake orientation there. Existing discrepancies between the second and the third terraces, however, must be discussed in detail.

Thermokarst lake evolution on both terraces reaches back at least to the early Holocene warming period (Schirrmeister et al. 2003, Schwamborn et al. 2002). Exogenous factors that have been discussed as causing or influencing lake orientation; for example, prevailing wind directions, solar radiation, etc. (e.g., Livingstone 1954, Mackay 1956, Carson & Hussey 1959), therefore, have affected both terraces in the same way for several thousand years. The different character of lake orientation implies a dependence of further endogenous; i.e., terrace-specific factors.

Lithology and cryolithology of the second and third main terraces differ considerably. Sediments on the second main terrace are Late Pleistocene fluvial sediments that consist of homogeneous fine- and medium-grained sands with massive cryogene structures. Large ice wedges are absent, and the ground ice content is generally rather low (15–25 wt%) (Schirrmeister et al. 2007). The sediments are comparable to those in the North American Arctic Coastal Plain where oriented lakes occur. The homogeneity of the sands allows for a uniform distribution of forces driving orientation processes. If these forces operate directionally, orientation can clearly develop. Sediments on the third main terrace, however, are mainly composed of the Yedoma Suite, with peat, sands, and silts with high ground-ice content (30–80 wt%) and inhomogeneous ice distribution (huge ice wedges and intrapolygonal sediments with segregated ground ice in the form of ice bands and small ice lenses) (Schirrmeister et al. 2003). This heterogeneity prevents a continuous distribution of external effects because of the different physical characteristics of the sediments; for example, bulk density or thermal conductivity. Orienting factors, therefore, cannot operate uniformly, and the development of a clear orientation is strongly impeded. The negative correlation between the lake *area* and the *degree of deviation from mean orientation* of

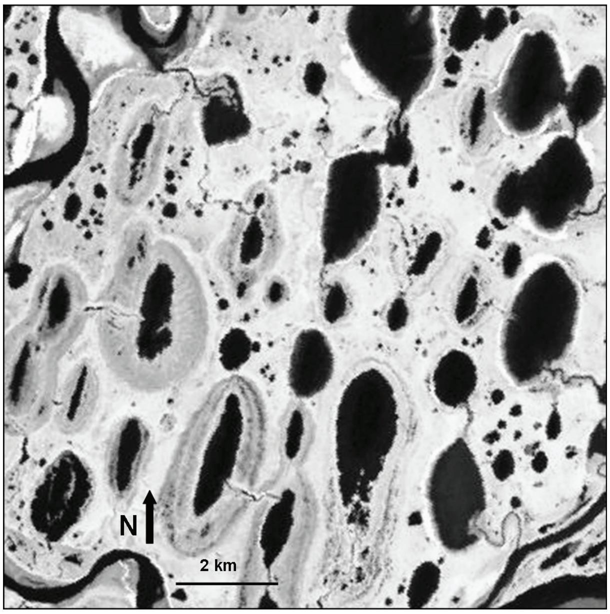

Figure 3. Section of oriented lakes in the western Lena Delta (subset of the Landsat-7 ETM+ mosaic).

the third terrace lakes may still implicate a tendency towards lake orientation in the course of lake growth. The mean NNE-SSW orientation of the poorly elongated third terrace lakes is consistent with that of the second terrace.

As for the cause of lake orientation in the Arctic Coastal Plain, several hypotheses have been discussed. The theory supported by most authors supposes preferential erosion of the lake shores at right angles to prevailing summer wind directions due to wind-driven currents and wave activity (e.g., Livingstone 1954, Mackay 1956, Côté & Burn 2002, Hinkel et al. 2005). The literature reports northern to northeastern main wind directions for the entire Lena Delta in the summer, and southern to southwestern in the winter (e.g., Grigoriev 1993, Gukov 2001). However, wind data of several meteorological stations scattered throughout the delta area show great differences in prevailing directions. Unfortunately, there is no station in the western Lena Delta close to the oriented lakes. Of the three stations closest to the western Lena Delta lakes (Fig. 1), two are situated directly at the Laptev Sea coast. On Dunay Island (73.9°E 124.6°N, data from 1955–1994), wind blows mainly from eastern directions; the Stannakh-Khocho station (73.0°E 121.7°N, data from 1981–1994) registered prevailing winds from southern directions with a minor peak from eastern directions for the whole time span, and from eastern directions at times of positive air temperatures, respectively. The third station is located in the central southern delta on Stolb Island (72.4°E 126.5°N, data from 1955–1991) and shows pronounced southern wind directions. All three stations may not reflect the actual wind situation of the second main terrace, as climate on Stannakh-Khocho and Stolb Island is supposedly influenced by the mountain ranges flanking the Lena Delta in the south. On the Island Dunay, which is a few kilometers off from the mainland of the second terrace, the marine influence has an impact on weather conditions. It can be suggested though, that, because of the flat relief of the second terrace, major wind directions in the inner part of the terrace do not differ much from the situation at its margins; thus wind data from Dunay Island might be the most suitable for assessing the situation on the second terrace. Assuming that the eastern prevailing wind direction measured over the forty-year time span was consistent throughout the lake orientation process, the wind hypotheses proposed for North American oriented lakes might also be applicable for the oriented lakes of the Lena Delta. However, little is known about the detailed conditions and factors that might be involved in lake-orientation processes in the Lena Delta or the stability of wind regimes over Holocene time scales. Further research is necessary to prove or reject any particular orientation theory for this unique Arctic environment.

Conclusions

The three main terraces of the Lena Delta vary largely in the occurrence of morphometric lake characteristics. This led to the deduction of one mean lake type for each terrace. The first main terrace, which represents the modern active delta, is characterized by small lakes of irregular shape, like abandoned lakes. Large oriented lakes with their major axes tending in NNE directions dominate on the second terrace, which consists of Late Pleistocene to Early Holocene homogeneous sands. On the third terrace, which is represented by relics of a Late Pleistocene accumulation plain with heterogeneous fine-grained and ice-rich deposits, typical thermokarst lakes with regular, circular shorelines prevail. Mean morphometric lake characteristics are consistent with the lithological and cryolithological conditions and geomorphological processes prevailing on each terrace. Wind hypotheses proposed for North American oriented lakes might also explain the orientation of lakes on the second terrace of the Lena Delta, but the detailed conditions and mechanisms of the evolution of the oriented lakes in the Lena Delta remain to be investigated.

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