# Reconstructing the Holocene Development of Lake Chaika as an Example of Wetland Formation within the Sand Spit Environment Dynamics: A Case Study from the Curonian Spit, Southeastern Baltic, Russia

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**Abstract:** The paper provides original data that shed light on the formation dynamics of Lake Chaika, which is situated in the central part of the Curonian Spit and is the only large water body in the sand spits of the southeastern Baltic. Based on the multi-proxy approach, incl. investigation of the lithological structure of the bottom sediment cores, loss-on-ignition analysis, diatom analysis, study of macrofossil remains, and radiocarbon dating, we revealed that Lake Chaika was formed already in historical time, around 200 years ago. Before this period, the lake kettle, presumably, has not submerged during the Littorina transgressions, enabling the terrestrial development of the ecosystems on the moraine protrusion. During the mid-late Holocene (6700–150 cal BP), this depression was occupied by the peat-forming fen and alder carr communities. The peat deposits are separated from the overlying layers of gyttja by the thin sand horizon. We consider it a time marker for the so-called "sand disaster", which occurred on the territory of the Curonian Spit in the 18th century (≈1700–1800). The change in the hydrological regime of the lake launched the ecosystem shifts during the last two centuries: from the water body to a wetland and vice versa. It is stated eight formation phases of the lake's ecosystem: the terrestrial development without wet habitats (8900–6700 cal BP), the period of alder carrs (6700–3400 calBP), the sedge fen period (3400–450 cal BP), the period of inundated forest (1500–1700 AD), the "sand disaster" period (1700–1800 AD), the period of eutrophic water body (1800–1900 AD), the period of terrestrialised wetland (1900–1950 AD), and the period of secondary development of eutrophic water body (after 1950 AD).

**Keywords:** palaeogeography, South-Eastern Baltic, paleolimnology, bottom sediments, diatoms, Curonian Spit, Holocene.

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Research Article

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## Introduction

The Curonian Spit, as well as the other sand spits in the southern and southeastern Baltic coast, is a specific geological formation vulnerable to anthropogenic impact. Despite numerous studies that have been carried out over the last two centuries, the origin of the Curonian Spit and the historical patterns of its landscape change are still under scientific discussion. In terms of the landscape heterogeneity of the Curonian Spit, it becomes essential to reconstruct the development history of its different parts and associated ecosystems.

One such area is located in the central part of the spit near Rybachy, where the Late Pleistocene moraine deposits form a rather broad plateau-like protrusion exposed on a surface, determining the development of vegetation different to the other parts of the sand spit. The main feature of this spit sector is the location of a freshwater Lake Chaika (Figure 1), with a surface area of about 0.22 km$^2$. This is the only relatively large water body on the entire Curonian Spit, which – together with areas of wet black-alder forests and lowland meadows – constitutes a peculiar natural complex unparalleled in other sandbars of the Baltic Sea.

Given that lake sediments are a reliable "natural archive" of past environmental conditions, the bottom sediments of Lake Chaika can serve as a source of data for the reconstruction of the development regarding both individual ecosystems and the environment in the whole area of the central part of the spit. It may also indicate anthropogenic influence that played a crucial role in the formation of the landscape on the Curonian Spit.

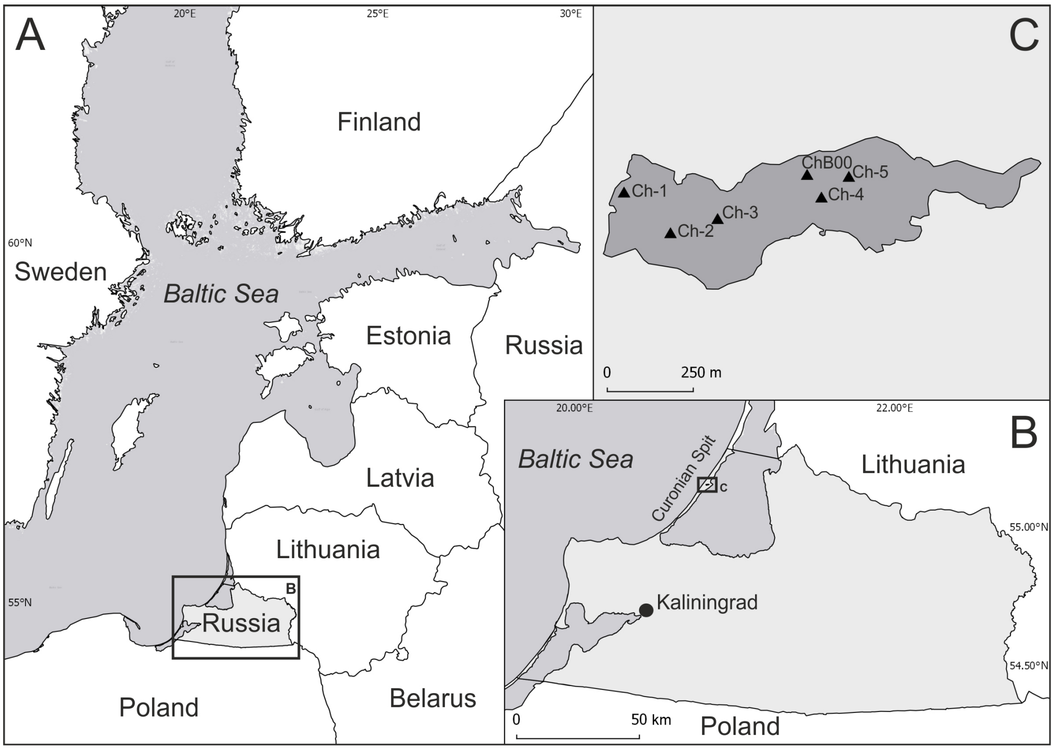


**Figure 1.** The location of the research area: Kaliningrad Province (a), a study site – Lake Chaika (b), coring and sampling points (c).

The human activity on the Curonian Spit was already noted in manuscripts from the 15th–16th centuries [*Mager*, 1938; *Paul*, 1944; *Schlicht*, 1927]. In particular, the authors pointed out the significant role of the territory as a transport route and settlement site (the number of settlements was several times higher than today). In the 17th and 18th centuries, massive clearance of the primary forests began, resulting in almost complete deforestation of the area and triggering the movement of the sand material. This event has gone down in history as the "sand disaster" that caused a radical change in the relief of the spit. Only in the middle of the 19th century, the sand movement was stopped by the construction of an alongshore foredune (the sand dyke) and seeding of the sand stabilising plant species. One of the earliest human settlements on the Curonian Spit originated in the area near Lake Chaika, and therefore, the ecosystem development may have been significantly affected by economic activity.

The previous investigations of Lake Chaika were mainly focused on estimation of its ecological state, biological diversity, and hydrochemical characteristics [*Gerb et al.*, 2014; *Gubareva, I. Yu. and Gerb*, 2014; *Kuzmin, S. Yu.*, 2006; *Tsibaliova and S. Yu. Kuzmin*, 2009]. There have been no palaeolimnological studies until the present day, except for particular aspects [*Napreenko et al.*, 2020].

This work aimed to identify the change in ecological conditions in Lake Chaika during the ecosystem development in the Holocene.

**Material and Methods**

The field survey on Lake Chaika was carried out in May 2018 and August 2019 from a makeshift floating platform attached to a catamaran for mountain rafting (model "Monya", Triton ltd.). To select coring locations, we preliminary performed depth measurement and probed the thickness of deposits in 25–50 m increments using a graduated Russian peat corer with a probe chamber (TBG-66 model).

Since the water level in the lake may differ in spring and summer due to seasonal changes in precipitation, we provide two depth scales for comparison (Figure 2) – for the higher water level in spring (May 2018) and the lower one in summer (August 2019). In the text, we refer to the summer depth scale, as this is the basis of the bathymetric and bottom relief map of Lake Chaika [*Napreenko et al.*, 2020].

Sediment cores were retrieved using the Russian peat corer equipped with semicylindrical sampling chambers of 100 cm in length, and 50/75 mm in diameter (TBG-66 model). Six sediment cores were collected for further laboratory analyses: Ch-1 (N 55.151,95°; E 20.8212°) 80 cm; Ch-2 (N 55.150,84°; E 20.823,32°) 121 cm; Ch-3 (N 55.151,21°; E 20.825,47°) 100 cm; ChB00 (N 55.152,36°; E 20.829,56°) 250 cm; Ch-4 (N 55.151,77°; E 20.830,21°) 100 cm; Ch-5 (N 55.152,31°; E 20.831,46°) 100 cm (Figure 1C). Sampling was carried out at locations as far away as possible from sites where dredging was conducted in the 1980s and 2017.

The loss-on-ignition analysis (LOI) was performed for 105 samples from Ch-2 and ChB00 using the standard methodology [*Santisteban et al.*, 2004; *Sergeeva*, 2011]. The samples were dried at 100 °C for 12 hours and then ignited at 550 °C for 4 hours.

Radiocarbon dating for 12 samples was performed using the accelerator mass-spectrometry method (AMS) at the Radiocarbon Dating and Electron Microscopy Laboratory, Russian Academy of Sciences (Moscow, Russia), together with The Center for Applied Isotope Studies (CAIS), University of Georgia (USA). The obtained radiocarbon dates were calibrated using the CALIB software, version 8.20 [*Stuiver et al.*, 2021] and the calibration curve IntCal20 [*Reimer et al.*, 2020].

The age-depth model for the sediments of the core ChB00 was generated with OxCal software, version 4.4.4 [*Bronk Ramsey*, 2021].

The diatom analysis was performed for the sediment core ChB00. The lab pretreatment followed the standard procedure, including organic matter removal by oxidation in 30% $H_2O_2$ and subsequent washing in distilled water [*Davydova*, 1985]. The size-fraction separation was made using repeated decantation. The slides were analysed with oil immersion at ×1000 magnification. At least 400 diatom valves were counted where possible. In other cases, valves were counted in 5 parallel horizontal transects. The percentages of each diatom species was subsequently calculated relative to the total diatom sum. Other siliceous microfossils, i.e. chrysophyte (golden algae, Chrysophyceae) cysts, spicules (skeleton elements of sponges, Porifera) and phytoliths (siliceous structures formed in plant tissues), were counted alongside with diatoms. Absolute abundances (concentrations per gram dry sediment) of each microfossil group were calculated following *Davydova* [1985]. Diatom diagrams were plotted using the palaeoecological software C2 Version 1.5 [*Juggins*, 2014].

A preliminary plant macrofossil analysis was performed for some peat samples from the core Ch-2 [*Napreenko et al.*, 2020]. The elutriation of peat was carried out on a 250 mm sieve (No. 025K). For the identification of plant macrofossils, a range of identification keys and guides were used [*Dombrovskaya et al.*, 1959; *Katz et al.*, 1977; *Korotkina*, 1939; *Matyushenko*, 1939a,b]. An estimation of peat decomposition degree was performed according to *Piavtchenko* [1963].

**Results**

**Structure of bottom sediments.** Figure 2 shows the 6 sediment cores of Lake Chaika correlated with each other in terms of their lithological structure.

Based on the lithological structure of the cores, the sediment sequence of Lake Chaika may be divided into four nominal parts: clays and loams, a thick layer of peat and peaty gyttja, a thin sand horizon, and an upper thin layer of gyttja.

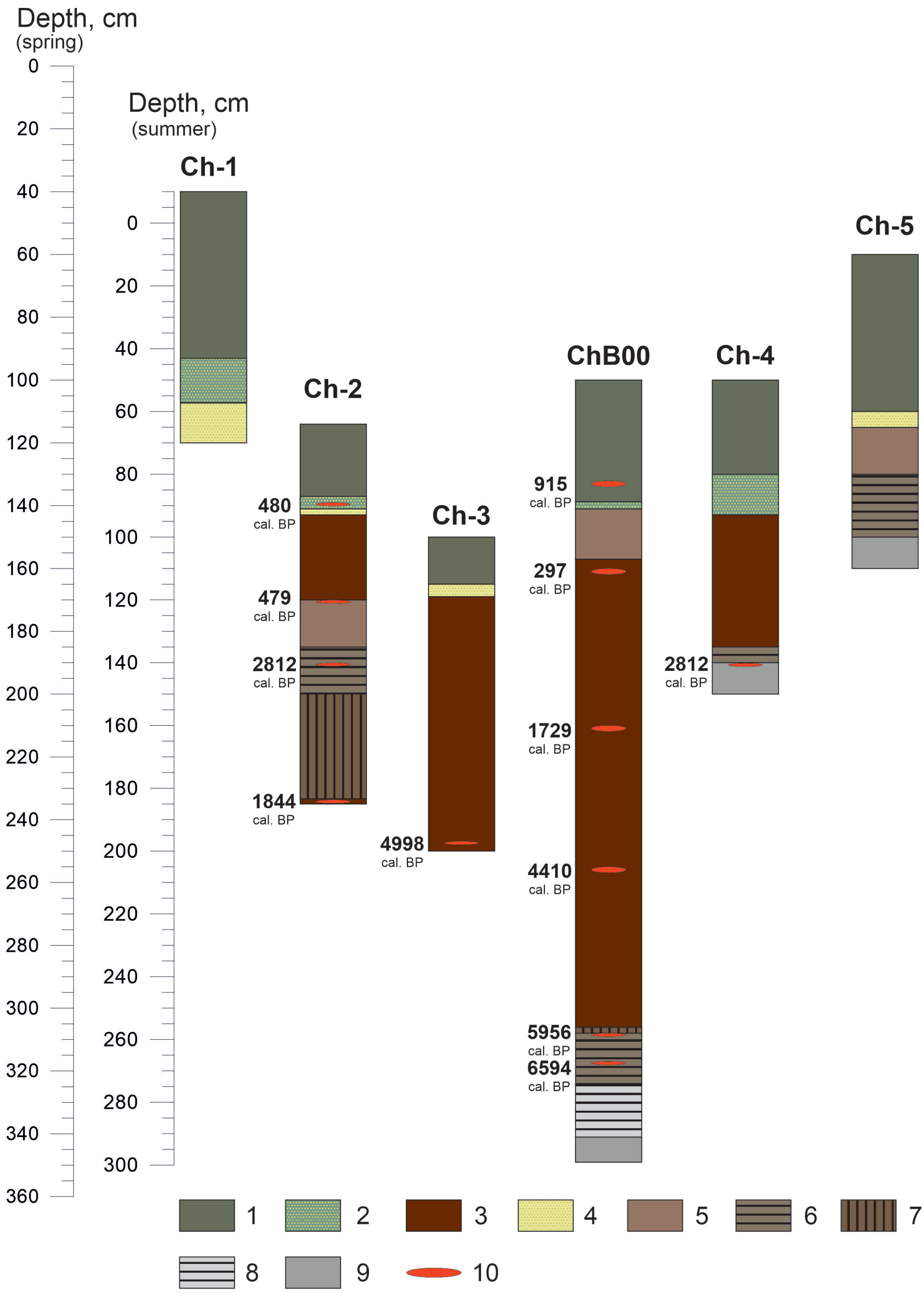


**Figure 2.** Lithological structure of bottom sediment cores from Lake Chaika: 1 – gyttja, 2 – sandy gyttja, 3 – fen/alder carr peat, 4 – fine-grained sand, 5 – peaty gyttja, 6 – transition layer (peat and loam), 7 – brown loam 8 – grey-blue loam, 9 – grey-blue clay, 10 – dated layer.

**Radiocarbon dating.** The AMS-dates for 12 bottom sediment samples from Lake Chaika are presented in Table 1.

The core ChB00 was chosen as a representative for the age-depth model (Figure 3) as the most complete one covering all sediment layers of Lake Chaika, including underlying deposits. The radiocarbon dates of the core Ch-2 were excluded from the age calculation as it showed a repeated inversion of the sediment age. This result may be related to the disturbance of the bottom sediments during dredging operations in Lake Chaika. Due to the same reason, the uppermost date in the core ChB00 (horizon 82–84 cm) was not used in the calculations.

**Table 1.** The absolute age of sediment samples from Lake Chaika based on radiocarbon dating

| Core | Description of sample | $IGAN_{AMS}$ | Radiocarbon age, BP | Calibrated age interval for 1s, cal yr BP | |
|---|---|---|---|---|---|
| | | | | beginning–end | probability |
| Ch-2 | 139–140 cm, TOC | 6839 | 385 ± 20 | 460–499 | 0.865 |
| | | | | 340–347 | 0.135 |
| Ch-2 | 170–171 cm, Plant. rs | 6835 | 420 ± 20 | 436–522 | 0.864 |
| | | | | 333–350 | 0.136 |
| Ch-2 | 190–191 cm, TOC | 6836 | 2740 ± 20 | 2792–2831 | 0.722 |
| | | | | 2837–2853 | 0.278 |
| Ch-2 | 234–235 cm, Plant. rs | 6837 | 1890 ± 20 | 1823–1865 | 1.000 |
| Ch-3 | 247–248 cm, Plant. rs | 6840 | 4430 ± 20 | 4973–5022 | 0.755 |
| | | | | 5027–5044 | 0.245 |
| Ch-4 | 190–191 cm, Plant. rs | 6838 | 2730 ± 20 | 2790–2833 | 0.846 |
| | | | | 2836–2845 | 0.154 |
| ChB00 | 82–84 cm, TOC | 7766 | 980 ± 20 | 904–925 | 0.468 |
| | | | | 805–808 | 0.050 |
| | | | | 827–847 | 0.333 |
| | | | | 856–866 | 0.149 |
| ChB00 | 110–112 cm, TOC | 7767 | 245 ± 20 | 288–306 | 0.814 |
| | | | | 157–163 | 0.278 |
| ChB00 | 160–162 cm, TOC | 7768 | 1840 ± 20 | 1710–1747 | 0.872 |
| | | | | 1766–1780 | 0.128 |
| ChB00 | 205–207 cm, TOC | 7769 | 3940 ± 20 | 4398–4422 | 0.495 |
| | | | | 4299–4327 | 0.297 |
| | | | | 4353–4372 | 0.208 |
| ChB00 | 258–259 cm, TOC | 7770 | 5240 ± 25 | 5936–5976 | 0.640 |
| | | | | 5984–6000 | 0.241 |
| | | | | 6092–6103 | 0.118 |
| ChB00 | 267–268 cm, TOC | 7771 | 5780 ± 25 | 6551–6637 | 0.954 |
| | | | | 6505–6511 | 0.046 |

**Organic matter content.** Using the loss-on-ignition analysis (LOI) for two sediment cores (ChB00 and Ch-2), we obtained data on the percentage content of mineral and organic matter that showed good correlation with the lithological structure of the cores (Figure 4).

The lower part of the core ChB00 is represented by loam and clay (300–260 cm). The percentage of organic matter is minimal and tends to zero. The lower part in the core Ch-2 (185–183 cm) contains highly decomposed ligneous peat with an organic content of

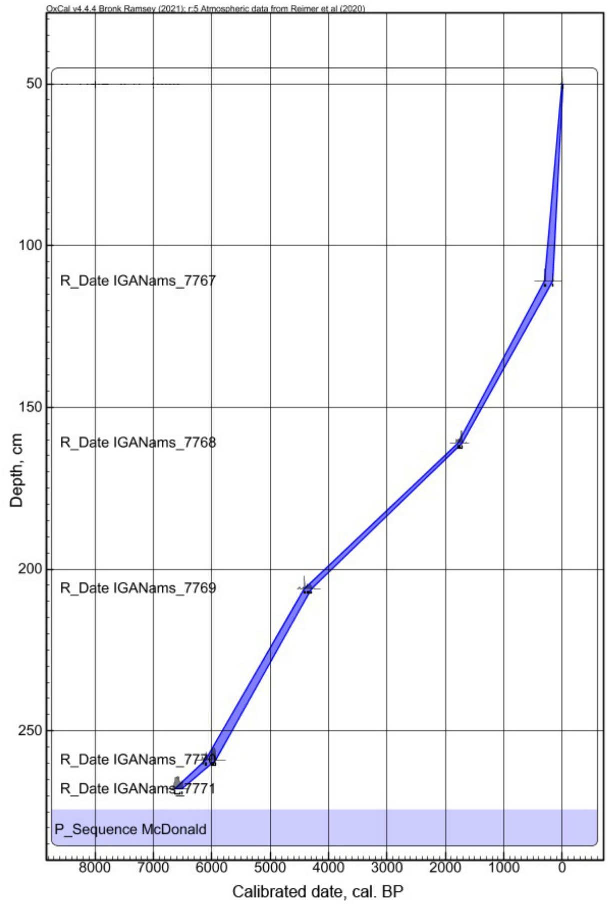


**Figure 3.** Age-depth model for the core ChB00, Lake Chaika.

75 to 82%. Further up the core (183–140 cm), the percentage of organic material drops sharply to 40% and gradually continues to decrease. The deposits are represented by brown loam. After this section, the LOI-curve changes are very similar in both cores.

The overlying deposits in the middle part of both cores are thick layers of the alder carr peat, fen peat, and peaty gyttja (256–91 cm in ChB00 and 140–93 cm in Ch-2) with the highest values of organic matter content. The sharp increase in the organic matter (50–60%), which indicates high rates of bioproductivity, could be associated with the changing environments in this period.

The minimum values of organic matter content (6–17 %) were registered in the very thin but distinct horizons of sandy gyttja that cover thick peat layers in both cores (91–89 cm in ChB00 and 91–87 cm in Ch-2). In core Ch-2, the sandy gyttja horizon is also underlain by the distinct horizon of the pale fine-grained sand (93–91 cm). The deposits of these horizons probably have the aeolian origin that has caused the allochthonous input of sandy material into the ecosystem.

The uppermost deposits in both cores (89–50 cm in ChB00 and 87–64 cm in Ch-2) consist of homogeneous water-logged gyttja with an organic matter content increasing to 25–50%.

In contrast to ChB00, the curve of Ch-2 has many small abrupt peaks despite the homogeneity of sediment layers. These differences may be related to disturbances in the continuous layering of the sediments caused by dredging near point Ch-2.

**Diatoms.** Four local diatom assemblage zones (DZ) were visually distinguished in the sediment core ChB00 based on the shifts in the composition of the diatom assemblages and siliceous microfossil concentrations (Figure 5).

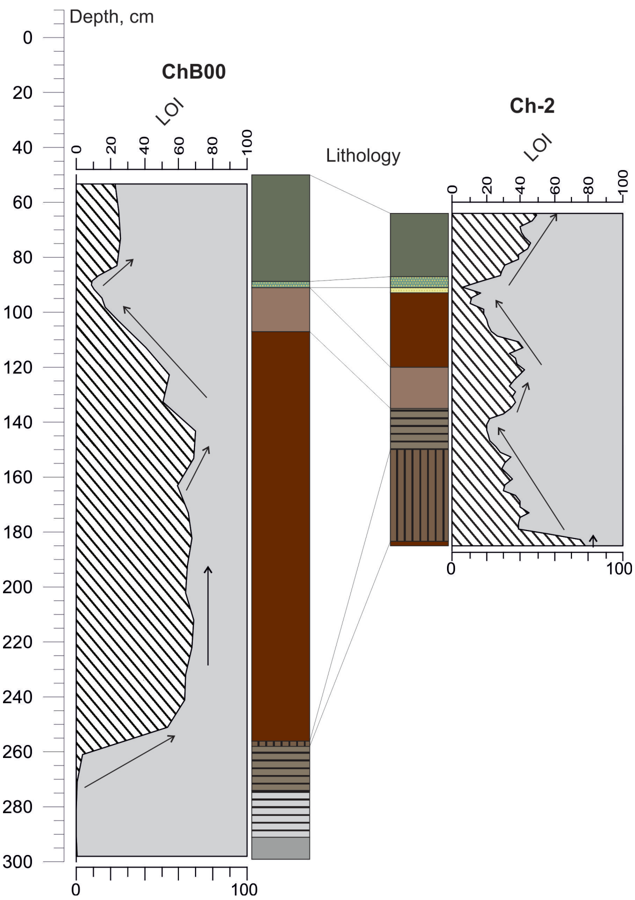


**Figure 4.** The diagram of the organic-minerogenic ratio (dashed and grey contour accordingly) in the cores ChB00 and Ch-2.

In the DZ-1 (270–116 cm), only sporadic valves and valve fragments of mainly benthic diatoms were found. In the 270–189 cm interval, no diatoms were recorded after examining five parallel transects. The diatom concentrations are low, and their increased values (17–37 thousand valves $g^{-1}$ dry sediment) were observed around 132–120 cm. Chrysophyte cysts were found in almost all sampled intervals (Figure 5b). Their concentrations are generally low, increasing to 0.18–1.4 million around 142–120 cm. In some samples, sponge spicules and phytoliths were also sporadically observed. Their absolute abundances are also low, slightly increasing in the upper part of the DZ-1.

The DZ-2 (116–86 cm) is characterized with the rapid increase in abundances of all groups of the siliceous microfossils. Their highest concentrations were recorded around 102–100 cm (3.4 million diatom valves, 1.2 million chrysophyte cysts, 339 thousand sponge spicules, and 193 thousands phytoliths). Benthic species dominate in the diatom assemblages, with small-celled colonial periphytic halophilous *Fragilaria sopotensis* (to 43%) and alkaliphilous salinity-indifferent *Staurosirella pinnata (*14–24%) being the most abundant (Figure 5a). In the lower part of DZ-2 freshwater periphytic *Eunotia implicata* and *Cymbella cuspidata*, and bottom-living *Navicula vulpina* and *Pinnularia* spp. were recorded as well.

In the lower and upper parts of the DZ-3 (86–56 cm), the diatom concentrations do not exceed 1 million while increasing to 5.9 million around 72–70 cm (Figure 5b). Chrysophyte cyst and phytolith abundances increase upwards (to 1.2 million and 0.6 million, respectively). Spicules concentrations vary from 0.16 to 0.2 million in $g^{-1}$ dry sediment. *F. sopotensis* disappears from the diatom record, while *S. pinnata* decrease in abundance (Figure 5a). Other small-sized colonial freshwater periphytic Fragilariaceae (*Staurosira con-*

*struens*, *S. binodis*, *S. venter*) dominate. The percentage of planktonic halophilous *Cyclotella meneghiniana* rapidly increases around 72–70 cm.

In the DZ-4, diatom concentrations rapidly decline to 0.15 million. A decrease in the abundance of the other siliceous microfossils is also recorded. Chrysophyte cysts are the most abundant in this zone (0.8 million). Periphytic Fragilariaceae and *Gomphonema* spp., as well as bottom-living *Amphora libyca* and *Pinnularia* spp., are found sporadically (Figure 5).

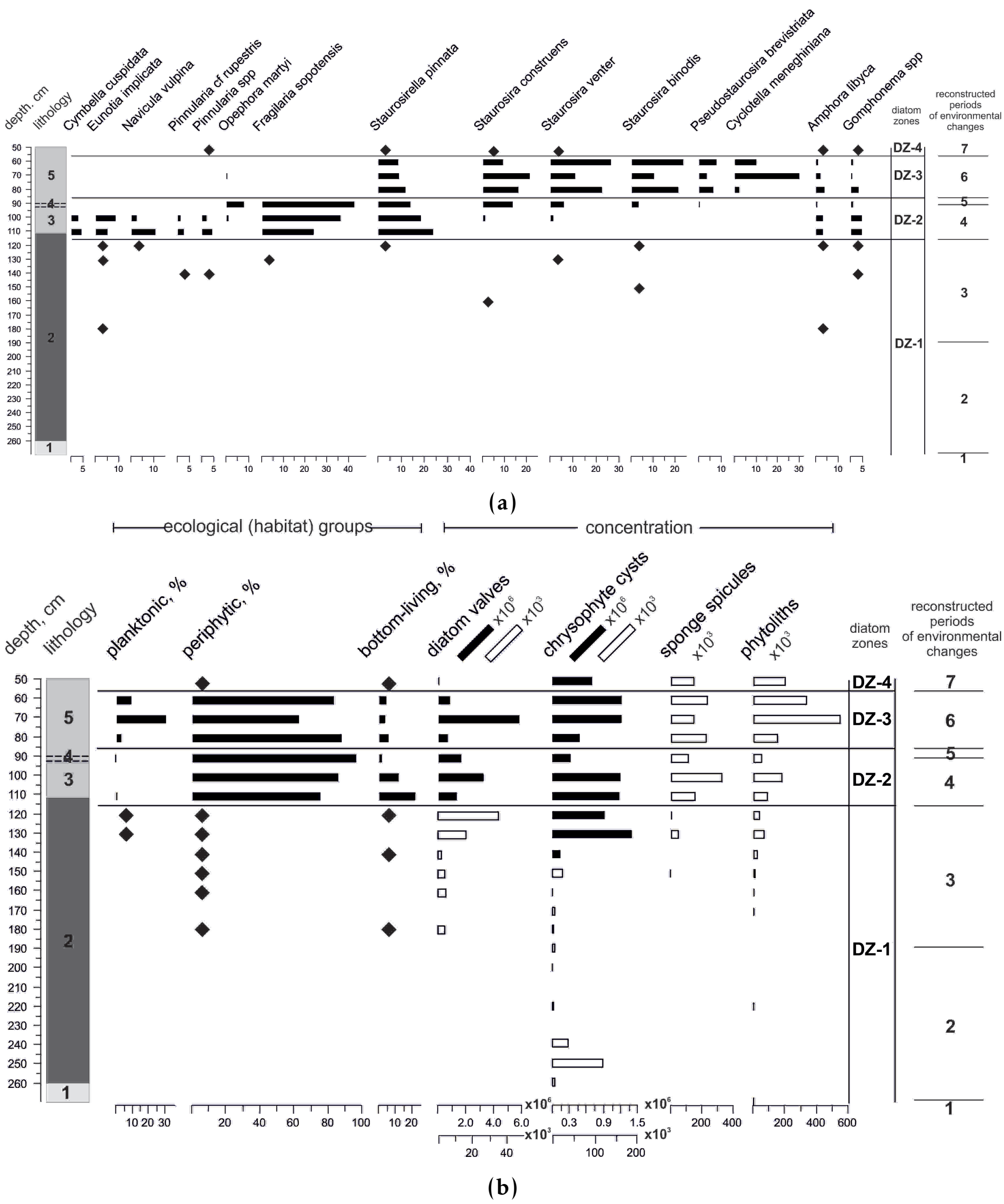


**Figure 5.** Diatom diagram in the sediment core ChB00 of Lake Chaika: (a) – proportions of the main diatom taxa, (b) – proportions of the diatom ecological groups and absolute abundances of the siliceous microfossils (in $g^{-1}$ dry sediment). ◆ (filled diamond) – presence in a sample. Lithology: 1 – silt, 2 – ligneous-sedge peat, 3 – peaty gyttja, 4 – sandy layer, 5 – gyttja.

**Composition of plant macrofossils.** The taxonomic analysis of plant macrofossils, performed for the six samples of the peat from the core Ch-2, revealed the structure of the peat and the nature of the peat-forming ecosystems.

The lower part of the peat core is represented by the alder peat with a very low percentage of herbaceous plants. In the higher horizons, we see the increases in percentage of sedges and other mire herbaceous plants while the abundance of alder residues decreases. The alder peat is replaced by several types of fen peat: ligneous-sedge peat, ligneous-sedge peat with *Menyanthes*, and sedge peat.

The similar structures of the peat cores were identified in Ch-3, Ch-4 and ChB00. The cores Ch-1 and Ch-5 have no peat parts. The detailed botanical composition of the peat samples from core Ch-2 is given in our previous paper [*Napreenko et al.*, 2020]

**1. Discussion**

The results obtained during the research enabled us to reveal the main periods of ecosystem development and characterise the depositional environments in the kettle of Lake Chaika.

**Stage 1. Terrestrial environments (~8900–6700 cal yr BP).** This stage is considered the earliest period of ecosystem evolution in the study area, which we correlate with a section 300–270 cm of the core ChB00 represented by a grey-blue loam. These sediments contain no biogenic palaeoindicators, and the character of the ecosystems existed here could not be ascertained. According to the published data on deglaciation in the south-eastern Baltic Sea [*Kazakauskas and Gaigalas*, 2004; *Lasberg and Kalm*, 2013; *Rinterknecht et al.*, 2008; *Uścinowicz*, 1999], this area became ice-free between 13600–13300 cal yr BP and should have developed in the terrestrial regime after the glacial water drainage. The lake kettle was presumably not submerged during the Littorina transgressions of the Baltic Sea, being located on a protruding moraine plateau. Nevertheless, the small absolute heights of the terrain and the sea level rise during the Littorina transgressions [*Damušytė*, 2011; *Uścinowicz*, 2006] may have increased the groundwater level and further development of wet biotopes thereafter.

**Stage 2. Black alder carr (6700–3400 cal yr BP).** This stage corresponds to the lower diatom zone DZ-1 (270–189 cm). The most unfavourable environments for the diatoms are inferred most probably due to moisture deficiency. It correlates with the sediment composition that is mainly ligneous peat except for the lowermost part represented by loam. Such peaty sediments could form under the black alder carr that are typical of the present-day Curonian Spit. The development of alder carrs has apparently launched more intensive peat accumulation [*Napreenko et al.*, 2020], which is reflected in the sharp increase of the organic matter content (Figure 4).

Although the development of a carr ecosystem requires wet or waterlogged soils, the open-water environments with sufficient depths suitable for aquatic biota could hardly exist in the area during this period. Thus, the "aquatic" microfossils sporadically found in the sediments, i.e. diatom valves, chrysophyte cysts, and sponge spicules (Figure 5), are apparently allochthonous.

**Stage 3. Sedge fen with local aquatic environments (3400–450 cal yr BP).** The stage corresponds to the upper DZ-1 (189–116 cm). Increased diatom and chrysophyte concentrations suggest gradual inundation of the area, resulting in the appearance of waterlogged habitats favourable for the colonisation of microalgae, primarily chrysophytes. The composition of the deposits, represented by the sedge-bogbean-ligneous peat [*Napreenko et al.*, 2020] indicates the transition from the black alder-dominated ecosystem to a fen with diverse herbaceous vegetation. The inundation of the area is probably associated with occasional flooding, which may have led to the formation of locally restricted aquatic environments where the microalgae could thrive. However, low abundances of "aquatic" microfossils indicate that subaerial conditions still prevailed in the area.

**Stage 4. Alder carr with the open inundated sites (450–250 cal yr BP / 1500–1700 AD).** The stage corresponds to DZ-2 where further increasing concentrations of diatoms and chrysophytes point out to sedimentation in subaquatic/aquatic environments as the inundation of the area proceeded. Thriving of the small-celled colonial diatoms from the Fragilariaceae family is characteristic of this period. High abundances of halophilous *Fragillaria sopotensis*, commonly inhabiting the coastal marshes along the Baltic Sea coast [*Witkowski et al.*, 2000], might indicate somewhat increased concentrations of mineral salts and periodically occurring moisture deficiency typical of such habitats. Periphytic *Staurosirella pinnata* and *Eunotia implicata*, abundant in the diatom record, can also thrive both in water bodies and in wet habitats [*Dam et al.*, 1994]. The former, however, is salinity-indifferent and tolerates a wide range of trophicity, while the latter is a halofobous species, preferring oligo- and dystrophic environments. Other common species in the diatom assemblages include oligotrophic *Cymbella cuspidata*, that can be found in periodic water, and meso-eutrophic *Navicula vulpina*, never occurring outside water bodies. The composition of the diatom assemblages may thus reflect the alternation of periods of higher and lower inundation, which is consistent with the structure of the deposits represented by peaty gyttja.

Among the macrofossil residues, the wood remains became again dominant here (> 40%), and the percentage of non-arboreal residues was also considerable [*Napreenko et al.*, 2020], while the organic matter content was still high (Figure 4). Such composition may reflect the development of a typical wet alder carr with some open places. One can also suggest that diverse habitats were characteristic for this time interval as permanently and periodically wet sites with different concentrations of nutrients and mineral salts could co-exist in the area. The presence of permanently wet (aquatic) habitats is also inferred from high abundances of sponge spicules, i.e. siliceous skeleton elements of aquatic invertebrates inhabiting lentic and lotic waters.

The above-mentioned ecosystem changes can be reasonably attributed to increased anthropogenic pressure. Higher concentrations of grass phytoliths may indicate an expansion of the open treeless sites in the surrounding area, probably resulted from the deforestation. It is also confirmed by historical literary sources [*Mager*, 1938; *Paul*, 1944; *Schlicht*, 1927] indicating on an active distribution of agricultural land plots in the vicinity of Rossitten village (nowadays, Rybachy) in the 16th and 17th centuries, which was associated with deforestation and the construction of drainage ditches. All this may have enhanced nutrient leaching and their release from the fields into the depression of the wetland ecosystem.

**Stage 5. Active dune migration: the "sand disaster" (250–150 cal yr BP / 1700–1800 AD).** The stage corresponds to the upper DZ-2 (91–86 cm). The macrofossil analysis [*Napreenko et al.*, 2020] revealed no textured plant residues in samples, as the LOI diagram (Fig. 4) showed an abrupt decline in the organic matter content. Decreased concentrations of all groups of the siliceous microfossils may reflect an increased input of the allochthonous material that resulted in the formation of the thin layer of sand or sandy gyttja. This layer, separating the lower thick peat deposits from the upper gyttja, can be attributed to the so-called "sand disaster" that resulted from the mass deforestation of the Curonian Spit.

The main developments during the "sand disaster" took place in the 17th and 18th centuries [*Mager*, 1938; *Paul*, 1944; *Schlicht*, 1927], which is in line with our age model. It was, presumably, during the period 1700–1800 AD, after forest destruction, when significant unstable masses of sand came into motion and swept up the territory around Lake Chaika in a short time. This event may have caused the loss of wetland communities and resulted in the deposition of a thin layer of fine-grained sand and sandy gyttja in Lake Chaika, which we met in all sampled sediment cores.

Deforestation of the lake's surroundings and degradation of mire communities may have led to the rise of the ground-water table and accumulation of water in the natural depression of Lake Chaika, where the permanent water body formed. It resulted in a change of depositional environments when peat-forming processes stopped, and the formation of lacustrine gyttja with occasional admixture of aeolian sand started.

**Stage 6. Shallow eutrophic lake (150–50 cal yr BP / 1800–1900 AD).** The period corresponds to DZ-3 (86–56 cm). The sediments rapidly turn to liquefied gyttja at this stage, where the textureless particles are predominant as the organic matter content (Figure 4) showed a distinct increase. This sediment type was found above in the sandy layer in all sediment cores collected in Lake Chaika. The sediment character and diatom assemblage composition indicate a shallow eutrophic lake with at least 1 m depth occurred in the area.

High abundances of planktonic *Cyclotella meneghiniana*, preferring higher nutrient and salt concentrations suggest larger water depths than during the previous stages. This species is also common in the freshwater parts of the Baltic Sea [*Snoeijs*, 1993]. The disappearance of *Fragillaria sopotensis* from the diatom record and the declined proportions of *Staurosira pinnata* reflect the reduction of periodically wet habitats. Small-celled periphytic *Staurosira construens*, *S. binodis* and *S. venter*, that form ribbon-like colonies on the submerged substrate, became abundant in the diatom record, indicating stable aquatic environments.

High concentrations of grass phytoliths and diatom-inferred nutrients may indicate the expansion of deforested areas along the lake shores. It may reflect the increased agricultural activity on the lake's catchment and the use of the lake as a sink, receiving catch-water from the local drainage system contributed to the eutrophication of Lake Chaika.

**Stage 7. Terrestrialised wetland with mosaic helophytic vegetation: Möwenbruch/ Chaika Mire (50–0 cal yr BP / 1900–1950 AD).** The recent stage of ecosystem development corresponds to DZ-4 (56–50 cm). The gyttja sediments became more liquefied, but the environments were unfavourable for diatoms, as suggested by their decreased concentrations. A simultaneous decline in abundance of the other siliceous microfossils may reflect increased sediment accumulation rates, which might result in the lake shallowing. New conditions, presumably, accelerated the processes of natural lake ageing, which triggered the mire-formation and caused the transition from the lacustrine to the wetland environments.

The shallow depths and high nutrient load of the water body have led to a rapid development of hygrophytes in the coastal zone and their gradual expansion towards the centre of the water body. As evidenced by literary sources [*Mager*, 1938; *Schlicht*, 1927] and archival data, the ecosystem was a mosaic of biotopes during this period, including patches of riparian and fen-like herbaceous vegetation, shallow areas with open water, and outcrops of gyttja.

Numerous photographs of the early 20th century indicate abundant gull colonies bred here and harvesting of gull eggs by local inhabitants. Toponymical data also support this suggestion indirectly since the pre-war name for Lake Chaika – "Möwenbruch" – is German for "gull mire", but not "lake".

Such environmental status of the ecosystem seems to be a result of both the gradual development of the natural lake ageing during the preceding phase and a rapid accumulation of nutrients from the fields in the Lake Chaika kettle. The low level of the groundwater table probably impeded inundation of the kettle due to a well-developed drainage system.

**Stage 8. Shallow eutrophic water body – Lake Chaika (after 1950 AD).** This stage is a recent period in the development of the ecosystem that has again become a shallow eutrophic water body. The changes were possibly caused by the abandonment of agricultural activities, poorly maintained drainage system and dredging operations. The average depths in the present-day lake are about 0.5 m, even in the places with thickest deposits (about 2 m). The deepest zones in the lake are located in the places of dredging, which do not exceed 1.6 m [*Napreenko et al.*, 2020].

The habitat alterations during stages 4–8 enable us to suggest that, over the last 500 years, the development of ecosystems in the kettle of Lake Chaika was determined by human activities, which might substantially change their hydrological regime and ecological characteristics, resulting in the transition from an aquatic habitat to a wetland

and vice versa. On the other hand, the Lake Chaika of the present day is a highly vulnerable site, affected by both environmental factors and anthropogenic activity.

**Conclusions**

Based on the results of our investigation, which embrace the lithological structure of the lake bottom sediment cores, loss-on-ignition analysis, diatoms, macrofossil remains, and radiocarbon dating, the following conclusions were made:

1. The development of Lake Chaika shows eight phases during the last 9000 years. The recent lacustrine environments were preceded by the period of terrestrial environments (~8900–6700 cal yr BP) and the long-term period (6700–150 cal yr BP) of alternating peat-forming ecosystems of the black alder carrs and sedge fens that formed thick layers of ligneous and sedge peat.
2. As a water body, Lake Chaika was formed in the recent past, around 200 cal yr BP (early 19th century).
3. The sand horizon, separating the gyttja layer from the peat deposits in the lake kettle, is considered to be a time marker for the "sand disaster", which occurred in the 18th century (~1700–1800 AD) on the Curonian Spit.
4. The formation of Lake Chaika was influenced by both environmental and anthropogenic factors. The former defined the ecosystem development during the most period of time (8900–450 cal yr BP, stages 1–3), while the latter factors dominated over the last 500 years (450 cal yr BP – present time, stages 4–8) and included agricultural activities, maintaining the drainage system, and dredging operations.
5. Changes in the hydrological regime of Lake Chaika over the last 200 years have presumably caused the transition of the aquatic ecosystem into a wetland and vice versa.

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