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**Review**

# Soil Cover Modifications in Vicinity of Disappearing Lakes as a Result of Climate Change

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Disappearance of lakes is one of the most dangerous processes affecting the entire natural environment, including soil. This phenomenon is considered natural, resulting from climate change, however in recent decades, a significant acceleration of this process has been observed due to the direct impact of human activity. In areas directly adjacent to lakes, organic soils usually predominate. Unfortunately, wetlands are increasingly being drained and used for agricultural purposes. Under such circumstances, changes in the physical and chemical properties of these soils are often irreversible, causing their degradation. As an effect of increased mineralization, a number of typical modifications occur in soils, such as carbon loss, increased degree of peat decomposition, and changes in soil structure. Long-term dehydration has led to muck formation. Additionally, lowering of lake water uncovers previously flooded areas and increases the intensity of soil-forming processes. However, the presence of the Subaquatic qualifier in the World Reference Base for Soil Resources (WRB) suggests that sediments in shallow water bodies no more than 200 cm deep can also be classified as soils. The progressive disappearance of lakes observed all over the world is therefore a process affecting not only the reduction of water bodies, but also changes in the properties and typology of soils and vegetation cover.

**Keywords:** lake disappearance, organic soils, water table fluctuations, climate changes, soil mineralization

## 1 Introduction

The process of lake disappearance is an issue occurring all over the world. According e.g. to Liu et al. (2006), Choiński et al. (2012), Ptak (2013) and Gross (2017), lakes have reduced their surface area in the last few decades mainly and/or are struggling with the problem of pollution. Research results from Central Europe indicate a dynamic disappearance of lakes. Considering the findings concerning Poland, about 2/3 of the lakes located in the northern part of the country have already disappeared since the beginning of the Holocene (e.g. Kalinowska, 1961; Choiński, 2006; Skowron and Jaworski, 2017). This phenomenon is regarded as a natural stage of landscape evolution (e.g. Marynowska, 2018; Kruczkowska et al., 2021), however a significant acceleration of the lake disappearance rate in recent decades is increasingly being determined by climate change and intense human impact, e.g., on lake catchments as a result of rapidly developing agriculture and other branches of the economy (Marszelewski et al., 2011). Human activity, mainly agriculture, contributes to a significant impact on the natural environment, including lakes. According to Dega et al. (2022), deterioration of the lake waters quality, which may result in its disappearance, is a direct consequence of prevailing land use type in the catchment area. Agriculture is the main source of pollution and mechanical filling of lakes by increased erosion, thereby leading to their gradual disappearance and progressive changes in soil properties in its immediate vicinity. According to Kruczkowska et al. (2021), one of the main factors influencing the water level fluctuations in lakes is also the intensive deforestation and the increase in the area of arable land. Shallow, extensive water reservoirs are the most threatened landforms by water level fluctuations (e.g., Langdon et al., 2012; Mendyk

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et al., 2015). Areas adjacent to lakes are usually wetlands covered with organic soils. There is an extensive literature on drainage-induced changes in the properties of organic soils. Modifications of the soil cover as a result of the disappearance of lakes, especially in the context of organic soils, are analogous to those resulting from the drainage of peatlands. Nevertheless, soils in lake catchments are often characterized by the presence of lacustrine deposits, which significantly affect the properties of peat accumulated on them. Rapid disappearance of water bodies is a key factor in the formation of gyttja land with lake bottom sediments deposited near the surface shaping the directions of soil cover development (Łachacz & Nitkiewicz, 2021). Peatlands are considered to be transitional environments between terrestrial and aquatic ecosystems (e.g. Mitra et al., 2005; Krueger et al., 2015). According to Chapman et al. (2003) and Łachacz (2004). It is acknowledged that these areas play a key role e.g., in the provision of global ecosystem services, shaping hydrological phenomena, and creating habitats for plants and animals. Disturbance of the natural cycle of water circulation as a result of dehydration caused, e.g., by changing the type of land use, induces irregularities in the functioning of such type of ecosystems and specific soils classified as Histosols (IUSS Working Group WRB, 2022). Soils as an element of natural environment are particularly vulnerable to changes in properties caused by fluctuations of the lake water level. As Mendyk et al. (2015) noticed, it is important to recognize directions of changes taking place in lacustrine soils in connection with the development of other elements of the natural environment. According to Kruczkowska et al. (2021), the first phase of lake disappearance took place in the Late Glacial and Holocene as a result of climate change. Human influence on accelerating the process of lake disappearance is noticeable since around the 19$^{th}$ century (Markiewicz et al., 2017). As Lemkowska and Sowiński (2018) noticed, thickness losses of organic soils averages 1 cm per year. Taking into account the varying thicknesses of peat sediments in the lake catchments, the process of organic soils disappearance may occur at different rates and lacustrine sediments may begin to play the major soil-forming role in former lakes areas (Lemkowska and Sowiński, 2018; Łachacz & Nitkiewicz, 2021).

The aim of this study was to compile literature data on changes in selected soil physical and chemical properties as a result of the disappearance of lakes, with particular emphasis on organic soils.

## 2 Material and methods

Data on the literature related to changes in soil cover as a consequence of the disappearance of lakes was retrieved mainly from a review of the research carried out in Poland.

Due to the prevalence of data relating to changes in the organic soils properties as a result of drainage, resources regarding this dehydration were also used without direct reference to the disappearance of lakes. The review was based on searches for the phrases „lake disappearance", „drained Histosols" and „lacustrine sediments".

## 3 Results and discussion

### *3.1 Soil morphology, selected physical properties and classification modifications as an effect of dehydration*

Disappearance of lakes is a gradual process, hence the organic soils located at further distances, once within the reach of the lake, are currently undergoing the greatest transformation. For this reason, morphology and properties of organic soils located in the vicinity of disappearing lakes are determined by the distance from lake. Peat thickness decreases with the progressing drainage (Rovdan et al., 2002). Based on the Rakutowskie Lake example (Kruczkowska et al., 2021), the thickness of peat material was 40–80 cm in profiles located near the lake to 0.2 m profiles furthest from the water surface of the modern lake area. Additionally, the degree of peat decomposition changed with the distance from the lake, from R1 and R2 in profiles located close to the lake to R3 in those without access to lake water (Fig. 1).

However, changes in soil morphology as a result of drainage are shaped over hundreds or even thousands of years, as can be seen from the example of radiocarbon dates obtained for the soils in the immediate vicinity of Rakutowskie Lake. According to Kruczkowska et al. (2021), distance from the lake has a key impact on the intensification of mineralization processes, soil moisture, the degree of peat decomposition, and thus soil classification. In dehydrated soils an increase of bulk density is observed. Bulk density of peat (depending on the peat type) with fully water-filled space pores usually oscillates around 0.02–0.26 g.cm$^{-3}$ (e.g. Przewoźna, 2013; Systematyka gleb Polski, 2019; Sinclair et al., 2020; Kruczkowska et al., 2021). This value increases significantly to about 0.35 g.cm$^{-3}$ in the initial phase of drainage to above 0.50 g cm$^{-3}$ in heavily drained organic soils (e.g. Mustamo et al., 2016; Kruczkowska et al., 2021) (Table 1).

According to Rezanezhad et al. (2016), pore sizes in undecomposed peat can exceed 5 mm. Significant changes of pore sizes result from dewatering, compression, and decomposition. The decrease of porosity of drained soils is particularly visible in its upper

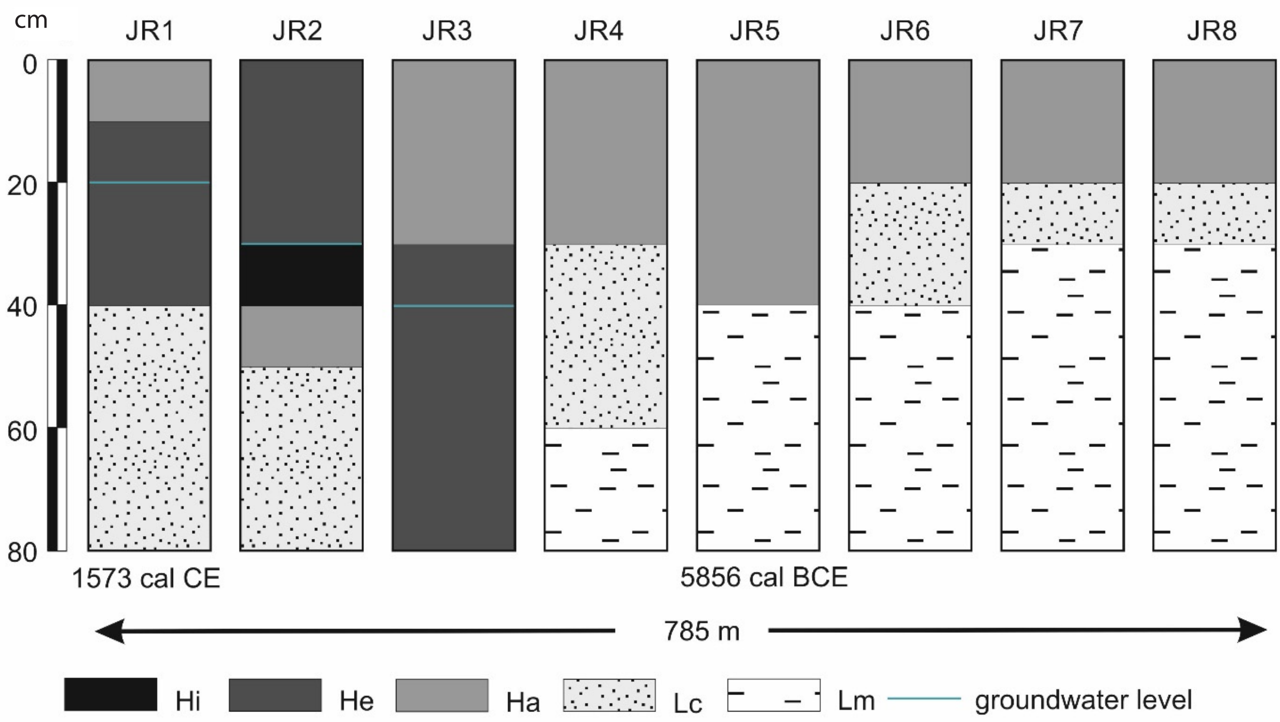


**Figure 1** A scheme of changes in soil morphology and peat thickness in the transect located in the direct vicinity of Rakutowskie Lake (Designations of soil horizons based on WRB, 2015)
Source: Kruczkowska et al., 2021

horizons. In deeper located horizons of soils where the groundwater level has dropped by about 0.2–0.3 m, a decrease of porosity (by about 1–4%) is also observed despite of its 100% humidity (Kruczkowska et al., 2021). Changes of pores sizes has an impact on water storage. For this reason, muck does not have such high water retention capacity as peat, and therefore one of the basic functions of peatlands is disturbed as a result of drainage (Moore et al., 2005; Bragazza et al., 2008; Rezanezhad et al., 2016).

Drainage also brings an alteration in soil typology, documented by many researchers (e.g. Gonet et al., 2010; Kruczkowska et al., 2021). Due to irreversible changes in peat properties caused by the mineralization process, soils originally classified as Histosols no longer meet the criteria for this type and are assigned to Regosols and Gleysols. These, occurring in limnic mineral deposits underlaying layers of peat or muck, often have relic features in the form of groundwater gleying marks (Gonet et al., 2010). Lacustrine sediments (e.g., highly calcareous gyttja) may also be found on the surface of areas adjacent to lakes, and then they are classified as Limnic Rendzinas (Lemkowska and Sowiński, 2008, 2009, 2018).

The evolution of lake shorelines and thus the direction of soil development is often also determined by the type of land use. The consequence of lake disappearance is a change in the use of once under-water areas. The intensification of erosion processes at undulated arable fields located in the direct vicinity of lakes contributes to increasing the area of colluvial soils (Gonet et al., 2010; Markiewicz et al., 2015; Mendyk et al.; 2016; Markiewicz et al., 2017; Lemkowska and Sowiński,

**Table 1** Examples of various peat types bulk density

| | Bulk density (g.cm$^{-3}$) |
|---|---|
| **Hi (fully saturated with water)** | 0.02–0.1 (Systematyka gleb Polski, 2019); 0.12–0.13 (Przewoźna, 2013; Kruczkowska et al., 2021) |
| **Hi (dehydrated)** | 0.17 (Glina et al., 2016); 0.21 (Przewoźna, 2013) |
| **He (fully saturated with water)** | 0.17 (Glina et al., 2016; Kruczkowska et al., 2021) |
| **He (dehydrated)** | 0.8–0.14 (Sinclair et al., 2020); 0.17–0.18 (Kruczkowska et al., 2021) |
| **Ha (dehydrated)** | 0.48–0.55 (Markiewicz et al., 2015); 0.16–0.23 (Glina et al., 2016); 0.21–0.63 (Przewoźna, 2013); 0.34–0.68 (Mendyk & Markiewicz, 2013); 0.37–0.51 (Kruczkowska et al., 2021) |

2018). The presence of colluvic sediments on the surface of organic soils provides protection against the progressive marshing process (Mendyk et al., 2016; Markiewicz et al., 2017). Drained areas are also often transformed into grasslands, pastures, and meadows (Choiński et al., 2012; Glina et al., 2016; Lemkowska and Sowiński, 2018) causing additional changes in soil properties (Mendyk and Markiewicz, 2013; Markiewicz et al., 2015; Kruczkowska et al., 2021).

### *3.2 Selected chemical properties of dehydrated soils*

Most peatlands in Central Europe have been transformed as a result of lakes overgrowth (Łachacz & Nitkiewicz, 2021). The occurrence of lacustrine sediments (e.g. gyttja) in the bottom of peat material exerts an impact on many chemical peat and muck properties. The highest pH values of calcareous gyttja often noticed in the littoral zone of the former lakes are caused by the high content of carbonates, often up to 90–95% (Rutkowski, 2007; Kruczkowska et al., 2021). The pH of organic soils lined with gyttja is relatively high and may even reach values above 7 (Gonet et al., 2010; Mendyk et al., 2014; Kruczkowska et al., 2021). Usually, the pH value increases with distance from the lake and thus with a decrease of peat thickness, which results from the greater availability of lake sediments rich in $CaCO_3$. However, pH of soils composed of transitional peat, is low (below 4) as an impact of humic acids. Additionally, acidification of top peat deposits may be also associated with a lower groundwater supply (Tokarz et al., 2015). On the other hand, high pH values, especially in the bottom horizons may result from the impact of ground water, rich in base cations (Smólczyński, 2006; Markiewicz et al., 2017).

According to Maciak and Liwski (1996), high content of $CaCO_3$ affects rapid organic matter decomposition and increased mineralization rate. High carbonates contents in lacustrine sediments are usually recorded in the zone of small-thickness organic layers, which additionally accelerates the process of peat transformation into muck (Łachacz et al., 2009). Shiel and Rimmer (1984) observed that an increase in soil pH leads to an increase in microbial activity, which may affect the mineralization of organic matter. However research results of Jenkinson (1977) showed that changing the soil pH from 4.9 to 8.1 had only little impact on the organic matter decomposition rate. Mineralization is most favoured by soil moisture of 60–70% by volume and 20–30% air content (Piaścik & Gotkiewicz, 2004). As Clark et al. (2011) noticed, peat drainage led to $CO_2$ emission to the atmosphere and also accumulation in groundwater. A decrease in total organic carbon (TOC) content and an increase in total nitrogen (TN) are observed in dehydrated peat soils. Another crucial phenomenon is also marked in C/N values. According to Truba and Oleszczuk (2014), C/N ratio in natural peat is wide – about 1 : 20, while in decomposed organic material and marsh reaches values about 1 : 12. This regularity has also been confirmed by Kruczkowska et al. (2021). However, according to Gonet et al. (2010), C/N ratio in undecomposed peat may reach values about 1 : 40. It should also be noted that the presence of mineral cover on organic sediments contributed to maintaining a wide C/N ratio in peat soils (Gonet et al., 2010). TOC and TN contents in peat varies depending on the peat type and thickness, degree of decomposition and moisture status (Liwski et al., 1984). According to Kruczkowska et al. (2021), one of the main factor determining the TOC content in peat soils was the groundwater level. Soil horizons with the same degree of decomposition but different moisture significantly differed in the TOC content. Hemic peat with fully water-filled space pores was characterized by the TOC content over 500 $g.kg^{-1}$, while in horizons with 85–89% filled with water these values were lower by about 30–180 $g.kg^{-1}$ (Kruczkowska et al., 2021). In dehydrated fibric peat studied by Gonet et al. (2010), the TOC content was relatively stable in surface horizons (327–328 $g.kg^{-1}$), however the factor influencing the stabilization of the TOC content at high level (>400 $g.kg^{-1}$) was the presence of colluvial sediments on the peat surface. As Lasota and Błońska (2021) noticed, total C store in dehydrated Histosols is only about half that in soils with normal water conditions.

Increase in TN is usually observed in strongly decomposed peat and marsh. TN content also varies with the distance from the present-day l lake water table and groundwater level. Research conducted by Gonet et al. (2010) shows that in Histosols covered with colluvic sediments, the TN content is about 20 $g.kg^{-1}$ lower than in peat soils located on the surface. A significant increase in nitrogen content is also observed in strongly decomposed peat and marsh soils (Okruszko, 1993; Łachacz et al., 2023). However this trend is not clearly visible in research results obtained by Kruczkowska et al. (2021).

## 4 Conclusions

Transformation of soil cover in the direct vicinity of disappearing lakes applies to both organic and mineral soils. In both cases, significant changes in physical and chemical properties occur as a consequence of dehydration (Fig. 2).

The properties of dried organic soils also depend largely on the characteristics of the lacustrine deposits occurring at their bottom. The rate of change in the primary soil properties is additionally closely related to the thickness

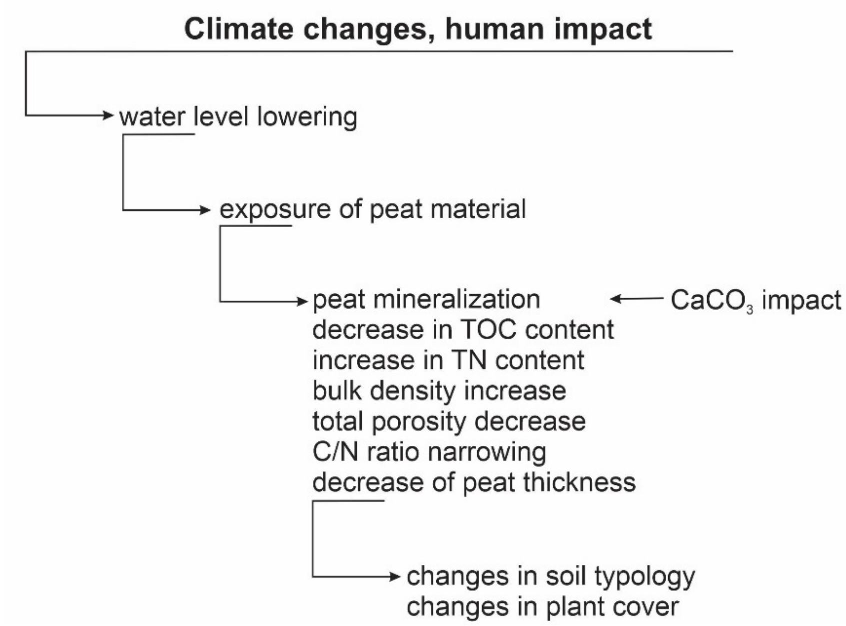


**Figure 2** A simplified diagram of the climate change and human activity impact on changes in soil cover in areas of disappearing lakes

of organic soils and the distance from the contemporary lake water level. As a result of drainage and progressive mineralization of organic soils, the original soil typology often changes completely, causing irreversible modifications in lake ecosystems and their catchments.

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