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Reconstruction of the primary bottom of a unique crater lake in the "Meteoryt Morasko Reserve" (Poland)

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Abstract. There are a total of several million lakes in the world, which includes only approximately 30 crater lakes. Due to this extreme global rarity, they are the subject of research in many scientific disciplines. In spite of the widespread interest in them, however, many issues still require detailed investigation. In the case of the Morasko crater lake (Poland), hydrological research has been weakly developed so far. The undertaken analysis, which employed a complex research procedure involving the use of georadar, geological corings and bathymetric measurements, aimed to determine the primary bottom of the lake, and further to determine the scale and rate of its evolution. The modern water level suggests that the lake basin is currently approximately 55% filled in with organic matter, and the rate of its sedimentation in the deepest place can be estimated at approximately 0.8 mm·y^{-1}.

Key words:
meteorite lake,
impact crater,
GPR,
Morasko

Introduction

Our understanding of the world can be generally defined as the knowledge of the processes and phenomena that occur there. In modern knowledge, extreme or exceptional situations that are peculiar in comparison to their surroundings are particularly interesting (Ptak et al. 2019). In hydrological research on lakes, one group of such features includes those whose existence is related to the impact of a meteor. Among the 76 genetic types of lake basin in the world (Hutchinson 1957), only the development of crater lakes is related not to processes occurring on Earth, but to an extra-terrestrial factor. According to various estimates (depending on the adopted classification), the number of lakes in the world can be estimated at several million (Choiński 2000). Of this very abundant group, only about 30 lakes are of meteoric origin, and occur alone or in groups. One of the very few places in Europe where crater lakes occur is the environmental reserve "Meteoryt Morasko" in western Poland (Fig. 1).

Due to the specificity of crater lakes, they are objects of interest in various scientific disciplines. This is confirmed by the abundance of literature (Vlierboom et al. 1986; Kristen et al. 2007; Ugalde et al. 2007; Antony et al. 2012; Mokate et al. 2014; Paul et al. 2016). Many scientific issues remain unclear, however. The object analysed in this paper has still not been investigated in a complex manner. While there is an extensive group of studies describing the analysed crater, the research has particularly focused on its geological or geomorphological aspects

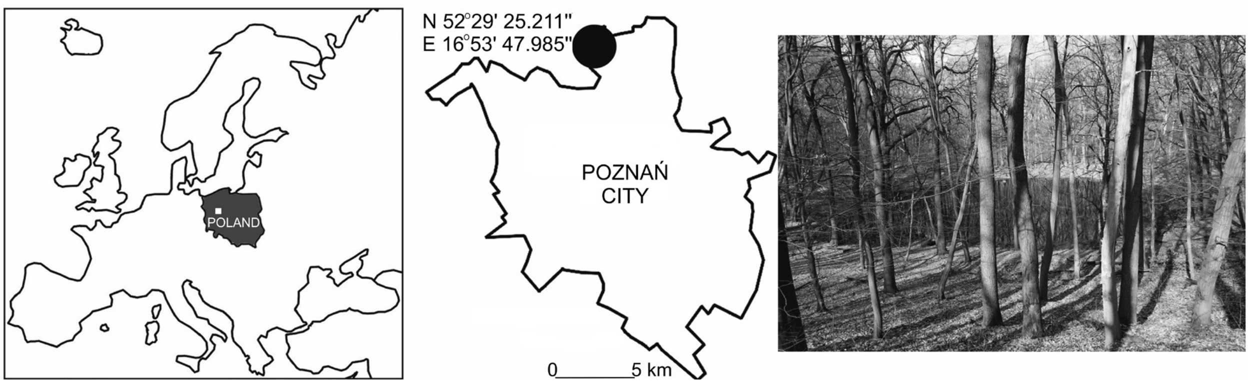

Fig. 1. Location of study

(Pokrzywnicki 1957; Hurnik 1976; Stankowski and Muszyński 2008; Duczmal-Czernikiewicz and Muszyński 2015; Karwowski et al. 2015; Miśta et al. 2015; Duczmal-Czernikiewicz et al. 2018). More broadly, however, i.e. in terms of research in other scientific disciplines, there are considerable deficits of information. This is also true of the hydrological approach. Certain papers concerning water parameters exist (Klimaszyk 1996; Świdnicki et al. 2016), but many issues (including elementary ones) have still not been investigated.

The objective of the paper is to reconstruct the primary bottom of the Morasko crater lake, and to attempt to determine the rate and causes of its evolution.

Study object

The data base on impact craters (EID) contains approximately 200 known places in the world. In 29 of them, lakes of various sizes occur (from hundreds of metres to several tens of kilometres across), and are mostly hidden in hard lithified rocks. The unique character of the crater lakes in the Meteoryt Morasko reserve consists in the fact that the impact occurred in soft glacigenic sediments approximately 5,000 years ago. Only in four other places in the world has the impact been recognised to have occurred in non-consolidated sediments and left a crater that was small but not filled with water (Wabar, Ilumetsa, Whitecourt and Carancas).

The impact type of the Morasko meteor is that of the small impact of an iron meteorite shower (IAB). The impact resulted in the appearance of seven meteor craters and a distribution ellipse (NE–SW) (strewn field) of approximately 4 km long. The largest crater being researched here has a diameter of approximately 100 m and is filled with water. The remaining craters have a diameter of 60 m to 20 m, are not all filled with water, and dry out periodically (Choiński and Ptak 2017).

Research on the Morasko meteor dates back to 1914, when, during a military training exercise, a lump of metal weighing 77.5 kg was encountered (Stankowski 2009). Over more than a hundred years, many studies have been published concerning the craters and meteor (Muszyński et al. 2012; Pilski et al. 2013). The latest research involved a new investigation of the geological structure around the meteor craters, and confirmed the young age of the impact and its range (Szokaluk et al. 2015; Szczuciński et al. 2016).

Data and Methods

The determination of the shape and thickness of the organic filling of the crater lake involved a complex research procedure employing, among others, georadar measurements, geological corings, and analyses with the application of an echosounder. The georadar method is a non-invasive geophysical technique that provides an image of sediment structures. A high-frequency electromagnetic wave is emitted by the transmitting antenna. Part of the signal is reflected at the boundaries between sediments of differing dielectric properties, and returns to the receiving antenna. The depth range and resolution of measurements depend on many factors such as the frequency of the emitted signal, the type of sediments building the substrate, and the groundwater level. The higher the frequency of the emitted electromagnetic wave, the higher the measurement resolution. However, this detail is gained at the cost of a shallower depth range than that provided by antennas emitting lower frequencies. Uniform sediments attenuate the electromagnetic wave, limiting the depth range (Van Heteren et al. 1998; Neal 2004; Sass et al. 2010). Detailed characteristics of the georadar method and examples of its application have been presented by Neal (2004), Lamparski (2004) and Karczewski (2007). A georadar has also been used in research on lakes and meteors. Kopeikin et al. (2013) used the methods in search of a meteor that fell in Lake Chebarkul (Russia) in 2013.

Geophysical measurements were performed by means of a MALA ProEx georadar equipped with 100-MHz and 250-MHz screen antennas. A clear image of the organic filling of the lake basin was obtained by means of a 100-MHz antenna. Images obtained by means of a 250-MHz antenna are not shown in the article because of a high number of disturbances, which made interpretation impossible. The measurements were performed along seven measurement lines (Fig. 2). The research was performed by placing an antenna on a pontoon and releasing a signal automatically every 1 second during movement. Due to the high number of fallen trees and the overgrown shores, georadar measurements were not possible in the near-shore zone of the lake.

The depth range of the georadar measurements was 3.6 m. It was determined based on the comparison of types of georadar reflexes, and data concerning the sediments filling the lake basin and the depth of their contact with the underlying loams. Greater depths were inferred based on the performed corings. Such data were obtained for 11 corings performed by means of a manual corer using a tube sampler (Fig. 2).

Georadar images were processed by means of ReflexW 5.0 software (Sandmeier 2008). The "move starttime" tool corrected the delay of the so-called "first break" (time of commencement of a measurement on a given georadar route). High and low frequency disturbances were removed using the "subtract-mean dewow", "time dependent bandpass", and "subtracting average" filters. The "Automatic Gain Control" tool was used to strengthen reflexes with low amplitudes. The "background removal" tool removed disturbances that occurred after strengthening the signal. The "time cut" tool was used to remove the bottom parts of particular georadar images containing information that was impossible to interpret. The description of results of research on depth is provided in reference to the lake bottom.

Moreover, the field works involved measuring water depth using a Lowrance Elite-3x echosounder. The works were performed in accordance with the assumptions adopted by Choiński et al. (2016). The position of each depth measurement, as well as the range of the lake shoreline, was determined by GPS.

Results

The presented echograms show wavy, horizontal and concave reflexes, and places where georadar reflexes are weak or absent (Fig. 3). The comparison of georadar profiles with data from the corings showed that wavy reflexes or the lack of reflexes in the bottom parts of the echograms signify loamy sediments. Reflexes occurring within loamy sediments may represent disturbances that could not be removed during the processing of echograms, or objects sunken in the preliminary period of the lake's functioning. Such reflexes are visible e.g. between 0 and 10 m of profile 2 at a depth of 1.5 m below the surface of the lake bottom (Fig. 3). The exception is the bottom part of profile 6, where reflexes are weak or absent in places where organic sediments occur.

Evidently concave reflexes occur at: 20–40 m of profile 1 at a depth of 0.9–1.4 m below the lake bottom (Fig. 3); 0–8 m and 20–44 m of profile 2 (depth: 0.9–1.4 m; Fig. 3); 0–23 m and 38–43 m of profile 3 (depth: 0.3–1.3 m; Fig. 3); and 0–12 m and 18–36 m of profile 4 (depth: 0.7–1.3 m; Fig. 3). They are also visible at: 0–15 m and 25–32 m of profile 5 (depth: 0.9–1.4 m); 0–15 m and 27–35 m of profile 6 (depth: 0.9–1.4 m); and over the entire length of profile 7 (depth: 0.9–1.3 m; Fig. 3). Such reflexes may be associated with contact between organic sediments filling the lake basin and the

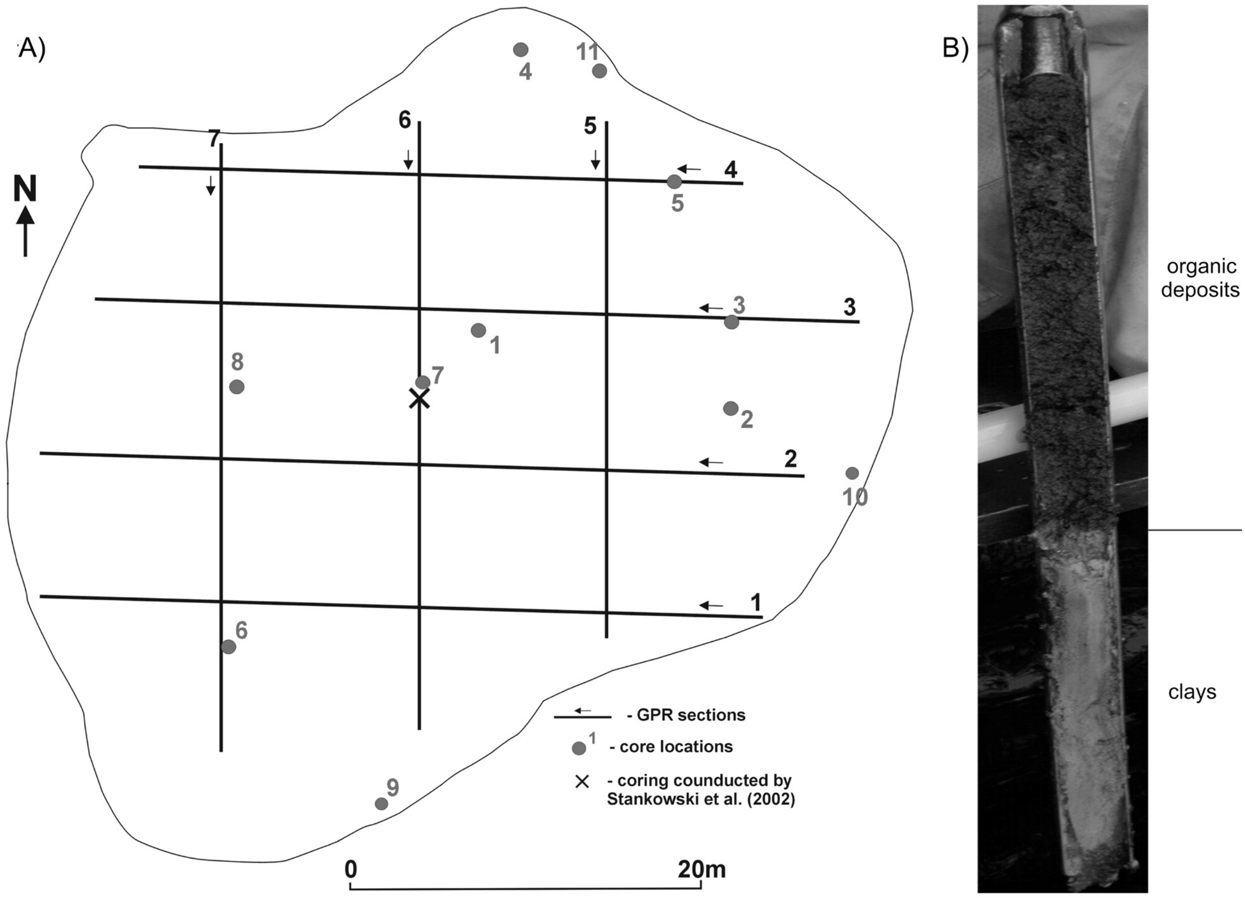

Fig. 2. Diagram of locations of georadar profiles and measurement sites (A); and example geological coring (site No. 2) presenting the place of contact of organic matter with primary rock (B)

loams occurring below. The contact corresponds with the primary lake bottom.

Wavy and horizontal reflexes occur over the entire length in all of the georadar profiles, at depths from 0.3 m to 1.4 m below the lake bottom. These may be associated with the occurrence of organic sediments. Research conducted by Stankowski et al. (2002) showed that the thickness of the sediments in the middle of the lake is 4.1 m. Their contact with the underlying loams, however, was not illustrated on echograms due to strong attenuation of the signal by water with a thick suspension and water-saturated organic sediments.

Wavy reflexes are clearly visible within the organic sediments. They occur in the middle parts of georadar profiles at: 8–38 m of profile 2 at a depth of 0.9–1.0 m (Fig. 3), 24–37 m of profile 3 at a depth of 0.9–1.2 m (Fig. 3), 10–15 m and 24–30 m of profile 4 at a depth of 1.0–1.4 m (Fig. 3); 12–32 m of profile 5 at a depth of 0.8–11 m; 18–28 m of profile 6 at a depth of 0.8–0.9 m; and 0–15 m of profile 7 at a depth of 0.5 m (Fig. 3). Such reflexes may signify interlayers of weakly decomposed plant macroremains occurring in the organic sediments. The presence of this type of material was recorded during corings.

The boundary between wavy reflexes and the lack of reflexes in the upper part of the echograms corresponds to the lake bottom. Reflexes in the shape of a hyperbole occurring above the lake bottom come from sunken objects such as tree branches (Fig. 3). The research permitted the determination of the primary (in reference to the modern water level) and current bathymetric plan of Lake Morasko (Fig. 4).

Discussion

In reference to meteor impacts in soft sediments, Uścinowicz (2014) mentions two possible situations.

The first involves the fast erosion and disappearance of the crater. The second situation occurs when the crater is larger, allowing it to be preserved in the environment, but active denudation processes can lead to difficulties in interpreting certain processes. The analysis of the Morasko crater lake's bottom relief conducted in the paper showed considerable transformations from the moment of its development. The first phase of transformations of the morphometry of the lake basin was related to processes occurring after the explosion. Ejected and mixed loose sediment developing the slopes of the crater was susceptible to the activity of gravitational forces. This led to overland flow and downhill creep, and further movement of matter within the developed basin. This process is associated with the deepest part of the lake located in its central point (Fig. 4a), which was not reached by such amounts of sediments from the newly developed slopes. The style of deformation and extent of disturbances of the substrate were not identified. The research only permitted the determination of the boundary between loams and organic matter. The presence of the latter is a result of the second phase of transformations in the morphometry of the lake basin caused by the appearance of vegetation in the vicinity of the crater. Its succession and seasonal changes in the vegetative cycle led to the accumulation of organic sediments, as presented in Figure 5.

Based on the above profiles it was calculated that the volume of filling of the lake basin with organic sediments amounts to approximately 55% of the primary volume of the lake (relative to the current water level). Assuming that the impact occurred approximately 5,000 years ago, the lake basin must have filled at a rate of $10\% \cdot 1000^{-1}$ years. Considerable filling of the primary lake basin occurs in a similar impact lake (Kaali), which is the nearest to the analysed object (it is in Estonia), as presented by Saarse et al. (1991). The depression is filled with a layer of at least 5–6 m of limnic sediments (Veski et al. 2004). In the case of Lake Morasko, the thickness of organic sediments is quite variable, and ranges from 1 to 4 metres (Fig. 6).

In reference to the deepest zone, it can be assumed that the accumulation rate of sediments averaged approximately $0.8 \text{ mm} \cdot \text{y}^{-1}$. The modern shores of the lake are overgrown by dense deciduous hornbeam–oak forest. Due to this, it is shaded by a specific "umbrella of branches". This supplies a high amount of organic matter to the water. Moreover, the steep neighbouring slopes cause intensive overland flows of surface waters that supply plant remains and clastic material to the lake. Due to their proximity to high slopes, crater lakes can be compared to mountain lakes located in glacial corries. One example of such an object, among others in Poland, is Lake Mały Staw in the Karkonosze Mountains. Similar research with the application of GPR showed that the primary basin of the lake is filled with sediments of considerable thickness (Gądek et al. 2015). Although the lithological composition of sediments is different than in the analysed case, in the considerable growth in both of the cases, slopes with high inclination were of key importance for transport of matter.

In the analysed case, the largest layer of sediments occurs in the central part of the lake. The matter there is deposited not only by direct sedimentation from the water depths, but also by transport (generated by circulation) from near-shore zones. Analogically, in the shallowest zone of the lake, organic sediments are washed out most intensively, and therefore their lowest thickness is observed. It should be emphasised that the evolution of the lakes is common. In general, in the majority of cases, from the moment of origin of the lakes, factors leading to filling and levelling of the concave landform start to have an influence (Choiński 2007; Choiński and Ptak 2020). The process of decline itself involves two components – horizontal (overgrowing) and vertical (water level fluctuations, sediment deposition) – and the dominance of particular processes is strictly related to the individual features of the lakes and their catchments. The results presented in the paper correspond with the global trend of research concerning the evolution of lakes. It should be emphasised that this issue constitutes one of the primary research problems in limnology (Lange 1993). There is a good number of papers discussing the evolution of lakes in reference to processes observed above the water surface (Gao et al. 2011; Ptak et al. 2013; Ptak 2015; Zhang et al. 2015; Nowak and Ptak 2018). The investigation of the decline of lakes, however, should consider their three-dimensional character. Very frequently, at a relatively stable water level, a decline of lakes

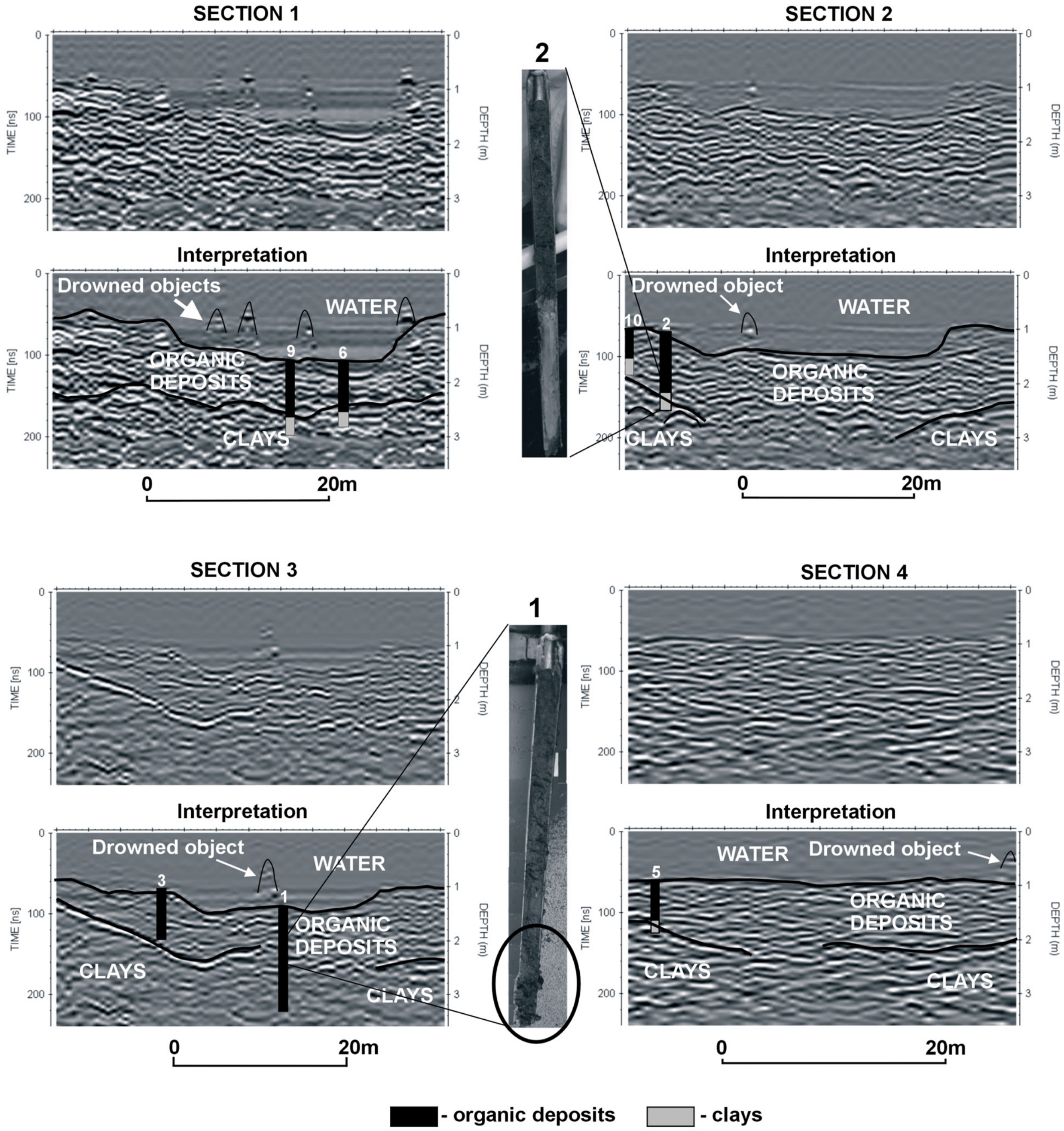

Fig. 3. Echograms illustrating the thickness of organic sediments and relief of the primary lake bottom

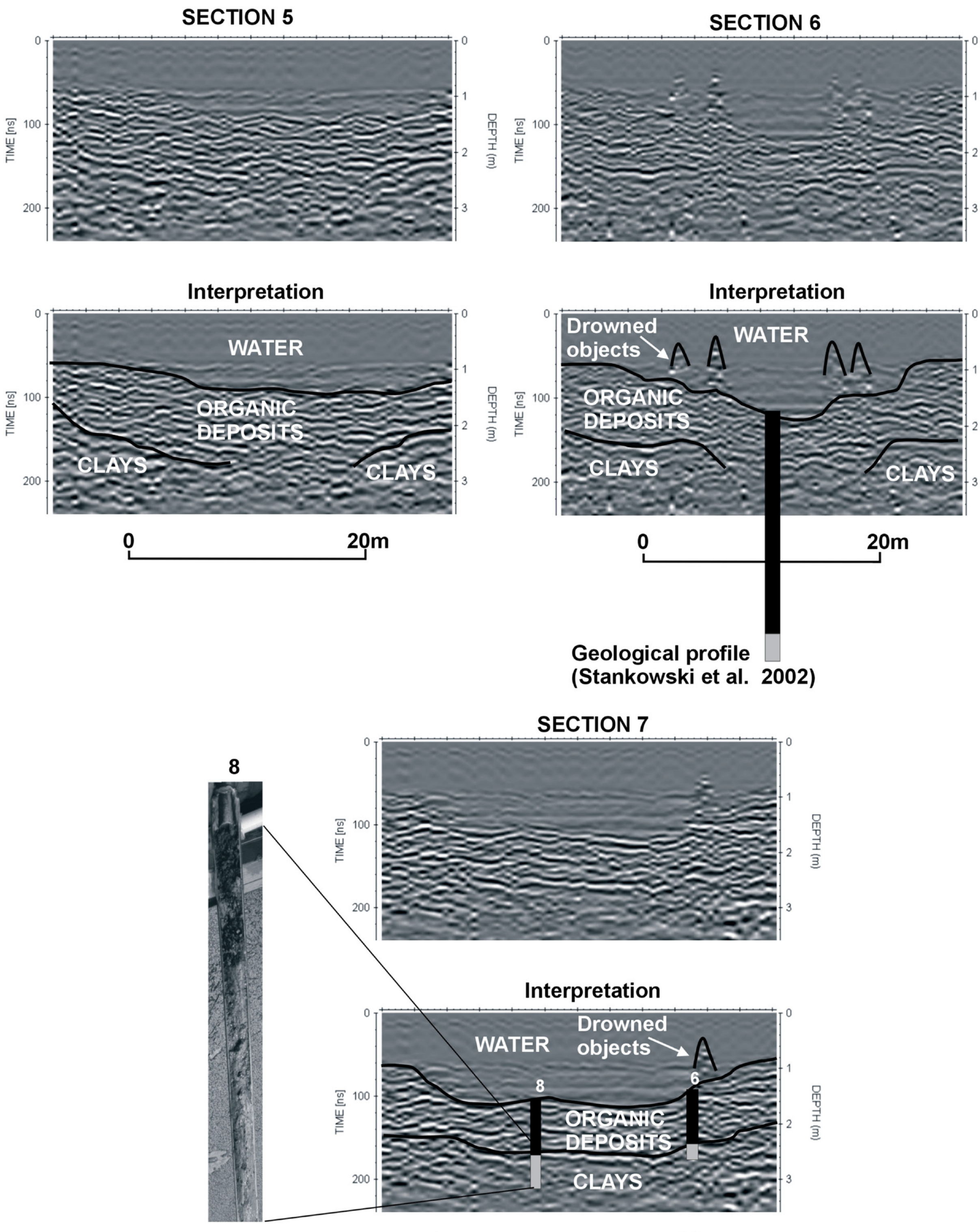

Fig. 3. Continuation

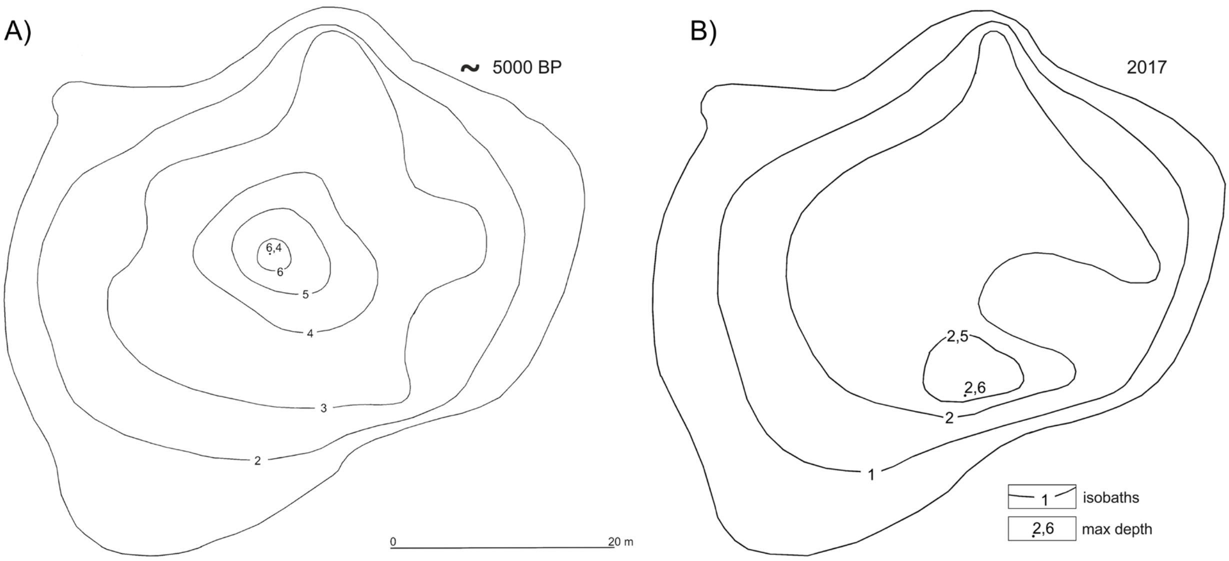

Fig. 4. Bathymetry of Morasko crater lake, primary (A); and modern (B) – after: Choiński and Ptak (2017)

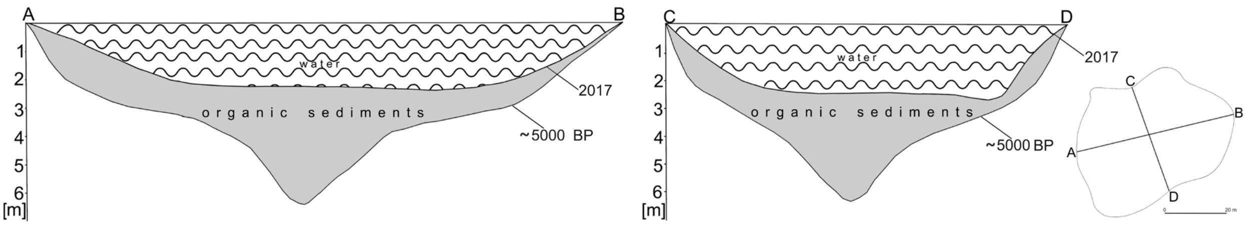

Fig. 5. Cross sections through Lake Morasko

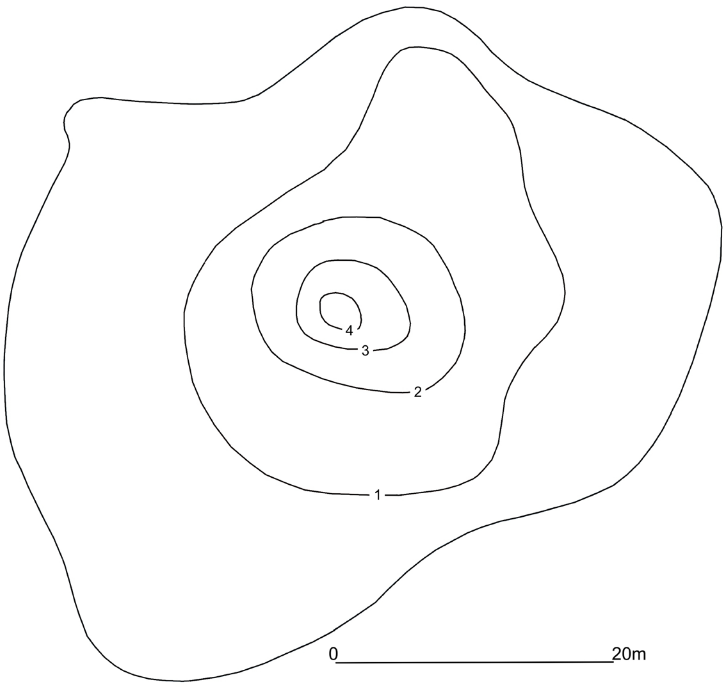

Fig. 6. Thickness of organic sediments deposited in Lake Morasko

occurs that is defined as a decline of water resources (Choiński and Ptak 2009). Therefore, it is important to use a complex approach to the issue, considering processes occurring above and below the water's surface. Research based on such assumptions is increasingly common (Wiśniewski and Wolski 2005; Choiński et al. 2014; Weis and Kubinský 2014; Fuska et al. 2015; Ławniczak-Malińska et al. 2018), and the results presented in the present paper enrich the related knowledge. An important fact in the broader aspect of hydrological research should also be emphasised. The paper expands knowledge on the functioning of shallow lakes, research on which according to Józsa (2014) still shows moderate level, and the issue is also noticed by other authors (Brillo 2016; Shirokova et al. 2016).

Conclusions

A very specific group of lakes in the world includes those whose genesis is related to more than just processes occurring on Earth. Due to their exceptional character, crater lakes are a subject of many studies. On the other hand, it should be emphasised that in many fields the current state of knowledge of crater lakes is still very poor. This is true, for example, of the hydrological aspect of the crater lake described in this paper. The undertaken analysis employed a complex research procedure aimed at determining the primary bottom of the lake, and further to determine the scale and rate of its evolution. It was determined that, from the moment of its origin, the lake basin was developed by two factors, namely processes related to transport of primary matter transported gravitationally from the slopes of the meteor impact crater, and sedimentation of organic matter. The modern water level suggests that the lake basin is currently approximately 55% filled in with organic matter, and the rate of its sedimentation in the deepest place can be estimated at approximately 0.8 mm·year^{-1}.

In addition to its purely descriptive character, the paper aims to be a starting point from which to initiate complex hydrological research (into, among others, water level fluctuations, determining the thermal regime, water balance, etc.) into one of the most unique lakes in the world. In the hydrological aspect, the obtained results correspond with two issues that are under-appreciated in the literature, namely those concerning small lakes and analyses of the evolution of lakes that treat them as three-dimensional objects.

Disclosure statement

No potential conflict of interest was reported by the authors.

Author Contributions

Study design: A.C., A.M., M.P., M.S.; data collection A.C., A.M., M.P., M.S.; statistical analysis: A.C., A.M., M.P., M.S.; result interpretation A.C., A.M., M.P., M.S.; manuscript preparation M.P., M.S.; literature review: A.C., A.M., M.P., M.S.

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