GEOGRAPHY AND TOURISM, Vol. 9, No. 2 (2021), 59-66, Semi-Annual Journal
eISSN 2449-9706, ISSN 2353-4524, DOI: 10.34767/GAT.2021.09.13

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Thermal conditions of freeze-thaw processes on the cliff face in winter 2019–2020 on the Jeziorsko Reservoir, central Poland

Abstract: The thermal conditions of freeze-thaw processes acting on the active cliff face of the Jeziorsko Reservoir were recognised based on temperatures of surface sediments measured directly on the monitored cliff face and data from the Kalisz weather station forming part of the network of the Institute of Meteorology and Water Management –National Research Institute (IMWM-NRI) in Warsaw, Poland. In the period from 15.01 to 04.05.2020, directly on the cliff face, 77 freeze-thaw cycles were recorded over 41 freeze-thaw days (FTD), which, on average, corresponds to two cycles per day. Concurrently, in the same period only 33 FTD were recorded in the instrument shelter, which is 20% less. In addition, the outcomes corroborate the view reported in literature; namely, that on the northern hemisphere vertical cliff faces exhibiting western exposure are advantaged in terms of the development of freeze-thaw processes.

Keywords: cliff recession, thermal conditions, freeze-thaw processes, freeze-thaw day (FTD), freeze-thaw cycle (FTC)

1. Introduction

Cliffs, that is, vertical or nearly vertical walls, are commonly observed land forms at the interface between water and land. These are forms with very diverse morphometric features and activity. This diversity is related to terrain relief and the lithological profile of formations in which such forms develop as well as factors and processes due to which they evolve. The evolution of coastal cliffs on inland still water bodies is initiated by wind waves undercutting the lower part of the cliff through the hydraulic and abrasive impact of water. The cliff face, apart from wave erosion, is also affected by subaerial erosion and denudation processes such as rill erosion, frost weathering and mass wasting (Joeckel and Diffendal, 2004; Brown et al., 2005; Davidson-Arnott, 2010, 2016; Kaczmarek, 2018). Their occurrence and activity depend on several factors, including – most importantly – the lithological profile of formations, exposure to sun radiation, plant cover as well as climate-determined amount and distribution of precipitation, soil temperature, soil moisture and snow cover. The combined impact of wave erosion and subaerial processes results in changes in the cliff's morphology leading to cliff recession. Insofar as the lithological profile of formations and the cliff's exposure should be considered a fixed factor unchanged for a specific location, climatic factors are highly variable. These are both changes due to the seasonality of climatic conditions and their long-term trends. One of the climatic factors significantly contributing to the transformation of cliffs at middle latitudes subject to both seasonal and long-term change is air temperature, and, in particular, temperature below and above 0°C (Bernatchez et al., 2011; Day et al., 2013; Boucher-Brossard et al., 2017). A common consequence of the resulting freeze-thaw process is loosening of the several-millimetre-thick upper layer of soil. For vertical or nearly vertical cliff faces developed in consolidated formations, the layer of sediments dislodged from their surface breaks away and leads to cliff recession with a simultaneous progression of frost and the freeze layer (Boucher-Brossard et al., 2017; Kaczmarek et al., 2019).

In the case of cliffs at the land-water boundary the material accumulated at their base is washed away into the water body by wave erosion, which prevents cliff flattening (Carter and Guy, 1988). In such conditions the impact of temperatures falling below and rising above 0°C on the cliff is equally efficient, and the rate of cliff recession resulting from freeze-thaw processes is directly dependent on the number of freeze-thaw cycles affecting the cliff (Bernatchez et al., 2011; Boucher-Brossard et al., 2017).

Previous studies have shown that, in areas where the temperature drops below and rises above 0°C, freeze-thaw processes can have a significant effect on the rate of recession of cliffs developed within the shore zone of inland water bodies. They account for 20 to 90% of annual displacement of cliffs due to the total impact of subaerial processes and wave erosion (Reid et al., 1988; Gatto, 1995; Egorov and Gleizer, 2012). In the case of the Jeziorsko Reservoir, cliff recession resulting from freeze-thaw processes in the winter season 2014–2015 accounted for 20% of annual recession (Kaczmarek, 2018; Kaczmarek et al., 2019). On average, recession due to this process was 3 cm, and at some points the maximum displacement reached 10 cm. The role this factor plays in cliff recession is directly determined by the number of freeze-thaw cycles the transformed cliff face is exposed to, so the significance of the factor changes along with climate change and the resulting shift in the number of freeze-thaw cycles.

This paper aims to describe the thermal conditions accompanying the freeze-thaw processes of sediments on the cliff face on the Jeziorsko Reservoir, central Poland, in winter 2019–2020. The analyses were based on own measurements and data provided by the Institute of Meteorology and Water Management –National Research Institute (IMWM-NRI) in Warsaw, Poland.

2. Material and methods

2.1. Study area

The Jeziorsko Reservoir is the second biggest artificial water reservoir in Poland. It is located within the meridionally running section of the Warta River valley in central Poland, stretching along 46 km (Fig. 1). Its shore zone comprises Pleistocene formations – mainly glacial and fluvioglacial sediments of the Warta Stage of Middle Polish (Saale) glaciation. The reservoir is surrounded by flat moraine upland rising 20–30metres above the bottom of the valley.

The study area is located in the temperate climate zone. The mean annual air temperature in this region in the period 1951–2018 was 8.5°C. Air temperatures below or above 0°C

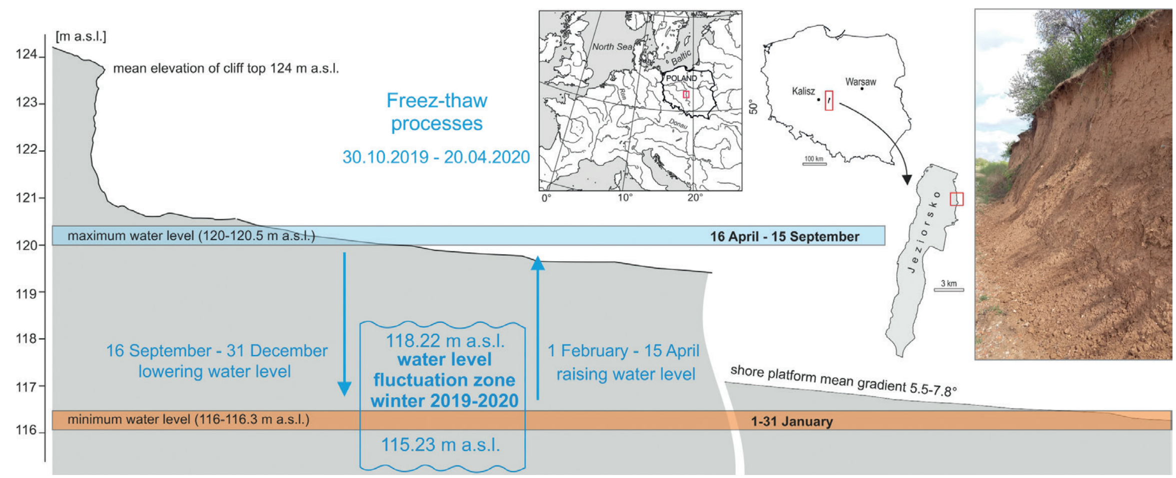

Figure 1. Location of the study area. In the photo effect of freeze-thaw process on the fragment of monitored cliff face and talus cones of a few mm-thick flake layer of the cliff material developed at the toe of the cliff. Winter season of 2019-2020 (Photo by S. Tyszkowski, May 2020)

occur from October until May, and sporadically in September and June (Bartczak et al., 2021). The frozen layer of the soil does not exceed 1 m in depth (Polska Norma PN-81 N-03020,128 1981).

The Jeziorsko Reservoir is a storage reservoir in which annual water level fluctuations reach 6 metres. The maximum water level in this body of water is observed in spring and summer. In contrast, the minimum water level is maintained in the winter months – from December to February. Given such significant changes in the water level at the land-water boundary, active cliffs are directly affected by wave erosion periodically – in summer months only. In winter months cliff transformations are due to subaerial processes, including freeze-thaw processes (Fig. 2).

Figure 2. Cliff face after winter period 2019–2020. Rock waste accumulated at the cliff toe (Photo by S. Tyszkowski, May 2020)

A vertical, more than 120-metre-long and nearly 4-metre-tall cliff along the eastern shore of the reservoir was selected for field study (Fig. 1, 2). From 2014 the cliff has been subject to morphodynamic monitoring, including both morphometric measurements and monitoring of thermal conditions (Kaczmarek 2018; Kaczmarek et al., 2019). The turf-covered slope within which the cliff is formed in the immediate vicinity of the reservoir faces eastwards – in the direction opposite to the land-water boundary. Due to the fast rate of cliff recession in the years 1991–2018 – i.e.1 m/y – and its verticality, there is no plant cover on the active cliff face (Kaczmarek et al., 2019). Also, in winter, its surface is not covered with snow. Single trees and shrubs grow on the crest of the cliff and their partially exposed roots form natural canopies shading the upper cliff face (Fig. 1, 2). The cliff develops in cohesive formations with a high content of silt and clay reaching 85% (Kaczmarek et al., 2019) that are highly susceptible to frost processes (Gatto, 1995; Matsuoka, 1996; Michalowski and Zhu, 2006).

2.2. Data type and methods

To determine the thermal conditions of freeze-thaw processes affecting the examined cliff in the 2019– 2020winter season, two sets of data were analysed. The first set is own data measured with a waterproof HOBO data logger (Pentant MX temp 2201) directly on the cliff face exposed to the west, 0.4 metres below the crest. The extreme dates of the measuring period are due to the water damming height in the reservoir making it possible to assemble or disassemble the sensor on the cliff. Since the sensor installed in October 2019 was stolen, only the results measured with a substitute sensor from 15 January to 4 May are available for the above-indicated winter period. Measurements were taken at 10-minute intervals with an accuracy of ±0.5°C. This paper uses averaged readings for one-hour periods (average of 6 measurements).

The second set of data comes from the station in Kalisz owned by the measuring network of the IMWM-NRI in Warsaw, one of the stations closest to the examined reservoir – 41 km away. The paper makes use of mean, minimum and maximum daily air temperatures. The results of previous studies imply a clear reference between the diurnal course of the mean air temperature in Kalisz and temperature on the surface of the examined cliff (Kaczmarek et al., 2021; Bartczak et al., 2021).

This study describes thermal conditions associated with freeze-thaw processes using the number of freeze-thaw cycles and freeze-thaw days. A freeze-thaw cycle (FTC) is a single switch in temperature below or above 0°C (freezing point) determined based on hourly temperature measurements. FTC informs us of the number of zero crossings that – theoretically – can reach 23 in 24 hours. Their number in the study was determined using data logger readings. The second parameter – freeze-thaw day (FTD) – is a day on which the maximum diurnal temperature is > 0°C and the minimum diurnal temperature is ≤ 0°C. FTD informs us only that on the specific day at least one zero crossing occurred. The criteria for determining FTC and FTD are described in more detail by H. Kaczmarek et al. (2021). The number of FTD was also determined using both data sets.

3. Results

In the period from October 2019 to May 2020 mean monthly air temperatures in Kalisz ranged from +14.7°C to +2.5°C. In the winter period of 2019–2020 air temperatures below or at zero degrees centigrade were observed from 30.10.2019 to 20.04.2020 and were recorded on 56 days. The period of their occurrence was 173 days. Only on one of the days – 25.01.2020 – was the air temperature negative all day and night. On the remaining 55 days zero (0°C) crossing occurred, so they were FTDs. Those days occurred as single days – eight times, or in cycles lasting from two to five days. Cycles of three to four days and five days were predominant, accounting for 22 and 27% of all FTD, respectively. The highest number of FTD was recorded in January, December and March – 13, 12 and 11 FTD, respectively (Fig. 3). The lowest monthly temperatures, +2.5°C and +3.6°C, were recorded in January and December, respectively.

In the period from 15 January to 4 May 2020, on the cliff 77 FTC were recorded during

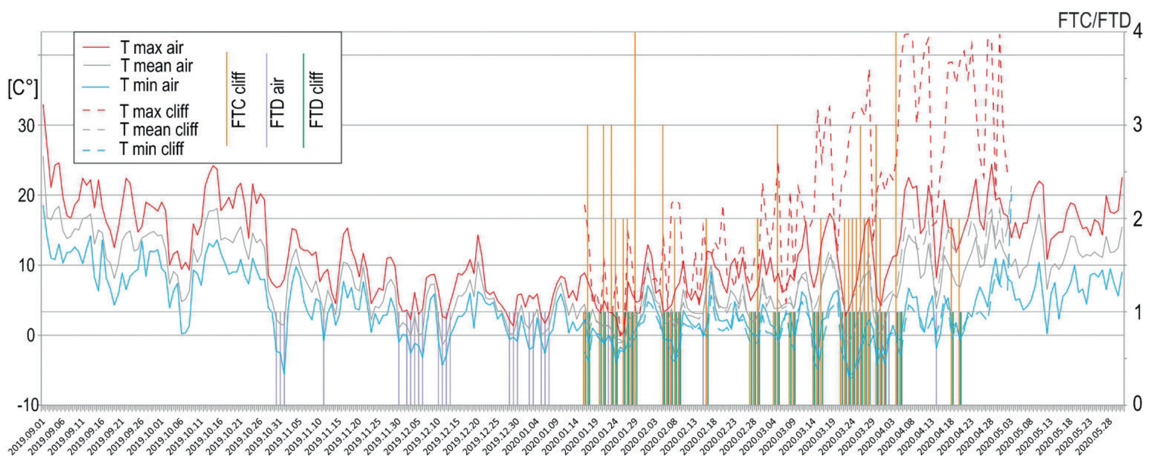

Figure 3. Ground temperature on the cliff face and air temperature in the instrument shelter in Kalisz IMWM-NRI weather station in the winter season of 2019–2020, Jeziorsko Reservoir (prepared based on: The raw data for the Kalisz station from the Institute of Meteorology and Water Management - National Research Institute, Poland; https://danepubliczne.imgw.pl/data/dane_pomiarowo_obserwacyjne/dane_meteorologiczne/dobowe/klimat/)

41 FTD. In the same period in Kalisz 33 FTD were recorded, which is 20% less. The dates of 30 out of 33 FTD recorded in Kalisz coincide with FTD dates on the cliff. In the course of one day, one to four FTCs were noted. Most frequently there was one zero crossing, which was noted on 16 days. The least frequently noted were four zero crossings and this happened on two days only (Fig. 3).

4. Discussion

The impact of freeze-thaw processes on cliff recession is directly determined by the number of times air temperature crosses zero (0°C). The maximum number of crossings occurs when the mean air temperature is close to 0°C (Baker and Ruschy, 1995; Dewez et al., 2015; Bartczak et al., 2021). Due to the availability of data, completeness and length of measuring sequences, they are commonly identified by using the maximum and minimum diurnal air temperature and are equivalent to the number of FTD (Gatto, 1995; Kreyling and Henry, 2011; Kjellström et al., 2016; Kaczmarek et al., 2021; Nilsen et al., 2021). Based on this data, one or no zero crossings are identified on one day. The number of crossings determined as mentioned above is equal to or lower than the actual number of zero crossings in soil. For the examined cliff the values of FTD in comparison to FTC are about 50% lower – on average two FTCs per one FTD. The obtained data corroborates the validity of using data relying on extreme diurnal temperature values in such analyses based on which the number of cycles actually experienced by soil is equal to or lower than their actual number, but it is never higher.

Freeze-thaw processes are a very sensitive indicator of climate change. The observed rise in temperature at high latitudes leads to an increase in the number of FTD (Persson et al., 2007; Dyrrdal et al., 2020; Rasmus et al., 2020), while at middle and low latitudes – conversely – to their decline (Grossi et al., 2007; Kreyling and Henry, 2011).

The 2019–2020 winter season is one of the warmest winter periods in Poland after 1960. In the multi-annual period 1961–2018, mean monthly air temperatures in Kalisz for the winter periods from December to February were negative values (Kejna and Rudzki, 2021), while in the 2019–2020 winter season they reached positive values, and were +3.6°C, +2.5°C and +4.4°C, respectively. Despite such high temperatures manifested in, for instance, the occurrence of only one day with negative diurnal air temperature during the 2019–2020 winter period, the intensity of freeze-thaw processes determined by the number of FTD was comparable to that observed in the second decade of the 20th century (Bartczak et al., 2021).

The area covered by the Jeziorsko Reservoir features the lowest number of FTD in Poland and, at the same time, its biggest decline (Kaczmarek et al. 2021; Bartczak et al., 2021). In the surroundings of the Jeziorsko Reservoir, on average in the multi-annual period 1951–2018 as many as 65.6 FTD were noted (Kalisz weather station) and a clear decline was observed by -4.2 FTD/10 years. In the sub-periods of this multi-annual period – 1951–1989 and 1990–2018 – the latter showed a decidedly lower number of FTD as the average number of FTD was 58.2 (Bartczak et al., 2021). The number of FTD in the winter period 2019-2020 in Kalisz was lower and amounted to 55.

A clearly higher number of FTD recorded from 15.01 to 20.04.2020 on the cliff in relation to the number of FTD identified in the instrument shelter – 41 and 33, respectively, i.e. nearly 1/4 more – is perhaps the result of the western exposure for which on the northern hemisphere more freeze-thaw cycles are recorded than for east- or north-facing cliffs (Hall, 2004) and is also due to the verticality of the cliff face increasing the angle of solar radiation that is conducive to FTD (Isard and Schaetzl, 1998; Zhang, 2005). A similar relationship was found here for an earlier measuring period, i.e., winter 2014–2015. In the period from 11 December 2014 to 12 March 2015 in Kalisz 30 FTD were recorded, compared to 48 FTD on the monitored cliff – nearly 3/5 more (Kaczmarek, 2018).

5. Conclusions

One of the processes having an impact on the rate of cliff recession on the water reservoir is mechanical weathering associated with freeze-thaw processes covering the surface layer of sediments on the cliff face. The efficiency of this process is conditioned by the number of sediments freeze-thaw cycles. The 2019–2020 winter season was one of the warmest since 1961. In the area of the Jeziorsko Reservoir 55 FTD were identified in that period.

The active cliff face on the Jeziorsko Reservoir in the 2019–2020 season was subject to one to four freeze-thaw cycles per day – on average nearly two cycles per day. In the period 15.01 to 04.05.2020, directly on the cliff face 77 freeze-thaw cycles were recorded over 41 freeze-thaw days (FTD). Concurrently, in the same period only 33 FTD were recorded in the instrument shelter, which is 20% less. The outcomes corroborate the view reported in literature, namely, that on the northern hemisphere vertical cliff faces exhibiting western exposure are advantaged in terms of the development of freeze-thaw processes.

Acknowledgements

This research was funded by Project Supporting Maintenance of Research Potential at Kazimierz Wielki University. My sincere thanks to Sebastian Tyszkowski, PhD for his invaluable assistance with the fieldwork.

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