Oecologia Montana 2020,
29, 39-52

Impact of climatic changes on the montane and alpine lake ecosystems (High Tatras, Western Carpathians)

K. HRIVNÁKOVÁ

Institute of High Mountain Biology, Žilina University, Tatranská Javorina 7, SK-059 56, Slovak Republic; e-mail: kristina.hrivnakova@gmail.com

Abstract. Climate models show that the frequency of irregular climatic phenomena (extreme rains and hot days) are increasing in mountain environments. 1. Extreme precipitation causing irregular (but more frequent) floods and impacting the leaching of dissolved organic material from the water column. Due to the morphology and poor vegetation of high-mountain lakes, there is no return of allochthon organic matter. However, the process mentioned above is responsible for faster recovery (after flood) of lower altitude lakes with plenty of surrounding vegetation. The second effect brings increased mobilization of elements and metals within the ecosystem, triggering the leaching of heavy metals from the littoral zone to the aquatic environment and changing their levels in surrounding vegetation. 2. Changes in the characteristically low temperatures at higher-altitude lakes are due to the sensitivity towards increasing and fluctuating air temperatures. All processes and interactions in lake ecosystems are influenced by the high altitudinal gradient and differences between dystrophic (below the tree-line) and oligotrophic alpine lakes.

Key words: impact of flood, organic matter, mobilization of elements and metals, recovery, warming, water temperature

Introduction

Lake ecosystems are often considered closed ecosystems without a significant impact from the surrounding terrestrial environment ("The Lake as a Microcosm" Forbes 1887). However, research showed that the littoral zone considerably contributes to organic matter turnover compared to the central part of the lake (Sala and Gude 2006). Most lakes are dependent on the supply of organic matter from the catchment area (Sobek *et al.* 2007).

It is the content of nutrients and organic matter that affects the entire ecosystem (Beracko *et al.* 2014). Two primary sources of organic matter are autochthons (from the lake) and allochthons (from the catchment area). Allochthons are responsible for most organic matter in the lake. The amount of organic matter depends on multiple physical (elevation, outflow, orientation, etc.) and climatic parameters (rainfall, droughts, etc.) (Hood *et al.* 2003; Sobek *et al.* 2007). Several parameters are used to indicate organic pollution, water quality, oxygen demand, and the total amount of organic matter (direct – COD, BOD and indirect – DOC, TOC)[1] (Seong-Tae *et al.* 2013).

Lakes located below the tree-line have significantly higher concentrations of dissolved organic matter than others situated above it (Hood *et al.* 2003). The lowest average amount of organic matter was recorded in alpine lakes (Sobek *et al.* 2007; Beracko *et al.* 2014). Such low values are due to the poorly drained soil and almost complete absence of vegetation (Kochjarová and Hrivnák 2017). On the contrary, an essential feature of lower located peat lakes is the high concentration of dissolved organic matter (Mladenov *et al.* 2005; Kapusta *et al.* 2018).

Water level fluctuation (WLF) is a neutral term commonly used to describe multimodal and predictable events. One example is snow melting in the springtime, which causes prolonged floods and changes in regularly flooded areas or periodic lakes. However, current climate models show that the frequency of these common hydrological phenomena is declining, while irregular climatic phenomena (extreme rains, prolonged droughts) are increasing (IPCC 2001; Christensen and Christensen 2003). These are responsible for unpredictable and drastic changes in water level fluctuation (for example, large-scale floods). Floods have proved to rapidly mobilize large amounts of organic matter and terrestrial organic inputs in water (Mladenov *et al.* 2005; Steven and Melack 2012).This displays an interesting relationship between leaching and the transfer of organic matter from the water column to ATTZ2 (Nogueira *et al.* 2002; Wantzen *et al.* 2008) and subsequent reverse washing out/leaching of organic matter from vegetation and soil, which increases nutrient content in water (Sobek *et al.* 2007; Steven and Melack 2012).

Floods represent hot biochemical events (McClain *et al.* 2003) for heavy metal concentration / accumulation in soil and sediments of aquatic environments (Szabó *et al.* 2008; Du Laing *et al.* 2009). They can trigger the leaching of heavy metals into the water environment within ecosystems (Chrastný *et al.* 2006). Water level fluctuation (also due to floods) has an undoubted impact on the ecology of aquatic habitats. Researchers have mainly observed this phenomenon in rivers (Junk *et al.* 1989; Tockner *et al.* 2000; Junk and Wantzen 2004), their deltas, swamps, regularly flooded areas, and lower altitude lakes tightly surrounded by vegetation (Coops *et al.* 2003; Mladenov *et al.* 2005; Mooij *et al.* 2005).

Attention has also been paid to recovery processes following this type of events (Sparks *et al.* 1998; Schiemer *et al.* 1999). How do floods affect specific aquatic alpine ecosystems with shallow coastal zone, little to no vegetation, and underdeveloped ATTZ? What is their recovery process?

Water temperature is a highly significant factor and environmental variable (Šporka *et al.* 2006). The surface water temperature fluctuates during the year depending on the season and current weather (Hrivnáková 2019). Alpine lakes show low water temperatures throughout most of their annual cycle (Šporka *et al.* 2006; Hrivnáková 2019). Temperature is important in the evaluation of oxygen ratios, the rate of degradation of organic matter, the acidity of the lake and the suitability of the environment for the occurrence of aquatic organisms, but also for entire lake ecosystems (Doláková and Janýšková 2012).

We consider ecosystems of High Tatra lakes to be ideal and critical locations for the study of global climate changes in the environment.

[1] COD (chemical oxygen demand) – non-specific and complex indicative measure (Judová *et al.* 2015), BOD (biochemical oxygen demand), DOC (dissolved organic carbon), TOC (total organic carbon) (Seong-Tae *et al.* 2013).
[2] ATTZ (The Aquatic-Terrestrial Transition Zone) – represents a flood zone in the event of level fluctuations (even in flood situations) between water and land.

Material and Methods

Study area

The High Tatras are a small mountain range (26 km long) with a typical alpine relief formed by glaciation (Kapusta *et al.* 2018). The youngest natural formations, "plesá" (glacial lakes), represent an important and characteristic component of these high mountains, and were precisely formed due to this glaciation (Lackovič 2015; Kapusta *et al.* 2018). Often, we mistakenly include lakes that were formed in the interglacial period which had nothing to do with glaciation. Nevertheless, even these lakes are still ecologically significant (Lackovič 2015). They represent more than 90 % of all lakes in Slovakia (Štefková and Šporka 2001). The High Tatras lakes lie on a relatively large altitude gradient, and the forest boundary is the most important ecological divide (Krno *et al.* 2010). The vast majority of lakes are located above the forest border, in the alpine zone (Štefková and Šporka 2001; Beracko *et al.* 2014). They are transparent, deep lakes with a shallow coastal area (Hanušin 2009) and a characteristic low content of nutrients (oligotrophic) due to insufficient supply of organic material from the subsoil and a lack of vegetation in the area (pH ≤ 7) (Beracko *et al.* 2014). Low temperatures are also typical during most of the annual cycle (Hrivnáková 2019).

The second type of formation are montane, shallow lakes, which gradually overgrow the surrounding vegetation (Kapusta *et al.* 2018). Their water is mostly colored brown from humic acids (leached from peat), and we classify them as dystrophic lakes (pH = 3.5-5.5) (Górniak *et al.* 1999; Slovenská lesnícka spoločnosť 2012a; Beracko *et al.* 2014). They have higher temperatures, especially during summer (Kochjarová and Hrivnák 2017).

Climatic conditions of the area

The climate of the High Tatras has a specific set of characteristics that significantly influence the existing ecosystems and environmental phenomena, as well as their further development. In terms of temperature and precipitation, the Tatras region is characteristic of its extreme and unstable weather (compared to other regions within Slovakia). The most general sign of this is a decrease in air temperature with increasing altitude (it decreases by 0.6 ˚ C every 100 m upward). In the future, this effect could be disrupted by gradual warming and dry seasons. Total precipitation increases at higher altitudes. Relatively high precipitation and low evaporation cause excessive outflow. Therefore, in the months with the highest precipitation and most significant storm activity, there is an increase in water levels, bringing more extensive erosion and devastating floods. All these extreme environmental phenomena can trigger (as they did in the past) significant changes in the ecosystems of mountain lakes (Slovenská lesnícka spoločnosť 2012a; Lacika 2020).

[3] Summer floods (1662; August 1813; July 1845; June 1958; July 2001; August 2008, 2011, 2019). Spring floods from melting snow are rather exceptional and do not cause as much damage as summer ones (Slovenská lesnícka spoločnosť 2012a).

Fieldwork

This study was part of a larger study of the Ecosystems of the High Tatras mountain lakes as environmental indicators. Fieldwork and sampling took place during the summer seasons (from May to October) of 2019 and 2020. Due to the longer summer, without snow or frost, we continued sample collection into November 2020.

To the extent possible, we aimed to collect samples from different lakes in the same weather conditions during warm and sunny days without any fluctuations or extremes, so that changes in climate would not influence content. We successfully collected samples from 101 lakes located in 14 valleys of the High Tatras, 17 in northern reaches and 84 in their southern counterparts (Appendix 1 and 2). Independent work taking place directly at the location of individual lakes consisted of water, (top) sediment from littoral zone4 , and bryophyte5 sampling (details in Table 1) followed by in situ measurements of physical parameters (Fig. 1).

[4] The littoral zone and its differences between alpine lakes and lakes under tree-line are characterized in the Study area. Due to the rocky subsoil and the absent littoral zone, it was not possible to take sediment samples at some of the above-located lakes. Conversely, in some significantly overgrown lower lakes, it was also impossible to take sediment samples from the littoral peat zone.
[5] We took one or two different samples of bryophytes near the water surface, mainly in the littoral and limouse ecophase and in the terrestrial ecophase (sensu Hejný 1960) from each locality.

		Container	Amount	Method
WATER	measurement of physical parameters: • water temperature [° C]; • pH; • electrical voltage [mV]; • salinity; • conductivity [μS/cm]; • resistance [kΩ*cm]; • TDS (Total Dissolved Solids) [mg/l]; • dissolved oxygen [mg/l ,%, mbar];	in situ		from the lake shore with a portable WTW 3430 multimeter (Geotech, Weiheim; Germany) with compatible probes: • IDS pH electrode Sen TixR 940-3; • conductivity electrode TetraCon 925-3; • optical oxygen electrode FDO 925-3;
	sampling for subsequent analysis	plastic bottle	0.7 l	from the lake shore
(TOP) SEDIMENTS	sampling for subsequent analysis	plastic vial	0.05 l	from the lake shore, surface sediments up to 15 cm from littoral zone[4]
BRYOPHYTES	sampling for subsequent analysis	plastic Zip Lock bag	1 - 2 sp.	on the shore of a lake, near a body of water, or in water[5]

Table 1. *Fieldwork:* sample collection (sample type, sample containers, sample quantity, sampling method).
Note: All containers were properly disinfected and labeled prior to sample collection. We made sure that the intervals between transport, storage, and subsequent analysis in the laboratory were as short as possible.

Fig. 1. Litvorové pleso and Zelené Kačacie pleso (no.96 and 97) (North 1860 and 1675 m asl..) are permanent lakes belonging to the oligotrophic category. Litvorové pleso is a kettle lake in the alpine zone, while Zelené Kačacie pleso is a transitional type of lake in the zone of mountain pine. (31.8.2020 side valleys of Bielovodská dolina – Litvorová and Kačacia dolina (photo: K. Hrivnáková).

Laboratory work

Chemical oxygen demand (COD) – Permanganate (Kubel) method

COD is a complex indicator of organic pollution, whether biodegradable or not (Judová *et al.* 2015). It is defined as the amount of oxygen consumed under specified conditions to oxidate organic matter in water by a potent oxidizing agent. This nonspecific parameter is expressed in mg/l (Diviš 2008).

We made measurements in three boiling flasks with the same sample (100 ml of lake water) to average the result for a more accurate measurement. The method used is based on the oxidation of organic substances with 20 ml of a solution of potassium permanganate (K_2MnO_4) (0.002 mol/l) in 5 ml of sulfuric acid (H_2SO_4, 96 %) diluted (1 : 2) at boiling for 10 minutes. We placed 4-5 cooking stones in each boiling jar and covered the jar with a watch glass. Oxidation occurs when there is an excess of permanganate. After oxidation is complete, unreacted $KMnO_4$ is reduced with an excess of standard oxalic acid $(COOH)_2$ solution (0.005 mol/l), which is added in the exact amount (20 ml) to the sample. The solution is then decolorized to a clear solution. It is back – titrated with potassium permanganate (0.002 mol/l) to $KMnO_4$ until it turns a faintly pink colour. Consumption during titration shows the consumption of manganese for the oxidation of organic substances.

Equations:

$MnO_4^- + 5e^- + 8H^- \rightarrow Mn^{2+} + 4H_2O$
$2MnO_4^- + 5(COO)_2^{2-} + 16H^+ \rightarrow 2Mn^{2+} + 10CO_2 + 8H_2O$

Photometry

To determine other chemical indicators of water quality ($Cl^-/NaCl/CaCO_3$, S/SO_4^{2-}, ammonia $N/NH_3/NH_4$, N/NO_3^-, P/PO_4^{3-} and the content of total water hardness $CaCO_3$) in the lakes, we used optical-analytical method – photometry. The essence of photometric methods is the passage of a substance and absorption by a portion of the light spectrum. The area of light absorbed by the substance and the absorption intensity measured by the photometer depends on the particular substance. Concentrations of ions in our samples were determined by the YSI EcoSense 9500 (YSI, USA) photometer and accessories compatible with this water analyser. Test procedures require different specific reagents for every chemical parameter. Measurement with this optical – analytical method was performed using the YSI EcoSense 9500 (YSI, USA) measurement instructions.

Drying of samples

Sediment and bryophytes samples were dried separately on Petri dishes (3 hours at 60° C) in an IF 160 Plus dryer (Memmert, Germany). Samples of bryophytes were divided into upper (photosynthetic) and lower parts, contaminated with soil, before drying. Only the top sections were used for further analysis.

Milling of samples

For further processing of the samples, it was important to homogenize it into one common sample – removing the pieces from stones, roots and grinding them. A ceramic mortar (used in some bryophytes) can be used for initial homogenization and grinding. We used a cryogenic ball mill (CryoMill Retsch, Germany), which uses ball impact and continuous cooling, grinding vessels, and liquid nitrogen – maintaining a temperature of –196 ° C.

- We ground the upper parts of the bryophytes for 30 seconds to 1 minute with a frequency of 20 Hz.
- The sediments were ground for 1 minute at a frequency of 30 Hz.
- Subsequently, we analysed the correctly homogenized samples for surface contamination by two methods.

X-ray spectrometry analysis

We used X-ray spectrometry to determine the values of some chemical elements (trace elements) in homogenized sediments (milled) and upper parts of bryophytes (milled). We used a DELTA handle ED–XRF spectrometer (Bas, Rudice, Czech Republic) with a Delta XRF Portable WorkStation tripod (Olympus, Innov-x Systems, USA). Samples were analysed in plastic cuvettes with plastic foil at the bottom for 240 s in three 80 s intervals, from which the average was calculated. The analytical methods and calibration procedures used in the laboratory shall comply with internationally accepted standards (Spectrapure Standards, Norway).

The detection limits were determined continuously for each measurement and each element by software using the Compton Normalization method.

Mercury analysis

Mercury concentrations in the upper parts of bryophytes (unmilled) and sediments (milled) were analysed with a DMA-80 mercury analyser (Milestone, USA) using nickel boats which were always cleaned after six measurements. The cleaning procedure was repeated until absorbance was stable and lower than 0.001. A dried sample is taken at a high temperature (650 degrees) and burned for decomposition in the apparatus. The temperature level guarantees complete decomposition and release of mercury. During and after decomposition, pyrolytic gases are blown by a stream of oxygen into the amalgamator. The mercury is retained in the amalgamator, and all other gases are eliminated from the system before measurement. The device provides us with an accurate measurement of the mercury content. The mercury concentration, measured in mg/kg, is calculated automatically when the measurements are calibrated to the weight of each sample. The accuracy of this method was determined by analysis of the reference material (tobacco leaves) (ICHTI, Poland). The determined value of tobacco leaves agreed well with the certified value of 0.0232 mg/kg (tobacco leaves) and fell within the limit of uncertainty specified for the material.

Statistics

The potential synergistic effect of the individual measured variables was evaluated by principal component analysis (PCA). Correlation between component (PC 1) value with elevation was plotted using polynomial regression curves and verified by F test ($p < 0.05$). One–way ANOVA and its nonparametric equivalent the ANOVA – Kruskal – Wallis test (and their graphical representation) were used for statistical comparison of individual factors with the properties of observed ecosystems and seasonality, with a disproportionate number of samples at a 95 % confidence level ($p < 0.05$). Some measured variables were summarized by means of standard deviation. Statistica 8 software for Windows (TIBCO, USA) was used for data analysis.

Results

In addition to the monitored physical and chemical parameters of water in lakes and mercury in bryophytes and sediments, we recorded ten elements in bryophytes and twelve elements in surface sediments of the littoral zone above the detection limit by X-ray spectrometry (Table 2).

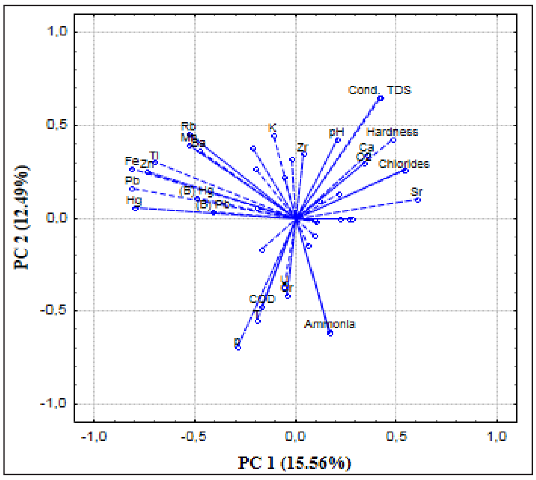
The analysis of the main components revealed 45 components, of which only seven factors explain more than 5 % of the interpretable variability[6].

[6] Our work focused on interpreting the first two components (PC 1 and PC 2) with the greatest interpretable variability due to the enormous scope of work.

The first component (PC 1), with the largest interpretable variability of 15.56 %, describes to us the combined relationship of descent/ascent of measured metals (Pb, Hg, Fe, Zn, Ti, Rb, Mn, Ba) in the upper layers of the littoral zone versus ascent/descent of dissolved substances (TDS, salts and chlorides) in the water in addition to hardness and conductivity (Fig. 2). The first factor also describes the interdependence of Hg and Pb concentrations in sediments and the concentration of these elements in bryophytes. The second factor (PC 2 – 12.49 %) is a bipolar vector that describes an increase/decrease in dissolved organic matter, ammonia, temperature, and water resistance, compared to changes in the number of solutes in water (TDS), its pH, conductivity, and hardness along with some elements in sediments (mostly cations) (Fig. 2).

Impact of vertical distribution

As the elevation increases, the content of dissolved substances (TDS, salts, and chlorides) in the lake



° Active

Fig. 2. Projection of the variables on the factor – plane (PC 1 x PC 2).
The graph shows the correlated structures between the variables of the first and second components. Variables located along the same directional axis are positively correlated with each other. The variables located on the opposite side of the graph are negatively correlated with each other. The variables placed in the middle are weak predictors, and their descriptions have been omitted for clarity. The horizontal axis explains 15.56 % and the vertical 12.49 % of the total variability.

Variable	PC 1	PC 2
(B) Hg	**-0.49**	**0.11**
(S) Hg	**-0.80**	0.06
(W) COD	-0.17	**-0.47**
(W) t	-0.19	**-0.55**
(W) pH	0.20	**0.42**
(W) U	-0.05	-0.37
(W) Concent. O_2	0.34	0.29
(W) O_2	0.22	-0.01
(W) Satur. O_2	0.09	-0.09
(W) Conduct.	**0.42**	**0.65**
(W) TDS	**0.42**	**0.65**
(W) p	-0.29	**-0.70**
(W) Cl^-	**0.54**	0.26
(W) NaCl	**0.54**	0.26
(W) Tot. hardness $CaCO_3$	**0.48**	**0.43**
(W) Chlorides $CaCO_3$	**0.54**	0.26
(W) SO_4^{2-}	0.27	0.00
(W) S	0.28	0.00
(W) Ammonia N-NH_4	0.17	-0.61
(W) Ammonia N	0.17	-0.62
(W) Ammonia N-NH_3	0.17	-0.62
(W) PO_4^{3-}	0.10	-0.02
(W) P	0.10	-0.01
(B) S	-0.17	-0.17
(B) K	0.12	0.09
(B) Ca	0.22	0.13
(B) Cr	0.07	-0.14
(B) Mn	-0.22	0.38
(B) Fe	-0.20	0.27
(B) Zn	-0.19	0.06
(B) Rb	-0.02	0.32
(B) Ba	-0.05	0.22
(B) Pb	**-0.41**	0.03
(Ls) K	-0.11	**0.45**
(Ls) Ca	0.35	0.34
(Ls) Ti	**-0.70**	0.30
(Ls) Cr	-0.04	**-0.41**
(Ls) Mn	**-0.53**	**0.40**
(Ls) Fe	**-0.81**	0.27
(Ls) Zn	**-0.74**	0.26
(Ls) Rb	**-0.53**	**0.45**
(Ls) Sr	**0.60**	0.10
(Ls) Zr	0.04	0.35
(Ls) Ba	**-0.48**	0.36
(Ls) Pb	**-0.81**	0.16
Variance %	**15.56**	**12.49**

Table 2. Weights of PC 1 and PC 2 with the percentage of variation in principal component analysis of the physical and chemical variables of water (W), 13 elements in the littoral (surface) sediments (Ls), and 11 elements in the bryophytes (B) (N = 83). Significant correlations are bold.

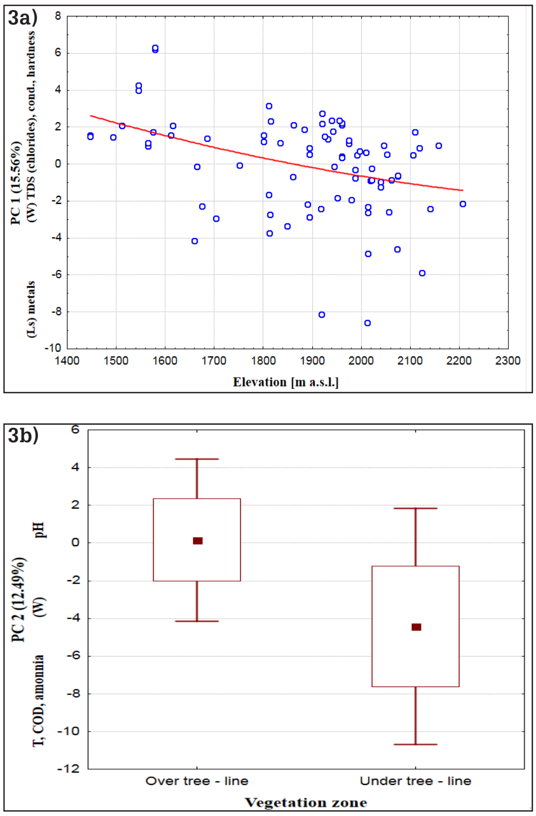


Fig. 3. Principal components PC 1 and PC 2 in relation to the vertical division. **3a)** Metal levels in the upper sediments of the littoral zone increase with elevation, while dissolved ion concentrations decrease. PC 1 = 19.4027 – 0.0157 * Elevation + 2.8425 E^{-6} * Elevation^2; r = – 0.3771, p = 0.001. **3b)** The higher temperature, the amount of dissolved organic material and ammonia in the water, and the lower pH are in the lakes below the tree-line than above the tree-line. PC 2: VEGETATION ZONE: KW ANOVA – H (1, 83) = 5.4857; p = 0.019. (means, box - mean SD, whisker - ±1,96*SD).

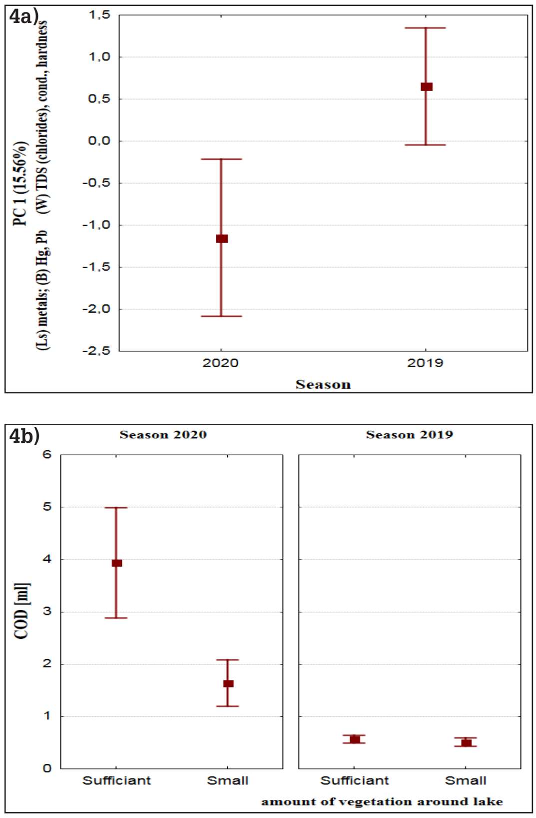


Fig. 4. Differences in concentrations of observed variables between the two seasons 2019 and 2020 for factors PC 1 and PC 2 denoted by Means with standard errors at 0.95 confidence interval. **a)** Levels of conductivity, dissolved substances (salts, chlorides), and water hardness decrease in 2020 compared to the rise of metals in the upper sediments and Hg, Pb in bryophytes. PC 1 : SEASON 2019/2020: KW Anova – H (1,83) = 10.448, p = 0.001. **b)** The levels of pH, conductivity, solutes (salts, chlorides), and water hardness together with cations in the upper sediments decreased in 2020 compared to the increase in the amount of organic matter, water temperature, voltage, resistance, and ammonia in the water. PC 2: Season 2019/2020: KW Anova – H (1,83) = 4.000, p = 0.046.

water decreases, along with its conductivity and hardness. However, in these higher-altitude lakes, the metal concentrations in the upper layers of the littoral zone are more pronounced (Fig. 3a; r = 0.38, p = 0.001). Lakes below the tree-line have higher temperatures and dissolved organic matter content (higher ammonia levels) in the water but lower pH values than alpine lakes (Fig 3b; p = 0.019).

Impact of seasonality

Even though the research took place during the summer season, we cannot rule out the influence of individual months. The effect was significant for both factors:
PC 1 – H (5, 83) = 14.9552, p = 0.001;
PC 2 – H (5, 83) = 30.0844, p = 0.000;

With both factors, the content of dissolved substances (salts, chlorides) increased in the autumn months.

However, in addition to the effect of individual months, we observed a surprising difference between the summer seasons of 2019 and 2020. This impact was also observed for the first (PC 1) and the second component (PC 2) (Table 2). The first component (PC 1) mainly describes an increase in water-soluble substances (cations and anions), their conductivity, and water hardness in 2019 against the growth of metal concentrations in the littoral zone of lakes and the growth of metals (Hg, Pb) in bryophytes in 2020 (Fig. 4a; p = 0.001). While the second factor (PC 2) is important to demonstrate the significant difference in water parameters between the two seasons. In addition to the already mentioned differences in conductivity, TDS (cations), and water hardness, the second factor shows us the relationship of the decrease in pH in 2019 antagonistically to the increase of COD levels, temperature, voltage, resistance, and ammonia in water in the 2020 season (Fig. 4b; p = 0.046). An important finding (Fig. 5), shows the effect of the amount of vegetation around the lake on the COD values in 2020, while we did not demonstrate this effect in 2019.

The average COD value for all monitored lakes for both summer seasons (2019 – 2020) was 1.82 (± 2.32) ml (Table 3). In 2019 it was around 0.55 (± 0.20) ml, and in 2020 the average COD value increased to 3.14 (± 2.58) ml. The minimum measured value of COD (0.22 ml) was measured in the summer season of 2019 (October), at the highest stand-

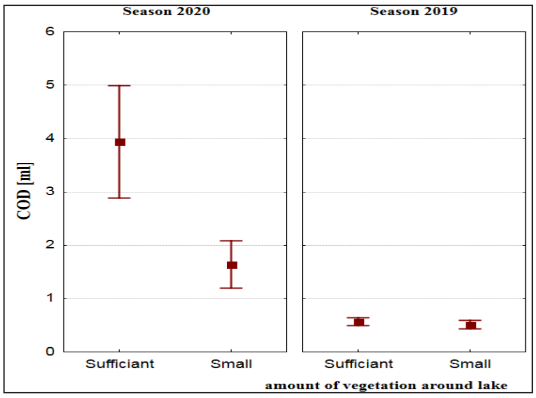


Fig. 5. The effect of the amount of vegetation on the growth of dissolved organic material in lakes in the 2020 season denoted by Means with standard errors at 0.95 confidence interval. In 2020, enough vegetation around the lake impacted the growth of the organic composition in the water and the decrease in pH. Season 2020 COD: amount of vegetation: KW Anova – H (1, 46) = 7.878, p = 0.005; Season 2019 COD: amount of vegetation: KW Anova – H (1, 53) = 0.913, p = 0.340.

ing lake, Modré pleso (no. 76). This year did not exceed the maximum value of 1.15 ml (September). There was only one such high COD value this season, measured in Slavkovské pliesko. In the summer season of 2020, there was a significant increase in the COD value, and some lakes had values exceeding 10 ml (the max. value set by us). This included both lakes under the tree-line zone (lakes Čierne pleso, no. 41 in valley Motykova dolina and Žabie pliesko, no. 52), as well as also alpine lakes (Prostredné Spišské pleso, no. 72 and Skalnaté oko, no. 78). However, throughout the study of alpine lakes, the mean COD values were significantly lower, at 1.55 (± 1.99) ml than for lakes under the tree-line zone 5.31 (± 3.52) ml. The average pH values in both seasons (Table 3), for both alpine lakes and lakes under tree-line zone, ranged from 7.337 to 7.765. The lowest measured pH (94.634), was measured in Trojrohé pleso (June 2020), while the highest measured pH (9.084) was measured in lake Skalnaté pleso, no. 77 (September 2020). The average value of the water temperature in the monitored lakes was 8.6° C. The lakes located in the alpine have an average temperature of 8.1° C in the summer season (with a minimum value of 0.9° C), while the lakes located under the tree-line zone reached an average value of up to 14.8 ° C (with a minimum value of 11.8° C) (Table 3). The highest measured temperature (20.1° C) of water was found in Čierne pleso, no. 41, in Motykova dolina (May 2020). However, some alpine lakes also reached high temperatures – up to 18.9° C - as was the case with Nižné studené pleso, no. 64 (August 2019).

Discussion

The interaction between individual components of aquatic mountain ecosystems (Table 2; Fig. 2) is a process sensitive to external changes and factors (Wathn *et al.* 1995).

The first crucial factor, explained by the first component (PC 1 – 15.56 %), that influences the environmental condition of mountain lakes is their mineralization. This relationship between concentrations of ions within the water column is expressed by the amount of total dissolved solids (TDS) in the form of cations and anions, as well as their connectivity (Tölgyessy *et al.* 1984; Judová *et al.* 2015) or inputs from the bedrock (in this case, elements from the littoral zone) (Du Laing *et al.* 2009). Higher TDS values and connectivity indicate higher solubility of substances in water, which are influenced by increased water hardness (mainly cations) (Diviš 2008) (Table 2).

This process and changes within aquatic ecosystems are also a result of influences from surrounding vegetation, which affect the amount of organic matter in lakes (Du Laing *et al.* 2009). More vegetation around the lakes affects the build-up of organic matter that increases the acidity of the water (Kopáček *et al.* 2006; Beracko *et al.* 2014) and ammoniacal nitrogen concentration (Doláková and Janýšková 2012) (Table 2; Fig. 2) The second component (PC 2) explains 12.49 % of the total variability.

Impact of vertical distribution

Vertical distribution undoubtedly impacts the factors mentioned above (Fig. 3a, b). The high altitudinal gradient of the High Tatras and tree-line de-

		COD [ml]			pH			t [° C] water temperature		
	N	Arithmetic Mean ± SD	Min.	Max.	Arithmetic Mean ± SD	Min.	Max.	Arithmetic Mean ± SD	Min.	Max.
2019 + 2020	99	1.82 ± 2.318	0.22	>> 10	7.624 ± 0.784	4.634	9.084	8.6 ± 4.231	0.9	20.1
2019	53	0.55 ± 0.196	0.22	1.15	7.765 ± 0.654	5.444	8.990	7.9 ± 4.064	1.7	18.9
2020	46	3.14 ± 2.581	0.56	>> 10	7.462 ± 0.891	4.634	9.084	9.4 ± 4.329	0.9	20.1
Lakes over tree-line	92	1.55 ± 1.991	0.22	>> 10	7.645 ± 0.780	4.634	9.084	8.1 ± 3.939	0.9	18.9
Lakes under tree-line	7	5.31 ± 3.518	0.40	>> 10	7.337 ± 0.844	5.777	8.138	14.8 ± 3.031	11.8	20.1

Table 3. The average values (± with standard deviations) of mercury and lead in bryophytes and upper sediments of lakes with mutual correlations. (Ls) – littoral (surface) sediments, (B) – bryophytes.

termining the amount of vegetation, as well as lake morphology, play an essential role in these processes (Krno *et al.* 2010; Beracko *et al.* 2014). In higher altitude lakes, their shallow coastal zone (Hanušin 2009) with a lack of vegetation affects the supply of organic matter (Beracko *et al.* 2014) and causes shortages of dissolved organic material in the water. The highest located permanent lake, Modré pleso (no. 76; 2189 m asl.), with a minimum value of 0.22 ml (2019), and Zamrznuté pleso (no. 92; 2040 m asl.), having a minimum value of 0.56 ml (2020), function as examples. These are typically clean, oligotrophic lakes with low concentrations of solutes in the water column (Beracko *et al.* 2014), and higher levels of metals stored in the littoral zone (Fig. 3a). However, this depends on the bedrock composition, its weathering, and inputs from the atmosphere (Slovenská lesnícka spoločnosť 2012b).

Although the majority of the High Tatra lakes are located in the alpine or sub-alpine zone (Štefková and Šporka 2001; Beracko *et al.* 2014) (Table 2), even the ones found under the tree-line (in the montane zone) are ecologically significant (Lackovič 2015). We mostly talk about shallower lakes with intended coastal zones and plenty of vegetation by which they are often gradually overgrown (Beracko *et al.* 2014; Kapusta *et al.* 2018). Their higher temperatures (Kochjarová and Hrivnák 2017) and surrounding vegetation cause higher concentrations of organic matter (Górniak *et al.* 1999; Hood *et al.* 2013) and more acidic environments (Kopáček *et al.* 2006) (Table 2; Fig. 3b). We classify them as dystrophic lakes while observing that many are on their way to extinction (Lackovič 2015; Kapusta *et al.* 2018). Examples of this include Trojrohé pleso (no. 83; 1611 m asl.), which had the lowest pH (4.634), and Jamské pleso (no. 5; 1447 m asl.), overgrown by mountain pine, with a pH of 5.777.

Temperature as an essential factor

The average temperature of examined lakes was 8.6° C. Decreasing air temperature with increasing altitude is the standard (it falls by 0.6° C every 100 m upward) (Slovenská lesnícka spoločnosť 2012a). In summer, alpine lakes represented by the highest located lake, Modré pleso (no. 76, 2189 m asl. – October 2019), reached an average temperature of 8.1° C (with a low of 0.9° C). The lakes located under the tree-line reached an average temperature of 14.8° C (with a low of 11.8° C). These mountain lakes (dystrophic) have significantly higher water temperatures than their higher-altitude counterparts (oligotrophic) (Fig. 3b). The highest temperature (20.1° C) within the examined lakes was recorded in the lowest-altitude dystrophic lake - Čierne pleso, in Motyková dolina (no. 41; 1235 m asl. – May 2020). Some alpine lakes also reached high values (18.9° C), as was the case of Nižné studené pleso (no. 64; 1811 m asl. – August 2019). However, this particular lake often dries out due to its shallowness (Lackovič 2015), and the "extremely" high water temperature was undoubtedly influenced by hot weather on the day when measuring took place.

Mountain lakes are sensitive to air temperature and react to it immediately, especially in the summer months (Šporka *et al.* 2006; Hrivnáková 2019). This will likely continue into the future, due to gradual warming and droughts (Slovenská lesnícka spoločnosť 2012a; Vido *et al.* 2015). Moreover, water temperature plays a significant role in evaluating oxygen ratios, acidity, water voltage, and organic matter degradation (Judová *et al.* 2015), which is apparent when looking at the correlations between these variables (Fig. 2).

Some effects mentioned above can be expected, based on the influence of seasonality. Increasing amounts of chloride (solute content) and organic matter (due to the leaching of decaying vegetation in autumn) are present with both factors (Mikuš 2012) (Results – Impact of seasonality). However, the contrast between the two summers is surprising (Fig. 4a,b). Even if the difference might seem insignificant, especially with such low water levels and concentrations, it should not be omitted.

Impact of floods on the mountain lakes and following recovery process

The chemical oxygen demand (COD), as a complex non-specific indicator of organic pollution (Judová *et al.* 2015), was low in the examined High Tatra lakes (Table 3). The average COD during both summers of our fieldwork was 1.82 (± 2.32) ml, reaching a low of 0.55 (± 0.20) ml in 2019 and subsequently increasing to 3.14 (± 2.58) ml in 2020. We can find exceptions similar to the previous chapter if we look at some examples from dystrophic lakes. In 2019, the maximum COD value of water in Slavkovské pliesko, (no. 51) did not exceed 1.15 ml (Table 3). The value was significantly low (Górniak *et al.* 1999), despite the dystrophic lake being on its way to extinction, overgrown by vegetation and mountain pine (Lackovič 2015). Even for such clean lakes, all other values during the season were surprisingly below 1 ml (Hrivnáková 2019). During the summer of 2020, there was a significant increase in COD (Fig. 4b), in some cases reaching values that exceeded 10 ml (which we set as our maximum). These included lakes under the tree-line (Čierne pleso, no. 41 in valley Motyková dolina and Žabie pliesko, no. 52), as well as alpine lakes (Prostredné spišské pleso, no. 72 and Skalnaté oko, no. 78) (Table 3). Organic matter concentration, as mentioned above, depends on lake water and its acidity (which functions as an antagonist to water voltage). The average water reaction value was 7.624 ± 0.784 for both summers, and fell with the increase in COD and water temperature in 2020 (Kopáček *et al.* 2006; Hrivnáková 2019) (Table 3; Fig. 4b).

But what is the cause of this? Here we need to consider the climatic conditions of Tatras, an area of extreme precipitation and intensive storm activity in summer (from July to August). This period is characterized by an increase in water levels and devastating floods (Slovenská lesnícka spoločnosť 2012a). During this seasonal research at Kolové pleso from 2017 until 2018 (Hrivnáková 2019), we recorded such extreme precipitation in July 2018. It triggered extensive floods throughout the High Tatras, which had a significant impact on the organic composition and acidity of the lake mentioned above, causing a COD decrease and pH increase from the exact day that flooding started (Hrivnáková *et al.* 2020). It has been concluded that floods are responsible for the rapid accumulation of organic matter in the lake (McClain *et al.* 2003; Mladenov *et al.* 2005; Steven and Melack 2012), while in similarly pristine aquatic ecosystems, their pH is significantly influenced by precipitation (Judová *et al.* 2015; Hrivnáková *et al.* 2020). Floods cause the leaching of dissolved organic matter into ATTZ (Wantzen *et al.* 2008), which is immediately followed by reverse and more effective washing out of allochthonous organic matter from the catchment area to the lake. Therefore, the levels of organic matter increase after the flood (Coops *et al.* 2003; Steven and Melack 2012).

While researching for this thesis and previously working at Kolové pleso, (no. 86) (Hrivnáková 2019), we observed that flooding affected all lake ecosystems in the High Tatras by extreme long-term reduction of COD (Hrivnáková *et al.* 2020, unpublished data from the ongoing study of Kolové pleso). The exact opposite effect was recorded in lakes surrounded by enough vegetation, where the COD value increases during floods (Steven and Melack 2012). However, this may be a result of one extreme value being recorded in the dystrophic and gradually disappearing Slavkovské pliesko, (no. 51) (Table 3) in 2019. It had a low level of COD, but was most likely influenced by washing out of allochthonous organic matter from the catchment area (Coops *et al.* 2003).

It is interesting to monitor the recovery of lakes from floods, which we compare to ongoing research of Kolové pleso, (no. 86). In the summer of 2020 (from August to September), we recorded changes and a subsequent increase in COD (unpublished data from the ongoing study of Kolové pleso). Our research shows the recovery of organic composition two years after the flooding occurred, thanks to COD increase, pH decrease, and changes in correlated parameters (Fig. 4b). We can state that according to our data from 2019, the COD values fell in all the lakes (average being 0.55 ± 0.196 ml). Due to the washing out of organic matter during the flood in 2019, we did not observe any demonstrable distinction between the lakes with enough and minimum vegetation. However, there have been apparent differences during the lake's recovery in 2020 (Fig. 5). Some of the lakes showed low COD, but others recorded the highest values observed (similar effect with pH). These were not just lakes below the tree-line with large amounts of organic matter.

The aforementioned lake morphology of higher-altitude lakes with shallow or missing ATTZ and a lack of vegetation plays an essential role (Mladenov *et al.* 2005). The amount of vegetation initially did not affect organic matter levels but (in the long term) plays a vital role in lake recovery. An increase (pH – KW Anova – $H(1,46) = 4.150$, $p = 0.042$) in COD was significantly faster (Fig. 5; KW Anova – $H(1,46) = 7.878$, $p = 0.005$) inside the lakes with enough surrounding vegetation, while their counterparts with less flora seemingly took longer to recover. We assume that the lowest-altitude dystrophic lakes with wide ATTZ and a lot of vegetation are fastest in their recovery, followed by lakes (even in higher altitudes) with enough surrounding flora and shallower coastal zones. The highest-altitude lakes are characterised by the slowest recovery due to inadequate vegetation and low organic input as a result of the limited (sometimes absent) coastal zone. This has an apparent impact on lake ecosystems.

Among other things, floods are responsible for the increased mobilization of elements and accumulation of heavy metals (Bradley and Cox 1990; Szabó *et al.* 2008; Chrastný *et al.* 2006; Hrivnáková *et al.* 2020). This effect is partially displayed in the first and second factors (Table 2; Fig. 4a). However, during floods, the mobility and speciation of elements/metals within ecosystems are influenced by different factors or processes (Chrastný *et al.* 2006; Du Laing *et al.* 2009). It is the organic matter that directly affects the increase or decrease in metal mobility (Du Laing *et al.* 2009). Similarly, pH that immediately rises due to floods (Hrivnáková *et al.* 2020) speeds up the transfer of trace elements as well as metals from water to sediments and vice versa; demonstrably, with metals like Pb, Hg, Zn, Cr (Salomons *et al.* 1987; Gambrell *et al.* 1991; Calmano *et al.* 1993). Therefore, floods can also change the solute content by dissolving chloride complexes (Hahne and Kroontje 1973) and increase the concentrations of major cations competing with heavy metal absorption sites (Tam and Wong 1999). These affect their toxicity and specialization, while Pb (and Cd) have the strongest effect (Du Laing *et al.* 2009).

Another necessary process is binding heavy metals to oxides and hydroxides, which are the primary carriers for these elements (especially Cd and Zn) (Salomons *et al.* 1987; Bradley and Cox 1990; Chrastný *et al.* 2006; Du Laing *et al.* 2009).

These after-flood processes caused the mobilization of metals in the littoral zone by decreasing their levels in 2019 (probably since 2018), except for the increase of cation concentrations (Ca, K,..). Subsequently, the number of total dissolved solids (TDS) and the number of chloride complexes improved, followed by increased connectivity and hardness of the water (Table 2; Fig. 4a). The affinity of metals for organic matter became evident during the after-flood recovery in 2020 by increasing their levels in the littoral zone and the amount of organic material in the water (Table 2) (Davis 1984; Grba *et al.* 2016).

In 2018, our research at Kolové pleso (Hrivnáková *et al.* 2020) showed that such catastrophic and unpredictable events could trigger the leaching of heavy metals from lake ecosystems, contaminating the aquatic environment (Chrastný *et al.* 2006; Du Laing *et al.* 2009). Therefore, the heavy metal concentrations in bryophytes should follow the rising tendency of metals in the littoral zone in 2020 (Fig. 4a). However, this was not the case for all species. In species that showed lower metal levels – *Sphagnum russowi, Sphagnum girgensohnii* and *Polytrichum commune*, recorded concentrations were higher in 2019 than in 2020. It seems that they absorbed these metals following their leaching from lake sediments. The surrounding vegetation (especially the macrophytic) of lakes can be significantly affected by floods (Wantzen *et al.* 2008). Fortunately, there already seems to be measurable recovery after two years, accompanied by an increased metal content in the littoral zone, reduced mineralization, and stabilization of the aquatic environment in 2020.

Acknowledgment

First of all, I would like to thank my consultant Mgr. Andrea Pogányová, PhD. for consultations during the first year of work and the supervisor of my study prof. RNDr. Marián Janiga for professional advice in the statistical evaluation and completion of this work. Secondly, I would like to thank Mgr. Filip Hrivnák for his professional help with English translation. In the end, I would like to thank all, who helped me a lot with working in the field, and also thanks to them, this work could be created.

References

Beracko, P., Bulánková, E. and Stloukalová, V. 2014: Sladkovodné ekosystémy, Vydavateľstvo Univerzity Komenského, Bratislava.

Bradley, B.S. and Cox, J.J. 1990: The significance of the floodplain to the cycling of metals in the river Derwent catchment, U.K. *Sci. Total Environ.*, **97/98:** 441-454.

Calmano, W., Hong, J. and Förstner, U. 1993: Binding and mobilisation of heavy metals in contaminated sediments affected by pH and redox potential. *Water Sci. Technol*, **28:** 223-235.

Chrastný, V., Komárek, M., Tlustoš, P. and Švehla, J. 2006: Effects of flooding on lead and cadmium speciation in sediments drom a drinkingwater reservoir. Department of Chemistry, University of South Bohemia, České Budějovice. Department of Agrochemistry and Plant Nutrition, Czech University of Agriculture, Praque.

Christensen, J.H., and Christensen, O.B. 2003: Climate modelling: Severe summertime flooding in Europe. *Nature,* **421:** 805-806.

Coops, H., Beklioglu, M. and Crisman, T.L. 2003: The role of water–level fluctuations in shallow lake ecosystems – workshop conclusions. *Hydrobiologia,* **506:** 23-27.

Davis, J.A. 1984: Complexation of trace metals by adsorbed natural organic matter. *Geochim. Cosmochim. Acta,* **46:** 2381-2393.

Diviš, M. 2008: Monitorováni vod. SPŠ Karviná. Online:
http://www.spskarvina.cz/web/uploady/File/chemie/Monitoring_vod.pdf (retrieved 12.9.2020).

Doláková, L. and Janýšková, R. 2012: Chemický rozbor vody, Hydrobiologie. Nový Jičín. Online: http://www.tznj.cz/uploads/dokumenty/dokumenty_projektu/Prirodovedne_vzdelavani /projden_rozborvody_agp_ebi_u%C4%8Deb_dol_jan.docx (retrieved 10.9.2020).

Du Laing, G., Rinklebe, J., Vandecasteele, B., Meers, E. and Tack, G.M.F. 2009: Trace metal behaviour in estuarine and riverine floodplain soils and sediments: A review. *Sci. Total Environ.,* **407:** 3972-3985.

Forbes, S.A. 1887: The lake as a microcosm. *Bulletin of the Peoria Scientific Association,* 77-87.

Gambrell, R.P., Wiesepape, J.B., Patrick, Jr., W.H. and Duff, M.C. 1991: The effects of pH, redox, and salinity on metal release from a contaminated sediment. *Water Air Soil Poll.*, **57-58:** 359-367.

Górniak, A., Jekatierynczuk–Rudczyk, E. and Dobrzýn, P. 1999: Hydrochemistry of three dystrophic lakes in Northeastern Poland. *Acta hydrochim. hydrobiol.,* **27:** 12-18.

Grba, N., Krčmar, D. and Maletić, S. 2016: Organic and inorganic priority substances in sediments of Ludas Lake, a cross–border natural resource on the Ramsar list. *Environ. Sci. Poll. Res.,* **24:** 1938-1952.

Hahne, H.C.H. and Kroontje, W. 1973: Significance of the pH and chloride concentration on the behavior of heavy metal pollutants Hg(II), Cd(II), Zn(II), Pb(II). *J. Environ. Qual.,* **2:** 444-450.

Hanušin, J. 2009: Prírodné Krásy Slovenska, Vody. Dajama, Bratislava.

Hejný, S. 1960: Ökologische Charakteristik der Wasser– und Sumpfpflanzen in den slowakischen Tiefebenen (Donau– und Theissgebieten), Vydavateľstvo SAV, Bratislava.

Hood. E., McKnight, M.D. and Williams, W.M. 2003: Sources and chemical character of dissolved organic carbon across an alpine/subalpine ecotone, Green Lakes Valley, Colorado Front Range, United States. *Water Resour. Res.,* **39:** 1188.

Hrivnáková, K. 2019: Seasonal variability of physical and chemical properties of the water in lake Kolové pleso, the West Carpathians. *Oecologia Montana,* **28:** 30-45.

Hrivnáková, K., Janiga, M. and Pogányová, A. 2020: Effects of flooding on the physical and chemical water composition of the alpine lake Kolové pleso (High Tatra, West Carpathians). *Oecologia Montana,* **29:** 23-27.

IPCC, 2001: Climate Change 2001: Synthesis Report, Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland.

Judová, J., Šalgovičová, D., Pavlovičová, D. and Kosová, I. 2015: Environmental monitoring/Enviromentálny monitoring, Institute of High Mountain Biology, University of Žilina.

Junk, W. J. and Wantzen, M.K. 2004: The flood pulse concept: New aspects, approaches, and applications - An update. In: *Proceedings of the 2nd Large River Symposium (LARS), Pnom Penh, Cambodia [Food and Agriculture Organization & Mekong River Commission. FAO Regional Office for Asia and the Pacific, Bangkok.* (eds. R. Welcomme and T. Petr), *RAP Publication,* **16:** 117-149.

Junk, W.J., Bayley, B.P. and Sparks, E.R. 1989: The flood pulse concept in river–floodplain systems. Special Publication of the *Can. J. Fish. Aquat. Sci.,* **106:** 110-127.

Kapusta J., Hreško J., Petrovič F., Tomko–Králo D. and Gallik J.2018: Water surface overgrowing of the Tatra's lakes. *Ekológia (Bratislava),* **37:** 11-23.

Kochjarová, J. and Hrivnák, R. 2017: Plant communities of the Tatry Mountain glacial lakes and man–made ponds at the foothills. *Bull. Slov. Bot. Spoločn.,* **39:** 85-98.

Kopáček, J., Stuchlík, E. and Hardekopf, D. 2006: Chemical composition of the Tatra Mountain lakes: *Recovery from acidification. Biologia,* **61:** 21-33.

Krno, I., Bitušík, P. and Šporka F. 2010: Bentická makrofauna, In: *Tatry – Príroda* (eds. Chovancová B., Koutná A., Ładygin Z. and Šmatlák J.), pp. 423-434. Baset, Praha.

Lackovič, M. 2015: Prírodné Krásy Slovenska, Plesá. Dajama, Bratislava.

McClain, M.E., Boyer, E.W., Dent, C.L., Gergel, S.E., Grimm, N.B., Groffman, P., Hart, S.C., Harvey, J., Johnston,C., Mayorga, E., McDowell, W.H. and Pinay, G. 2003: Biogeochemical hot spots and hot moments at the interface of terrestrial and aquatic ecosystems. *Ecosystems*, **6:** 301-312.

Mikuš, P. 2012: Proudění, chemismus a izotopové složení vody v nenasycené zóně kvádrových pískovců Klokočských skal. Diplomová práca, Ústav hydrogeologie, inženýrské geologie a užité geofyziky, Univerzita Karlova v Prahe, Praha.

Mladenov, N., McKnight, M.D.,Wolski, P. and Ramberg, L. 2005: Effects of annual flooding on dissolved organic carbon. Dynamics within a pristine wetland, the Okavango delta, Botswana. *Wetlands,* **25:** 622-638.

Mooij, W.M., De Senerpont Domis, L.N., Nolet, B.A., Bodelier, P.L.E., Boers, P.C.M., Pires, L.M.D., Gons, H.J., Ibelings, B.W., Noordhuis, R., Portielje, R., Wolfstein, K. and Lammens, E.H.R.R. 2005: The impact of climate change on lakes in the Netherlands: a review. *Aquatic Ecol.,* **39:** 381-400.

Nogueira, F., Couto, E.G. and Bernardi, C.J. 2002: Geostatistics as a tool to improve sampling and statistical analysis in wetlands: a case study on dynamics of organic matter distribution in the Pantanal of Mato Grosso, Brazil. *Braz. J. Biol.,* **62:** 861-870.

Sala, M.M. and Gude, H. 2006: Seasonal dynamics of pelagic and benthic (littoral and profundal) bacterial abundances and activities in a deep prealpine lake (L. Constance). *Archiv Für Hydrobiologie,* **167:** 351-369.

Salomons, W., de Rooij, N.M., Kerdijk, H. and Bril, J. 1987: Sediments as a source for contaminants? *Hydro-*

biologia, **149:** 13-30.
Schiemer, F., Baumgartner, C. and Tockner, K. 1999: Restoration of floodplain rivers: the 'Danube restoration project'. *Regul. Rivers: Res. Manage.*, **15:** 231-244.
Seong-Tae, L., Young-Han. L., Kwang-Pyo, H., Sang-Dae, L., Min-Kyeong, K., Jong-Hwan, P. and Dong-Cheol, S. 2013: Comparison of BOD, COD, TOC and DOC as the indicator of organic matter pollution of agricultural surface water in Gyeongnam Province. *Korean J. Soil Sci. Fert,* **46:** 327-332.
Slovenská lesnícka spoločnosť. 2012a: Klimatické pomery Vysokých Tatier, Odborná štúdia k projektu OPVV 26220220087 *Vývoj ekologických metód pre kontrolu populácií vybraných druhov lesných škodcov v zraniteľných vysokohorských oblastiach Slovenska,* Scientica.sk.
Slovenská lesnícka spoločnosť. 2012b: Hydrologické a hydrobiologické pomery Vysokých Tatier, Odborná štúdia k projektu OPVV 26220220087 *Vývoj ekologických metód pre kontrolu populácií vybraných druhov lesných škodcov v zraniteľných vysokohorských oblastiach Slovenska,* Scientica.sk.
Sobek, S., Tranvik, L.J., Prairie, Y.T., Kortelainen, P. and Cole, J.J. 2007: Patterns and regulation of dissolved organic carbon: an analysis of 7,500 widely distributed lakes. *Limnology and Oceanography,* **52:** 1208-1219.
Sparks, R. E., Nelson, J.C. and Yin, Y. 1998: Naturalization of the flood regime in regulated rivers. *BioScience*, **48:** 706-720.
Šporka, F., Livingstone, D.M., Stuchlík, E., Turek, J. and Galas, J. 2006: Water temperatures and ice cover in lakes of the Tatra Mountains. *Biologia, Bratislava,* **61:** 77-90.
Štefková, E. and Šporka, F. 2001: Long–term ecological research of high mountains lakes in the High Tatras (Slovakia). *Ekológia (Bratislava),* **20:** 101-106.
Steven, S. and Melack, M.J. 2012: The Effect of an extreme rain event on the biogeochemistry and ecosystem metabolism of an oligotrophic high–elevation lake. *Arct. Antarct. Alp. Res.*, **44**: 222-231.
Szabó, S., Posta, J., Gosztonyi, G., Mészáros, I. and Prokisch, J. 2008: Heavy metal content of flood sediments and plants near the river Tisza. *AGD Landscape & Environment,* **2:** 120-131.
Tam, N.F.Y. and Wong, Y.S. 1999: Mangrove soils in removing pollutants from municipal wastewater of different salinities. *J. Environ. Qual.*, **28**: 556-564.
Tockner, K., Malard, F. and Ward, J.V. 2000: An extension of the flood pulse concept. *Hydrol. Process.,* **14:** 2861-2883.
Tölgyessy, J., Betina, V., Frank, V., Fuska, J., Lesný, J., Moncmanová, A., Palatý, J., Piatrik, M., Pitter, P. and Prousek, J. 1984: Chémia, biológia a toxikológia vody a ovzdušia, Vydavateľstvo Slovenskej akadémie vied, Bratislava.
Vido, J., Tsegaye T., Šustek, Z., Kandrík, R., Hanzelová, M.,Škvarenina, J., Škvareninová, J. and Hayes, M. 2015: Drought occurrence in central european mountainous region (Tatra National Park, Slovakia) within the period 1961–2010. *Advances in Meteorology,* **1.**
Wantzen, K.M., Wolfgang, J.J. and Rothhaupt, K.O. 2008: An extension of the floodpulse concept (FPC) for lakes. *Hydrobiologia,* **613:** 151-170.
Wathne, B.M., Patrick, S.T., Monteith, D.T. and Barth, H. 1995: AL:PE, acidification of mountain lakes; palacolimnology and ecology. European Commision, D–G XII, Luxembourg. *Ecosystems research Report,* **9:** 296.

Received 23 November 2020; accepted 13 December 2020.

Appendix 1: Sampling sites

The following abbreviations have been used in the list of sites for the names of valleys: **KD** – Kôprová dolina, **VD** – Važecká dolina, **FD** –Furkotská dolina, **MD** – Mlynická dolina, **MeD** – Mengusovská dolina, **ZD** – Zlomiská dolina, **BaD** – Batizovská dolina, **VeD** – Velická dolina, **SlD** – Slavkovská dolina, **VSD** – Veľká Studená dolina, **MSD** – Malá Studená dolina, **SD** – Skalnatá dolina, **DKBV** – Dolina Kežmarskej Bielej vody, **JD** – Javorová dolina, **BD** – Bielovodská dolina. All samples were collected by author.

Way of registering the site:
Lake: valley – side valley, elevation, orientation, GPS coordinates of sampling, type of shore, bottom type: nutrient content; date of sampling;

1. Nižné Temnosmrečinské pleso: KD – Temnosmrečinská dolina, 1677 m asl., S, 49˚11'40.6"N, 20˚01'47.0"E, rocky – overgrown shore, rocky bottom: oligotrophic; 7.11.2020;
2. Vyšné Temnosmrečinské pleso: KD – Temnosmrečinská dolina, 1725 m asl., S, 49˚11'22.0"N, 20˚02'11.7"E, rocky shore, rocky bottom: oligotrophic; 7.11.2020;
3. Nižné Terianske pleso: KD – Nefcerská dolina, 1940 m asl., S, 49˚10'08.1"N, 20˚00'43.5"E, rocky – overgrown shore, rocky bottom: oligotrophic; 28.10.2020;
4. Vyšné Terianske pleso: KD – Nefcerská dolina, 2124 m asl., S, 49˚10'02.6"N, 20˚01'15.7"E, rocky shore, rocky bottom: oligotrophic; 28.10.2020;
5. Jamské pleso: VD – Jamy, 1447 m asl., S, 49˚08'01.0"N, 20˚00'42.1"E, overgrown shore, gravely – sandy bottom: dystrophic; 20.5.2020; KH.
6. Malé kriváňske pliesko: VD – Zadný Handel, 2004 m asl., S, 49˚09'26.9"N, 20˚00'23.3"E, shore – under snow, rocky bottom: oligotrophic; 30.10.2020;
7. Zelené kriváňske pleso: VD – Zadný Handel, 2012 m asl., S, 49˚09'27.1"N, 20˚00'25.9"E, shore – under snow, rocky bottom: oligotrophic; 30.10.2020;
8. Vyšné rakytovské pleso: FD – Rakytovec, 1307 m asl., S, 49˚07'35.6"N, 20˚01'29.0"E, overgrown shore, peat bottom: dystrophic; 20.5.2020;
9. Nižné rakytovské pleso: FD – Rakytovec, 1323 m asl., S, 49˚07'30.2"N, 20˚01'34.2"E, overgrown shore, peat bottom: dystrophic; 20.5.2020;
10. Vyšné smrekovické pliesko: FD – Smrekovica, 1355 m asl., S, 49˚07'31.9"N, 20˚02'05.9"E, overgrown shore, peat bottom: dystrophic; 20.5.2020;
11. Nižné smrekovické pliesko: FD – Smrekovica, 1350 m asl., S, 49˚07'31.2"N, 20˚02'08.5" E, overgrown shore, peat bottom: dystrophic; 20.5.2020;
12. Prvé Sedielkové pliesko: FD, 1876 m asl., S, 49˚09'03.9"N, 20˚01'32.6"E, rocky – overgrown shore, rocky bottom with an organic layer of sediment: oligotrophic; 20.10.2020;
13. Nižné Wahlenbergovo pleso: FD, 2053 m asl., S, 49˚09'33.0"N, 20˚01'35.4"E, rocky shore, rocky bottom: oligotrophic; 1.9.2019; .
14. Soliskové pliesko: FD, 2073 m asl., S, 49˚09'38.2"N, 20˚01'31.4"E, rocky shore, rocky bottom: oligotrophic; 28.10.2020;
15. Vyšné Wahlenbergovo pleso: FD, 2157 m asl., S, 49˚09'50.4"N, 20˚01'39.4"E, rocky shore, rocky bottom: oligotrophic; 1.9.2019;
16. Štrbské pleso: MD, 1347 m asl., S, 49˚07'25.2"N, 20˚03'13.2"E, overgrown shore, gravely – sandy bottom: dystrophic; 20.5.2020;
17. Pliesko pod Skokom: MD, 1685 m asl., S, 49˚09'06.5"N, 20˚02'49.5"E, overgrown shore, gravely – sandy bottom: oligotrophic; 1.9.2019;
18. Pleso nad Skokom: MD, 1801 m asl., S, 49˚09'16.8"N., 20˚02'43.0"E, ocky – overgrown shore, rocky bottom with an organic layer of sediment: oligotrophic; 1.9.2019;
19. Vyšné Volie pliesko: MD, 1980 m asl., S, 49˚09'42.3"N, 20˚02'32.2"E, rocky – overgrown shore, rocky bottom: oligotrophic; 1.9.2019;
20. Malé Kozie pleso: MD, 1932 m asl., S, 49˚09'44.2"N, 20˚02'30.5"E, rocky shore, rocky bottom: oligotrophic; 1.9.2019;

21. Nižné Kozie pleso: MD, 1942 m asl., S, 49° 09'48.0"N, 20° 02'37.4"E, rocky – overgrown shore, rocky bottom: oligotrophic; 1.9.2019;
22. Vyšné Kozie plesá: MD – Kozí kotol, 2109 m asl., S, 49° 10'03.3"N, 20° 02'41.6"E, rocky shore, rocky bottom: oligotrophic; 1.9.2019;
23. Capie pleso: MD, 2075 m asl., S, 49° 10'04.5"N, 20° 02'16.4"E, rocky shore, rocky bottom: oligotrophic; 1.9.2019;
24. Okrúhle pleso: MD, 2105 m asl., S, 49° 10'12.2"N, 20° 02'07.9"E, rocky shore, rocky bottom: oligotrophic; 1.9.2019;
25. Popradské pleso: MeD – Beginning of the Zlomiská dolina, 1494 m asl., S, overgrown shore, gravely – sandy bottom: dystrophic; 4.9.2019;
26. Ľadové pleso in valley Zlomiská dolina: MeD – ZD (Ľadová kotlina), 1925 m asl., S, 49° 09'48.7"N, 20° 06'18.2"E, rocky – overgrown shore, rocky bottom with an organic layer of sediment: oligotrophic; 4.9.2019;
27. Dračie pleso: MeD – ZD (Dračia dolinka), 2019 m asl., S, 49° 09'56.7"N, 20° 05'16.7"E, rocky shore, rocky bottom: oligotrophic; 4.9.2019;
28. Malé Dračie pleso: MeD – ZD (Dračia dolinka), 1951 m asl., S, 49° 09'55.3"N, 20° 05'27.6"E, rocky shore, rocky bottom: oligotrophic; 4.9.2019;
29. Dračie oko: MeD – ZD (Dračia dolinka), 2020 m asl., S, 49° 09'55.3"N, 20° 05'22.3"E, rocky shore, rocky bottom with an organic layer of sediment: oligotrophic; 4.10.2019;
30. Rumanovo pleso: MeD – ZD (Rumanova dolinka), 2090 m asl., S, 49° 10'09.9"N, 20° 06'00.9"E, rocky shore, rocky bottom: oligotrophic; 4.9.2019;
31. Nižné Rumanovo pliesko: MeD – ZD (Rumanova dolinka), 2088 m asl., S, 49° 10'07.9"N, 20° 06'00.0"E, rocky shore, rocky bottom: oligotrophic; 4.9.2019;
32. Veľké Žabie pleso: MeD – Žabia dolina (Žabia kotlinka), 1921 m asl., S, 49° 10'21.7"N, 20° 04'34.9"E, rocky shore, rocky bottom: oligotrophic; 14.7.2020;
33. Malé Žabie pleso: MeD – Žabia dolina, 1919 m asl., S, 49° 10'22.4"N, 20° 04'34.2"E, rocky shore, rocky bottom: oligotrophic; 14.7.2020;
34. Predné Žabie pleso: MeD – Žabia dolina, 1917 m asl., S, 49° 10'20.9"N, 20° 04'25.6"E , rocky – overgrown shore, rocky bottom: oligotrophic; 14.7.2020;
35. Vyšné Žabie pliesko: MeD – Žabia dolina (Volia kotlinka), 2046 m asl., S, 49° 10'31.4"N, 20° 04'23.8"E, rocky shore, rocky bottom: oligotrophic; 14.7.2020;
36. Malé Satanie pliesko: MeD – Satania dolinka, 1894 m asl., S, 49° 10'11.6"N, 20° 03'43.9"E, rocky – overgrown shore, rocky bottom with an organic layer of sediment: oligotrophic; 14.7.2020;
37. Satanie pleso: MeD – Satania dolinka, 1894 m asl., S, 49° 10'12.0"N, 20° 03'39.7"E, rocky – overgrown shore, rocky bottom with an organic layer of sediment: oligotrophic; 14.7.2020;
38. Hincové oká: MeD – Hincová kotlina, 1 940 m asl., S, 49° 10'31.5"N, 20° 03'47.3"E, rocky shore, rocky bottom: oligotrophic; 14.7.2020;
39. Malé Hincovo pleso: MeD – Hincová kotlina, 1921 m asl., S, 49° 10'28.2"N 20° 03'28.8"E, rocky – overgrown shore, rocky bottom: oligotrophic; 14.7.2020;
40. Veľké Hincovo pleso: MeD – Hincová kotlina, 1945 m asl., S, 49° 10'35.0"N, 20° 03'41.3"E, rocky – overgrown shore, rocky bottom: oligotrophic; 14.7.2020;
41. Čierne pleso in valley Motyková dolina: HT, BaD – Motyková dolina, 1235 m asl., S, 49° 07'36.5"N, 20° 07'47.6"E, overgrown shore, peat bottom: dystrophic; 20.5.2020;
42. Batizovské pleso: BaD – Nižná Batizovská roveň, 1883 m asl., S, 49° 09'05.5"N, 20° 07'46.4"E, rocky shore, rocky bottom: oligotrophic; 23.10.2019;
43. Malé Batizovské pleso: BaD – Nižná Batizovská roveň, 1920 m asl., S, 49° 09'11.0"N, 20° 07'27.5"E, rocky – overgrown shore, rocky bottom with an organic layer of sediment: oligotrophic; 23.10.2019;
44. Pliesko pod Kostolíkom: BaD – Vyšná Batizovská roveň, 2075 m asl., S, 49° 09'38.1"N, 20° 07'15.8"E, rocky shore, rocky bottom: oligotrophic; 23.10.2019;
45. Velické pleso: VeD, Velické pleso, 1665 m asl., S, 49° 09'31.4"N, 20° 09'22.1"E, rocky – overgrown shore, rocky bottom: oligotrophic; 11.9.2019;
46. Kvetnicové pliesko (1): VeD – Kvetnica, 1815 m asl., S, 49° 09'44.9"N, 20° 09'12.6"E, overgrown shore, gravely – sandy bottom: oligotrophic; 11.9.2019;
47. Kvetnicové pliesko (2): VeD – Kvetnica, 1890 m asl., S, 49° 09'52.9"N, 20° 08'44.3"E, rocky – overgrown shore, gravely – sandy bottom: oligotrophic; 23.10.2019;
48. Dlhé pleso in valley Velická dolina: VeD – Horná Kvetnica, 1939 m asl., S, 49° 09'55.0"N, 20° 08'40.9"E, rocky – overgrown shore, rocky bottom: oligotrophic; 23.10.2019;
49. Vyšné Velické pliesko – dolné: VeD – Velická kotlina, 2118 m asl., S, 49° 10'20.4"N, 20° 08'13.2"E, rocky shore, rocky bottom: oligotrophic; 23.10.2019;
50. Vyšné Velické pliesko – horné: VeD – Velická kotlina, 2141 m asl., S, 49° 10'20.7"N, 20° 08'09.1"E, rocky shore, rocky bottom: oligotrophic; 23.10.2019;
51. Slavkovské pliesko: SlD – under Senná kopa, 1676 m asl., S, 49° 09'09.0"N, 20° 10'59.6"E, overgrown shore, rocky – peat bottom: dystrophic; 11.9.2019;
52. Žabie pliesko: SlD – over Starý Smokovec, 1050 m asl., S, 49° 08'41.0"N, 20° 13'02.5"E, overgrown shore, peat bottom: dystrophic;3.10. 2020;
53. Vareškové pleso: VSD – Varešková kotlina, 1834 m asl., S, rocky – overgrown shore, rocky bottom: oligotrophic; 21.10.2019;
54. Dlhé pleso in valley Veľká Studená dolina: VSD, 1894 m asl., S, 49° 10'30.0"N, 20° 10'10.3"E, rocky – overgrown shore, rocky bottom with an organic layer of sediment: oligotrophic; 21.10.2019;
55. Nižné Sesterské pleso: VSD – Zbojnícka pláň, 1974 m asl., S, 49° 10'38.6"N, 20° 09'59.4"E, rocky – overgrown shore, rocky bottom: oligotrophic; 21.10.2019;
56. Starolesnianske pleso: VSD – Zbojnícka pláň, 1988 m asl., S, 49° 10'48.9"N, 20° 09'58.4"E, rocky – overgrown shore, rocky bottom: oligotrophic; 29.9.2019;
57. Nižné zbojnícke pleso: VSD – Zbojnícka pláň, 1955 m asl., S, 49° 10'38.8"N, 20° 09'41.6"E, rocky – overgrown shore, rocky bottom: oligotrophic; 29.9.2019;
58. Prostredné zbojnícke pleso: VSD, 1960 m asl., S, 49° 10'42.6"N, 20° 09'37.6"E, rocky – overgrown shore, rocky bottom with an organic layer of sediment: oligotrophic; 12.8.2019;
59. Zbojnícke pleso: VSD, 1960 m asl., S, 49° 10'41.3"N, 20° 09'40.6"E, rocky – overgrown shore, rocky bottom with an organic layer of sediment: oligotrophic; 29.9..2019;
60. Vyšné (Veľké) zbojnícke pleso: VSD, 1962 m asl., S, 49° 10'44.0"N, 20° 09'32.0"E, rocky – overgrown shore, rocky bottom: oligotrophic; 12.8.2019;
61. Ľadové (zbojnícke) pleso: VSD – Rovienková kotlina, 2057 m asl., S, 49° 11'00.2"N, 20° 09'39.9"E, rocky shore, rocky bottom: oligotrophic; 12.8.2019;
62. Pusté pleso: VSD – Rovienková kotlina, 2056 m asl., S, 49° 10'54.5"N, 20° 09'15.7"E, rocky – overgrown shore, rocky bottom: oligotrophic; 12.8.2019;
63. Malé pusté pleso: VSD – Rovienková kotlina, 2061 m asl., S, 49° 10'59.7"N, 20° 09'17.6"E, rocky shore, rocky bottom: oligotrophic; 12.8.2019;
64. Nižné studené pleso: VSD – Strelecká plošina, 1811 m asl., S, 49° 10'44.7"N, 20° 10'39.8"E, rocky – overgrown shore, rocky bottom with an organic layer of sediment: oligotrophic; 12.8.2019;
65. Vyšné studené pleso: VSD – Strelecká plošina, 1812 m asl., S, 49° 10'47.8"N, 20° 10'35.0"E, rocky bottom, rocky bottom with an organic layer of sediment: oligotrophic; 12.8.2019;
66. Nižné sivé pleso: VSD – Ostrý kotol, 2012 m asl., S, 49° 10'59.8"N, 20° 10'31.2"E, rocky – overgrown shore, rocky bottom: oligotrophic; 12.8.2019;
67. Prostredné sivé pleso (Sivé pleso): VSD – Ostrý kotol, 2013 m asl., S, 49° 11'02.4"N, 20° 10'29.5"E, rocky shore, rocky bottom: oligotrophic; 12.8.2019;
68. Tretie Nižné strelecké pliesko: VSD – Strelecká kotlina, 2021 m asl., S, 49° 11'02.3"N, 20° 10'52.5"E, rocky – overgrown shore, rocky bottom with an organic layer of sediment: oligotrophic; 30.8.2020;

69. Prvé Nižné strelecké pliesko: VSD – Strelecká kotlina, 2013 m asl., S, 49° 11'03.2"N, 20° 10'59.3"E, rocky – overgrown shore, rocky bottom with an organic layer of sediment: oligotrophic; 30.8.2020;

70. Malé spišské pleso: MSD – Kotlina Piatich spišských plies, 1997 m asl., S, 49° 11'24.8"N, 20° 12'00.6"E, rocky – overgrown shore, rocky bottom with an organic layer of sediment: oligotrophic; 7.8. 2020;

71. Nižné spišské pleso: MSD – Kotlina Piatich spišských plies, 1992 m asl., S, 49° 11'25.8"N, 20° 11'48.6"E, rocky – overgrown shore, rocky bottom: oligotrophic; 7.8.2020;

72. Prostredné spišské pleso: MSD – Kotlina Piatich spišských plies, 2010 m asl., S, 49° 11'27.8"N, 20° 11'54.1"E, rocky – overgrown shore, rocky bottom: oligotrophic; 7.8.2020;

73. Veľké spišské pleso: MSD – Kotlina Piatich spišských plies, 2013 m asl., S, 49° 11'38.9"N, 20° 11'43.7"E, rocky shore, rocky bottom: oligotrophic; 7.8.2020;

74. Vyšné spišské pleso: MSD – Kotlina Piatich spišských plies, 2018 m asl., S, 49° 11'41.0"N, 20° 11'45.0"E, rocky shore, rocky bottom: oligotrophic; 7.8. 2020;

75. Baranie pliesko: MSD – Kotlina pod Baraními rohmi, 2207 m asl., S, 49° 11'55.1"N, 20° 11'42.4"E, rocky shore, rocky bottom: oligotrophic; 7.8.2020;

76. Modré pleso: MSD – Dolina pod Sedielkom, 2189 m asl., S, 49° 11'31.7"N, 20° 11'07.0"E, rocky shore, rocky bottom: oligotrophic; 22.10.2019;

77. Skalnaté pleso: SD, 1751 m asl., S, 49° 11'18.7"N, 20° 13'54.6"E, rocky – overgrown shore, rocky bottom: oligotrophic; 20.9.2020;

78. Skalnaté oko: SD, 1546 m asl., S, 49° 11'10.1"N, 20° 13'47.1"E, rocky – overgrown shore, rocky bottom: oligotrophic; 1.11.2020;

79. Zelené (Kežmarské) pleso: DKBV – Dolina Zeleného plesa, 1546 m asl., S, 49° 12'35.1"N, 20° 13'17.2"E, rocky – overgrown shore, rocky bottom with an organic layer of sediment: oligotrophic; 29.9.2019;

80. Čierne pleso: DKBV – Dolina Zeleného plesa, 1579 m asl., S, 49° 12'27.8"N, 20° 13'28.5"E, rocky – overgrown shore, rocky bottom with an organic layer of sediment: oligotrophic; 29.9.2019;

81. Červené pleso: DKBV – Červená dolinka, 1811 m asl., S, 49° 12'47.5"N, 20° 12'50.8"E, rocky – overgrown shore, rocky bottom: oligotrophic; 29.9.2019;

82. Belasé pleso: DKBV – Červená dolinka, 1862 m asl., S, 49° 12'53.8"N, 20° 12'41.6"E, rocky shore, rocky bottom: oligotrophic; 29.9.2019;

83. Trojrohé pleso: DKBV – Dolina Bielych plies, 1611 m asl., S, 49° 13'09.9 N, 20° 13'45.6 E, overgrown shore, peat bottom: dystrophic; 24.6.2020;

84. Veľké Biele pleso: DKBV – Dolina Bielych plies, 1615 m asl., S, 49° 13'17.1"N, 20° 13'51.1"E, rocky – overgrown shore, rocky bottom with an organic layer of sediment: oligotrophic; 24.6.2020;

85. Malé Biele plesá: DKBV – Dolina Bielych plies, 1660 m asl., S, 49° 13'28.3"N, 20° 13'10.9"E, rocky – overgrown shore, rocky bottom with an organic layer of sediment: oligotrophic; 24.6.2020;

86. Kolové pleso: JD – Kolová dolina, 1565 m asl., N, 49° 13'15.7"N, 20° 11'33.5"E, rocky – overgrown shore, rocky bottom with an organic layer of sediment: oligotrophic; 1.8.2019;

87. Zelené Javorové pleso: JD – Zelená Javorová dolina, 1815 m asl., N, 49° 12'21.6"N, 20° 08'31.7"E, overgrown shore, rocky bottom with an organic layer of sediment: oligotrophic; 22.10.2019;

88. Zelené Javorové oko (väčšie): JD – Zelená Javorová dolina, 1814 m asl., N, 49° 12'23.5"N, 20° 08'34.9"E, overgrown shore, rocky bottom with an organic layer of sediment: oligotrophic; 22.10.2019;

89. Predné rígľové oko: JD, 1512 m asl., N, 49° 11'40.1"N, 20° 09'29.9"E, rocky – overgrown shore, gravely – sandy bottom: oligotrophic; 22.10.2019;

90. Malé Žabie Javorové pleso: JD – Žabia Javorová dolina, 1704 m asl., N, 49° 12'09.0"N, 20° 08'57.8"E, rocky – overgrown shore, rocky bottom with an organic layer of sediment: oligotrophic; 22.10.2019;

91. Žabie Javorové pleso: JD – Žabia Javorová dolina, 1878 m asl., N, rocky shore, rocky bottom: oligotrophic; 22.10.2019;

92. Zamrznuté pleso: BD – Zamrznutý kotol, 2040 m asl., N, 49° 10'34.0"N, 20° 08'14.6"E, rocky – overgrown shore, rocky bottom: oligotrophic; 31.8.2020;

93. Zamrznuté oká: BD – Zamrznutý kotol, 2056 m asl., N, 49° 10'39.1"N, 20° 08'14.5"E, rocky – overgrown shore, rocky bottom with an organic layer of sediment: oligotrophic; 31.8.2020;

94. Hrubé pleso: BD – Svišťová dolina, 1929 m asl., N, 49° 10'53.1"N, 20° 08'01.4"E, rocky – overgrown shore, rocky bottom with an organic layer of sediment: oligotrophic; 31.8.2020;

95. Svišťové plieska: BD – Svišťová dolina, 1929 m asl., N, 49° 10'53.9"N, 20° 08'01.0"E, rocky – overgrown shore, rocky bottom with an organic layer of sediment: oligotrophic; 31.8.2020;

96. Litvorové pleso: BD – Litvorová dolina, 1860 m asl., N, 49° 10'39.8"N, 20° 07'47.9"E, rocky – overgrown shore, rocky bottom: oligotrophic; 31.8.2020;

97. Zelené Kačacie pleso: BD – Kačacia dolina, 1575 m asl., N, 49° 10'40.4"N, 20° 06'59.6"E, rocky – overgrown shore, rocky bottom with an organic layer of sediment: oligotrophic; 31.8.2020;

98. Zmrzlé pleso: BD – Ťažká dolina, 1762 m asl., N, 49° 10'53.2"N, 20° 06'02.5"E, rocky shore, rocky bottom: oligotrophic; 31.8.2020;

99. Ťažké pleso: BD – Ťažká dolina, 1611 m asl., N, 49° 11'11.6"N,m20° 06'26.0"E, rocky – overgrown shore, rocky bottom with an organic layer of sediment: oligotrophic; 31.8.2020;

100. Nižné Žabie Bielovodské pleso: BD – Žabia Bielovodská dolina, 1675 m asl., N, 49° 11'53.8"N, 20° 05'41.1"E, rocky – overgrown shore, rocky bottom with an organic layer of sediment: oligotrophic; 4.10.2020;

101. Vyšné Žabie Bielovodské pleso: BD – Žabia Bielovodská dolina, 1699 m asl., N, 49° 11'46.3"N, 20° 05'37.9"E, rocky – overgrown shore, rocky bottom: oligotrophic; 4.10.2020.

Appendix 2.
Map with the exact location of examined High Tatras lakes (101 in total - Appendix 1).
Source: Google Earth – Maxar Technologies © 2021 CNES / Airbus Modified by Hrivnáková K.