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The impact of forests covering the crater of Lake Sfânta Ana on the hydrological characteristics of the lake, suggestions for forest management

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1. Introduction and objectives

Lake Sfânta Ana is one of Transylvania's best-known tourist attractions. The crater lake is located in the Eastern Carpathians, in the Ciomatu, the southernmost volcanic cone of the Hargita Mountains.

The inner crater wall of the Ciomatu is currently 95.9% covered with forest, made up of old beech stands, mixed-age beech stands and beech-spruce-fir mixtures, middle-aged spruce, young and middle-aged beech-spruce stands.

The need for research is justified by the significant changes in the bathymetric characteristics and water quality of Lake Sfânta Ana.

During the last century, the maximum depth of the lake decreased by more than one meter, and the area of the water surface decreased by more than one hectare. The change in water volume may be partly the result of the lake's water level decrease, partly the result of the fill-up process. The lake's water quality has also changed significantly over the last decade.

Research examining the interactions between the lake and the tree stands in the crater can form the basis of the most suitable forest management in the crater in terms of the lake's survival. The main issue is whether it is possible to intervene with silvicultural activities in the composition of tree species and other stand structure characteristics in such a way that the forests of the crater promote the long-term maintenance of the lake in terms of their overall effect on the water budget and water quality.

Objectives of the research:

- Identification of the main tree-stand structures in the Sfânta Ana crater.
- Getting to know the significance of the individual stand structures from the point of view of soil erosion, evaluation of the different tree stands and other land cover categories (grass plots, dirt trails) in the crater from the point of view of erosion protection.
- Determination of the water balance components of the lake and understanding the role of the forests on the inner crater slopes that make up the watershed of the lake.

- The detection of the appearance of free water in the soil of the stands of the interior of the crater, which can form a feeding component of the water balance of the lake and the detection of the differences between the individual tree stands in this regard.

2. Materials and methods

2.1. Mapping of stand structures

During the stand surveys, the aim was to identify the typical tree stand structures and record their structural characteristics, the knowledge of the main structures forms the basis of comparative studies from the point of view of the studied processes (infiltration rate, development of soil moisture exceeding the value of the open field water capacity). During the surveys, circular sampling plots were used, 500 m^2 plots were used in middle-aged stands, and 1000 m^2 in old and mixed-age stands.

During the data processing, the main structural characteristics of each stand category were determined, and after being presented, comparative tests of stand structure characteristics less dependent on age, the live crown ratio and the crown base height were carried out. Middle-aged beech, old beech, mixed-age beech and middle-aged spruce tree stand categories were compared. During statistical processing, a 5% significance level was chosen. Normality checks of distributions were done using the Shapiro-Wilk test. Since for the majority of the samples the normality condition was not met either in in the case of live crown ratio data or the crown base height, the comparisons were made using the Kruskal-Wallis ANOVA test.

2.2. Examination of water infiltration rates in soils for the different stand structures and various land cover categories

The purpose of the study is to compare the infiltration rate of soils in the case of different land cover categories (different tree stands, grass plots, dirt trails) on the inner slopes of the crater. The goal is to

identify the sediment sources that contribute to the fill-up of the lake during high-intensity rainfall events.

Sampling took place on slopes with an inclination angle of up to 20º, in three land cover categories: forests, grass plots and dirt trails. For the forest cover category, three stand categories were defined, these are old beech stands, middle-aged spruce stands and small regeneration plots in old beech stands.

The steady-state infiltration rates were determined with float-valve double-ring infiltrometers, using the constant water head method. The measurements continued until the infiltration rate stabilized.

At each infiltration measurement location, 250 cm^3 soil samples were taken from the upper horizon of the soil by vertical impact of a steel cylinder. Dry weight, skeleton weight and volume, soil texture, soil volumetric mass, soil skeleton volume ratio was determined. The organic carbon contents of the samples were determined using the potassium dichromate method. Soil compactness was measured using a soil penetrometer.

Statistical processing was performed at a 5% significance level. In the case of the three tree-stand categories, the differences were investigated using a one-way analysis of variance. The normality test was performed with the use of the Shapiro-Wilk test. The equality of variances was verified using Levene's test. Tukey Unequal N HSD post-hoc test was used to evaluate differences between categories.

The effect of the land use category (forests, grass plots, dirt trails) was investigated using Kruskal-Wallis ANOVA, because the normality condition was not met in the case of the dirt trails category.

After the analysis of the effects described above, correlation analyzes were performed to reveal possible correlations between the value of the infiltration rate and the examined soil properties (volumetric mass, skeleton content, organic carbon content and soil compaction). The differences between the soil compactness in the individual land use categories (tree stands, grass plots, dirt trails) were determined with the help of Kruskal-Wallis ANOVA, because the condition of equality of variances was not met.

2.3. Examination of the water balance components of the Lake Sfânta Ana

Clarifying the role of the tree stands in the crater in terms of the water balance of Lake Sfânta Ana is only possible with a more precise understanding of the latter, therefore the research of the components of the water balance was essential for the evaluation of the forest-lake relationship system. The method used was based on the water budget approach, which is generally used for the analysis of hydrological systems and is based on the law of conservation of masses.

Based on the assumption that the water balance in the case of the lake is decisively influenced by precipitation and evaporation, the field measurements were aimed at determining the precipitation and evaporation components, the changes in the reservoir were expressed by the water level changes in the lake. The overall effect of the other components of the water balance can be defined as changes in the water level of Lake Sfânta Ana that cannot be explained by precipitation and evaporation.

Changes in precipitation and water level were determined based on direct measurements, the values of the lake's water surface temperature, air temperature, wind speed and relative humidity were recorded to calculate evaporation. The high-resolution (data reading and recording at every 10 minutes) data collection was carried out between March 23, 2020 and October 28, 2021. The statistical method of multiple linear regression was used to estimate the predictive ability of the independent variables of precipitation and evaporation of the change in the water storage of the lake as a dependent variable.

2.4. Examination of the appearance of free gravitational water in the soil under different tree stands

Maintaining the water level of the lake, stopping and reversing of the unwanted tendencies may be possible by studying and improving the feeding parameters of the water balance. It is not possible to shape the annual precipitation amounts, so the solution can be a more efficient use of this water quantity by increasing the amount of subsurface inflow. The possibility of subsurface inflow can be confirmed

or disproved by examining the dynamics of soil moisture under individual stands, and by the occurrence of values of soil moisture exceeding the open field water capacity of the soil.

A comparative study was conducted on the frequency of free gravitational water in stands with different tree species composition and age structure (old beech stand, middle-aged beech stand, middle-aged spruce stands, mixed-age beech stand) and in small regeneration plots formed in an old beech stand. Three sample areas were selected in each category to carry out the study. In the sample areas, the stand structures were mapped during the stand surveys.

For each sample area, a soil moisture sensor was installed with the corresponding data recorder, which recorded the soil moisture at a depth of 50 centimeters at 10-minute intervals. The recorded data were evaluated for the period May 1, 2020 and August 1, 2021.

For different forest structures, the statistical evaluation of the differences in the frequency of appearance of free water was carried out using the X^2 test. For the evaluation, the frequency of occurrence of free water was calculated from the measurement results of the individual sensors.

The homogeneity of the three sample areas of the categories characterized by the same stand structure (old beech, middle-aged beech, middle-aged spruce, mixed-age beech) was checked in terms of the frequency of occurrence of free water with a X^2 homogeneity test.

The dependence of the frequency of appearance of free water on the different stand structure categories was checked with a X^2 independence test. Pairwise comparisons were made using the Bonferroni post-hoc test.

3. Results and conclusions

3.1. Results of the stand structure surveys

The main characteristics of the stands determined by the stand structure surveys are contained in Table 1 below. The comparative studies of the live crown ratio and the crown base height were carried out in the case of the different tree stand categories (middle-aged beech, old beech, mixed-age beech, middle-aged spruce) and in the case of the

sample areas that were the test sites for the study of the appearance of free water.

Table 1: Main stand structures and their characteristics in the Sfânta Ana crater (NS – Norway spruce, B – European beech, SF – Silver fir, SB – Silver birch, ME – Mountain elm, EA – European aspen, NM – Norway maple, SM – Sycamore maple)

	Middle aged spruce					**Middle aged beech**			**Old beech**			**Uneven aged beech**		
Sample plot	13	4	12	16	17	1	2	3	9	10	7	5	15	14
Stand identifier	33C	34C	37	35C	35C	35B	35B	35B	33D	33D	34A	34A	33D	33D
Inclination (°)	18	17	19	12	12	30	36	30	22	18	18	31	18	21
Exposition	DNY	ÉK	DNY	DK	DK	K	K	ÉK	ÉNY	ÉNY	ÉNY	ÉNY	NY	NY
Stand composition (%)	NS 100%	NS 95 B 4ME 1%	NS 100%	NS 99 B 1%	NS 84 SF 10 SB 4 B 2%	B 83 NS 5 SB 5 EA 4 SF 1ME 2%	B 88 SB 10 NM 1 SM 1%	B 90 SM 6 SB 3 NS 1%	B 100%	B 100%	B 100%	B 100%	B 79 NS 21%	B 84 NS 15 SF 1%
Age (yr)	65	65	60	65	65	65	65	65	130	130	130	-	-	-
Canopy closure (%)	100	90	90	85	85	100	100	100	95	100	100	90	90	90
Diameter (cm)	27,6	29,5	18,5	30,5	29,8	19,1	15,8	19,5	47,3	35,3	37,2	43,5	43	50,3
Height (m)	28,4	30,4	21,4	29	31,1	23	21,8	23	33	32,1	33,2	34,3	29,7	32,9
Arithmetic mean height (m)	26,4	28,6	20,6	26,2	27,4	20,2	17,6	19,1	31,9	30	32,0	17,3	18,1	23,3
Dominant height (m)	30,2	33,9	24,2	31,3	34,5	25,2	23,7	27,1	34,9	34,8	35,2	36,7	32,7	35,7
Basal area (m^2/ha)	64,8	75,2	56,9	57	43,1	48,2	41,7	44,3	45,7	43,1	41,3	52	40,6	51,6
Volume (m^3/ha)	826	1049	601	741	606	546	453	507	796	702	695	977	606	883
stem no. (pc/ha)	1080	1100	2120	780	620	1680	2140	1480	260	440	380	350	280	260
Mean stem distance (m)	3,3	3,2	2,3	3,8	4,3	2,6	2,3	2,8	6,7	5,1	5,5	5,7	6,4	6,7
Yield class	I	I	II	I	I	II	III	III	II	II	II	II	III	II
Current growth ($m^3yr^{-1}ha^{-1}$)	18,3	18,3	16,4	18,3	18,3	11,4	9,4	9,4	8,6	8,6	8,6	-	-	-

According to the results of the Kruskal-Wallis test (*H(11, 677) = 299.5412 p = 0.000*) there is a statistically significant difference between the compared groups in terms of the live crown ratio. Based on the results of the pairwise comparisons, the middle-aged spruce stand category can be characterized by a lower crown proportion value, middle-aged beech and mixed-age beech stands have significantly higher live crown ratio for all the sample areas. At the same time, it was found that in the case of the middle-aged beech and mixed-aged beech stand

categories, no significant differences can be detected in any sample area in terms of crown proportions.

According to the result of the Kruskal-Wallis test (*H(11, 677) = 341.0370 p = 0.000*), there is a statistically significant difference between the compared groups with regard to crown base height. In the studied stand categories, the crown height of the old beech is significantly higher than that of the middle-aged beech and the mixed-aged beech, but there is no significant difference between the latter two stand categories. In the case of middle-aged spruce, the crown base height is significantly higher than in the sample areas of middle-aged beech. The significant differences in crown base height values express a clear difference in stand structure especially in the comparison of old beech and mixed-age beech stand categories, which consist of the same tree species, and are characterized by a similar biological top height. The trunk spaces of middle-aged spruce test plots are more open than in the case of middle-aged beech test plots, and the trunk spaces of old beech test plots are also more open than the trunk space of middle-aged beech and mixed-age beech test plots.

3.2. Results of soil infiltration tests

The steady-state infiltration rate values were very high (>145 mm/h) in all samples for spruce and old beech stands, very high values were also measured in small regeneration plots in beech stands, except for one measurement, which fell into the very low category (1.1-5.0 mm/h). In the case of grass plots, the values of the infiltration rate were located in the interval between low (5.1-30 mm/h) and very high infiltration rates. The lowest infiltration values were measured for dirt trails, their values were located between the very low and medium (30.1 - 70 mm/h) categories, with the exception of one measurement, which could be classified in the high (70.1 - 145 mm/h) infiltration rate category.

The one-way analysis of variance showed a statistically significant difference between the groups (*F(2, 28) = 5.950, p = 0.007*) in the comparison of different tree stand types. The Tukey Unequal N HSD post hoc test revealed a statistically significant difference between the steady-state infiltration rates of spruce and old beech stands.

Considering that under these stands the value of the steady-state infiltration rate was higher than 200 mm/h in all measurements, the

probability of the formation of surface water flows under all tree stand structures is very low.

Statistically significant differences can be shown in the comparison between the different land use categories, based on the results of the Kruskal-Wallis test ($H(2, 51) = 28.97883, p < 0.0001$). The measured averages of the hydraulic conductivity of forest soils are much higher than in the case of grass plots and dirt trails.

Despite the fact that the average value of the steady infiltration rate of grass plots can be classified as a high infiltration rate, in the comparison with tree stands it represents a significantly lower value, which reflects a less favorable situation. In several sampling locations, the results of the measurement are low, which prove that surface water flows can form in some areas of the grass plots during intense rainfall events.

The dirt trails and paths were formed as a result of constant human treading, the soil surface was completely stripped of vegetation. The results of the measurements show low, very unfavorable values of the stable infiltration rate, these dirt trails feed Lake Sfânta Ana with surface flows with high sediment content during intense rainfall events.

In order to reveal the reasons for the significant differences between the permanent infiltration rates of different tree stand structures and land use categories, correlations between certain properties of the surface layer of the soil and the permanent infiltration rate were investigated.

A very weak, negligeable correlation was detected between the sand content and the value of the permanent infiltration rate ($r(49) = -0.0379, p = 0.792$). The steady state infiltration rate and the organic carbon content of the soil also had a very weak negative correlation with each other ($r(49) = -0.0599, p = 0.676$). Similarly the comparison of soil volumetric mass and steady-state infiltration rate resulted in a very weak negative correlation ($r(49) = -0.1701, p = 0.233$).

The relationship between the stabilized infiltration rate and the skeleton content of the soil can be characterized by a moderate negative correlation ($r(49) = -0.4214 p = 0.002$).

A strong negative correlation was detected between the steady-state infiltration rate and the compactness of the soil ($r(49) = -0.6184, p<0.001$).

The results of the Kruskal-Wallis test show a significant difference between the soil compaction under forests and under other land use categories (grass plots, dirt trails). There is no significant statistical difference between the compactness values of the soil of grass plots and dirt trails. No significant statistical differences in terms of soil compaction can be detected between the tree stand categories (middle-aged spruce, old beech, and small regeneration plots in old beech).

3.3. Results of the examination of the water balance components of the Lake Sfânta Ana

Examination of the coefficients of the independent variables of precipitation and evaporation shows that they are statistically significant. The fitted regression model is: $\Delta S = 0.04662 + 1.04259P - 1.02487E$ (where ΔS represents the change in the storage of the reservoir, P represents precipitation and E represents evaporation).

From a predictive point of view, the model is significant ($R^2 = 0.9688$, $F(2, 409) = 6586$, $p < 0.0001$). It can be said that 96.9% of the variance of water level changes is explained by the precipitation and evaporation components of the water balance.

The remaining difference can be explained by the influence of other components of the water balance. Knowing the existence and magnitude of subsurface inflow and deep infiltration requires further research. A more complete understanding of surface inflow events, which only occur during heavy rainfall or rapid snowmelt, also requires further investigations regarding the conditions of their appearance and the magnitude of the phenomenon, just like the clarification of the amount and effects of microprecipitation.

3.4. Results of study of the appearance of free water in the soil of different tree stands

Soil moisture exceeding the open field capacity of the soil water content appeared in the soil of the forest stands of the Lake Sfânta Ana crater during rainy periods characterized by a higher amount of precipitation and during snow melt.

According to the results of the homogeneity test of the frequencies of occurrence of free water in the three sample areas designated in each category, the homogeneity of the samples within each category

could not be rejected at the 5% significance level. The sample plots chosen in the same stand structure category can be considered as belonging to the same population.

The result of the independence test performed at the level of the categories is significant at the 5% significance level, the frequencies of the appearance of free water are not independent of the different stand structure categories in at least one case ($X^2(4, 422) = 13.854$, $p = 0.0078$).

For pairwise comparisons, the corrected significance level of the Bonferroni post-hoc test is $\alpha_B = \alpha/10 = 0.005$, the study shows a significant result in the comparison of the old beech stand and the mixed-age beech stand, as well as the middle-aged beech and old beech stand categories. The frequency of appearance of free water cannot be considered independent of which category it belongs to.

In the case of measurements under even aged old beech stands, free water appeared less frequently than in middle-aged and mixed-aged stands. According to this, the stand structure somehow affects the appearance of free water. The research does not reveal exact cause-effect relationships between the stand structure factors and the frequency of occurrence of open water, further investigations are necessary for this.

The results of the measurements confirm the appearance of free water in the soil of the inner slopes of the crater of Lake Sfânta Ana. The coarse, sand, loamy-sand texture of the soil ensures the rapid infiltration of gravitational water in the direction of the bedrock. This amount of water can form a feeding component of the lake's water balance through subsurface runoff.

4. Theses

The most important scientific results are the following:

1: The different age structure of the medium-yielding, even-aged and mixed-aged beech stands of the crater of Lake Sfânta Ana does not imply significant difference in the live crown ratio. In the middle-aged beech plots and the mixed-aged beech plots the live crown ratios do not differ from each other, based on the results of the Kruskal-Wallis test, the identity of the medians cannot be rejected during pairwise comparisons of the samples. In the comparison of old beech with middle-aged and mixed-aged beech, a significant difference can be shown in the case of a single sample area. The mixed-age structure cannot be clearly characterized by a higher live crown ratio compared to the even-age structure in the stands of the Lake Sfânta Ana crater.

2: The crown base height depends on the age structure in the medium-yielding beech stands of Lake Sfânta Ana. There is a significant difference in crown base height of the sample plots with old beech and mixed-age beech, despite the fact that both stands have a similar biological top height. The crown base height of the old beech stand is significantly higher.

3: The tree stands of the inner slopes of the crater of Lake Sfânta Ana cannot be held responsible for the fill-up process of the lake as a result of soil in-wash. In the case of the distric andosol soil type of the forests, having a sand or loamy-sand texture, the average steady-state infiltration rate of water in the soil can be classified as very high (> 145 mm/h), the possibility of the formation of surface water flows is minimal, even in the case of the most unfavorable category, the small regeneration plots in old beech stands, characterized by the lowest infiltration rates. The forests on the crater slopes thus provide adequate protection against soil erosion (Szmolka and Frank, 2022a).

4: There is a significant difference between the soil infiltration rates of middle-aged spruce and old beech stand categories. Based on

the comparison of the measurement results of the steady-state infiltration rates of the stand structures located on the inner slopes of the crater of Lake Sfânta Ana, using one-way analysis of variance, there is a significant difference between the groups at the 5% significance level. The value of the steady-state infiltration rate in the small regeneration plots of old beech stands is significantly lower than in the case of middle-aged spruce stands, despite the fact that there is no statistically verifiable difference between the infiltration rates of the old beech (in which the small regeneration plots were formed) and the middle-aged spruce stands (Szmolka and Frank, 2022a). The formation of gaps causes a decrease in the steady-state infiltration rate.

5: There is a significant difference in the steady-state infiltration rates of the soils in the crater of Lake Sfânta Ana with regard to the different land cover categories. In the case of forests, the steady-state infiltration rate is significantly higher than in the case of grass plots and dirt trails. The grass plots and dirt trails contribute to the filling of the lake by bringing in sediment with the surface flows formed during intense rainfall events (Szmolka and Frank, 2022a). This result confirms the protective role of forests in the crater.

6: The very low values of the steady-state infiltration rate in the case of dirt trails and grass plots are explained by the compactness of the soil. There is a strong negative correlation between the steady-state infiltration rate and soil compaction ($r(49) = -0.6184, p < 0.001$). Soil compaction is a consequence of human treading, which is obvious on dirt roads and trails, but lakeside grass plots are also strongly exposed to this effect due to the high tourist traffic (Szmolka and Frank, 2022a). In order to conserve Lake Sfânta Ana, it is necessary to reduce the soil compaction of grass plots and dirt trails.

7: Precipitation and evaporation largely explain the changes in the water level of Lake Sfânta Ana according to the equation calculated using the multiple linear regression method ($\Delta S = 1.04259P – 1.02487E + 0.04662$). The regression is statistically significant ($R^2 = 0.9688, F(2, 409) = 6586, p < 0.0000$) at the 5% significance level. Precipitation significantly explains the changes in the water level

($\beta = 1.04259$, $P < 0.00001$), similarly, evaporation also significantly explains the changes in the water level ($\beta = -1.05487$, $p < 0.00001$). Precipitation and evaporation explained 96.9% of the variance in water level in the case of Lake Sfânta Ana, these two components are the most important determinants of the water balance (Szmolka and Frank, 2022b).

8: In the soil of the tree stands covering the inner crater slope of Lake Sfânta Ana, episodes of soil moisture content exceeding the open field water capacity of the soil occur, and the free water appearing in the soil can thereby contribute to the subsurface inflow component of the water balance of Lake Sfânta Ana. In at least one case, the frequency of the appearance of free water is not independent of the tree stand category, the result of the independence test is significant at the 5% significance level. In the soil of old even-aged beech stand category, the moisture content exceeding the open field water capacity of the soil occurs significantly less often than in the middle-aged and mixed-aged beech stands (Szmolka and Frank, 2022d). In terms of the appearance of free water, old even-aged beech stands have a less favorable effect on the development of the moisture conditions of the sand, loamy-sand textured soils of Lake Sfânta Ana than the middle-aged and mixed-aged beech stands.

5. List of the author's more important publications related to the topic

SZMOLKA, P., FRANK, N., (2022a): Analysis of infiltration rates of soils on the inner slopes of the Lake Sfânta Ana crater. *Carpathian Journal of Earth and Environmental Sciences* 17(1): 101–110. DOI:10.26471/cjees/2022/017/204

SZMOLKA, P., FRANK, N., (2022b): Estimation of the water budget components of the Sfânta Ana crater lake in the Eastern Carpathians. *Russian Meteorology and Hydrology* 47(9): 685–691. DOI:10.3103/S1068373922090060

HERCZEG Á., DÓSA L., SZMOLKA P., (2022c): Landscape History, Land Use, and Tourism of the Ciomadul– Balvanyos Region. In: Karatson D., Veres D., Gertisser R., Magyari E., Jánosi C., Hambach, U. (szerk.) *Ciomadul (Csomád), The Youngest Volcano in the Carpathians.* Cham (Germany), Germany, Springer International Publishing: 249-269. DOI: 10.1007/978-3-030-89140-4

SZMOLKA, P., FRANK, N., (2022d): Szabad víz megjelenése a talajban különböző faállományok alatt a Szent Anna-tó kráterének belső lejtőin. *Erdészettudományi Közlemények* 12(1-2), 43–55. DOI: 17164/EK.2022.03