Water balance and temperature regime in the bottom part of the Snezhnaya cave system (Western Caucasus)

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Abstract

Snezhnaya cave system, located in the alpine karst Khipsta massif, is the largest cavern in the Caucasus (total length 41 km, amplitude 1760 m, volume $2.7 \cdot 10^6$ m^3). The hydrological network of the cave includes two main separate rivers. We present the results of the analysis of monitoring data for water level and temperature and air temperature in 2015-2019 on both rivers in the bottom galleries of the cave system. Seasonal changes in water and temperature regimes in the cave are investigated. The correlations between air and water temperatures in both parts of the cave system were studied. The regimes of flashfloods are considered in detail. Based on the data of the 3D map of the cave and changes in water volume at the end of single flashfloods, a water balance model was reconstructed for both rivers in the approximation of Bernoulli's principle for a perfect fluid. The water discharges at the entrances to the bottom galleries of the cave system and at the exits from it was estimated. The results indicate the existence of two separate hydrological and climatic systems with significant differences in the morphology and catchment area of the two parts of the cave system.

1. Introduction

Snezhnaya cave system is located on the southern slope of the Caucasus (Khipsta massif of the Bzyb ridge). In terms of morphometric parameters, it is the longest karst cavity in the Caucasus (total length of passages 40840 m) and the fourth deepest cave in the world (amplitude 1760 m). Six known entrances to the system are located at the altitudes from 2389 m a.s.l. (Illyuzia) to 1318 m (Fantazia) (SHELEPIN *et al.* 2019). The three lower entrances are in the forest zone, the upper entrances are in the meadow zone.
The volume of the cave system is estimated at $2.7 \cdot 10^6$ m^3 (MAVLYUDOV 2016). Most of the volume falls on the bottom of the cave system, where the largest halls of the system are located (SHELEPIN *et al.* 2019).

The cave system has a well-developed hydrological network, which includes two main underground rivers and many smaller tributaries (GUSEV 2018; MAVLYUDOV 2016). The uniqueness of the cavity lies in the presence of two independent hydrological systems that have not yet been connected. The Guzhva cave river has been studied for 6.3 km ("old" part of the system). On the opposite side, under the same bottom blockage the same large Tatianina cave river flows, studied for more than 1 km ("new" part of the system). The deepest point of the system (−1760 m) is currently a siphon in the bottom of Morozov Lake, located on the Tatianina River (Fig. 1).

In recent years, a complex system of vertical passages and pits has been discovered at the bottom of the cave system. In several places it was possible to descend below the level of −1740 m. Under the blockage, it was possible to reach the Lebedinaya River (apparently, the continuation of the Guzhva River).

The cave system is formed in a southern wing of a large anticlinal fold in limestones and dolomites of the Upper Cretaceous (MAVLYUDOV 2016). Tracing tests indicated the complex nature of the movement of groundwater in the karst massif. The cave has at least three water flow exits into the surface (GUSEV 2018).

Systematic monitoring measurements of the water level, water and air temperature in the bottom part of the cave system have not been previously carried out. The practical purpose of the study is to evaluate the parameters of unknown lower passages to search for possible extensions of the system and to analyze the flood regime for recommendations on the safety of caver expeditions.

2. Monitoring experiment, data reduction, and water balance estimation method

The monitoring used sensors produced by Solinst Canada Ltd. A pair of sensors consists of two devices: a barologger, which measures the air temperature, t_{air}, and compensation level (analogue of atmospheric air pressure), l_{comp}, and a levelogger, which measures the temperature, t_{water}, and pressure (level) of water, h_{exp}. Barologger is a sensor whose readings are used as a correction for atmospheric pressure. The parameters were measured with an interval of 1 hour.

The accuracies of loggers are 0.05% FS for the levels and 0.05˚C for the temperatures.

The first pair of sensors was installed in the area of Penelopa Hall (levelogger location at 645 m a.s.l.), the second pair was installed near Morozov Lake (635 m a.s.l.; Fig. 1).

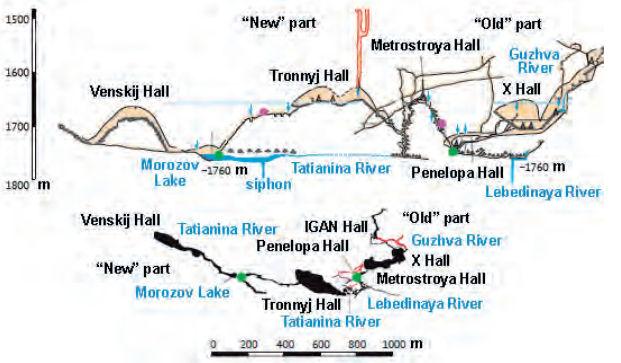

Figure 1: Profile and plan of the bottom part of the Snezhnaya cave system (from SHELEPIN et al. 2019) indicating the locations of the loggers. Places of leveloggers are marked by green circles, barologgers are by magenta circles (only on the profile).

At the first stage of data reduction, complete data series of t_{air}, l_{comp}, t_{water}, and h_{exp} were built for all four sensors. Both leveloggers have worked stable for 4.5 years, from January 2015 to July 2019. Both barologgers have work stable for only 12.5 months until early February 2016. The periods of unstable operation of the devices were excluded from further consideration.

At the second stage, the water levels were corrected for the level of compensation of the barologger. In cases where the values of the compensation level were measured, the correction was carried out according to the formula $h = h_{exp} - l_{comp}$, where h is the corrected water level.
We found the average compensation levels for the Penelopa Hall (l_{comp}=0.86±0.05 m) and Morozov Lake (l_{comp}=0.87±0.05 m). The analysis showed that the l_{comp} values are distributed according to the Gauss law, thus, their average values were used for cases when the values of the compensation level were not determined: $h = h_{exp} - 0.86$ for the Penelopa Hall and $h = h_{exp} - 0.87$ for the Morozov Lake.
The corrected data series are shown in Fig. 2. A detailed description of the monitoring experiment and data reduction is given in GUSEV *et al.* (2020).

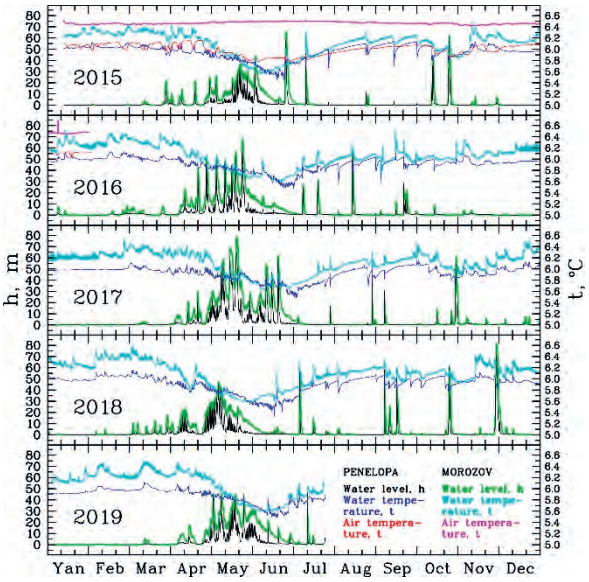

Figure 2: Profiles of the corrected water level (black and green curves), water (blue and cyan) and air temperature (red and magenta) in the Penelopa Hall (black, blue, red) and on the Morozov Lake (green, cyan, magenta curves).

Water balance was estimated based on the continuity equation for a liquid flow: $Q_1 - Q_2 - |Q_3| = 0$, where Q_1 is the inlet water discharge, Q_3 is the outlet water discharge, Q_2 is the change in water volume in the measured reservoir.
The water volume V_2 was calculated using a 3D map of the cave system. We estimated the areas of horizontal sections S_2 depending on the height h above the measurement sites for both the "old" (Penelopa Hall) and the "new" (Morozov Lake) parts with a step of 1 m by h and approximated $S_2(h)$ by a piecewise linear function. We estimate the error ΔS_2 at 20%. Received volume $V_2(h) = S_2(h)h$.

We assume that at the end of powerful summer single flashfloods (see Fig. 2), $Q_1 << |Q_2| \approx |Q_3|$. Knowing the morphology of the cave, we also adopt that $S_3 << S_2$, where S_3 is the area of outlet section for water flow. Thus, we can use Torricelli's law as a particular case of Bernoulli's principle for a perfect fluid: $v=(2gh)^{0.5}$, where v is the water velocity at an exit and g is the gravitational acceleration.

Note that we have previously found the absence of a hydrological connection between the "old" and "new" parts of the cave system (see fig. 14 in GUSEV *et al.* 2020), i.e., both reservoirs can be considered separately. Another condition for the correct use of the Torricelli's law is the absence of numerous upper water outlets.
Thus, we use the final equation $|Q_2| = S_3(2g(h+y))^{0.5}$, where y is the difference in altitude between the levelogger and the outlet.

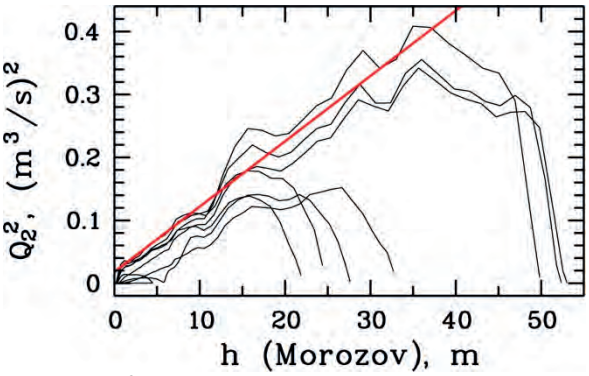

Figure 3: Q_2^2 vs. h diagram at the end of single summer flashfloods on the Morozov Lake (black curves). Red line shows the resulting linear regression.

Finding the linear regression coefficients in diagram Q_2^2 vs. h (see Fig. 3), we can obtain both S_3 and y: if $Q_2^2=Ah+B$, then $S_3=(A/2g)^{0.5}$ and $y=B/A$. In the absence of upper water outlets, S_3 and y are constants, so we can use formula $|Q_3|=S_3(2g(h+y))^{0.5}$ for any water regimes, including periods of low water. Such a situation is observed on the Morozov Lake, where there is one main gallery, and the water goes into a siphon (Fig. 1).

The "old" part of the cave is a complex 3D labyrinth with numerous blockages, vertical, horizontal and inclined passages. The analysis of the dependence Q_2^2 vs. h for the Penelopa Hall showed that the linear dependence Q_2^2~h persists up to the level h≈5.7 m, and the obtained y=–5.3 m, i.e., the water outlet is above the levelogger. For the low water level in the Penelopa Hall, Toricelli's law is not applicable. Therefore, we studied dependence ΔQ_2 on h for h<5.7 m in diagram log Q_2 vs. log h and obtained empirical correlation Q_2~$h^{2.42}$, where the power 2.42 depends on the geometric shape of the extended outlet. We also took into account the lower water discharge of ≈200 l/s of the Guzhva River when calculating the minimal water discharges.

Knowing Q_2 and Q_3, we can find input water discharge $Q_1=Q_2+Q_3$. Correctness of the method used is supported by the fact that calculated Q_1>0 within errors in every case. Correctness of Torricelli's law using is confirmed by the linear dependence between experimental data in diagram Q_2^2 vs. h.

Here and below, we do not give formal errors for Q_n and regression coefficients due to the significant contribution of errors in determining the function $S_2(h)$. We estimate the error in measuring Q_n at 20%.

3. Main results and discussion

The seasonal features of the water and temperature regimes in the bottom of the system are clearly visible (Fig. 2). The winter low-water period is characterized by a complete absence of large floods and by relatively constant high temperatures of water and air. During spring flood period, the water temperature begins to decrease, and the air temperature reaches its minimum values (in the Penelopa Hall). The summer-autumn period is characterized by rare but powerful flashfloods. The temperature of water and air (in the "old" part of the cave) gradually increases.

The minimum values of air and water temperature in the bottom of the cave system are recorded in June, by the end of the spring flood. Hourly changes in water temperature on the Morozov Lake are systematically larger than in the Penelopa Hall, and reach values of ±0.1-0.15˚C during the winter low-water period. The maximum jumps in water temperature are recorded during powerful summer floods, when hourly temperature changes Δt_{water} reach of -0.30...+0.26˚C/hour in the Penelopa Hall and -0.27...+0.49˚C/hour on the Morozov Lake.

The average t_{water} in the Penelopa Hall is +5.92±0.13˚C and lies in the range from +5.32˚C to +6.16˚C, and on the Morozov Lake is +6,08±0,21˚C ranging from +5.56˚C to +6.60˚C.

The air temperature changes are much smaller. In the Penelopa Hall, t_{air} lies in the range from +5.77 to +6.16˚C with an average value of +6.00±0.10˚C, and hourly changes Δt_{air} only during flashfloods can reach -0.13...+0.06˚C/hour (see GUSEV *et al.* (2020) for more details). The air temperature on the Morozov Lake is 0.3-0.7˚C higher and does not change throughout the year, it is ranging from +6.41 to +6.53˚C with an average value of +6.47±0.02˚C (a small peak up to +6.70˚C in 4 p.m. on January 8, 2016 is apparently associated with anthropogenic impact).

Significant differences are observed between the values and nature of seasonal changes in both the water and air temperatures in the Penelopa Hall and on the Morozov Lake (see Fig. 2 and GUSEV *et al.* 2020).

During periods without flooding, the correlation between water temperature on the Morozov Lake, t_{water}(M) and in the Penelope Hall, t_{water}(P), is well described by a linear law t_{water}(M)~$2t_{water}$(P) with t_{water}(M)>$2t_{water}$(P). During floods, t_{water}(M)≈$2t_{water}$(P).

Most of the large summer floods in the cave are not single, but have two, three and, occasionally, more maximums. Maximum water levels were 71.5 m in the Penelopa Hall and 81.4 m on the Morozov Lake during the flood of 28 November - 3 December 2018.

The rate of water rise in the cave is higher during single floods, and it is higher in the Penelope Hall than on the Morozov Lake. The highest rate of water rise Δh was 38.5 m/hour.

An important difference between the flood regime in the Penelopa Hall and on the Morozov Lake is the smoother nature of the flood flow in the latter. Equality of absolute water levels (above sea level) is achieved in the Penelopa Hall and on the Morozov Lake not simultaneously, but at those moments when the water in the Penelopa Hall begins to subside, and on the Morozov Lake it continues to rise. The flood profiles show that the water reservoirs in the "old" and "new" parts of Snezhnaya system do not communicate with each other.

For a more detailed analysis of air and water temperatures, its correlations, and regimes of flashfloods, see GUSEV *et al.* (2020).

Water balance analysis showed an average water discharge of 1.0 m^3/s in the Penelopa Hall and 0.22 m^3/s on the Morozov Lake. Maximum discharges at the entrance to the

Penelopa Hall and Morozov Lake are 69.2 and 5.04 m^3/s, respectively. Maximum discharges at the exit from the Penelopa Hall and Morozov Lake are, as expected, lower: 22.7 and 0.93 m^3/s, respectively. Maximum water volume in the cave system is $5.3 \cdot 10^5$ m^3, which is 20% of the total volume of Snezhnaya cave system. Obtained annual drainage is 0.04 km^3, close to estimates of 0.03 km^3 of MAVLYUDOV (2016), with 4/5 accounted for by the "old" part of the system.

Note that although 80% of the water flows through the Penelopa Hall, the average (6.6 versus 5.3 m^3) and maximum volumes ($4.1 \cdot 10^5$ versus $1.3 \cdot 10^5$ m^3) of water in the reservoir, V_2, are greater on the Morozov Lake. This is due to the lower capacity of the "new" part of the cave system.

One of the consequences of the analysis of the dependence of Q_2^2 on h is to find the maximum low-water discharge of 135 l/s on the Tatianina River. The second consequence is an estimate of the outlet area of 0.63 m^2 for the "old" part of the cave system.

Although the distance between the loggers in the Penelopa Hall and on the Morozov Lake does not exceed 800 m, the results obtained indicate the existence of two independent hydrological and climatic systems in the bottom of Snezhnaya cave system and can be interpreted by as a result of significant differences in the morphology of the "old" and "new" parts of the cave system.

The air temperature in the Penelopa Hall correlates with the water temperature, it reflects the temperature of air masses strongly cooled by water currents.

The discharge of the Tatianina River is estimated on average 4-5 times lower than the discharge of the Guzhva River. The catchment area of the hydrological system of the "new" part should also be approximately 4-5 times less.

Based on the study of catchment area of Snezhnaya cave system in GUSEV (2018) and the study of geology of massif in MAVLYUDOV (2016), the minimal and maximal catchment areas of cave rivers (Guzhva and Tatianina) are estimated at 15 and 18.5 km^2, respectively. Using these data and obtained annual drainage, we estimated the annual precipitation at 2100-2600 mm (without 500-800 mm of annual evaporation). Our estimates are close to the data of GIGINEJSHVILI (1979), who gave 2100-2300 mm taking into account the annual evaporation.

The catchment area of the Tatianina River is only 3 km^2 and it is apparently located entirely in the forest zone (see maps in GUSEV 2018).

4. Conclusion

Water and air temperatures as well as water levels were obtained and studied in the bottom galleries of "old" and "new" parts of Snezhnaya cave system based on monitoring data of 2015-2019. Such systematic monitoring measurements in this cave system have not been carried out before.

Water balance model was reconstructed for both cave rivers using the main hydrodynamic equations.

Obtained results indicate the existence of two separate hydrological and climatic systems with significant differences in the morphology and catchment area of the two parts of the cave system.

The developed water balance estimation method can be used for study the water balance in other caves with Snezhnaya-like morphology.

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