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RELATIONS BETWEEN AIR TEMPERATURE, PRECIPITATION AND SURFACE AND VERTICAL WATER TEMPERATURE VARIATIONS IN THE THREE KRIŠKO LAKES (JULIAN ALPS, NW SLOVENIA) IN JULY 2002

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ABSTRACT

Daily air temperatures and amount of precipitation were measured at Pogačnikov dom at Kriški podi in July 2002. Surface lake water temperatures in the three Kriško lakes, i.e. Zgornje Kriško lake, Srednje Kriško lake and Spodnje Kriško lake, were also recorded. Vertical lake water temperatures were additionally measured in Srednje Kriško lake and the heat content was calculated. Remarkable fluctuations of surface lake water temperatures were observed. Changes in the mean air temperature and amount of precipitation correlated well with variations of the surface lake water temperature. In the deeper water layers, a correlation between the lake water temperature and changes of meteorological parameters was lower. Lower lake water temperature variations were also observed in this lake section. Nevertheless, the thickness of the epilimnion and the metalimnion varied during the study. The former increased, while the latter shrank, as the days got warmer. The calculation of heat content showed that around 65% of the total heat content in Srednje Kriško lake was stored in the upper two meters of the lake.

Key words: air temperature, water temperature, heat content, alpine lakes

RELAZIONI TRA TEMPERATURA DELL'ARIA, PRECIPITAZIONI E VARIAZIONI DELLA TEMPERATURA SUPERFICIALE E VERTICALE DELL'ACQUA NEI TRE LAGHI DI KRIŠKO (ALPI GIULIE, SLOVENIA NORD-OCCIDENTALE) NEL LUGLIO 2002

SINTESI

La temperatura diurna dell'aria e l'ammontare delle precipitazioni sono stati misurati al Rifugio di Pogačnik, località Kriški podi, nel luglio 2002. È stata inoltre registrata la temperatura superficiale dell'acqua nei laghi Zgornje Kriško jezero, Srednje Kriško jezero e Spodnje Kriško jezero. La temperatura verticale dell'acqua è stata misurata solo nel Srednje Kriško jezero. Sono state osservate notevoli fluttuazioni nella temperatura superficiale dell'acqua del lago. Le variazioni della temperatura media dell'aria e dell'ammontare delle precipitazioni sono state correlate con le variazioni della temperatura dell'acqua superficiale. Negli strati più profondi la correlazione tra la temperatura dell'acqua e le variazioni dei parametri meteorologici è risultata minore. In questo strato sono state rilevate anche le variazioni della temperatura dell'acqua. Gli spessori di epilimnion e metalimnion sono tuttavia cambiati nel corso dello studio. Il primo è aumentato, mentre il secondo si è ridotto con il riscaldarsi dei giorni.

Parole chiave: temperatura dell'aria, temperatura dell'acqua, contenuto in calore, laghi

INTRODUCTION

Water temperature is an important parameter in lakes (Wetzel, 1983). It has a strong impact on the biological activity and growth of aquatic organisms, since most aquatic organisms are cold-blooded. Water temperature is also important due to its influence on water chemistry. Some chemical parameters in turn affect biological activity and aquatic life. The rates of chemical reactions, solubility and toxicity of compounds are all temperature dependent (Stumm & Morgan, 1996). An example of the effects of water temperature on water chemistry is its impact on the oxygen concentration. The oxygen concentration in warmer lake water is lower than in cooler lake water. Thus, warmer lake water may be saturated with oxygen but it would still not contain enough oxygen for the survival of aquatic life. Since climatic changes have been observed in the last decades, modelling of water temperature and dissolved oxygen concentration in lakes has received considerable attention over the years in order to asses impact of these two parameters on lakes and their aquatic life in the future (e.g., Antonopoulos & Gianniou, 2003; Ottosson & Abrahamsson, 1998).

Seasonal water temperature changes in lakes are mostly correlated with seasonal changes in air temperature. Parameters, such as lake volume, transparency and hydrology all affect water temperature (Wetzel, 1983). Solar radiation is absorbed directly by lake water, while the heat in lake is distributed by mixing of lake water. However, upper water layers are heated more rapidly than the rest of the lake water. As the surface water is warmed, it becomes less dense and the relative thermal resistance of mixing increases. As a consequence, a thermal stratification of lakes is generally observed in the summer. The upper water layers, called the epilimnion, are warm and less dense, while the deeper water layers, called the hypolimnion, remain cold and dense. In the metalimnion, a remarkable drop of water temperature is observed. The epilimnion and the hypolimnion do not mix with each other. Thus, physical, chemical and biological characteristics are usually significantly different in the two layers. In spring and autumn, the water column is mixed completely and spring and autumn turnovers occur.

Mountain lakes are specific ecosystems in many aspects. They are remote and not exposed to direct anthropogenic impact. On the other hand, they are small and consequently sensitive ecosystems. Thus, they have been often used as valuable sensors of environmental change (Wathne & Rosseland, 2000). Mountain lakes are covered with ice for a long period of the year. In the Julian Alps, ice cover periods as short as five and as long as nine months per year were observed (Brancelj, 2002). The duration of ice cover period significantly affects physical and, in turn, chemical and biological conditions in lakes. Also, it has been demonstrated that even small average air temperature changes of 1 to 2°C can lead to evident changes in water chemistry, hydrology and biota (Koinig *et al.*, 1998; Skjelkvale & Wright, 1998). Similar conclusions were found in the study on Slovenian mountain lakes (Muri & Brancelj, 2003).

The aim of the present work was to study surface and vertical lake water temperature variations in three remote high altitude Slovenian alpine lakes. Three Kriško lakes were selected as study sites, since they are located at different elevation, but close to each other and are similar in size. At the lodge Pogačnikov dom at Kriški podi, the air temperature was measured three times per day, the minimum and maximum temperature was also obtained and precipitation was collected after each rain event in July 2002. Surface water temperatures in Zgornje, and Spodnje Kriško lakes were simultaneously recorded four times per day. In addition, the vertical profile of water temperature in Srednje Kriško lake was measured twice per week and the heat content was calculated. Finally, all parameters were correlated and relation between the air temperature, precipitation amount, lake water temperature and heat content was studied. Since water temperature is an important physical parameter in lakes, this study contributes to a better understanding of physical and subsequently chemical and biological processes and their changes in mountain lakes.

MATERIAL AND METHODS

Sampling sites

Zgornje, Srednje and Spodnje Kriško lakes are situated in the Julian Alps, NW Slovenia. These mountain lakes are of glacial origin and surrounded by steep slopes. They all lie above the tree level and are relatively small and shallow. Their topographical characteristics are summarized in Table 1, while geographical position is shown in Fig. 1. On average, these lakes are covered with ice for at least seven and even nine months per year (Brancelj, 2002). The mean annual precipitation rate is high, averaging to 3.200 mm per year (Kastelec, 1999). The lakes have no permanent surface inflows. The main bedrock is limestone. Since the lakes are situated in the protected area of Triglav National Park, direct anthropogenic impact on the lakes is scarce and the lakes are still relatively pristine.

Tab. 1: Topografske značilnosti merilnih mest (podatki iz Brancelj, 2002).
Tab. 1: Topographical characteristics of sampling stations (from Brancelj, 2002).

Sampling site	Altitude [m]	Surface area [ha]	Max. depth [m]
Zgornje Kriško jezero	2150	0.66	9
Srednje Kriško jezero	1950	0.29	9
Spodnje Kriško jezero	1880	0.86	9

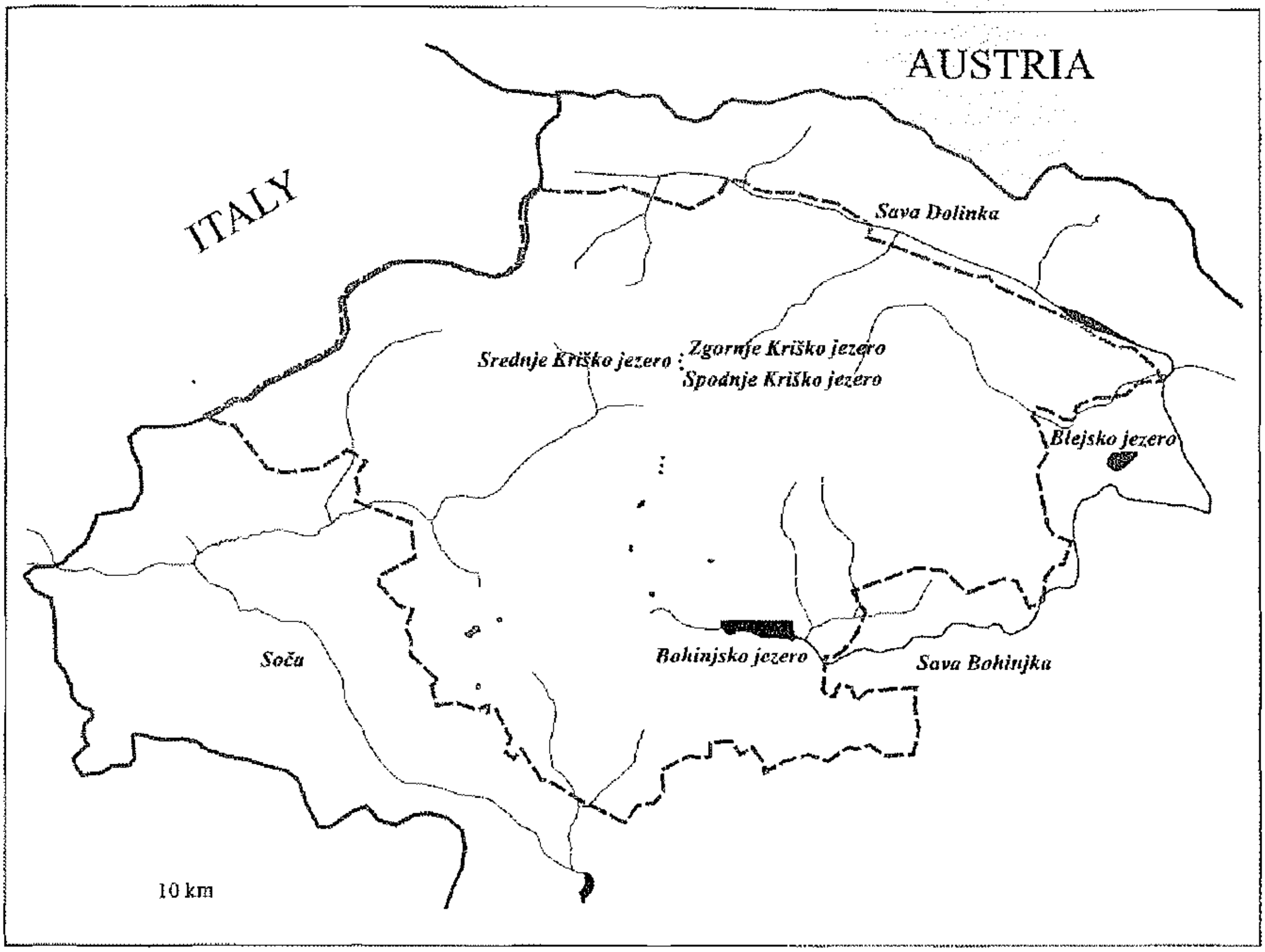

Fig. 1: Geographical position of Zgornje, Srednje and Spodnje Kriško lakes.
Sl. 1: Geografska lega Zgornjega, Srednjega in Spodnjega Kriškega jezera.

Measurements of air and water temperature and precipitation

The air temperature was measured with a glass thermometer at the lodge Pogačnikov dom at Kriški podi, 2050 m, which is located 100 m (in altitude) above Srednje Kriško lake. Air temperatures were recorded three times per day, *i.e.* at 7 AM, 2 PM and 9 PM. A minimum and maximum thermometer was also used to obtain the minimum and maximum air temperatures of the day. All thermometers were placed two meters above the ground in a shaded area protected from strong winds but open to air circulation.

Precipitation was also collected at Pogačnikov dom at Kriški podi using a metal canister. Amount of precipitation was measured and emptied manually just after each rain event.

Minithermistors (MINILOG-TR, Vemco) were used to monitor surface lake water temperatures. They were actually positioned approximately 0.25 m below the water surface in order to avoid the highest water temperature fluctuations that occurred on the surface water layer due to changes in intensity of solar radiation. The range of minithermistors was from -4 to 20°C, with a resolution of 0.1°C. The surface water temperature was recorded four times per day. On comparing surface water temperatures in the lakes, the late afternoon values were taken, when the daily highest values were observed. Vertical lake water temperatures were measured using a Pt 1000 probe. Its resolution was 0.1°C in the range from -30 to 100°C. The temperature profile was measured in 1 m intervals above the deepest part of the lake.

RESULTS AND DISCUSSION

Air temperature and amount of precipitation

Air temperatures at the lodge Pogačnikov dom at Kriški podi varied considerably in July 2002 (Fig. 2).

Maximum air temperatures ranged from 8.0 to 20.0°C, while minimum air temperatures ranged from 3.5 to 11.0°C. The highest minimum and maximum air temperatures were observed at the beginning of the month, on July 11, reaching 11.0 and 20.0°C, respectively. The lowest minimum and maximum air temperatures were also observed on the same day, on July 26. They dropped to 3.5 and 8.0°C, respectively. Variations of the minimum air temperature were not substantial. The minimum air temperature averaged 8.2°C. Higher values were observed in the second week of July and in early August. Nevertheless, much lower values were observed around July 26. In contrast, variations of the maximum air temperature were more pronounced (Fig. 2). The warmest weather was observed in the second week of July. During this period, the maximum air temperatures ranged around 19.0°C and evidently exceeded the average maximum air temperature, which amounted to 14.7°C. In the rest of the month, the maximum air temperatures were mostly bellow the average value.

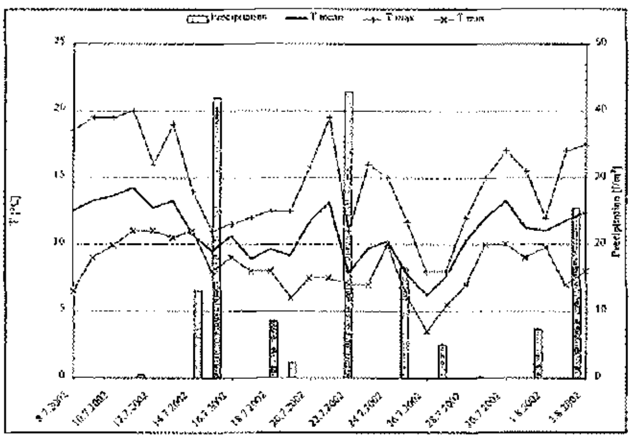

Fig. 2: Variations of the daily mean (T mean), minimum (T min) and maximum (T max) air temperatures and amount of precipitation at the lodge Pogačnikov dom at Kriški podi in July 2002.
Sl. 2: Spreminjanje povprečne dnevne (T mean), minimalne (T min) in maksimalne (T max) temperature zraka in količina padavin pri Pogačnikovem domu na Kriških podih v juliju 2002.

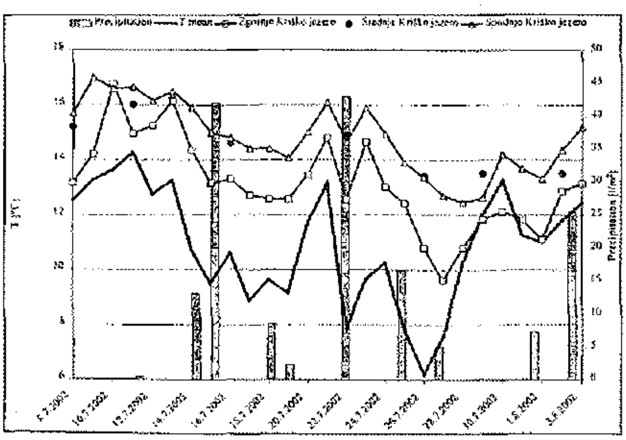

Fig. 3: Relations between air temperatures, amount of precipitation and surface water temperatures in Zgornje, Srednje and Spodnje Kriško lakes in July 2002.
Sl. 3: Odnos med temperaturo zraka, količino padavin in površinsko temperaturo vode v Zgornjem, Srednjem in Spodnjem Kriškem jezeru julija 2002.

There were eleven days with rain events (Fig. 2). In total, 164 mm of rain fell. The highest amount of precipitation was observed on July 22, when 43 mm of rain was recorded. Substantial rain events were also observed on July 15 and August 3, with 42 and 25 mm of rain, respectively. During the rest of rain events, less than 17 mm of rain was observed.

It can be concluded from Fig. 2 that precipitation had a strong impact on air temperatures. During all days, when precipitation events were observed, the mean, minimum and maximum air temperatures decreased remarkably.

Surface lake water temperatures

Variations of surface lake water temperatures in Zgornje Kriško lake, Srednje Kriško lake and Spodnje Kriško jezero are presented on Fig. 3. Surface water temperatures in Zgornje Kriško lake and Spodnje Kriško lake closely followed each other. Nevertheless, higher values were observed in the latter lake. Surface water temperatures in Spodnje Kriško lake varied from 12.5 to 17.0°C. In Zgornje Kriško lake, they ranged from 9.6 to 16.8°C. In both lakes, the highest surface water temperatures were observed in the second week of July. During the rest of the month, they were mostly lower and averaged to 14.2°C in Spodnje Kriško lake and to 12.5°C in Zgornje Kriško lake. The surface water temperature in Srednje Kriško lake was mostly intermediate between the values observed in the other two lakes (Fig. 3).

Remarkable surface water temperature variations were observed and correlated well with the mean air temperature and intensity, as well as frequency of precipitation events (Fig. 3). Between July 8 and July 11, the weather was fine with clear sky. The mean air temperature increased and surface water temperatures in all lakes also increased. Between July 12 and July 19, the weather was mostly cloudy. The mean air temperature dropped considerably, by 5°C. Surface water temperatures also decreased remarkably. Frequent rain events were additionally observed during this period. After rain events, a drop in surface water temperature was even more pronounced. Although the weather was mostly fine between July 20 and July 25, surface water temperature dropped by 2.2 and 1.4°C in Zgornje and

Spodnje Kriško lakes, respectively, when the mean air temperature dropped by 5.2°C on a single rainy day (July 22, 43 l m^{-2} of rain). However, on the next day, when the weather improved, almost the same surface water temperatures were observed than before that cold day. A period of very cold and rainy weather followed between July 25 and July 27. The mean air temperature dropped down to 6.2°C and surface water temperatures also decreased steeply. The surface water temperature in Spodnje Kriško lake was 1.8°C lower than the average value, while in Zgornje Kriško lake the difference was even higher and amounted to 2.9°C. In the late July and early August, the mean air temperatures were again higher and so were surface water temperatures.

It was also noted that surface water temperatures decreased with increasing altitude of the lakes. In Zgornje Kriško lake they were generally from 1.5 to 2.0°C lower than in Spodnje Kriško lake. Surface water temperatures obtained in Srednje Kriško lake were generally higher than in Zgornje Kriško lake but lower than in Spodnje Kriško lake and were closer to the values obtained in the latter lake since their altitudes are more comparable (Table 1).

In Zgornje and Spodnje Kriško lakes, surface water temperatures were recorded four times per day. Thus, surface water temperature variations in different periods of the day were also observed. Surface water temperatures in the two lakes were normally the highest in the late afternoon but varied as much as 4°C during sunny days with clear sky. In contrast, they varied for less than 0.5°C during cold and cloudy days. Most of the solar radiation that affects the lake water temperature is absorbed in the surface water layers (Wetzel, 1983). Remarkable variations of surface water temperatures during the day are thus expected.

Vertical lake water temperatures and heat content

Vertical water temperature profiles were measured only in Srednje Kriško lake. Water temperature decreased with depth (Fig. 4). It was quite uniform in the upper water layers (the epilimnion). The highest values were observed at the water surface and ranged from 13.4 to 16.0°C. Between depths of approximately two and five meters, water temperature dropped remarkably, by about 5°C (the metalimnion). In the deeper water layers (the hypolimnion), only slight variations of water temperature were observed. It varied from 5.7 to 7.7°C.

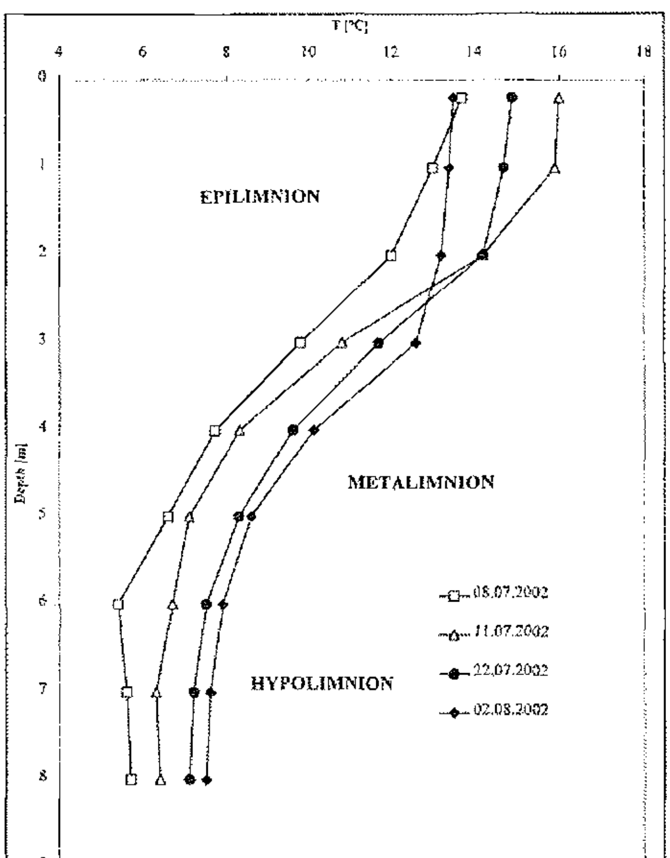

Fig. 4: Vertical profiles of water temperatures in Srednje Kriško lake in July 2002.
Sl. 4: Globinski profili temperature vode v Srednjem Kriškem jezeru julija 2002.

Vertical water temperatures in Srednje Kriško lake were also compared with changes in the mean air temperature and amount of precipitation. A higher correlation between meteorological parameters and water temperatures was observed in the epilimnion than in the hypolimnion. Vertical water temperature profiles (Fig. 4) showed that deeper water layers were much less susceptible to outside conditions, such as precipitation events and intensity of solar radiation than surface waters. Lower variations of the water temperature were also observed in this lake section. Deeper water layers have a certain heat capacity and cannot be so quickly warmed up or cooled down than the upper water layers (Wetzel, 1983). Additionally, epilimnion and hypolimnion waters do not mix due to differences in water density, thus further retarding the heat transfer through the water column.

The thickness of the epilimnion, the metalimnion and the hypolimnion also changed with time (Fig. 4). On July 8, the epilimnion was only two meters thick, whereas one month later, on August 2, it amounted to three meters. The thickness of the metalimnion and the temperature drop in it also changed. The metalimnion was thick as much as four meters on July 8, but shrank to two meters on August 2. Also, the water temperature dropped by nearly 7°C on the former day but only by 4.5°C on the later day. The thickness of the hypolimnion remained nearly the same throughout the time of experiment, amounting to around two meters and starting at a depth of approximately six meters. These water layers are thus relatively independent from outside conditions.

The vertical distribution of heat content was also calculated for Srednje Kriško lake (Fig. 5). Meter by meter distribution of the heat content was initially calculated, according to the formula $m\ C_p\ \Delta T$. m is the mass of the layer (calculated as $\rho\ S\ h$; ρ is the density of water (1 kg dm^{-3}), S the area of the layer and h the height (1m). C_p is specific heat of water (4.2 J g^{-1} K^{-1}), while ΔT delineates the temperature difference of the layer relative to 0°C. The total heat content was finally calculated as a sum of the heat stored in all layers of the lake. It was normalized to the surface area of the lake. The lake was subsequently divided into three different sections. The upper section extended from 0 to 2 meters, the second one from 2 to 5 meters, and the bottom one from 5 to 8 meters. These lake sections roughly represented epilimnetic, metalimnetic and hypolimnetic waters, respectively. During July 2002, the total heat content of the lake averaged to 138 MJ m^{-2}. This value is comparable to the values that were determined in other lakes of similar size and depth (*e.g.* Ambrosetti & Barbanti, 2001). The average contribution of the epilimnetic waters was 90 MJ m^{-2}, while metalimnetic and hypolimnetic waters contributed 43 and 6 MJ m^{-2} to the total heat content, respectively (Fig. 5). The calculation hence showed that the upper section of the lake (0-2 m) comprised from 62 to 68% of the total heat content. Most of the heat in the lake was thus stored in the epilimnion. In addition, it was found that the relative contribution of this layer to the total heat content decreased during the study, since the lake warmed up (Figs. 4 and 5). The 2-5 m section contributed from 29 to 33% to the total heat content. Its contribution in contrast increased slightly during the study. The bottom section (5-8 m) contributed only 4% to the total heat content and its contribution remained very uniform during the study. Only a minor part of the heat was thus stored in the hypolimnion.

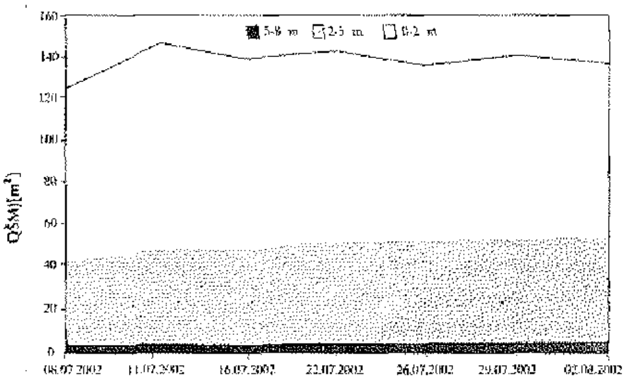

Fig. 5: Vertical distribution of heat content in Srednje Kriško lake in July 2002.
Sl. 5: Vertikalna porazdelitev toplote v Srednjem Kriškem jezeru julija 2002.

Effects of lake water temperature on lake condition

The lakes, selected in this study, are relatively small lake systems. Thus, a fast response between the air temperatures, amount of precipitation and surface water temperature was observed. Surface water temperatures in the lakes changed daily. In contrast, a longer time period (of weeks) was needed for an evident change of water temperature in the deeper water layers.

Water temperature changes are important, since they affect chemical and biological processes in lakes and have a significant impact on the overall condition in them. Aquatic species have preferred temperature ranges for living, but in general biological activity and growth rate of aquatic organisms are higher when water temperature increases (Lampert, 1984). During the study carried out in three other Slovenian mountain lakes (*i.e.* Krnsko jezero, Jezero v Ledvicah and Jezero na Planini pri Jezeru), primary producers were less abundant in the years with long duration of snow and ice cover and consequently cold lake water temperatures. The overall conditions in these lakes have improved in comparison with those in the years with warmer lake water (Muri & Brancelj, 2003).

CONCLUSIONS

Changes of the daily air temperature and amount of precipitation were measured at the lodge Pogačnikov dom at Kriški podi in July 2002. These changes were compared with the surface water temperature variations in Zgornje, Srednje and Spodnje Kriško lakes. Significant correlation was found between the three measured parameters. Vertical water temperatures were additionally measured in Srednje Kriško lake and the heat content was calculated. It was established that water temperature variations in the deeper layers of the water column were less correlated with the changes of meteorological parameters. A longer time was also needed to warm up its bottom water layers. The calculation of heat content showed that approximately two thirds of the total heat content is stored in the upper, epilimnetic waters. The metalimnetic waters comprised around one third of the total heat content, while the heat stored in the hypolimnetic waters was of minor importance.

Water temperature changes in lakes are important, since they affect chemical and biological processes in them, and can thus change their overall conditions.

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ODNOS MED TEMPERATURO ZRAKA, PADAVINAMI TER NIHANJEM POVRŠINSKE IN GLOBINSKE TEMPERATURE VODE V TREH KRIŠKIH JEZERIH (JULIJSKE ALPE, SZ SLOVENIJA) V JULIJU 2002

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POVZETEK

Pri Pogačnikovem domu na Kriških podih smo julija 2002 merili dnevno temperaturo zraka in količino padavin. Poleg tega smo odčitavali površinsko temperaturo vode v Zgornjem, Srednjem in Spodnjem Kriškem jezeru, medtem ko smo v Srednjem Kriškem jezeru merili temperaturo vode tudi po globini vodnega stolpca, iz česar smo nato izračunali porazdelitev toplote v tem jezeru. Opazili smo precejšna nihanja površinske temperature vode. V Zgornjem Kriškem jezeru je površinska temperatura vode nihala za 7.2°C, v Spodnjem Kriškem jezeru pa za 4.5°C. Spremembe povprečne dnevne temperature zraka in količine padavin so bile medsebojno povezane s spremembami površinske temperature vode. Korelacija med temperaturo vode v globljih plasteh vodnega stolpca in meteorološkimi parametri je bila slabša. Tudi nihanja temperature vode so bila v globljih plasteh vodnega stolpca manjša, saj je v hipolimniju Srednjega Kriškega jezera temperatura nihala le za 2°C. Spreminjali pa sta se debelini epilimnija in metalimnija v času študije v tem jezeru. Debelina epilimnija je narasla od dva na tri metre, medtem ko se je debelina metalimnija skrčila iz štirih na dva metra, ko so dnevi postajali toplejši. Debelina hipolimnija je bila v času študije enaka in je znašala okrog dva metra. Izračun porazdelitve toplote v Srednjem Kriškem jezeru je pokazal, da je vrhnja plast vode (0-2 m) vsebovala približno 65% celotne toplote v jezeru. Območje 2-5 m je vsebovalo okrog 31%, predel 5-8 m pa le še 4% celotne toplote v jezeru.

Ključne besede: temperatura zraka, temperatura vode, toplota, alpska jezera

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