Polish J. of Environ. Stud. Vol. 17, No. 5 (2008), 835-840

Letter to Editor

Thermal Characteristics of Waters of Wielki Staw in the Karkonosze Mountains and Morskie Oko in the Tatras, July 2006

A. Choiński, G. Łyczkowska

Departament of Hydrology and Water Management, Adam Mickiewicz University,
Institute of Physical Geography and Environmental Planning, Dzięgielowa 24, 61-680 Poznań, Poland

Received: 17 March, 2008
Accepted: 27 June, 2008

Abstract

The temperature of standing water is one of the most frequently measured abiotic parameters of lakes. While some of the Tatra lakes have been investigated in modern times, those in the Karkonosze Mountains have never been an object of planned, systematic thermal studies.

Our article presents the results of a unique methodology of research on the thermal characteristics of waters of Wielki Staw and Morskie Oko. They yielded full information about the vertical distribution of water temperatures in both lakes in an exceptionally warm month - July 2006. By employing gradient thermal probes, it was possible not only to give a general description of the thermal conditions of the lakes and the current development of stratification, but also to grasp the pattern of momentary fluctuations in the water temperatures of both lakes.

The research has proved that the thermal conditions of the two mountain lakes largely result from their individual morphometric diversity. Also, in terms of thermal characteristics, the lakes should not be treated on a par with those of the other geographical regions of Poland; in favourable circumstances, the temperatures of their surface waters can reach values rarely met even among lowland lakes.

Keywords: thermal characteristics, mountain lakes

Introduction

Wielki Staw in the Karkonosze Mountains and Morskie Oko situated in the Tatras have many features in common. One of them is that they are both located in national parks. They are extremely precious, and because of their location are protected under law. Each year both lakes are admired by hundreds of thousands of tourists, the difference between them being that of accessibility. There is a tourist trail encircling Morskie Oko, hence the lake is directly accessible. Wielki Staw, in turn, can only be viewed from a trail running more than 100 m above the lake surface, offering no direct access.

A study was made of changes in lake water temperatures in July 2006. The time was chosen for two reasons. One was the fact that this was the time when measurements happened to be performed in both lakes. The other was the exceptional warmth of their waters brought about by a heat wave. A comparison of the measurement results allowed defining differences and similarities in the thermal characteristics of their waters. This is especially significant in the case of Wielki Staw, whose thermal conditions have never been studied over a long period of time [1].

Material and Methods

Characteristics of the Lakes

Wielki Staw in the Karkonosze Mountains and Morskie Oko in the Tatras are among the few lakes in Poland which have preserved their natural environmental conditions, with only limited human interference.

Wielki Staw occupies the bottom of a cirque and lies at an altitude of 1,225 m a.s.l. in the catchment of Łomnica creek. The relative height between the water surface and the southern peaks towering above the lake is up to 200 m. All the tributaries enter the lake from the south. In its eastern part there is a surface outflow, which is one of the headwater streams of Łomnica creek.

The lake has an elongated shape. Its northwestern part forms a north-pointing bay separated from the main water body by a barrier of rocks.

Because of the steepness of the slope on the southern side of the lake, this part of the shore is bare of trees and shrubs. In the north there are compact and patchy covers of dwarf mountain pine. A considerable proportion of the Wielki Staw surroundings also supports grasses and mosses, while in low-gradient areas permanent waterlogged peatbogs have formed. The Wielki Staw cirque is strictly protected within the Karkonosze National Park and the lake shore is not made directly accessible to tourists.

Morskie Oko is the largest and most famous postglacial lake in the Tatra massif. It lies at an altitude of 1,395.8 m a.s.l. on the northern side of the High Tatras at the foot of Mięguszowieckie Peaks, in the Rybi Potok catchment. The lake fills a rock basin at the close of the postglacial Rybi Potok valley. The height difference between the lake surface and the surrounding peaks exceeds 1,000 m.

In terms of mean and maximum depths, the lake comes fourth among Polish mountain water bodies; among lowland lakes, only Hańcza shows a greater mean depth.

Morskie Oko is also fourth in terms of the index of compactness, which is equal to 0.298. This means that, while small in area, the lake has an abundance of water. At 13º the lake basin shows a very great mean gradient of the bottom. Morskie Oko is also remarkable for its great fluctuations of water stages exceeding 1 m in a multi-year period.

The lake is situated in the cool altitude zone and surrounded by vegetation typical of the upper subalpine Tatra forest. Forest ecosystems (with Eurasian stone pine in the tree stands) and patches of dwarf mountain pine come down to the lake shores. Morskie Oko is under strict protection, which excludes, completely and permanently, any direct form of human interference with nature. Still, tourist trails

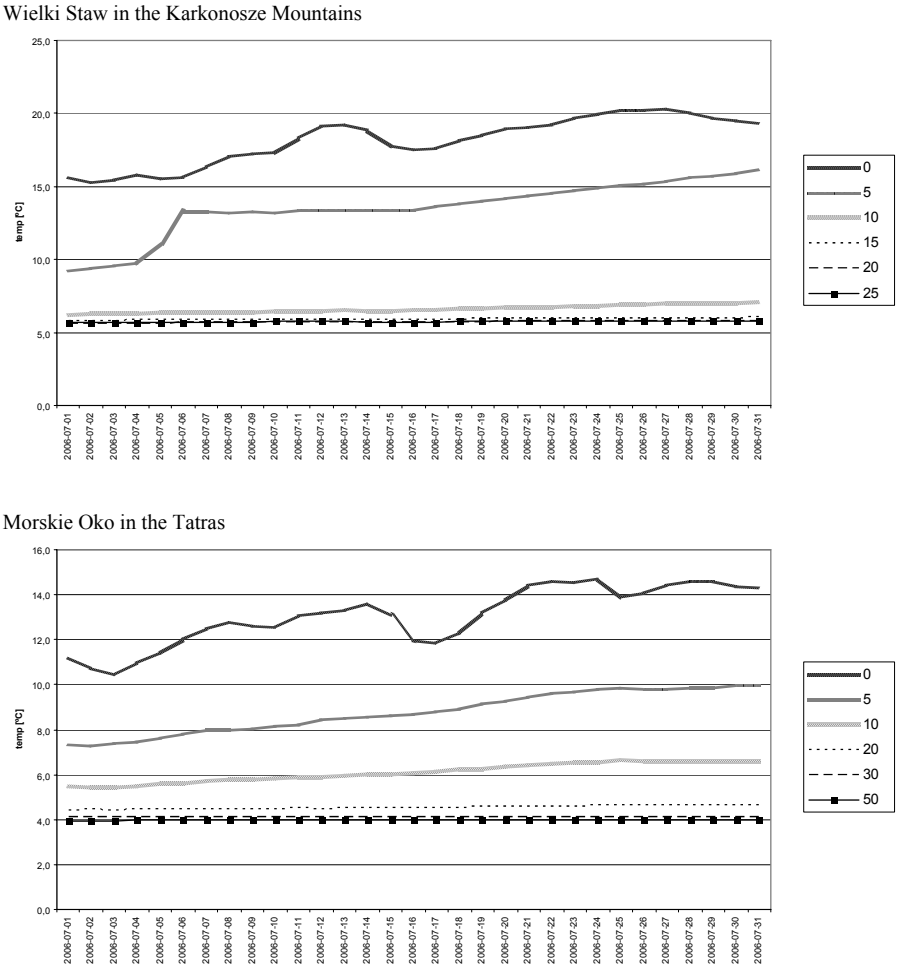

Fig. 1. Mean diurnal water temperatures in Wielki Staw and Morskie Oko at various depths [m].

have been laid out around the lake, so tourist penetration in the immediate neighbourhood of the littoral zone is possible. Selected morphometric parameters of Wielki Staw and Morskie Oko are presented in Table 1.

Study Methods

So far research of vertical thermal structures in lake district waters have taken place using of traditional measuring equipment (standard thermometers). These measurments in difficult high-mountain conditions had sporadic and quite often accidental aspects. Generally, the measurments have been accomplished out of the boat and the effect of work was fully subordinated from propitious or unfavorable weather conditions.

In both lakes (Wielki Staw and Morskie Oko) thermal probes were employed to register temperature telethermometers. Sets of gradient probes of water temperature (RTW8-042 model) have been made in the A-STER Industrial Electronics and Automation Plant in Kraków, and their temperature sensors have individual calibration certificates guaranteeing measurement reliability. The devices were anchored in the deepest places of the lakes, i.e. at depths of 23.5 m in Wielki Staw and 51.8 m in Morskie Oko. The temperature sensors were installed, respectively, at depths of 0.5, 5.0, 10.0, 15.0, 20.0 and 23.5 m, and 0.5, 5.0, 10.0, 20.0, 30.0 and 50.0 m. Temperatures were recorded in July 2006 every 10 minutes to an accuracy of ± 0.1ºC. Thus, the mean diurnal water temperature at a given point is the arithmetic mean of 144 measurements. This means that the analysis given below rests on nearly 54,000 measurements. The analysis of the data was performed on the basis of Standard Methods for the Examination of Water and Wastewater [3].

In the case of Morskie Oko, the results could be compared with the thermal characteristics of its surface waters from earlier years [2]. There was no such possibility for Wielki Staw because no water temperature measurements had been performed there on a continuous basis. The method of high-frequency measurements, i.e. every 10 minutes employed in the present research, made it possible to analyse diurnal variations in the temperature of surface waters, and to establish changes (if any) in the temperature with depth and their scale.

Comparison of the Thermal Characteristics of Morskie Oko and Wielki Staw Waters

With more than 50,000 measurement data obtained, it was possible to establish not only mean temperatures, but also the pattern of momentary fluctuations in the temperatures of both lakes.

The mean diurnal and monthly water temperatures of the two lakes are listed in Table 2 and presented in Fig. 1. The mean temperature of Morskie Oko surface waters in July 2006 was 13.1ºC. This is an exceptionally high figure; the published 1967-1983 data show the average for this period to be 9.9ºC, with the highest value recorded being

Table 1. Selected morphometric parameters of Wielki Staw and Morskie Oko.

Parameter	Wielki Staw in Karkonosze	Morskie Oko in Tatras
Area	P = 8.32 ha	P = 34.54 ha
Length	D = 616.5 m	D = 830 m
Maximum width	S max. = 193.5 m	S max. = 520 m
Mean width	S av. = 138.5 m	S av. =416.1m
Length of shoreline	L = 1,540.0 m	L = 2,510 m
Maximum depth	H max. – 23.5 m	H max. = 51.8 m
Mean depth	H av. = 9.5 m	H av. = 28.4 m
Volume	V = 741,503 m^3	V = 9,935,000 m^3

12.9ºC (July 1968). The mean temperature of Wielki Staw surface waters in July 2006 reached as much as 18.1ºC, i.e. 5.0ºC higher than in Morskie Oko. Such a big difference can result from differences in the altitudes of the two lakes, from different proportions of their alimentation (rain, snow, overland flow), and from differences in the exposure of the basin. These factors control the intensity of water mixing, and hence are responsible for differences in the thermal balance.

With depth, water temperatures and their amplitudes tend to decline. While the curves illustrating the variability of water temperatures are basically similar, the scale of changes in the two lakes differs significantly (Fig. 1). The drop in the mean monthly temperature between the surface and the 5th m in Morskie Oko is 4.6ºC, while in Wielki Staw, 5.3ºC. The situation is reversed for temperatures between the 5th and the 10th m: in Morskie Oko the drop amounts to as much as 6.9ºC, and in Wielki Staw, a mere 2.7ºC. At a depth of 10 m the curves of temperature growth over the month are similar in both cases, with the registered increase being equal to 1ºC. At depths of 20 m and lower, the temperature is highly stable – variations as a rule do not exceed ± 0.2ºC. The variability of the vertical distribution of temperatures in both lakes is presented in Fig. 2. Readily visible is the advancing warming of waters near the surface and at depths intermediate between the surface and the bottom. Below the 20th m there are practically no changes. While at the start of the month both temperature curves are roughly parallel, with time they come closer to each other at a depth of 10m. This is due to more intensive mixis in Morskie Oko, as a result of which its water at this depth grows warmer earlier than in Wielki Staw.

The maximum temperature recorded on the surface of Morskie Oko was 15.5ºC (24 July); in Wielki Staw it was as high as 21.2ºC (25 and 26 July). In the case of Morskie Oko, this was a temperature unprecedented so far. In the 1967-1983 data [2], the maximum temperature recorded was 14.3ºC (1967 and 1968). In the case of Wielki Staw, the recorded maximum was so high that even among lowland lakes it is not found every year. It should be kept in mind

Table 2. Mean diurnal and monthly water temperatures in ºC at various depths.

	Wielki Staw						Morskie Oko					
Date	**0.4 m**	**5 m**	**10 m**	**15 m**	**20 m**	**25 m**	**0.4 m**	**5 m**	**10 m**	**20 m**	**30 m**	**50 m**
2006-07-01	15.6	9.2	6.3	5.8	**5.6**	5.7	11.2	7.3	5.5	4.4	4.1	**3.9**
2006-07-02	15.2	9.4	6.3	5.8	**5.6**	5.7	10.7	7.3	5.5	4.4	4.1	**3.9**
2006-07-03	15.4	9.6	6.3	5.8	**5.6**	5.7	10.4	7.4	5.5	4.4	4.1	4.0
2006-07-04	15.8	9.7	6.3	5.8	**5.6**	5.7	11.0	7.4	5.5	4.5	4.1	4.0
2006-07-05	15.5	11.1	6.4	5.8	**5.6**	5.7	11.4	7.6	5.6	4.4	4.1	4.0
2006-07-06	15.6	13.2	6.4	5.8	**5.6**	5.7	12.0	7.8	5.6	4.4	4.1	4.0
2006-07-07	16.3	13.3	6.4	5.9	**5.6**	5.7	12.5	8.0	5.8	4.5	4.1	4.0
2006-07-08	17.1	13.2	6.4	5.9	5.7	5.7	12.8	8.0	5.8	4.4	4.1	4.0
2006-07-09	17.3	13.3	6.4	5.8	5.7	5.7	12.6	8.0	5.8	4.4	4.1	4.0
2006-07-10	17.4	13.2	6.5	5.9	5.7	5.7	12.6	8.1	5.9	4.5	4.1	4.0
2006-07-11	18.3	13.4	6.5	5.9	5.7	5.7	13.1	8.2	5.9	4.5	4.1	4.0
2006-07-12	19.1	13.3	6.5	5.9	5.7	5.7	13.2	8.4	5.9	4.5	4.1	4.0
2006-07-13	19.2	13.4	6.5	5.9	5.7	5.7	13.3	8.5	6.0	4.5	4.1	4.0
2006-07-14	18.8	13.4	6.5	5.9	5.7	5.7	13.6	8.6	6.0	4.5	4.1	4.0
2006-07-15	17.8	13.4	6.5	5.9	5.7	5.7	13.1	8.6	6.1	4.5	4.1	4.0
2006-07-16	17.5	13.4	6.5	5.9	5.7	5.7	11.9	8.7	6.1	4.5	4.1	4.0
2006-07-17	17.6	13.6	6.6	5.9	5.7	5.7	11.9	8.8	6.2	4.5	4.1	4.0
2006-07-18	18.2	13.8	6.7	5.9	5.7	5.7	12.3	8.9	6.3	4.5	4.1	4.0
2006-07-19	18.5	14.0	6.7	5.9	5.7	5.8	13.2	9.1	6.3	4.6	4.1	4.0
2006-07-20	19.0	14.2	6.8	5.9	5.7	5.8	13.8	9.3	6.4	4.6	4.1	4.0
2006-07-21	19.1	14.3	6.8	5.9	5.7	5.8	14.4	9.4	6.4	4.6	4.1	4.0
2006-07-22	19.2	14.5	6.8	6.0	5.8	5.8	14.6	9.6	6.5	4.6	4.1	4.0
2006-07-23	19.6	14.7	6.8	5.9	5.8	5.8	14.5	9.7	6.6	4.6	4.1	4.0
2006-07-24	19.9	14.9	6.9	6.0	5.8	5.8	**14.7**	9.8	6.6	4.6	4.1	4.0
2006-07-25	**20.3**	15.0	6.9	6.0	5.8	5.8	13.9	9.8	6.7	4.6	4.1	4.0
2006-07-26	20.2	15.2	6.9	6.0	5.8	5.8	14.1	9.8	6.6	4.6	4.1	4.0
2006-07-27	**20.3**	15.4	7.0	6.0	5.8	5.8	14.4	9.8	6.6	4.6	4.1	4.0
2006-07-28	20.0	15.6	7.0	6.0	5.8	5.8	14.6	9.9	6.6	4.6	4.1	4.0
2006-07-29	19.7	15.7	7.0	6.0	5.8	5.8	14.6	9.9	6.6	4.6	4.1	4.0
2006-07-30	19.5	15.9	7.1	6.0	5.8	5.8	14.4	9.9	6.6	4.6	4.1	4.0
2006-07-31	19.3	16.1	7.1	6.0	5.8	5.8	14.3	9.9	6.6	4.6	4.1	4.0
Mean temperature	**18.1**	**13.5**	**6.6**	**5.9**	**5.7**	**5.7**	**13.1**	**8.8**	**6.1**	**4.5**	**4.1**	**4.0**

Maximum mean diurnal water temperature in July

Minimum mean diurnal water temperature in July

that the above maximum temperatures were measured at the greatest depths, hence in places farthest from the shore. One can suppose, therefore, that they were even higher in the littoral zone (where routine measurements are taken), first, because in the shallower zone water gets warmer sooner, and secondly, because water absorbs warmth through its contact with boulders, which derive heat from insolation.

The high frequency of measurements (every 10 minutes) made it possible to determine at what point in the diurnal pattern the temperatures reached their minima and maxima. In Wielki Staw the lowest water temperatures were recorded between 5:00 and 11:00 (94% of measurements) and between 23:00 and 24:00 (4% of measurements). The hours when no minimum temperatures were recorded were 0:00 to 4:00 and 13:00 to 22:00. In Morskie Oko water temperature minima were registered between 5:00 and 9:00 (76% measurements) and between 21:00 and 24:00. Sporadically, minima could appear at any hour. The periods of no minimum temperatures were 0:00 to 3:00, 11:00 to 15:00, and 17:00 to 21:00.

Maximum water temperatures in Morskie Oko occurred at various hours during the day. 60% of cases were recorded between 18:00 and 23:00, 23% between 14:00 and 18:00, and 14% between 0:00 and 1:00. Maximum temperatures were never observed from 3:00 to 11:00. In Wielki Staw, maximum temperatures were much more restricted in time: 57% of the highest figures were recorded between 17:00 and 20:00, and between 15:00 and 22:00 as many as 82%. Also, 17% of such cases were observed between 0:00 and 1:00. There were no maximum temperatures from 1:00 to as late as 13:00. The mean diurnal amplitude of surface water temperatures in the analyzed period was 1.18ºC for Morskie Oko and 1.25ºC for Wielki Staw. The highest diurnal amplitudes recorded were 2.0ºC (24 July) for Morskie Oko and 2.3ºC (6 and 18 July) for Wielki Staw.

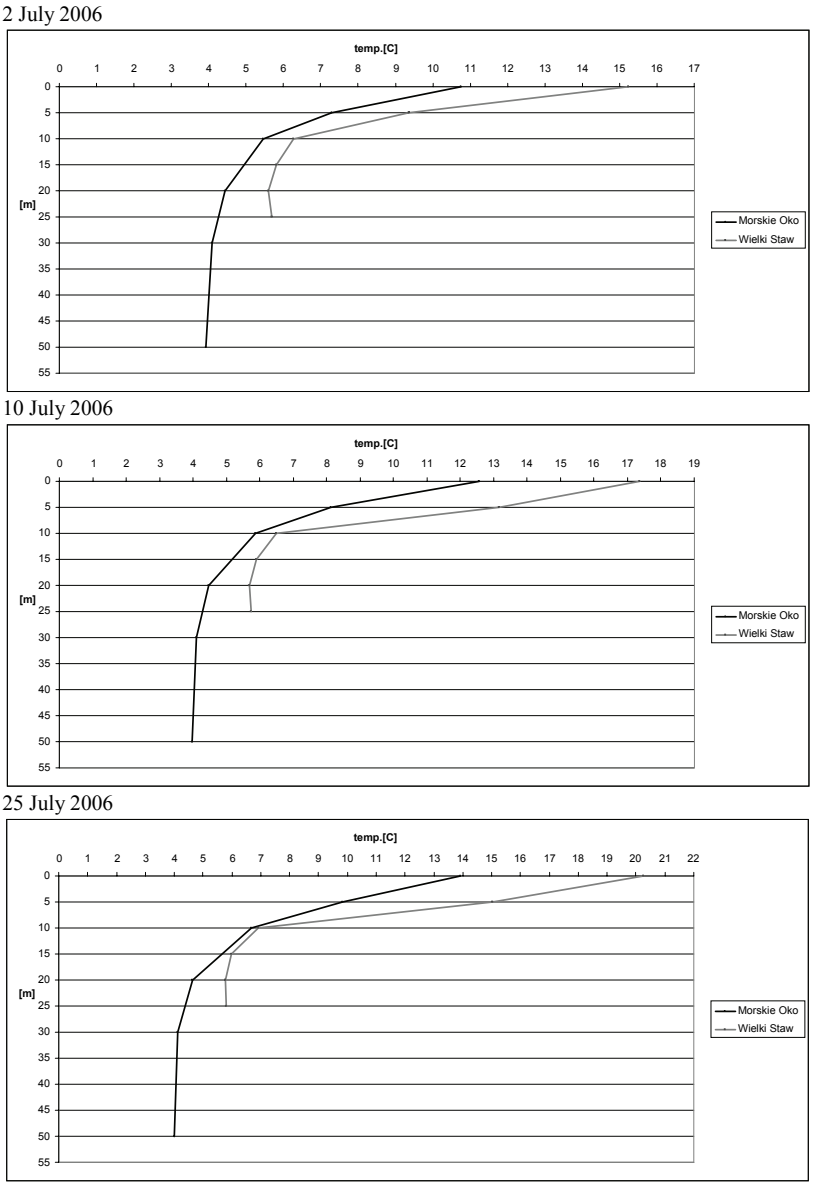

Fig. 2. Examples of vertical variability in water temperatures in Wielki Staw and Morskie Oko [depth - m].

Conclusions

On the basis of the results of the July 2006 study of the thermal characteristics of the waters of Wielki Staw in the Karkonosze Mountains and Morskie Oko in the Tatras, the following general remarks on water temperatures in the two lakes were formulated:

- In the waters of both lakes normal (anothermal) stratification was observed, i.e. the water temperatures and their amplitudes declined with depth;
- In both lakes the waters were warmer near the surface and at depths intermediate between the surface and the bottom. Below the 20th m thermal changes practically did not occur;
- The curves illustrating vertical variability in the temperature patterns of Morskie Oko and Wielki Staw are basically similar, but the scale of change in the two lakes differs significantly;
- The thermal curves of Wielki Staw and Morskie Oko are roughly parallel, but with time one can observe in Morskie Oko intensive mixis at a depth of 10 m, which is absent with such intensity from Wielki Staw;
- July 2006 was an exceptionally warm month. The mean temperatures of surface waters in both mountain lakes were unusually high. The maximum one recorded in Wielki Staw (21.2ºC) would be a rarity even among lowland lakes;
- In the case of Morskie Oko it was possible to compare the obtained results with the surface temperatures from earlier years, but such high surface water temperatures had never been recorded between 1967 and 1983;
- The vertical distribution of water temperatures in both lakes was studied in the deepest zones; since the results were unexpectedly high, it might be presumed that near the shores the temperatures in both lakes were even higher at that time,
- The high frequency of measurements made possible by the use of gradient thermal probes allowed grasping the pattern of momentary fluctuations in the water temperatures and determining at what point in the diurnal pattern the temperatures reached their minima and maxima;
- In both lakes maximum water temperatures usually occurred in the afternoon and evening as well as in the small hours. Minimum water temperatures were recorded in the early morning and pre-noon hours as well as late at night;
- The research results are being prepared for a future broader-based statistical processing with the help of chemometric methods.

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