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The morphometric parameters of glacial lakes in the Bohemian Forest

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Abstract
We provide the most updated geographic survey of all eight lakes in the Bohemian Forest (Böhmerwald in German, Šumava in Czech), conducted between 1994 and 2015 using modern methods and devices. The results are presented in the form of bathymetric maps, as well as summary tables with morphometric characteristics of the depth levels at 1-m or 0.5-m intervals (in the deep and shallow lakes, respectively). The recent results are compared with earlier studies.

Key words: bathymetric map, morphometry, glacial lakes, Šumava, Böhmerwald, Bavarian Forest

Introduction

There are eight natural lakes of glacial origin in the Bohemian Forest. Five of them (Černé, Čertovo, Plešné, Prášilské, and Laka) are situated in the Czech Republic and three (Rachelsee, Großer Arbersee, and Kleiner Arbersee) in Germany. Their mapping is based on the tradition of geographic exploration of the Bohemian Forest lakes established by Václav Švambera at the beginning of the 20th century (Švambera 1912, 1913, 1914a–c, 1939, Kuchař 1939, 1947). Professor Švambera encouraged his followers to take bathymetric measurements of the Bohemian Forest lakes regularly, in order to monitor the rate of their siltation (Kuchař 1947). The first bathymetric measurements were prompted by the demand for water to transport timber, and it was assumed that the lakes were a valuable source of accumulated water.

The first estimates and measurements of the lake surface areas and depths were made as early as in the 18th century. More precise data (based on the first maps) became available at the end of the 19th century (Bayberger 1866, Wagner 1897). Černé and Čertovo lakes were explored by Frič & Vávra (1897), and Plešné Lake by Frejlach (1898). Measurements were taken in all of the Bohemian Forest lakes in 1903 and again during 1906–1911 by Švambera (1912, 1913, 1914a–c) and were completed during further excursions in 1919, 1921, 1922, 1928, and 1938 (Švambera 1939, Kuchař 1947). Other bathymetric measurements of Černé Lake were taken from the ice surface in December 1926 and in January 1927 by Reissinger (1930). The recent measurements are included in a series of diploma theses by Zbořil (1994), Vránek (1999), Šobr (1999), and Kocum (2004) that focused on Prášilské, Plešné, Laka, and Čertovo lakes, respectively. Weilner (pers. comm.) provided a map with isobaths at 1-m intervals from 1981 (Großer Arbersee and Kleiner Abersee) and 1984 (Rachelsee), however, without calculating morphometric characteristics. The history of bathymetric measurements of the Czech glacial lakes has been summarised in greater detail by Janský et al. (2005). The

aim of this contribution was to summarise the results of recent bathymetric measurements of all the Bohemian Forest lakes. The study is based both on the published data (Zbořil 1994, Šobr 1999, Kocum 2004) and on new measurements of Plešné Lake, Černé Lake, Rachelsee, Großer Arbersee, and Kleiner Arbersee.

Material and methods

Bathymetric mapping of all lakes was carried out between 1994 and 2015. A detailed description of the methodology of the bathymetric mapping can be found in Česák & Šobr (2005). The methodology is based on approaches which have been used for more than one hundred years. In the first step, a top view map of the shoreline (including islets) is created. The second step includes the bathymetric measurement along the established profiles. In the final step, the cartographic processing of the measured data and the creation of the final bathymetric map takes place.

Given the relatively long time period between taking the measurements of the individual lakes, the methods and devices that were used obviously differed (Table 1). The shoreline mapping was carried out by means of three methods. Prášilské and Laka lakes were mapped using the orthogonal method (Čapek et al. 1992) and the horizontal angles of the polygon were measured by means of a theodolite, THEO 080A. All lengths (polygon sides) and the values of the rectangular coordinates (perpendicular distances and stationing) were established by means of a tape measure (Šobr 2007), and digitised by using the MapInfo computer programme in 2005. The plan view of Plešné Lake was based on detailed aerial imagery, and its shoreline was digitised by J. Žaloudík (Biology Centre CAS, České Budějovice). The plan views of other lakes were created by means of the polar method using the geodetic total station Leica (Čapek et al. 1992). The measurements connected to the creation of the lake plan view, with the help of this device, resulted in the detailed x-y-z coordinates (measured in meters: x – easting, y – northing, z – altitude). For the measurements of the Czech lakes, a system of coordinates S-JTSK (System of singular trigonometrical cadastral network – used for geodetical measurements in Czechia) was used, for the German lakes a Gauss-Krüger (DHDN – Deutsches Hauptdreiecksnetz) Zone 4 was chosen.

Before surveying the lake shoreline, positions of the depth profile starting points were designated by means of numbered discs. Along these lines, water depth at 2.5-m or 5-m intervals was measured (Fig. 1). For the demarcation of depth profiles, a solid thin string with markings was used, while the individual depth values were measured at the markings from an inflatable boat, moving along the established line. The number of the depth profiles and the measured depths is given in Table 1. In comparison to the previous measurements (Švambera 1939), it can be stated that our measurements are significantly more detailed than any formerly taken. The depth measurement was taken by means of sonar (with the exception of Laka Lake, where the thick vegetation prevented using this method; see Table 1 for details). The 0.1-m accuracy of the sonar measurement was substantiated by means of a calibrated string with a weight. The sonar equipment can measure only depths >0.5 m. Smaller depths were measured by means of a self-reading rod (with a 0.1-m calibration) with an underlay, preventing the rod sinking into sediment.

In the case of Prášilské and Laka lakes, a method of manual drawing and bathymetric maps interpolation (using a scale of 1:250 and 1:500, respectively) was applied (Zbořil 1994, Šobr 1999). The manual interpolation was used according to Kunský et al. (1959). The computer processing of the bathymetric data by Kuchařová (2009) confirmed the accuracy of the manual interpolation, as well as the precision of the cartometrically established morphometric characteristics. For the other lakes, the measured data on the shoreline, as well as the

Table 1. Methods and equipment used for bathymetric measurements. MDP – measured depth points.

Lake	Year	Ground plan	Depth measurements	Number of profiles	Number of MDP	Number of MDP by Švambera	Distance between MDP (m)	Lake area per MDP (m^2)
Černé Lake	2003	total station Leica TCR 705	sonar Garmin Fishfinder 240	99	4815	1473	5	39.0
Čertovo Lake	2003	total station Leica TCR 705	sonar Garmin Fishfinder 240	69	2746	931	5	39.1
Plešné Lake	2009	aerial photo	sonar Garmin GPSMAP 178C	27	830	555	5	87.1
Prášilské Lake	1994	theodolite Theo 080A, tape measure	sonar Interphase DG-1	33	1095	258	5	38.4
Laka Lake	1999	theodolite Theo 080A, tape measure	calibrated lath	36	563	1	5	41.9
Rachelsee	2015	total station Leica TPS 1200	sonar Garmin GPSMAP 178C	34	1502	233	2.5	32.1
Großer Arbersee	2015	total station Leica TPS 1200	sonar Garmin GPSMAP 178C	26	1570	208	2.5	50.1
Kleiner Arbersee	2015	total station Leica TPS 1200	sonar Garmin GPSMAP 178C	69	1634	127	2.5	45.4

depth points were processed using the MapInfo, Surfer and ArcGIS computer programmes. Based on a cluster of points, the shoreline polygons were drawn. Subsequently, depth profiles were set out by means of connecting the previously marked points (numbers in Fig. 1), and bathymetric point measurements were taken at these profiles. At the relevant intervals, data from our bathymetric measurement were added to these profiles at the corresponding points together with the values of the measured depths functioning as z-coordinates. In the next step, a set of shoreline points combined with measured depth values were used for the interpolation and graphical representation of the spatial modules of lake basins. The data were interpolated by means of the "kriging" (Černé, Čertovo, Plešné, Prášilské, and Laka lakes) or "natural neighbour" (Rachelsee, Großer Arbersee, and Kleiner Arbersee) methods. Based on these interpolations, the values of the volume, surface, and perimeter of the individual depths were calculated. Other morphological parameters of the lakes according to Hutchinson (1957), Čapek & Kudrnovská (1982), and Wetzel (2001) were also measured and calculated (Tables 2a,b).

Detailed morphometric characteristics are further given by 1-m depth intervals for the deep lakes and by 0.5-m intervals for the shallow lakes (Laka and Kleiner Arbersee). The results for each lake are divided into two sub-tables (parts a and b). In part a, only surface areas of isobaths and their percentage share of the total lake surface are given, as well as the lengths and the developments of the contour line (the closer the development of an isobath is to 1, the more its shape resembles a circle). In part b, we provide the surfaces and volumes of individual water layers, their percentage shares of the total lake volume, and their average gradient.

The bathymetric maps are represented graphically by using both isobaths and colour shades. A unified arrangement was chosen to compare the individual lakes with each other. The basic interval of the isobaths is 1 m for the deep lakes and 0.5 m for the shallow lakes. Each fifth contour line is labelled and accentuated.

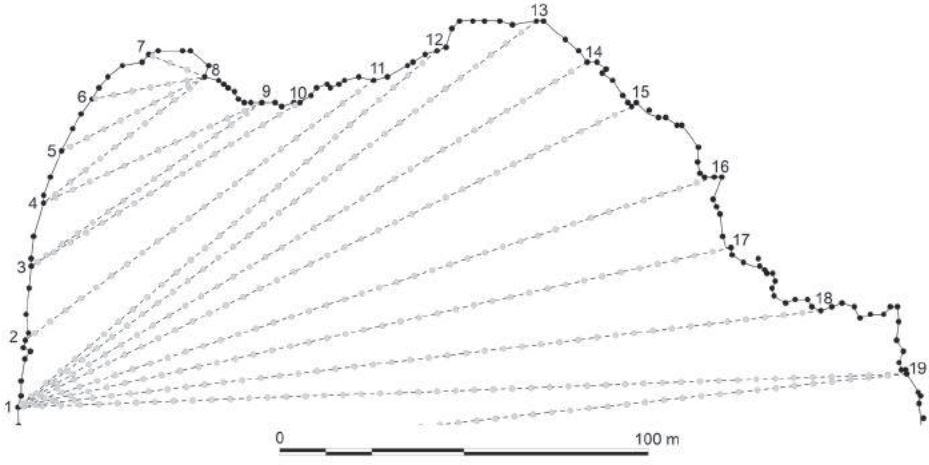

Fig. 1. Example of measured points at Čertovo Lake. Black points are points measured with the Leica total station on the lake shore (numbers represent the starting and ending points of depth profiles); the black line is at a distance of 5 m along the profile (dashed line).

Table 2a. Morphometric characteristics of the Bohemian Forest lakes.

Lake	Lake area (A) (m^2)	Area of water surface (m^2)	Area of islands (m^2)	Area of islands (%)	Altitude of water level (m a.s.l.)	Shore line (L) (m)	Shore line of islands (m)	Maximum length (l) [a] (m)	Maximum breadth (b) [b] (m)	Mean breadth ($\bar{b}$) [c] (m)
Černé Lake	187929	187929	–	–	1007.5	2111	–	693	459	271.2
Čertovo Lake	107409	107409	–	–	1027.2	1466	–	498	306	215.7
Plešné Lake	72320	72320	–	–	1087.0	1531	–	512	178	141.3
Prášilské Lake	42044	42044	–	–	1079.0	819	–	306	204	137.4
Laka Lake	25771	23570	2201	8.5	1084.9	818	568	345	95	68.3
Rachelsee	48180	48180	–	–	1070.7	963	–	359	207	134.2
Großer Arbersee	104630	78730	25900	24.8	935.0	1826	1440	565	255	139.3
Kleiner Arbersee	93500	74153	19347	20.7	917.2	1718	1484	596	212	124.4

[a] Maximum length (l) – the distance on the lake surface between the two most distant points on the lake shore without land interruption.
[b] Maximum breadth (b) – the maximum distance on the lake surface at a right angle to the line of maximum length between the shores.
[c] Mean breadth ($\bar{b}$) – the lake area divided by the maximum length.

Table 2b. Morphometric characteristics of the Bohemian Forest lakes.

Lake	Development of shore line (D_L) [a]	Volume (V) (m^3)	Maximum depth (z_m) (m)	Mean depth ($\bar{z}$) [b] (m)	Development of volume (D_V) [c]	Relative depth (z_r) [d] (%)	Mean inclination of the lake basin
Černé Lake	1.37	2924775	40.1	15.6	0.39	8.2	13°51'11"
Čertovo Lake	1.26	1859019	35.4	17.3	0.49	9.6	17°41'31"
Plešné Lake	1.61	553338	17.7	7.7	0.43	5.8	11°58'27"
Prášilské Lake	1.13	349920	17.2	8.3	0.48	7.4	12°31'53"
Laka Lake	1.44	48819	3.5	1.9	0.54	1.9	4°55'07"
Rachelsee	1.24	249046	13.3	5.2	0.39	5.4	9°02'39"
Großer Arbersee	1.59	492748	16.5	4.7	0.29	4.5	8°17'54"
Kleiner Arbersee	1.58	255179	9.7	2.7	0.28	2.8	4°16'25"

[a] Development of shore line (D_L) – the ratio of the length of the shore line (L) to the circumference of a circle of area equal to that of the lake.
[b] Mean depth ($\bar{z}$) – the lake volume divided by its surface area.
[c] Development of volume (D_V) – the ratio of the volume of the lake to that of a cone of basal area A and height z_m.
[d] Relative depth (z_r) – the ratio of the maximum depth as a percentage of the mean diameter of the lake at the surface, expressed as a percentage.

Results and discussion

Černé Lake

The bathymetric map of Černé Lake is shown in Fig. 2 and its individual morphometric characteristics are summarised in Tables 3a and 3b. If we compare the results that we obtained with the map by Švambera (1939), there are no significant differences. The maps, volumes of individual layers, and gradient ratios of the lake basin are almost identical. The mean volumetric depth is identical. The siltation of Černé Lake was therefore negligible during the 20th century.

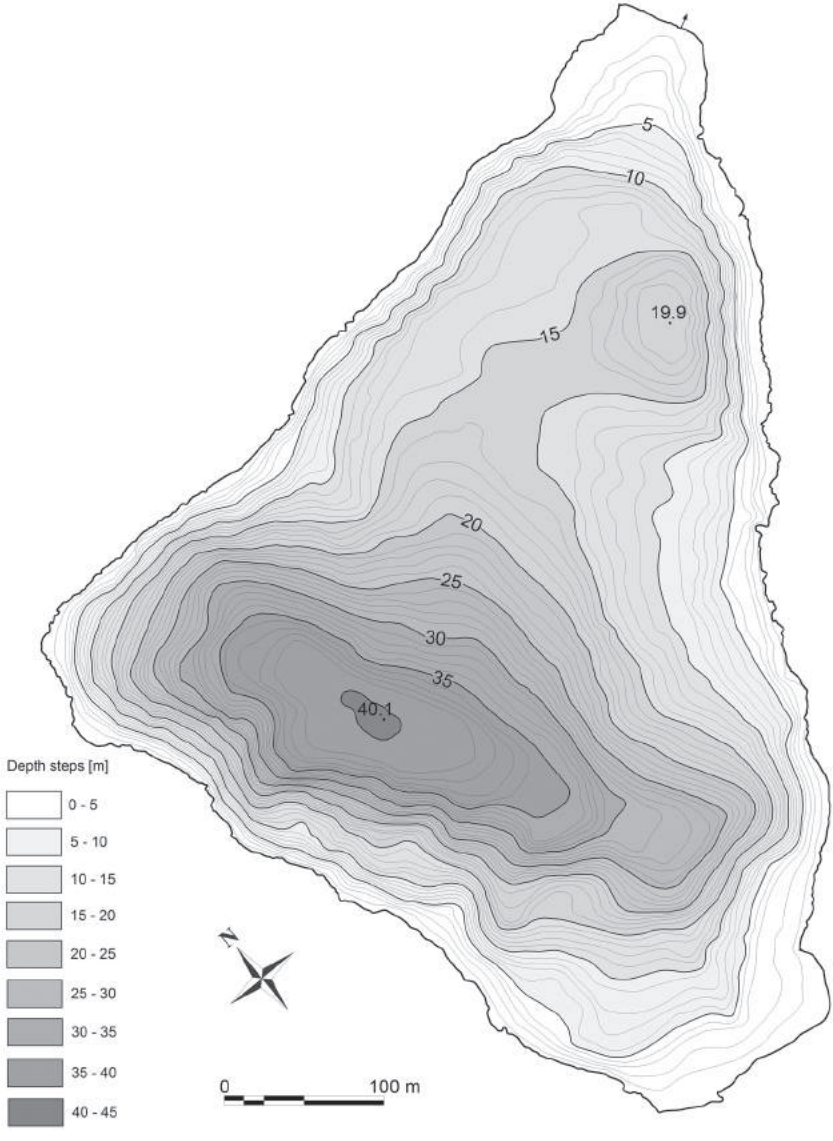

Fig. 2. Bathymetric map of Černé Lake.

Table 3a. Morphometric characteristics of the Černé Lake basin.

Depth (m)	**Area** (ha)	**Area** (%)	**Length of the contour line** (m)	**Development of the contour line**
0	18.7900	100.00	2111	1.37
1	17.6514	93.94	1812	1.22
2	16.9158	90.03	1759	1.21
3	16.2938	86.72	1720	1.20
4	15.7448	83.79	1692	1.20
5	15.2216	81.01	1665	1.20
6	14.7111	78.29	1663	1.22
7	14.2085	75.62	1634	1.22
8	13.6968	72.89	1607	1.22
9	13.1260	69.86	1574	1.22
10	12.5238	66.65	1587	1.27
11	11.9067	63.37	1571	1.28
12	11.2493	59.87	1588	1.34
13	10.5010	55.89	1571	1.37
14	9.4702	50.40	1591	1.46
15	8.4590	45.02	1542	1.50
16	7.3787	39.27	1444	1.50
17	6.7557	35.95	1349	1.46
18	6.2356	33.19	1270	1.43
19	5.7498	30.60	1191	1.40
20	5.2820	28.11	1024	1.26
21	4.9652	26.42	997	1.26
22	4.6705	24.86	977	1.28
23	4.3823	23.32	953	1.28
24	4.1111	21.88	934	1.30
25	3.8539	20.51	904	1.30
26	3.5984	19.15	883	1.31
27	3.3433	17.79	855	1.32
28	3.0839	16.41	822	1.32
29	2.7852	14.82	770	1.30
30	2.5225	13.42	711	1.26
31	2.2864	12.17	371	0.69
32	2.0804	11.07	653	1.28
33	1.8802	10.01	631	1.30
34	1.6717	8.90	611	1.33
35	1.4170	7.54	553	1.31
36	1.1640	6.19	489	1.28
37	0.9551	5.08	439	1.27
38	0.7359	3.92	385	1.27
39	0.5393	2.87	329	1.26
40	0.0602	0.32	105	1.21

Table 3b. Morphometric characteristics of the Černé Lake basin.

Depth step (m)	**Area of the depth step** (ha)	**% of total area**	**Volume of the depth step** (m^3)	**% of total volume**	**Mean inclination of the step**
0–1	1.1386	6.06	181765	6.21	9°46'30"
1–2	0.7356	3.92	172705	5.90	13°38'34"
2–3	0.6219	3.31	165904	5.67	15°37'32"
3–4	0.5491	2.92	160168	5.48	17°15'36"
4–5	0.5232	2.78	154802	5.29	17°47'16"
5–6	0.5104	2.72	149637	5.12	18°03'19"
6–7	0.5027	2.68	144610	4.94	18°09'23"
7–8	0.5117	2.72	139511	4.77	17°34'20"
8–9	0.5707	3.04	134177	4.59	15°34'18"
9–10	0.6022	3.21	128265	4.39	14°42'18"
10–11	0.6171	3.28	122196	4.18	14°21'12"
11–12	0.6574	3.50	115819	3.96	13°30'39"
12–13	0.7484	3.98	108926	3.72	11°55'04"
13–14	1.0308	5.49	99817	3.41	8°43'11"
14–15	1.0111	5.38	89793	3.07	8°48'24"
15–16	1.0804	5.75	78960	2.70	7°52'06"
16–17	0.6230	3.32	70536	2.41	12°38'06"
17–18	0.5201	2.77	64905	2.22	14°07'59"
18–19	0.4858	2.59	59929	2.05	14°12'46"
19–20	0.4678	2.49	55083	1.88	13°19'07"
20–21	0.3168	1.69	51206	1.75	17°41'35"
21–22	0.2947	1.57	48173	1.65	18°30'52"
22–23	0.2882	1.53	45244	1.55	18°30'55"
23–24	0.2712	1.44	42458	1.45	19°10'47"
24–25	0.2572	1.37	39802	1.36	19°39'43"
25–26	0.2555	1.36	37267	1.27	19°16'32"
26–27	0.2551	1.36	34710	1.19	18°48'36"
27–28	0.2593	1.38	32143	1.10	17°55'06"
28–29	0.2987	1.59	29292	1.00	14°55'18"
29–30	0.2628	1.40	26526	0.91	15°44'15"
30–31	0.2361	1.26	24038	0.82	12°54'06"
31–32	0.2060	1.10	21822	0.75	13°57'24"
32–33	0.2002	1.07	19799	0.68	17°46'52"
33–34	0.2085	1.11	17785	0.61	16°35'14"
34–35	0.2547	1.36	15469	0.53	12°52'19"
35–36	0.2530	1.35	12874	0.44	11°38'15"
36–37	0.2089	1.11	10598	0.36	12°31'19"
37–38	0.2192	1.17	8423	0.29	10°38'39"
38–39	0.1966	1.05	6340	0.22	10°17'30"
39–40	0.4791	2.55	3285	0.11	2°35'36"
40–40.1	0.0457	0.24	13	0.00	6°33'12"

Čertovo Lake

The bathymetric map of Čertovo Lake is shown in Fig. 3 and its individual morphometric characteristics are summarised in Tables 4a and 4b. The modifications of the lake dam in the 1930s resulted in the present shallower maximum depth compared to that measured by Švambera (1939) (35.4 *vs.* 36 m).

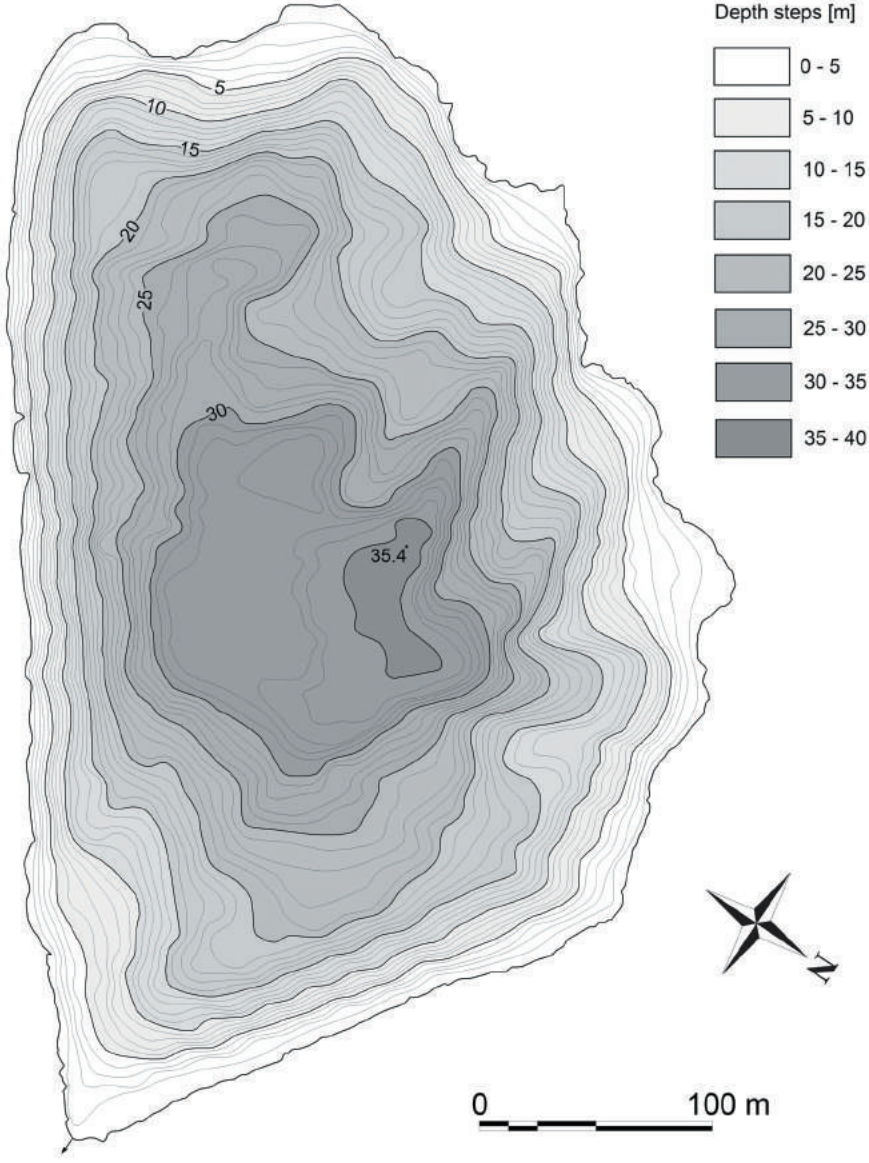

Fig. 3. Bathymetric map of Čertovo Lake.

Table 4a. Morphometric characteristics of the Čertovo Lake basin (Kocum 2004).

Depth (m)	**Area** (ha)	**Area** (%)	**Length of the contour line** (m)	**Development of the contour line**
0	10.7400	100.00	1466	1.26
1	10.2046	95.02	1306	1.15
2	9.8173	91.41	1252	1.13
3	9.4830	88.30	1223	1.12
4	9.1995	85.66	1213	1.13
5	8.9301	83.15	1193	1.13
6	8.6687	80.71	1187	1.14
7	8.4130	78.33	1170	1.14
8	8.1521	75.90	1166	1.15
9	7.8938	73.50	1148	1.15
10	7.6419	71.15	1143	1.17
11	7.3859	68.77	1129	1.17
12	7.1146	66.24	1127	1.19
13	6.8190	63.49	1128	1.22
14	6.5167	60.68	1127	1.25
15	6.2095	57.82	1101	1.25
16	5.8851	54.80	1100	1.28
17	5.5681	51.84	1064	1.27
18	5.2602	48.98	1043	1.28
19	4.9164	45.78	997	1.27
20	4.5979	42.81	953	1.25
21	4.2954	39.99	932	1.27
22	3.9621	36.89	917	1.30
23	3.5846	33.38	891	1.33
24	3.2315	30.09	883	1.39
25	2.9129	27.12	844	1.39
26	2.6078	24.28	818	1.43
27	2.2769	21.20	772	1.44
28	2.0086	18.70	743	1.48
29	1.7648	16.43	637	1.35
30	1.5616	14.54	576	1.30
31	1.3940	12.98	533	1.27
32	1.1956	11.13	503	1.30
33	0.6354	5.92	478	1.69
34	0.4023	3.75	297	1.32
35	0.0905	0.84	199	1.87

Table 4b. Morphometric characteristics of the Čertovo Lake basin (Kocum 2004).

Depth step (m)	**Area of the depth step** (ha)	**% of total area**	**Volume of the depth step** (m^3)	**% of total volume**	**Mean inclination of the step**
0–1	0.5354	12.73	104430	5.62	14°30'52"
1–2	0.3874	9.21	100054	5.38	18°16'19"
2–3	0.3342	7.95	96443	5.19	20°19'06"
3–4	0.2836	6.74	93392	5.02	23°14'42"
4–5	0.2693	6.41	90641	4.88	24°04'06"
5–6	0.2614	6.22	87988	4.73	24°28'24"
6–7	0.2557	6.08	85404	4.59	24°44'39"
7–8	0.2609	6.21	82836	4.46	24°06'55"
8–9	0.2583	6.14	80222	4.32	24°07'58"
9–10	0.2519	5.99	77677	4.18	24°26'59"
10–11	0.2560	6.09	75147	4.04	23°55'40"
11–12	0.2712	6.45	72510	3.90	22°34'57"
12–13	0.2957	7.03	69698	3.75	20°52'29"
13–14	0.3023	7.19	66686	3.59	20°27'10"
14–15	0.3071	7.30	63638	3.42	19°56'11"
15–16	0.3245	7.72	60515	3.26	18°44'04"
16–17	0.3170	7.54	57261	3.08	18°50'52"
17–18	0.3079	7.32	54132	2.91	18°53'24"
18–19	0.3438	8.18	50924	2.74	16°31'26"
19–20	0.3185	7.58	47556	2.56	17°01'08"
20–21	0.3024	7.19	44449	2.39	17°18'31"
21–22	0.3334	7.93	41349	2.22	15°30'01"
22–23	0.3774	8.98	37658	2.03	13°28'09"
23–24	0.3531	8.40	34099	1.83	14°06'03"
24–25	0.3186	7.58	30693	1.65	15°09'55"
25–26	0.3051	7.26	27603	1.48	15°14'08"
26–27	0.3309	7.87	24406	1.31	13°30'35"
27–28	0.2683	6.38	21411	1.15	15°45'52"
28–29	0.2438	5.80	18836	1.01	15°48'09"
29–30	0.2032	4.83	16580	0.89	16°37'14"
30–31	0.1676	3.99	14781	0.80	18°18'35"
31–32	0.1984	4.72	13017	0.70	14°37'55"
32–33	0.5602	13.32	9070	0.49	5°00'14"
33–34	0.2331	5.54	5033	0.27	9°26'19"
34–35	0.3118	7.42	2775	0.15	4°32'52"
35–35.4	0.0905	2.15	102	0.01	6°16'27"

Plešné Lake

The bathymetric map of Plešné Lake is shown in Fig. 4 and its individual morphometric characteristics are summarised in Tables 5a and 5b. Janský et al. (2005) showed that almost identical morphometric characteristics were measured by Švambera (1939) and Vránek (1999). The bathymetric map of the lake by Vránek (1999) is, however, more rugged. His measurements were completed before the final modifications of the infringed lake outlet, and therefore the results did not reflect the contemporary situation. Consequently, a new measurement was taken in 2009 (Table 1). According to Kopáček et al. (2003), silting rate at this location was probably the highest of all of the Bohemian Forest lakes, throughout their history. The present rate of silting, however, cannot be estimated by comparing the historical and current bathymetric maps, due to the manipulation of the altitude of the lake outlet in recent history.

Fig. 4. Bathymetric map of Plešné Lake.

Table 5a. Morphometric characteristics of the Plešné Lake basin.

Depth (m)	**Area** (ha)	**Area** (%)	**Length of the contour line** (m)	**Development of the contour line**
0	7.2320	100.00	1531	1.61
1	5.8725	81.20	1130	1.32
2	5.2803	73.01	1065	1.31
3	4.9774	68.82	1032	1.30
4	4.6728	64.61	1011	1.32
5	4.3860	60.65	992	1.34
6	4.1078	56.80	974	1.36
7	3.8069	52.64	949	1.37
8	3.5146	48.60	922	1.39
9	3.2370	44.76	902	1.41
10	2.9205	40.38	876	1.45
11	2.5080	34.68	833	1.48
12	2.1255	29.39	794	1.54
13	1.7374	24.02	739	1.58
14	1.3090	18.10	693	1.71
15	0.7619	10.54	545	1.76
16	0.2808	3.88	219	1.17
17	0.1014	1.40	131	1.16

Table 5b. Morphometric characteristics of the Plešné Lake basin.

Depth step (m)	**Area of the depth step** (ha)	**% of total area**	**Volume of the depth step** (m^3)	**% of total volume**	**Mean inclination of the step**
0–1	1.3595	18.80	66330	11.99	5°35'22"
1–2	0.5922	8.19	55875	10.10	10°29'57"
2–3	0.3029	4.19	51315	9.27	19°05'37"
3–4	0.3046	4.21	48330	8.73	18°32'21"
4–5	0.2868	3.97	45300	8.19	19°14'57"
5–6	0.2782	3.85	42600	7.70	19°27'38"
6–7	0.3009	4.16	39690	7.17	17°43'15"
7–8	0.2923	4.04	36480	6.59	17°44'50"
8–9	0.2776	3.84	33890	6.12	18°11'13"
9–10	0.3165	4.38	30675	5.54	15°41'21"
10–11	0.4125	5.70	27060	4.89	11°42'12"
11–12	0.3825	5.29	23190	4.19	12°00'24"
12–13	0.3881	5.37	19290	3.49	11°10'20"
13–14	0.4284	5.92	15332	2.77	9°29'18"
14–15	0.5471	7.56	10620	1.92	6°27'18"
15–16	0.4811	6.65	5010	0.91	4°32'23"
16–17	0.1794	2.48	2015	0.36	5°34'17"
17–17.7	0.1014	1.40	336	0.06	3°41'45"

Prášilské Lake

The bathymetric map of Prášilské Lake is shown in Fig. 5 and its individual morphometric characteristics are summarised in Tables 6a and 6b. Data on this lake exhibit the largest differences between the more recent (Zbořil 1994) and historical (Švambera 1914b) measurements, with the most pronounced difference in the maximum depths (17.2 *vs*. 14.9 m, respectively) and the lake surface areas (4.2 *vs*. 3.7 ha, respectively). The lower values observed by Švambera (1914b) could have resulted either from a lower water level caused by use of water for timber transportation or due to high evaporation (his measurements were taken in August and September 1906). For example, the water level of Prášilské Lake was more than 1 m lower in August 2015 than during previous summers due to dry weather conditions. Otherwise, the basin of the lake was similar in both the recent and the early studies.

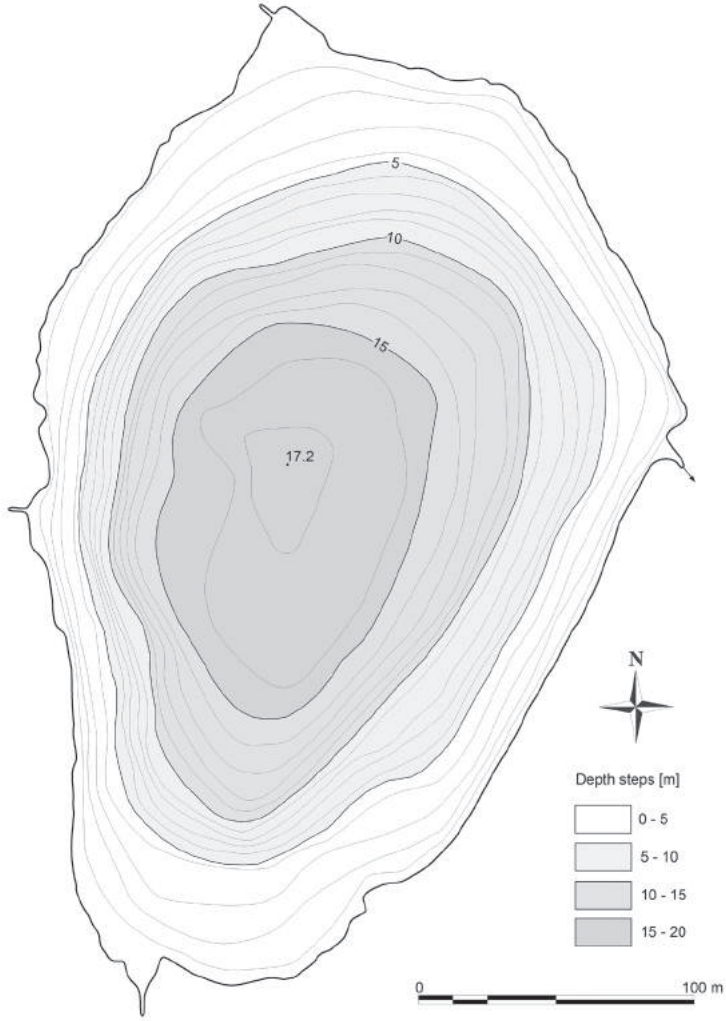

Fig. 5. Bathymetric map of Prášilské Lake.

Table 6a. Morphometric characteristics of the Prášilské Lake basin (Zbořil 1994).

Depth (m)	**Area** (ha)	**Area** (%)	**Length of the contour line** (m)	**Development of the contour line**
0	4.2044	100.00	819	1.13
1	3.9367	93.63	761	1.08
2	3.5829	85.22	719	1.07
3	3.2242	76.69	673	1.06
4	2.8229	67.14	625	1.05
5	2.6223	62.37	601	1.05
6	2.4610	58.53	583	1.05
7	2.2847	54.34	564	1.05
8	2.1009	49.97	543	1.06
9	1.8990	45.17	521	1.07
10	1.7202	40.91	498	1.07
11	1.5864	37.73	480	1.08
12	1.4201	33.78	452	1.07
13	1.2001	28.54	411	1.06
14	0.9863	23.46	379	1.08
15	0.7701	18.32	331	1.06
16	0.4751	11.30	275	1.13
17	0.0788	1.87	110	1.11

Table 6b. Morphometric characteristics of the Prášilské Lake basin (Zbořil 1994).

Depth step (m)	**Area of the depth step** (ha)	**% of total area**	**Volume of the depth step** (m^3)	**% of total volume**	**Mean inclination of the step**
0–1	0.2677	6.37	40560	11.59	16°26'30"
1–2	0.3538	8.41	37400	10.69	11°48'48"
2–3	0.3587	8.53	33960	9.71	10°58'51"
3–4	0.4013	9.54	30040	8.58	9°11'11"
4–5	0.2006	4.77	27080	7.74	16°59'32"
5–6	0.1613	3.84	25200	7.20	20°09'14"
6–7	0.1763	4.19	23480	6.71	18°01'10"
7–8	0.1838	4.37	21480	6.14	16°45'33"
8–9	0.2019	4.80	19840	5.67	14°45'42"
9–10	0.1788	4.25	17800	5.09	15°54'18"
10–11	0.1338	3.18	16440	4.70	20°04'33"
11–12	0.1663	3.96	15080	4.31	15°39'13"
12–13	0.2200	5.23	13040	3.73	11°05'48"
13–14	0.2138	5.09	10960	3.13	10°28'03"
14–15	0.2162	5.14	8680	2.48	9°19'29"
15–16	0.2950	7.02	6120	1.75	5°51'52"
16–17	0.3963	9.43	2680	0.77	2°46'51"
17–17.7	0.0788	1.87	80	0.02	7°56'48"

Laka Lake

The bathymetric map of Laka Lake is shown in Fig. 6 and its individual morphometric characteristics are summarised in Tables 7a and 7b. The first reliable results of bathymetric measurements in this lake were presented by Šobr (1999). All previously published characteristics were incomplete and imprecise. For example, Wagner (1897) found the lake completely dry, and Švambera (1914c) found its surface area to be 2.8 ha and the maximum depth of 3.9 m. The islands in the lake were not floating during our study but their position was stable due to the relatively shallow lake depth and their connection to the lake bottom. The water volumes reported in Tables 2a, 7a, and 7b do not include the islands and only refer to the total water volume in the lake.

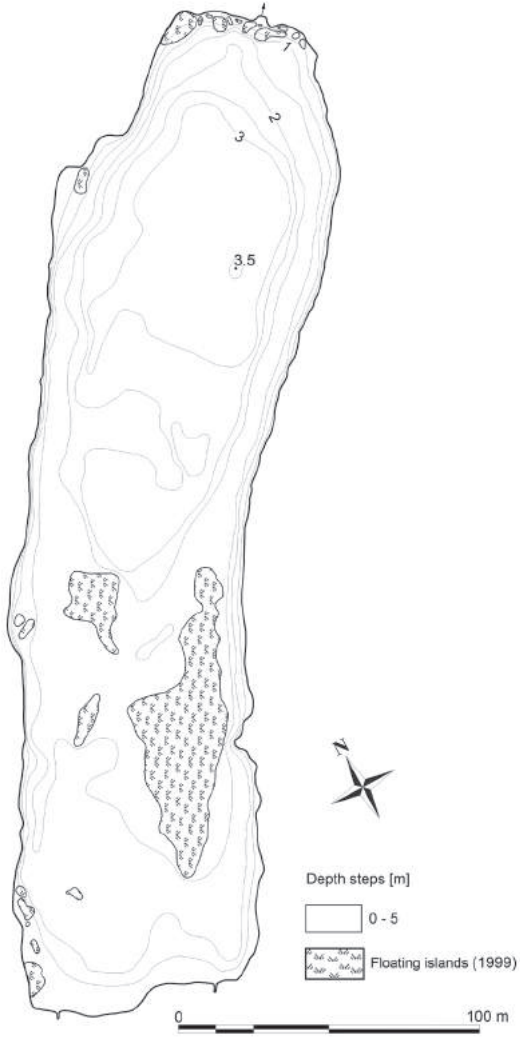

Fig. 6. Bathymetric map of Laka Lake.

Table 7a. Morphometric characteristics of the Laka Lake basin.

Depth (m)	**Area** (ha)	**Area** (%)	**Length of the contour line** (m)	**Development of the contour line**
0	2.5771	100.00	818	1.44
0.5	2.3926	92.84	759.5	1.39
1	2.2047	85.55	776	1.47
1.5	1.7844	69.24	754	1.59
2	0.9403	36.49	482	1.40
2.5	0.7186	27.88	470.5	1.57
3	0.3633	14.10	361	1.69
3.5	0.0013	0.05	14.5	1.13

Table 7b. Morphometric characteristics of the Laka Lake basin.

Depth step (m)	**Area of the depth step** (ha)	**% of total area**	**Volume of the depth step** (m^3)	**% of total volume**	**Mean inclination of the step**
0–0.5	0.1845	4.39	12610	25.83	23°08'49"
0.5–1	0.1879	4.47	12149	24.89	22°13'29"
1–1.5	0.4203	16.31	10028	20.54	10°18'56"
1.5–2	0.8441	32.75	7005	14.35	4°11'15"
2–2.5	0.2217	8.60	4103	8.40	12°07'26"
2.5–3	0.3553	13.79	2820	5.78	6°40'27"
3–3.5	0.3633	14.10	104	0.21	2°57'30"

Rachelsee

The bathymetric map of Rachelsee Lake is shown in Fig. 7 and its individual morphometric characteristics are summarised in Tables 8a and 8b. The characteristics of the lakes in the Bavarian Forest could be compared with the results by Kuchař (1947) and Weilner (pers. comm.). A comparison of the new map from 2015 with that of Weilner shows only negligible differences. In contrast to a map by Kuchař (1947), there are certain differences in the lake surface (4.82 *vs*. 3.41 ha, respectively), the length of contour lines (for details see the table in Kuchař 1947) and the lake volume (249046 *vs*. 131700 m^3, respectively). These differences are most probably the result of the different densities of measurements: Kuchař (1947) took one measurement per 160 m^2, while we took one measurement per 31 m^2.

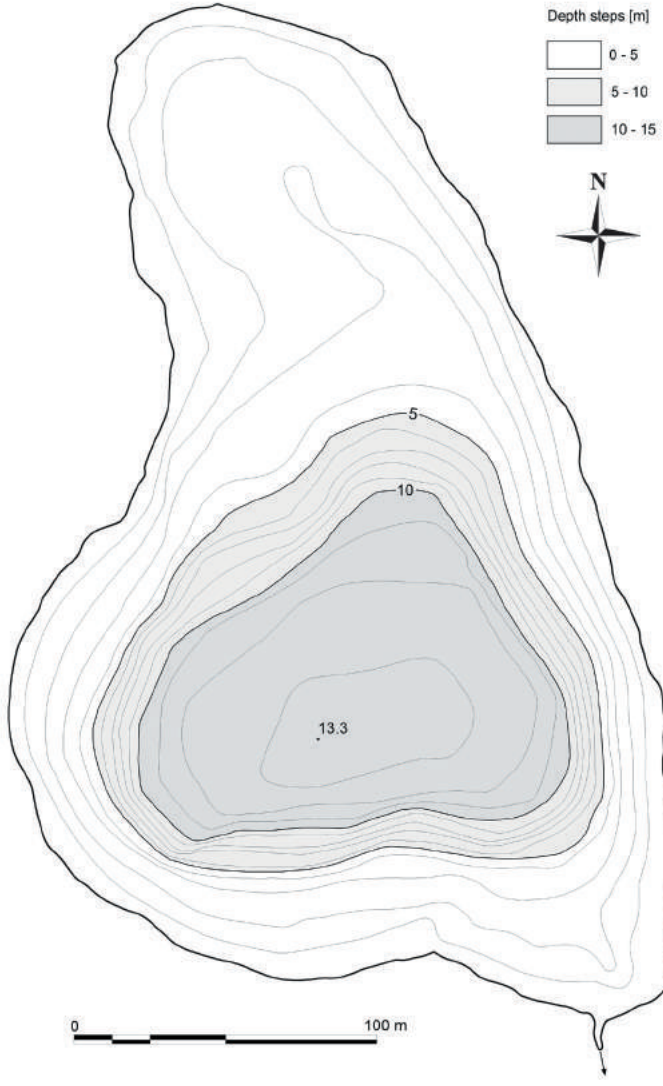

Fig. 7. Bathymetric map of Rachelsee.

Table 8a. Morphometric characteristics of the Rachelsee lake basin.

Depth (m)	**Area** (ha)	**Area** (%)	**Length of the contour line** (m)	**Development of the contour line**
0	4.8180	100.00	963	1.24
1	4.2279	87.77	894	1.23
2	3.5380	73.45	861	1.29
3	2.5681	53.31	725	1.28
4	2.1254	44.12	556	1.08
5	1.8810	39.05	522	1.07
6	1.6916	35.12	496	1.08
7	1.5317	31.80	472	1.08
8	1.3853	28.76	453	1.09
9	1.2426	25.80	436	1.10
10	1.0962	22.76	416	1.12
11	0.8963	18.61	374	1.11
12	0.6432	13.35	317	1.12
13	0.1236	2.57	184	1.48

Table 8b. Morphometric characteristics of the Rachelsee lake basin.

Depth step (m)	**Area of the depth step** (ha)	**% of total area**	**Volume of the depth step** (m^3)	**% of total volume**	**Mean inclination of the step**
0–1	0.5901	12.25	44876	18.02	8°58'50''
1–2	0.6899	14.32	38205	15.34	7°14'55''
2–3	0.9699	20.13	29995	12.04	4°29'
3–4	0.4427	9.19	22503	9.04	7°49'12''
4–5	0.2444	5.07	19440	7.81	12°26'13''
5–6	0.1894	3.93	17378	6.98	15°02'33''
6–7	0.1599	3.32	15735	6.32	16°50'26''
7–8	0.1464	3.04	14301	5.74	17°31'56''
8–9	0.1427	2.96	12931	5.19	17°18'05''
9–10	0.1464	3.04	11584	4.65	16°13'27''
10–11	0.1999	4.15	9969	4.00	11°10'39''
11–12	0.2531	5.25	7734	3.11	7°46'24''
12–13	0.5196	10.79	4303	1.73	2°45'37''
13–13.3	0.1236	2.57	92	0.04	4°15'25''

Großer Arbersee

The bathymetric map of Großer Arbersee is shown in Fig. 8 and its individual morphometric characteristics are summarised in Tables 9a and 9b. The comparison of our results with those of Švambera (1914a) shows better agreement than the comparison with Weilner's map (pers. comm.). The probable reason for this discrepancy is the fact that Weilner placed the isobath in the western part, one meter from the lakeshore, which is essentially a moorland, while he should have placed it under the floating bog as Švambera correctly did in the course of his measurement in 1908, and as we have done repeatedly in our measurements. The determination of the lake morphometry was complicated due to the presence of a considerably large moorland part on the western shore of the lake. It is more appropriate to specify in detail where exactly the water ends and the shore begins, preferably with the help of divers. Consequently, the shoreline was mapped twice: First, as a borderline of a floating island (moorland) at the edge of which the depth values of up to 6 meters were measured; and second, as a borderline between the moorland and the stabilized shoreline (see the second and third columns in Table 2a and the bathymetric map, Fig. 8). The surface area of the mouth of the large south-western lake inlet was included in the total lake surface, as well as its shoreline in the total lake shoreline. The whole moorland in the lake is water-saturated. However, according to our present knowledge, we are not able to estimate the water volume in the moorland, and therefore the numbers presented in Tables 2a, 9a, and 9b do not include this volume.

Table 9a. Morphometric characteristics of the Großer Arbersee lake basin.

Depth (m)	**Area** (ha)	**Area** (%)	**Length of the contour line** (m)	**Development of the contour line**
0	10.4630	100.00	1826	1.59
1	7.2360	69.16	1294	1.36
2	5.7560	55.01	1289	1.52
3	4.9814	47.61	1249	1.58
4	4.3776	41.84	1203	1.62
5	3.8516	36.81	1126	1.62
6	3.3858	32.36	1081	1.66
7	2.9667	28.35	1021	1.67
8	2.5682	24.55	964	1.70
9	2.1748	20.79	884	1.69
10	1.7607	16.83	662	1.41
11	1.5377	14.70	531	1.21
12	1.3582	12.98	504	1.22
13	1.1691	11.17	470	1.23
14	0.9656	9.23	433	1.24
15	0.7392	7.06	384	1.26
16	0.4148	3.96	340	1.49

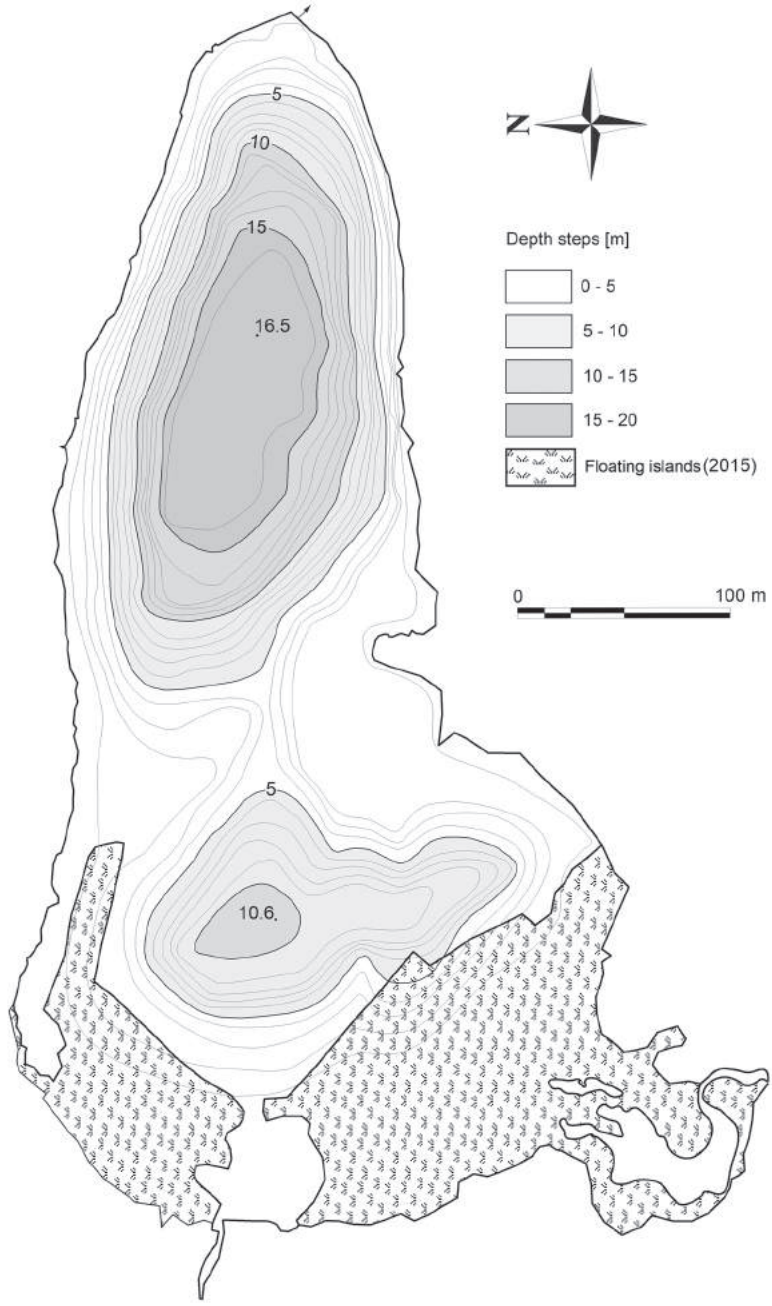

Fig. 8. Bathymetric map of Großer Arbersee.

Table 9b. Morphometric characteristics of the Großer Arbersee lake basin.

Depth step (m)	Area of the depth step (ha)	% of total area	Volume of the depth step (m^3)	% of total volume	Mean inclination of the step
0–1	3.2270	40.99	87950	17.85	2°46'04''
1–2	1.4800	18.80	62800	12.74	4°59'14''
2–3	0.7746	9.84	52650	10.68	9°18'14''
3–4	0.6038	7.67	45440	9.22	11°28'40''
4–5	0.5260	6.68	39918	8.10	12°29'00''
5–6	0.4658	5.92	35155	7.13	13°19'40''
6–7	0.4191	5.32	30879	6.27	14°04'41''
7–8	0.3985	5.06	26973	5.47	13°59'08''
8–9	0.3934	5.00	23157	4.70	13°13'04''
9–10	0.4141	5.26	19201	3.90	10°34'25''
10–11	0.2230	2.83	15978	3.24	14°58'31''
11–12	0.1795	2.28	14243	2.89	16°04'56''
12–13	0.1891	2.40	12469	2.53	14°26'31''
13–14	0.2035	2.58	10582	2.15	12°30'34''
14–15	0.2264	2.88	8473	1.72	10°13'41''
15–16	0.3244	4.12	6021	1.22	6°22'02''
16–16.5	0.4148	5.27	859	0.17	2°20'49''

Kleiner Arbersee

The bathymetric map of Kleiner Arbersee is shown in Fig. 9 and its individual morphometric characteristics are summarised in Tables 10a and 10b. A comparison of our data with those of Švambera (1913) is not possible, because the older measurements were taken at a very low water level (almost 3 m lower than today). The comparison with Weilner (pers. comm.) shows that floating islands are moving in the lake and their position in the maps differs. The value of the calculated lake volume presented in this study included also the volume of the floating islands, because we were not able to determine their thickness and volume with the technique used. The volume of these islands was therefore roughly estimated on the basis of the isobaths that were interpolated below the floating islands. It is necessary to use divers to acquire a more detailed measurement of the volume of these floating islands.

Conclusions

Approximately 160 years have elapsed since the first measurements of the Bohemian Forest lake bathymetry. For almost one hundred years, the most cited studies were those by V. Švambera. His measurements, although taken at the beginning of the 20th century, have proven themselves to be very precise. Unfortunately, since Švambera took his measurements, the dams and the outlet facilities of several lakes have been repeatedly modified, causing changes in the mid-altitude of the water surface level. On the basis of the depth ratio comparison, it is therefore not possible to evaluate the siltation dynamics of the lakes. Nevertheless, the newly created maps enable detailed analyses of the morphology of the lake basins and bottoms. It is possible to compare the values of volumes at individual depth levels, as well as to evaluate the development of the water volume with depths in the lakes.

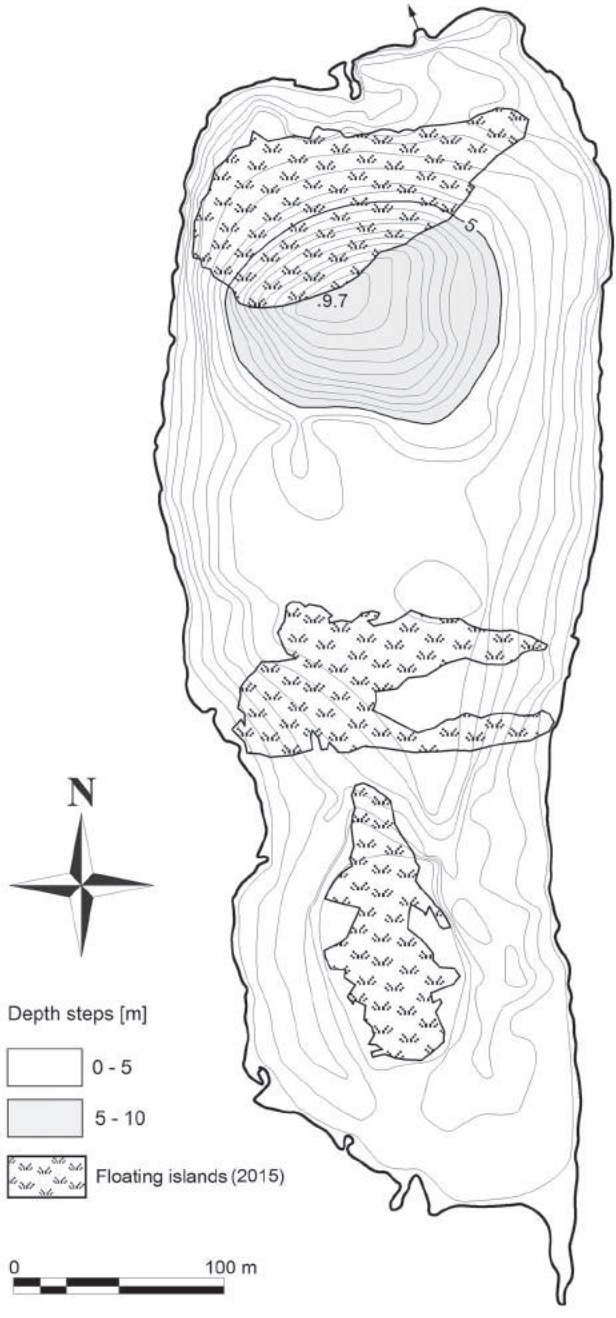

Fig. 9. Bathymetric map of Kleiner Arbersee.

Table 10a. Morphometric characteristics of the Kleiner Arbersee lake basin.

Depth (m)	**Area** (ha)	**Area** (%)	**Length of the contour line** (m)	**Development of the contour line**
0	9.3500	100.00	1718	1.58
0.5	8.7640	93.73	1394	1.33
1	6.9641	74.48	1685	1.80
1.5	5.9722	63.87	1557	1.80
2	5.0046	53.53	1182	1.49
2.5	4.3630	46.66	881	1.19
3	3.7800	40.43	819	1.19
3.5	3.1070	33.23	799	1.28
4	2.4761	26.48	670	1.20
4.5	1.3023	13.93	484	1.20
5	1.0740	11.49	379	1.03
5.5	0.9073	9.70	347	1.03
6	0.7680	8.21	323	1.04
6.5	0.6428	6.87	300	1.06
7	0.5387	5.76	276	1.06
7.5	0.4196	4.49	246	1.07
8	0.3213	3.44	216	1.07
8.5	0.2288	2.45	184	1.09
9	0.1299	1.39	144	1.13
9.5	0.0550	0.59	94	1.13

Table 10b. Morphometric characteristics of the Kleiner Arbersee lake basin.

Depth step (m)	**Area of the depth step** (ha)	**% of total area**	**Volume of the depth step** (m^3)	**% of total volume**	**Mean inclination of the step**
0–0.5	0.5860	6.27	45475	17.82	3°27'59''
0.5–1	1.7999	19.25	38215	14.98	9°01'26''
1–1.5	0.9919	10.61	32225	12.63	8°18'59''
1.5–2	0.9676	10.35	26433	10.36	9°52'14''
2–2.5	0.6416	6.86	23410	9.17	10°11'55''
2.5–3	0.5830	6.24	20400	7.99	9°56'56''
3–3.5	0.6730	7.20	17325	6.79	6°18'43''
3.5–4	0.6309	6.75	14204	5.57	4°01'42''
4–4.5	1.1738	12.55	9605	3.76	7°31'48''
4.5–5	0.2283	2.44	5850	2.29	11°12'20''
5–5.5	0.1667	1.78	4975	1.95	12°10'03''
5.5–6	0.1393	1.49	4175	1.64	12°41'19''
6–6.5	0.1252	1.34	3368	1.32	13°15'11''
6.5–7	0.1041	1.11	2870	1.12	13°56'36''
7–7.5	0.1191	1.27	2325	0.91	12°14'23''
7.5–8	0.0983	1.05	1805	0.71	11°31'50''
8–8.5	0.0925	0.99	1280	0.50	11°21'36''
8.5–9	0.0989	1.06	790	0.31	8°43'00''
9–9.5	0.0749	0.80	435	0.17	6°23'30''
9.5–9.7	0.0138	0.15	14	0.01	19°54'59''

Some differences between the recent and historic morphometric characteristics also resulted from more detail in the present measurements. Our study shows more precisely the form of the isobaths that are longer and may therefore also contribute to the observed differences in lake volumes. Fig. 10 allows for a direct areal comparison of all eight glacial lakes in the Bohemian Forest in their actual geographic positions. In addition, recent aerial photographs of individual lakes and their catchments with characteristic forest vegetation cover (Figs. 11–18) are shown in Appendix 1.

New bathymetric measurements have confirmed (where possible) a very slow sedimentation and silting of the lakes. The new morphometric characteristics are more precise and we recommend using them in future studies on the Bohemian Forest lakes.

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References

Bayberger F., 1886: Geographisch-geologische Studien aus dem Böhmerwalde. *Petermanns Geographische Mitteilungen, Gotha*, Ergänzungsheft 81: 1–63 (in German).

Čapek R., Mikšovský M. & Mucha L., 1992: *Geografická kartografie* [*Geographic cartography*]. Státní Pedagogické Nakladatelství, Praha, 373 pp. (in Czech).

Čapek R. & Kudrnovská O., 1982: *Kartometrie* [*The Cartometry*]. Státní Pedagogické Nakladatelství, Praha, 162 pp. (in Czech).

Česák J. & Šobr M., 2005: Metody batymetrického mapování českých jezer [Methods of bathymetric mapping of Czech lakes]. *Geografie – Sborník ČGS*, 110: 141–151 (in Czech).

Frejlach J., 1898: Bathymetrická mapa jezera Plöckensteinského [Bathymetric map of Plešné Lake]. *Věstník Československé Akademie Nauk*, 7 (4): 267–270 (in Czech).

Frič A. & Vávra K., 1897: Untersuchungen über die Fauna der Gewässer Böhmens. III. Untersuchung zweier Böhmerwaldseen, des Schwarzen Sees und des Teufelsees. *Archiv der Naturwisseschaftlichen Landesdurchforschung von Böhmen*, 10 (3): 1–74 (in German).

Hutchinson E.G., 1957: A *Treatise on Limnology. Volume I, Geography, physics and chemistry*. John Wiley & Sons, New York, 1015 pp.

Janský B., Šobr M., Kocum J. & Česák J., 2005: Nová batymetrická mapování glaciálních jezer na české straně Šumavy [New bathymetric mapping of the Bohemian forest glacial lakes]. *Geografie – Sborník ČGS*, 110: 176–187 (in Czech).

Kocum J., 2004: Limnologická studie Čertova jezera a režim odtoku v českém povodí Řezné [The limnological study of Čertovo Lake and runoff regime in the catchment area of Řezná River]. Ms., diploma thesis, Charles University, Prague, 210 pp. (in Czech). (Geographical library of the Faculty of Science, Charles University, Prague)

Kopáček J., Brzáková M., Hejzlar J., Kaňa J., Porcal P. & Vrba J., 2003: Mass balance of nutrients and major solutes in the Plešné watershed–lake ecosystem in the 2001 hydrological year. *Silva Gabreta*, 9: 33–52.

Kuchař K., 1939: Příspěvky k výzkumu šumavských jezer [Contributions to the research of Bohemian Forest lakes]. *Sborník České Společnosti Zeměpisné*, 45: 87–90 (in Czech).

Kuchař K., 1947: Mapy šumavských jezer podle měření prof. V. Švambery [Maps of Bohemian Forest lakes according to prof. V. Švambera measuring]. *Kartografický přehled*, 2 (3–4): 41–42 (in Czech).

Kuchařová J., 2009: Možnosti interpolace jezerních pánví různých genetických typů [Possibilities of interpolating lakes basins of various genetic types]. Ms., bachelor thesis, Charles University, Prague, 35 pp. (in Czech). (Geographical library of the Faculty of Science, Charles University, Prague)

Kunský J., Louček D. & Sládek J., 1959: *Praktikum fysického zeměpisu* [*Practise of Physical Geography*]. Nakladatelství ČSAV, Praha, 266 pp. (in Czech).

Reissinger A., 1930: Der Schwarze See im Böhmerwald. *Die ostbayerischen Grenzmarken, Monatsschrift der Institut für Ostbayerische Heimatforschung, Passau*, 3 (in German).

Šobr M., 1999: Jezero Laka [Laka Lake]. Ms., diploma thesis, Charles University, Prague, 89 pp. (in Czech). (Geographical library of the Faculty of Science, Charles University, Prague)

Šobr M., 2007: Jezera České republiky – fyzickogeografické a fyzikálně-limnologické poměry [Lakes of the Czech Republic – physicogeographical and physico-limnological characteristics]. Ms., Ph.D. thesis, Charles University, Prague, 235 pp. (in Czech). (Geographical library of the Faculty of Science, Charles University, Prague)

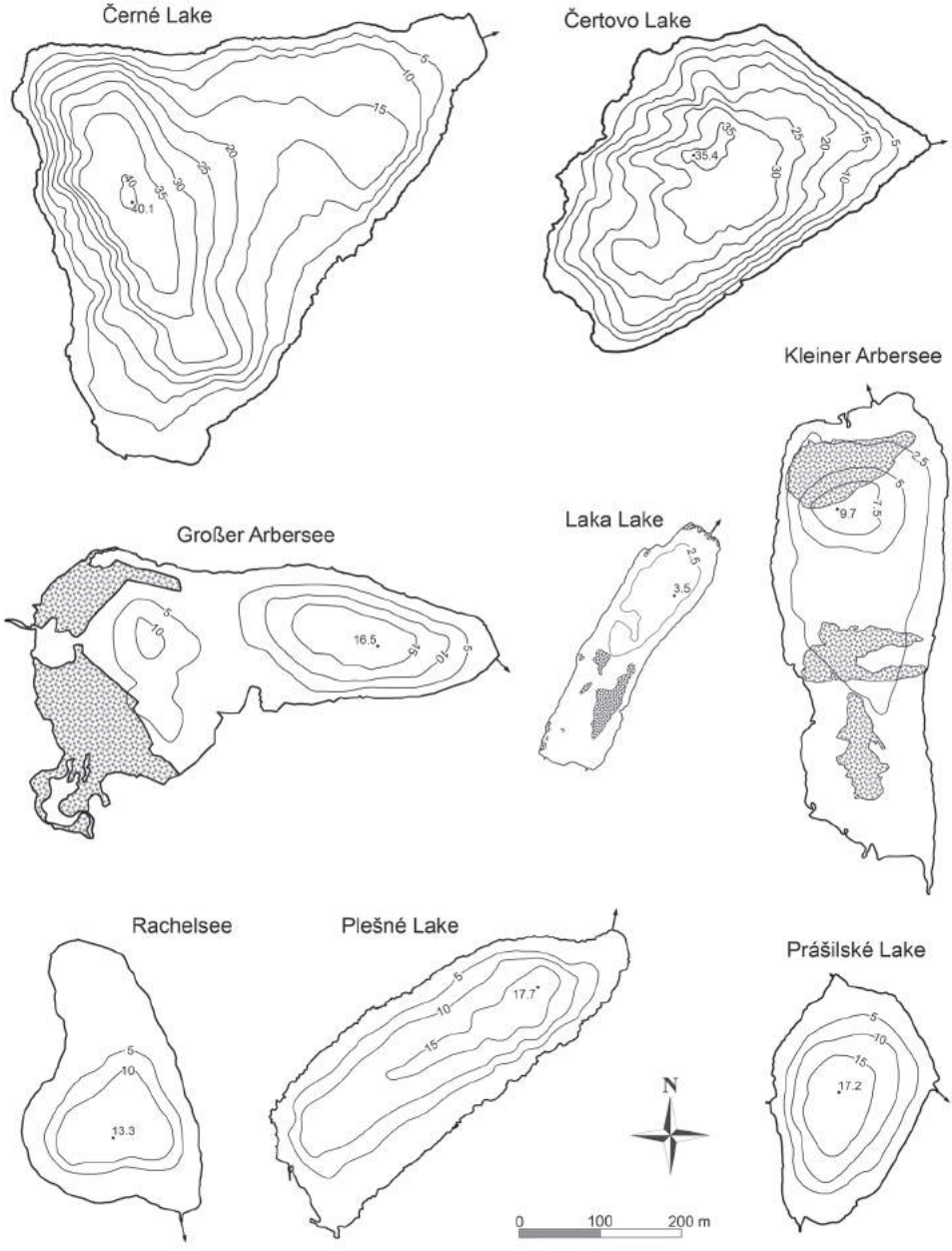

Fig. 10. Areal comparison of all Bohemian Forest lakes (floating islands in grey).

Švambera V., 1912: Výzkum šumavských jezer [Research of the Bohemian Forest lakes]. *Sborník České Společnosti Zeměpisné*, 18: 250–257 (in Czech).
Švambera V., 1913: Šumavská jezera I. Malé Javorské jezero [The Bohemian Forest lakes I. Kleiner Arbersee]. *Rozpravy České Akademie Císaře Františka Josefa pro Vědy, Slovesnost a Umění, tř. II*, 23 (9): 1–25 (in Czech).
Švambera V., 1914a: Šumavská jezera II. Velké Javorské jezero [The Bohemian Forest lakes II. Großer Arbersee]. *Rozpravy České Akademie Císaře Františka Josefa pro Vědy, Slovesnost a Umění, tř. II*, 23 (16): 1–19 (in Czech).
Švambera V., 1914b: Šumavská jezera III. Prášilské jezero [The Bohemian Forest lakes III. Prášilské Lake]. *Rozpravy České Akademie Císaře Františka Josefa pro Vědy, Slovesnost a Umění, tř. II*, 23 (16): 1–19 (in Czech).
Švambera V., 1914c: Šumavská jezera IV. Laka [The Bohemian Forest lakes IV. Laka Lake]. *Rozpravy České Akademie Císaře Františka Josefa pro Vědy, Slovesnost a Umění, tř. II*, 23 (20): 1–8 (in Czech).
Švambera V., 1939: Jezera na české straně Šumavy [Lakes on the Czech side of the Bohemian Forest]. *Sborník České Společnosti Zeměpisné*, 45: 15–23. (in Czech).
Vránek T., 1999: Plešné jezero [Plešné Lake]. Ms., diploma thesis, Charles University, Prague, 96 pp. (in Czech). (Geographical library of the Faculty of Science, Charles University, Prague)
Wagner P., 1897: *Die Seen des Böhmerwaldes* [*Lakes of the Bohemian Forest*]. Duncker und Humbolt, Leipzig, 54 pp. (in German).
Wetzel R.G., 2001: *Limnology. Lake and River Ecosystems. Third Edition.* Academic Press, Elsevier Science (USA), San Diego, 1006 pp.
Zbořil A., 1994: Prášilské jezero [Prášilské Lake]. Ms., diploma thesis, Charles University, Prague, 94 pp. (in Czech). (Geographical library of the Faculty of Science, Charles University, Prague)

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Appendix 1. Recent (August 2016) aerial photographs of glacial lakes in the Bohemian Forest by Petr Znachor (Biology Centre CAS, České Budějovice).

Fig. 11. Černé Lake.

Fig. 12. Čertovo Lake.

Fig. 13. Plešné Lake.

Fig. 14. Prášilské Lake.

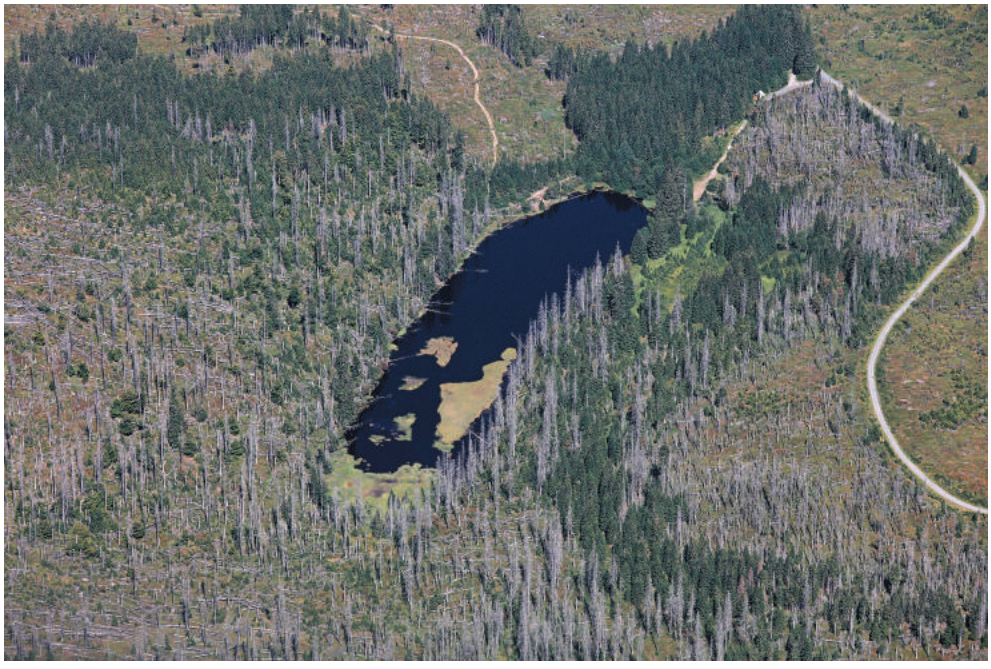

Fig. 15. Laka Lake.

Fig. 16. Rachelsee.

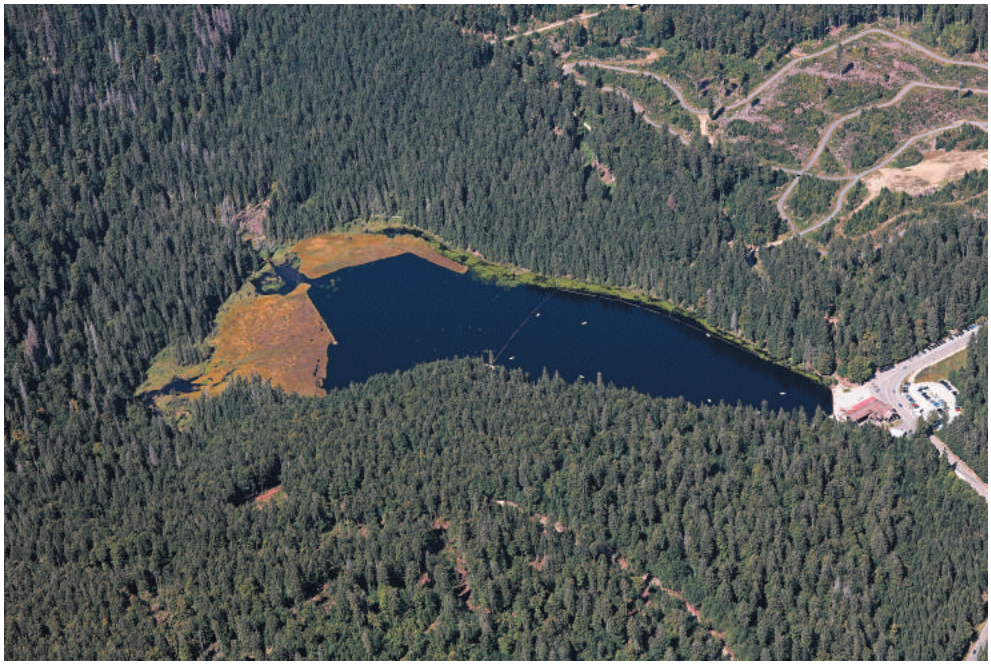

Fig. 17. Großer Arbersee.

Fig. 18. Kleiner Arbersee.