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The use of sonar data for mapping the muddy bottom of water reservoir

Abstract. The goal of the work was to find a method to determine the structure of the subsurface of the bottom of a water reservoir with relatively soft ooze-muddy sediments using the recorded parameters of the first and second sonar echoes. This would allow avoiding the use of expensive devices such as sub-bottom profilers.

Sonar measurements were taken on the entire lake commencing from the depth accessible to the measuring boat with outboard transducers. The sonar screen image and the first and second echo parameters were recorded and used according to the RoxAnn method. In order to verify and extend the scope of the sonar data, measurements of the bottom depth and hardness were made using a pole at 40 control points located along five cross sections.

Finally achieved numerical models of sediment structures under the bottom surface of the water reservoir for three reference surfaces: depths for initial top surface of the colloidal state (ooze) layer, top surface of dense muddy bottom and surface of solid bottom under muddy layer. Each of them was obtained by two independent methods, in which the input data was the depth measured by the sonar for the initial top surface of the colloidal state layer or roughness of the first echo.

The volume between the numerical surfaces for the colloidal state layer, which is important for environmental protection purposes, was calculated using three different methods. The results were very similar. The difference of volume was within 1.7–5.7%. Each of the method of measuring any layer volume using a single beam echo sounder / sonar can be used to assess the scope of work and the costs of required restoration measures or water reservoir by removal of colloid suspension layer. The advantage of the developed method is the possibility of performing the work using a single beam echo sounder / sonar instead of an expensive sub-bottom profiler.

Keywords: mapping of bottom, colloid suspension layer, muddy reservoir, restoration of muddy reservoir, Digital Terrain Model

Acronyms

- D_0 – base of depths equal zero meters, surface of reservoir [m]
- D_1 – depth of water column measured by the sonar [m]
- D_2 – depth, at which the existence of ground resistance was first observed by measure pole [m]
- D_3 – depth, at which the limit of the possibility of further driving the measuring stick into the bottom of the water reservoir was observed [m]
- d_s – distance to closest shoreline [m]
- E_1 – power of initial part of the first reflected echo
- E_2 – total power of the second echo
- H_a – height of *Myriophyllum* algae [cm]
- N_e – number of echoes reflected from bottom and registered by the sonar
- p – statistical significance
- PV – peak value of first echo
- r_s – correlation coefficient
- R^2 – coefficient of determination

1. Introduction

The mapping of muddy bottom of water reservoirs is important for at least few reasons. Some of them are related to navigation. At first, it is important to know type of bottom for anchor ships, it means some types of bottom are good or bad holding ground and it is used in academic clarification (Driemljung, 1974; Nowicki, 1978; Pastusiak, 1985). It is especially important during stormy weather due to risk of drifting ship to the bank. Secondly, there is fluid-mud or ooze (colloid suspension) on the bottom of navigational channels in many parts of the world where ships elbow in between it. In fact, ships are navigating inside the river or sea bed. Long time ago, the manual lead line sounders were used and the depth recorded was the solid bottom layer. The overlying fluid-mud or ooze (colloid suspension) layer was not usually detected. In modern times the echo sounders shown the top of colloid suspension layer as the river or water reservoir bottom. Due to it there is difficult to define navigational depth for ships (PIANC, 1983). The lack of clear definition of water-mud interface can cause unnecessary depth restriction and possibly excessive dredging. The depth recorded was to fairly solid bottom and any overlying mud layer was not usually detected. When echo sounders were introduced, the water-mud interface was not always clearly defined. The interface shown on the records may depend on the instrument used and the frequency employed.

Knowledge of a depth of the top of colloid, soft and solid level of a bottom is useful for calculating volumes of particular layers of water and bottom (Kistowski, 1996). It is important information for restoration of water reservoirs (Kowalczewska-Madura et al., 2024). Especially when they are polluted and is necessary take protective and restoration measures by removal of colloid suspension layer. It can be used also to design foundations of hydrotechnical structures such as piers and artificial islands.

Normally, sonars (echo sounders) are used to measure a surface of the bottom of a water reservoir (sea, lagoon, lake, river, etc.). Such devices operate at frequencies of 25–200 kHz. On other hand, to study a structure of the bottom deeper, below a bottom surface, devices such as sub-bottom profiler or parameter echo sounder are used (Grelowska & Kozaczka, 2014; Kozaczka et al., 2013; Papenmeier & Hass, 2018). This device operates at lower frequencies than sonar, specifically below 15 kHz. Examples of applications of the sub-bottom profiler include mapping (cartography) of a sediment cross-section and estimating a volume of sediments (Wunderlich & Wendt, 2001). It has been pointed out that sub-bottom profiler (parametric echo sounder) measuring devices are very expensive and may be useless on small depth water reservoirs like small lagoons, rivers and lakes. In this work, an attempt was made to determine a structure of a subsurface bottom of a water reservoir with relatively soft ooze-muddy sediments using the recorded parameters of the first and second sonar echoes. Such parameters are used in the RoxAnn method (Humborstad et al., 2004; Papenmeier & Hass, 2018; Poulain et al., 2010; Tseng, 2009; Wilson et al., 2006).

For this purpose, a small lake with an area of 28,860 sq. meters located in the northern part of Poland was examined in the period of time from 9 August, 2016 till 11 September, 2016. The north-eastern part of the lake was surrounded by high hills covered with tall trees, which significantly limited access to the lake for sunlight. This part of the lake had relatively large depths and a very extensive area of deep central part, with depths of up to 2.4 meters, measured by the sonar (Figure 1). The southwestern part of the lake was surrounded by flat marshy areas covered with relatively low trees. Hence, the southwestern part of the lake was better exposed to the sun. This part of the lake was shallow. Depths did not exceed 1.2 meters. The southern shore of the lake was surrounded by a marshy zone. Analysis of the bottom slope showed only two main directions: north-west and south-east, with a clearly defined demarcation line (Figure 1). The colour scales of the data presented on Figure 1 and also on Figures 2, 3, 4, 5 and 9 are not representing scientific colour tables. There are used more intuitive colour tables for non-scientific readers. In this specific case, the author followed the rule offered by Spreen et al. (2008) for the ice concentration maps.

2. Research method

When undertaking the previously defined research goal, it was assumed that an accuracy

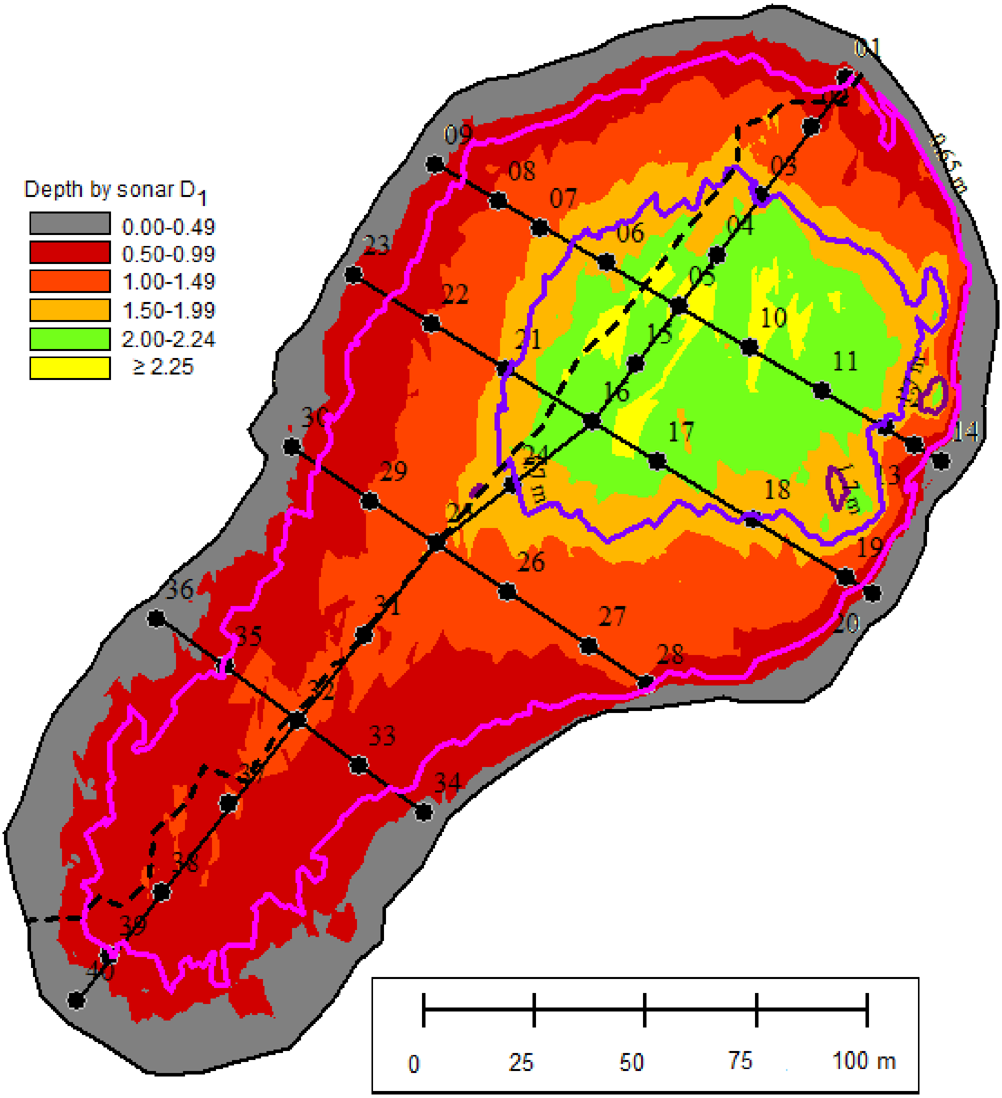

Figure 1. Bathymetry of the basin, solid line – profile, black dot reference point, magenta line – thermocline in August, rose line – thermocline in September, dash line – demarcation line in between direction of slope

of reflecting the studied reality increases with the number of variables taken into account, i.e. information layers. So the author will strive to obtain an image of the phenomenon being studied using as many variables (input data) as possible, i.e. to develop a multi-variable function (Peterka et al., 2018). It should be emphasized that this is not a multi-criteria analysis method (Dean, 2022). The previously mentioned RoxAnn method consists in using information about two variables recorded automatically by a sonar and is used to determine a nature of a bottom, a grain size of a bottom sediments and an occurrence of algae based only on a hardness E_2 and roughness E_1 of a bottom of a water reservoir (Humborstad et al., 2004; Papenmeier & Hass, 2018; Poulain et al., 2010; Tseng, 2009; Wilson et al., 2006). Information about factors E_1 and E_2 is included in a log of individual echo sounder / sonar pings. For example, fluidized mud (soft ooze) and mud are characterized by a very low value of hardness E_2 and a very low value of roughness E_1. On other hand, uniform rock is characterized by a very high value of hardness E_2 and a very high value of roughness E_1.

It was initially assumed that all information layers available through automatic sonar recording and manual recording of data obtained on the basis of an image of a vertical cross-section of a water column would be used for the research. An image of a water column is saved in a form of a classic single-beam echo sounder image and, for example, in a form of DownView Imaging along with position coordinates of received data.

The information layers recorded automatically by the sonar could be analysed in the full scope of the database according to the RoxAnn method. Sonars and transducers currently available on the market can automatically record three layers of information: a power of the initial part of a first echo E_1 returning from a bottom of a reservoir, a peak power PV of a first echo, and a total power of a second echo E_2 returning from the bottom of a reservoir, i.e. a signal that was reflected from a bottom of a reservoir, then reflected from a water surface of a reservoir, and then reflected from a bottom of a reservoir again to reach and be received by a sonar transducer. Factor E_1 is identified with a roughness of a bottom of a reservoir. Factor E_2 is identified with a hardness of a bottom of a reservoir. Factor PV is identified with a hardness of a bottom of a reservoir. Factor PV is sometimes used instead of factor E_2 when a signal of a second echo looks to be incorrectly recorded.

The remaining parameters, apart from the above-mentioned ones recorded automatically by the sonar factors E_1, E_2 and PV, could be analysed to a limited extent due to the time-consuming nature of manual data processing. The subsequent information layers included: height of algae H_a, number of echoes N_e reflected from the bottom of the reservoir and distance to the closest shoreline d_s. Next, the bottom depths for initial top of the colloidal state (ooze) layer D_1, top of dense muddy bottom D_2 and solid bottom D_3 under muddy layer as well as the thicknesses and hardness of colloidal-ooze and muddy layers of the bottom of the reservoir should be collected manually with the pole. The purpose of measuring the depth and hardness of the bottom using a pole was to verify the data obtained from the sonar measurements with reality for the designated 40 points located in characteristic places of the longitudinal and cross sections of the water reservoir (Figure 1). It was decided to include additional information layers regarding depth (shallow water and deep water), directions of bottom slope, shape and depth of the reservoir (wide part and narrow part), influence of sunlight (geographic directions) and the reservoir surroundings (height of trees growing along the shoreline. This required dividing the reservoir into 4 parts analysed in nine combinations (whole reservoir and its parts – NE, SW, NW, SE, N, E, S and W). A total of 17 information layers were designated.

3. Measurement equipment

Measurements were taken on the entire lake commencing from the depth available to the measuring boat with outboard transducers. The limitation was a minimum depth of 0.3 meters. Initial measurements were made using two side scan sonars: Lowrance HDS5 and Lowrance ELITE-5Ti with Chirp and DownScan Imaging functions. The Lowrance HDS5 sonar could use several transducers: HST-WSBL for shallow depths at 83 and 200 kHz, HST-DFSBL for deep depths at 50 and 200 kHz, AIRMAR TM 260-BL for very deep depths with 1 kW power at 50 and 200 kHz and StructureScan LSS-1 side scan transducer at 455 and 800 kHz. The Lowrance ELITE-5Ti side scan sonar could use a little other set of transducers plus Chirp with DownScan Imaging functions: HST-WSBL for shallow depths at 83 and 200 kHz, HST-DFSBL for deep depths at 50 and 200 kHz, AIRMAR TM 260-BL for very deep depths with 1 kW power at 50 and 200 kHz and TOTALSCAN side sonar transducer with Chirp function at 455 and 800 kHz. Side sonars records served for identification of shore line of the reservoir and possible existence of artefacts or dangers at the beginning of survey. It was practiced by the author before various works (Błaszczyk et al., 2021; Pastusiak, 2011, 2012, 2016, 2020).

Total of 21,858 pings were recorded. The measured depth D_1 of the lake was no more than 2.4 meters. The AIRMAR TM 260-BL 1 kW transducer recorded the bottom deeper than 1 meter and the HST-DFSBL deep transducer recorded the bottom deeper than 2 meters. The measurements recorded with both of the above devices were rejected. Finally, the measurements recorded for the sonar Lowrance ELITE-5Ti for shallow depths at the working frequency of 200 kHz (7,559 pings) and TOTALSCAN side sonar transducer with Chirp function at 800 kHz with DownScan Imaging function were selected. From this list, pings indicating unreliable, much greater depths were removed. At the end, 7,528 pings were used for further analysis. In case ping depth was incorrect due to any reason, it was amended according to sonar screen image of water column (Pastusiak, 2020). The above data were automatically saved by the sonar to files. Additionally, based on the image of the depth cross-section on the sonar screen, 492 points were manually saved for the number of echoes returned and 801 points for the height of *Myriophyllum* algae.

In order to verify the data recorded by the sonar, 40 control points located along the

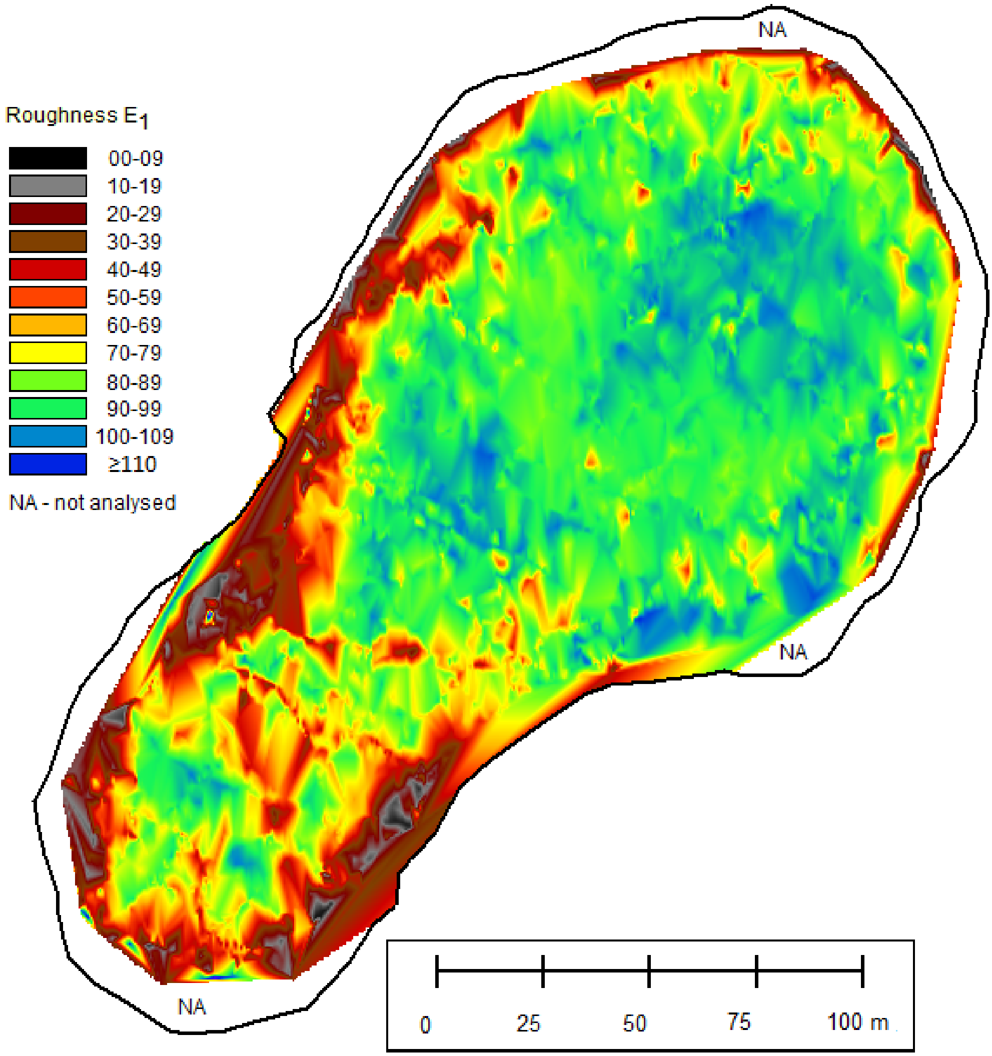

Figure 2. Geographic distribution of roughness E_1

cross sections were established (Figure 1). These were one cross section along the lake and four across it. At the control points, measurements of the depth and hardness of the bottom were taken using the 3-meter pole (pipe). For measurements of water column temperature the Yellow Springs YSI Model 33 S-C-T Meter was used.

4. Results of sonar measurements

4.1. Roughness E_1

The maximum of roughness E_1 value occurred in the entire lake area, and more precisely in the central north-eastern part of the lake. It surrounded the area defined by hardness measurements with a pole as an "absence of the second and third bottom" up to depth of 3 meters (for depths measured with a sonar of 1.7–2.4 meters) or as a "barely perceptible" second bottom (for depths measured with an sonar of 1.0–2.2 meters, Figure 2). The reservoir was overgrown with algae in the water column range from the bottom of the reservoir to 0.2 meters from the water surface. In this reservoir there were point objects identified on the sonar image and being algae along with a large number of air bubbles (indicating high production of plant mass).

In the southwestern part of the lake, the maximum of roughness E_1 value occurred in most of the central part of the lake. The greatest depths in this part of the lake occurred there and were over 0.7–1.1 meters. The bottom hardness measurement using the pole showed a very poorly perceptible second bottom. The column of water was overgrown with algae in the water column range from the bottom of the body of water to 0.2 meters below the water surface (normally indicating high production of plant mass).

The minimum of roughness E_1 value occurred exactly in the western part of the lake in the shallow water area in the strip with depths of 0.4–0.6 meters (Figure 2). There was usually an increase in the depth gradient (coastal slope). There were no algae in this water area (no plant production). The bottom hardness estimated by means of pole measurements showed for the second bottom "moderately hard" and for the third bottom "hard", and descriptively "sandy, some mud". In the water area with the minimum of roughness E_1 value the difference in depth of the first and second bottom was usually 0.3 meters and the difference in depth between the first and third bottom was 1.0 meter.

4.2. Hardness E_2

The maximum of hardness E_2 value occurred in the southwestern part of the north-eastern part of the lake at depths of 0.8–1.2 meters (Figure 3). The bottom hardness estimated by means of the pole measurements showed a "barely perceptible" second bottom and a "soft" third bottom. The area was characterized by a gentle and even increase in depth (constant depth gradient). It was outside the zone of a "no second bottom" or "no third bottom" up to 3 meters deep, as determined by the pole measurements, with depths determined by the sonar greater than 1.7 meters. So the difference between the first and second and third bottoms was clearly greater than 1.3 meters. This area was covered with algae. There were no point objects identified on the sonar image and being algae along with a large number of air bubbles (that normally suggesting high plant mass production).

The maximum of hardness E_2 value then occurred in the narrow transverse strip at the beginning of the narrower part of the lake at depths of 0.8–1.1 meters. This strip separated the north-eastern, deeper part of the lake from the southwestern shallow part of the lake. The maximum of hardness E_2 value also occurred in several smaller areas in the south-western part of the lake at depths of 0.7–1.0 meters. In these places, pings with high E_1 and E_2 values were located. In the southwestern part of the lake, vascular and non-vascular algae occurred, with a predominance of non-vascular algae.

With the exception of the northern part of the lake, the maximum of hardness E_2 value occurred also at the smallest areas with depths of 0.4–0.6 meters. In these places, there were no vascular algae. Visual observations indicated the occurrence of a hard sandy-pebble or peaty second or third bottom. In such places, the second or third bottom was usually 0.0–0.1 meters deeper than the first bottom detected by the sonar.

The bottom hardness estimated by means of the pole measurements for the second or

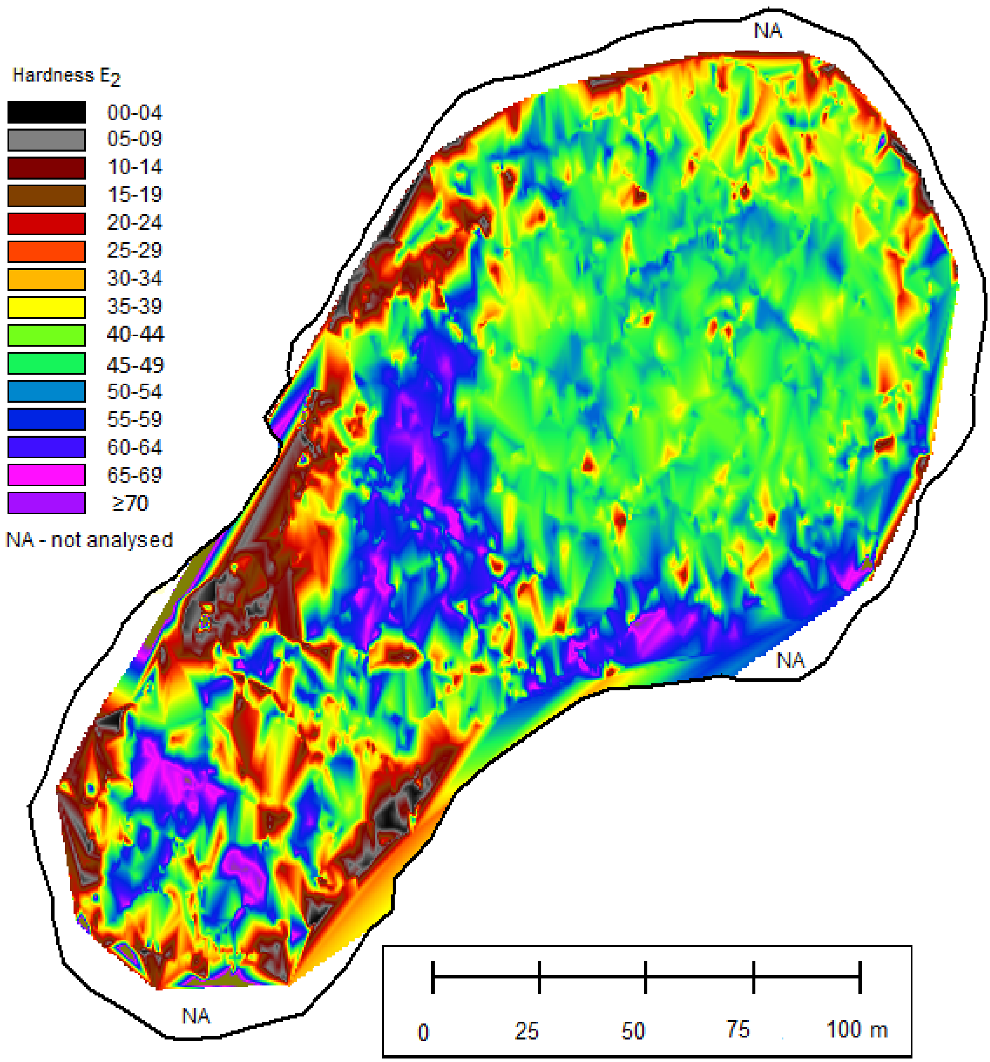

Figure 3. Geographic distribution of hardness E_2

third bottom usually showed a poorly recognizable bottom boundary – "something to feel" for the second bottom and "soft" for the third bottom. In the water area where the maximum of hardness E_2 value occurred, the difference in depth of the first and second bottom was usually 1.1 meters and the difference in depth between the first and third bottom was usually 1.9 meters.

The minimum of hardness E_2 value occurred along the shore except only in the south-western part of the north-eastern part of the lake (Figure 3). Depths of 0.35–0.6 meters occurred there. There were no vascular algae. In three other places, including the strip separating the deeper part of the lake from the shallow part of the lake, depths were 0.7–1.2 meters. The bottom hardness estimated by means of pole measurements showed for the second or third bottom usually a clearly recognizable bottom boundary – "hard" or "soft". In the minimal of hardness E_2 area the difference in depth of the first and second bottom was usually 0.9 meters and the difference in depth between the first and third bottom was 2.3 meters.

Visual observations showed that higher hardness E_2 values corresponded to higher value of height of algae (mainly vascular), eutrophication, hard sandy, stony or peaty sediment (remains of undecomposed plant parts such as leaves, needles, cones). However, these results were not always completely consistent.

4.3. Peak value of first echo *PV*

The maximum of peak value *PV* of the first echo occurred along the shore in the western part of the north-eastern part of the lake and also occupied most of the south-western part of the lake at shallow depths of 0.5–1.0 meters (Figure 4). In this water area, very high and high values of roughness E_1 and hardness E_2 were most common. The peak value *PV* of the

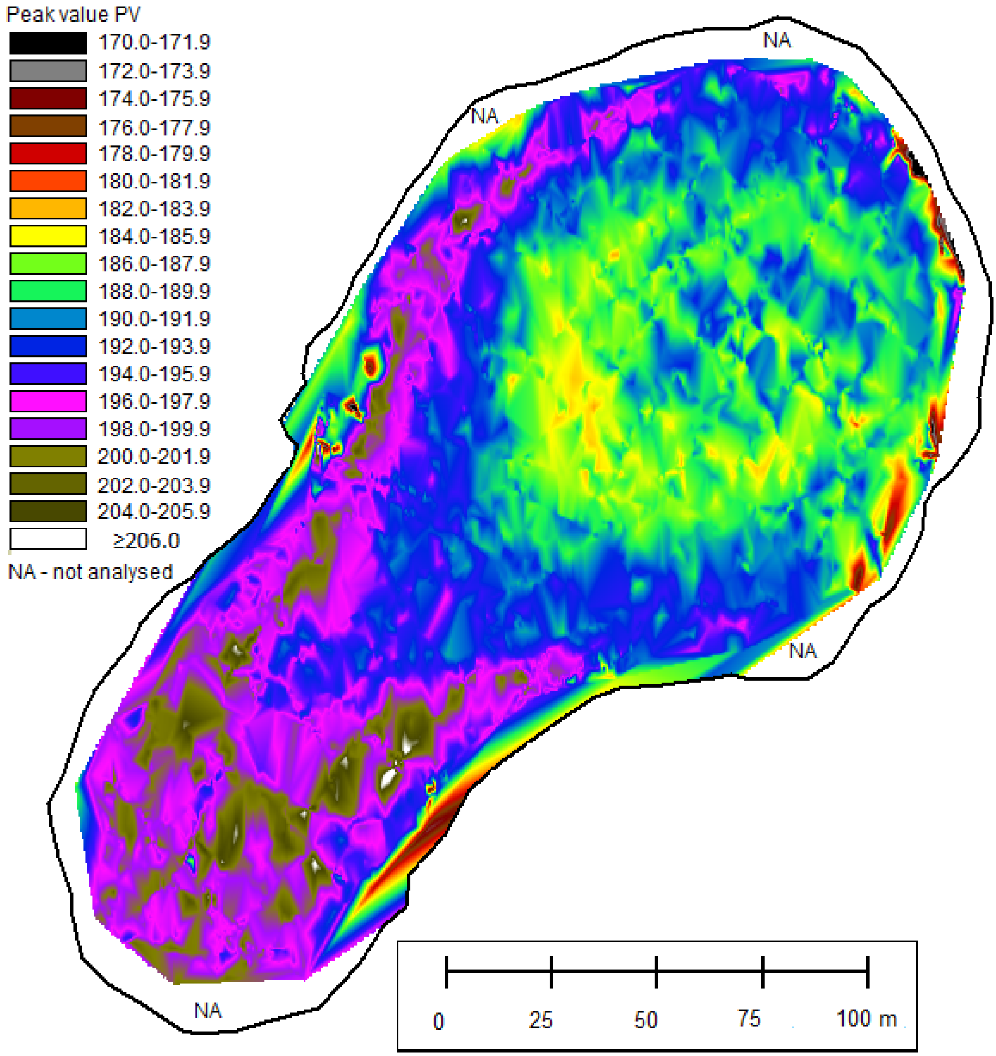

Figure 4. Geographic distribution of peak value *PV*

first echo was outside the zone of “barely perceptible second bottom” and outside the zone of “no second and third bottom” till 3 meters depth, determined by means of the pole measurements. The depths determined by the sonar were at least 1.7 meters in this area. The shape of the bottom was very variable in places. In this part of the lake, the occurrence of vascular and non-vascular algae usually ended. Bottom hardness measurements taken with the pole showed from “barely perceptible” to “soft” for the second bottom and “soft” for the third bottom. The depth difference between the first and second bottom was usually 0.9 meters and the depth difference between the first and third bottom was 2.2 meters.

The minimal peak value *PV* of the first echo occurred sporadically along the shore in several places at the smallest depths studied of 0.35–1.0 meters (Figure 4). It did not occur in the western part of the southwestern part of the lake. Based on visual observations, the bottom was defined as hard “sand” or “sand with pebbles”. In the area of occurrence of the minimal peak value *PV* the difference in depth of the first and second bottom was usually 0.3 meters and the difference in depth between the first and third bottom was 0.5 meters. In these parts of the lake, there were no vascular or non-vascular algae.

4.4. Hardness of bottom based on measure pole

The purpose of measuring the depth and hardness of the bottom using the pole was to verify the data obtained from the sonar measurements with reality for the designated 40 points located in characteristic places of the longitudinal and cross sections of the water reservoir (Figure 1).

The scale of hardness of bottom based on the measure stick illustrated the subjective feeling of the hardness of the bottom and the depth of its detection (Table 1). It can be compared to the compactness of the ground or the density of the ground at the place and depth of the measurement. A uniform scale of ground hardness was used for the depth D_2, at which the existence of ground resistance was first observed, and for the depth D_3, at which the limit of the possibility of further driving the measuring stick into the bottom of the water reservoir was observed.

Table 1. Scale of hardness of bottom based on measure stick

Subjective feeling	Digital value assigned
Lack of sensation	0
Very soft (barely perceptible, something to feel)	1
Soft	2
Relatively hard	3
Hard (this feeling is accompanied by organoleptic or visual detection of sand, gravel, pebbles, peat, organic residues with silt or clay)	4

4.5. Height of algae H_a

No algae were found along the shoreline at depths of less than 0.6–0.8 meters in the south-western part and at depths of less than 0.6–1.2 meters in the north-eastern part of the lake (Figure 5). At a greater distance from the shoreline, no algae were found in the south-western part, where depths were 0.8–0.9 meters.

The greatest height of algae of 60–80 centimeters in the southwestern shallow-water part of the lake was found along the lake axis, where the greatest depths occur in the range of 0.8–1.2 meters. In the western part of the north-eastern part of the lake, the greatest height of algae occurred at depths of 0.9–2.2 meters. In the southern part of the north-eastern part of the lake, the greatest height of algae occurred at depths of 1.0–1.8 meters. In the central, western and southern deep parts of the north-eastern part of the lake, algae mostly reached a height of 20–40 centimetres.

A high coefficient of determination R^2 (0.98) was observed for the dependence of algae height H_a on depth D_1 for the entire lake. The greatest height of algae occurred at depths of 1.34 meters (Figure 6). The geographical distribution of the greatest height of algae (Figure 5) was consistent with the distribution of the depth of the D_1 (Figure 1). At the same time, an inverse proportionality of the relationship in

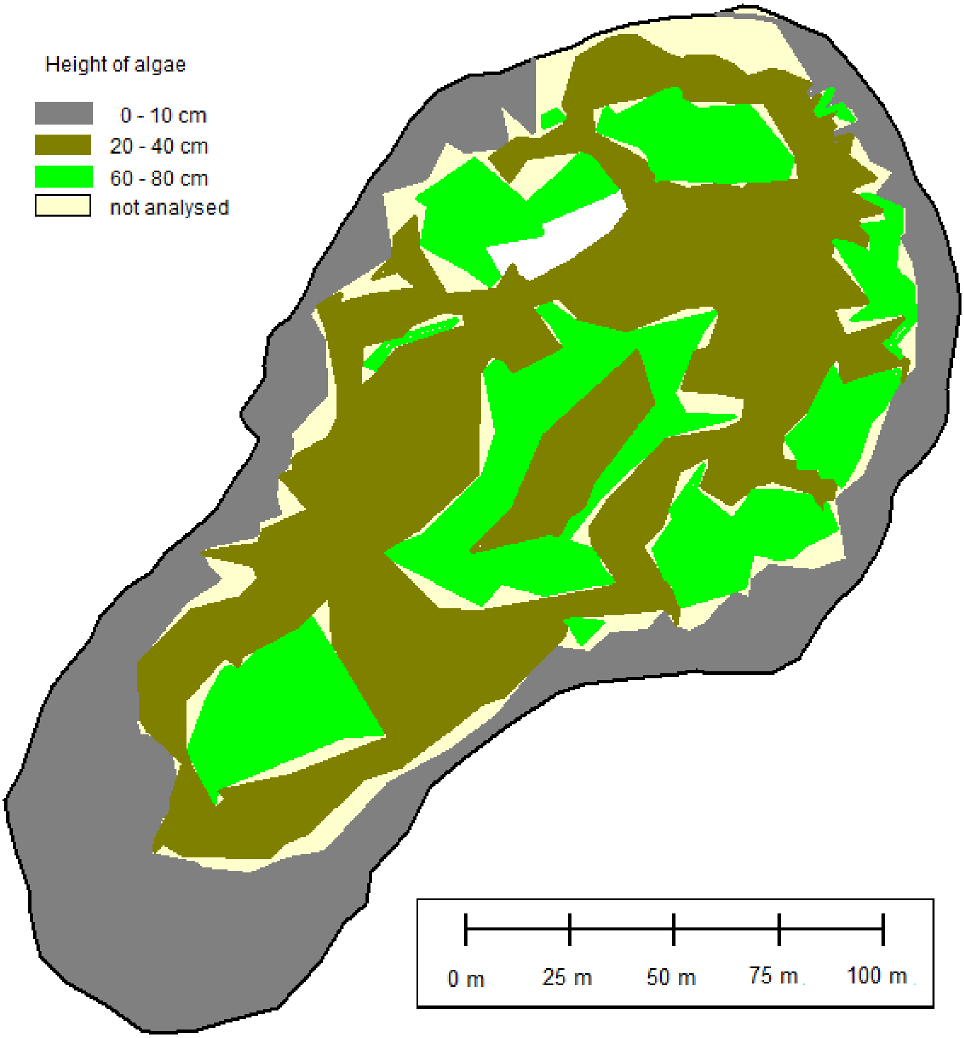

Figure 5. Geographic distribution of algae height H_a

between hardness of bottom on depth D_2 (density of sediment) measured by stick and height of algae H_a in the whole basin was observed (Figure 7) with the coefficient of determination R^2 equal to 0.45.

4.6. Number of echoes reflected from the bottom of the lake

The number of echoes reflected from the bottom of the water body was determined for the sharp edge of the boundary of the deepest subsequent echo. In the case where the line of occurrence of the deepest echo was blurred but continuous – half of the total value was added to the number of echoes. Sample of this interpretation presented on Figure 8.

The smallest number of N_e echoes reflected from the bottom (1 echo) occurred mostly in the southwestern shallow part of the lake at depths of 0.4–1.3 meters (Figure 9). However, it did not occur in the south-eastern part of the

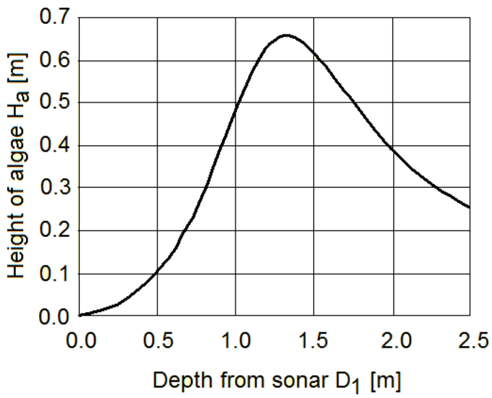

Figure 6. Relationship between depth by sonar D_1 and height of algae H_a in the whole reservoir

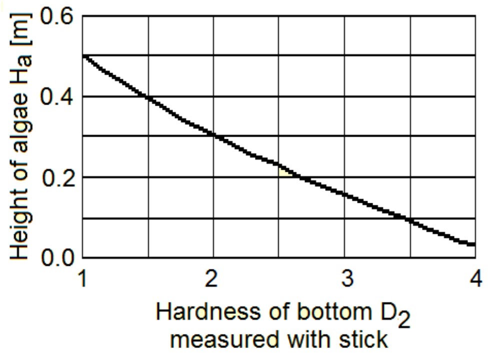

Figure 7. Relationship between hardness of bottom measured with stick on depth D_2 (like density of sediment) measured by stick and height of algae H_a in the whole reservoir

southwestern part of the lake. The low number of echoes area (1.0–1.5 echoes) in the south-western shallow part of the lake was found throughout the southwestern shallow part of the lake except for the south-eastern part at depths of 0.4–1.3 meters. In the north-eastern deep part of the lake, the low number of echoes area (1.0–1.5 echoes) covered most of the southern, western and north-western parts of

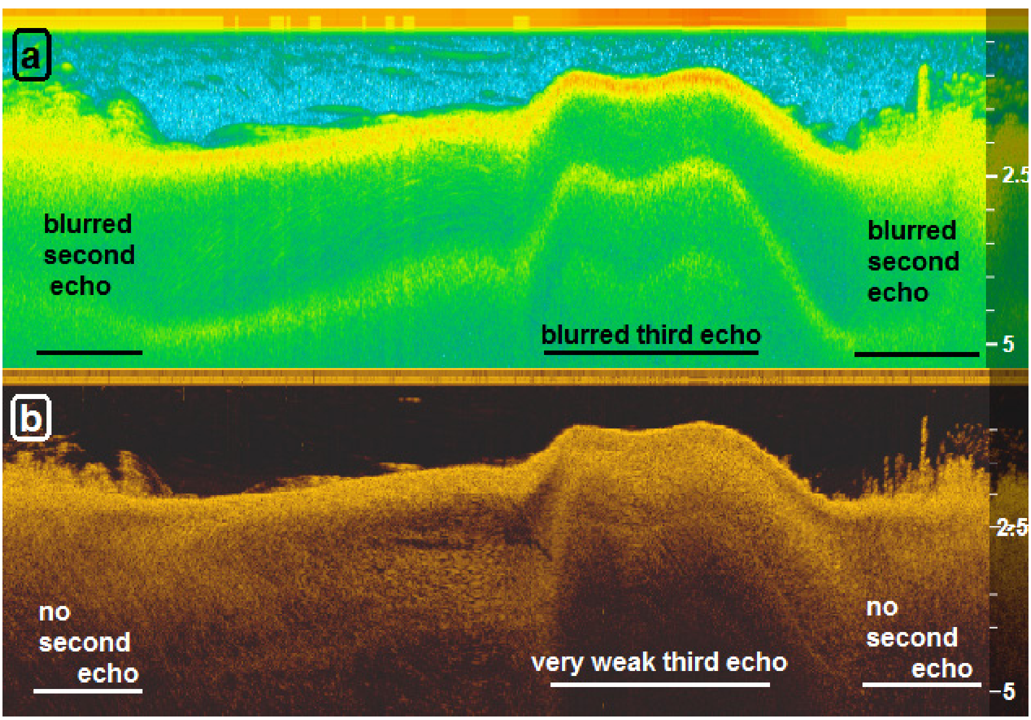

Figure 8. Interpretation of number of echoes on sonar screen: a – standard echo sounder presentation; b – sonar DownVue Imaging

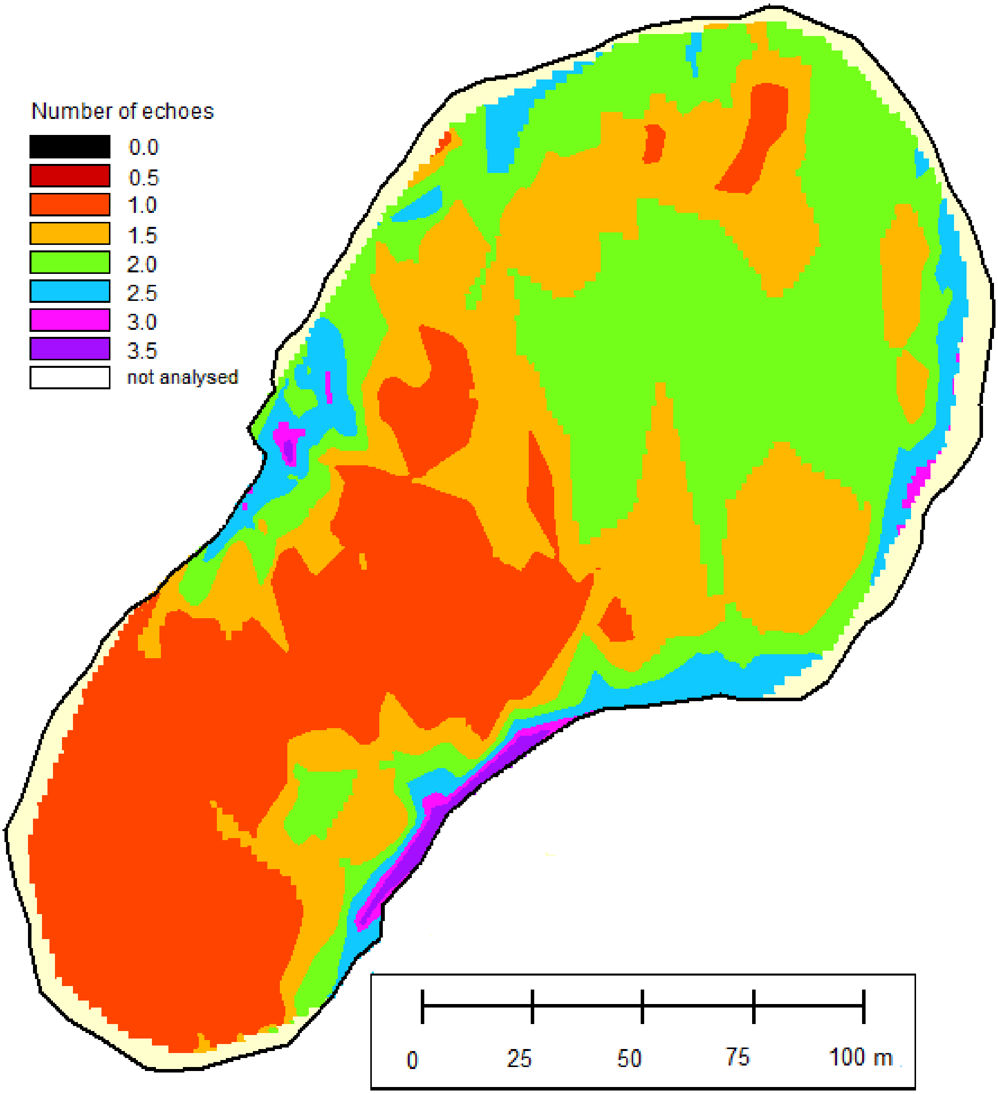

Figure 9. Geographical distribution of number of sonar echoes N_e

the lake at depths of 0.7–2.0 meters. The low number of echoes area did not occur at great depths or in the eastern part of the north-eastern part of the lake.

In the central, deep part of the north-eastern part of the lake, two echoes occurred at depths of 0.4–2.5 meters. A larger number of echoes (2.5–3.5 echoes) occurred along the shoreline at depths of no more than 1.4 meters. The number of 3 echoes occurred at depths of up to 1.3 meters, but mostly till 0.7 meters. Areas of 3.5 echoes occurred at depths of up to 0.5 meters. At the same time, an inversely proportional relationship was observed between the number of echoes N_e and the total thickness of the soft bottom layer in the whole basin ($D_3 – D_1$) with a coefficient of determination R^2 equal to 0.33 (Figure 10).

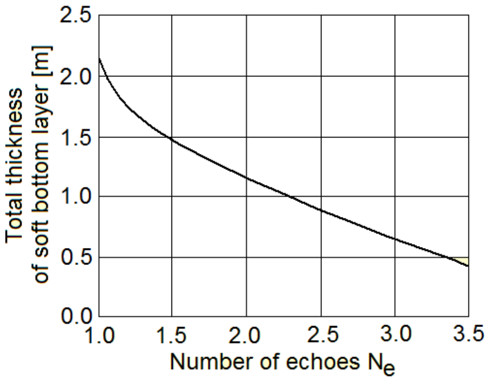

Figure 10. Relationship between number of echoes N_e and total thickness of soft bottom layer in the whole reservoir

4.7. Analysis of thermocline

The sonar screen images showed a thermocline of 17°C. The thermocline at a depth of 1.7 meters occurred on August 9, 2016. This was the peak summer day characterized by the highest air temperatures. The water temperature at the lake surface was 24°C. It decreased with depth to reach 17°C at the thermocline. Below the thermocline, the temperature did not change. The second time the thermocline occurred at a depth of 0.65 meters. It was on September 11, 2016, when the air temperatures were much lower, autumnal. The position of the thermoclines indicated the depth of the Epilimnion, which is the uppermost and warmest layer of a lake. It serves for safe swimming in the summer. Below thermocline temperatures rapidly cool down and may be dangerous for swimmers. The position of both thermoclines was plotted on the depth map of the reservoir (Figure 1). For comparison with the depth of the measured thermoclines, the depth of surface water mixing (Epimillion) in August was calculated using Equation 1 (Czerwińska, 1975).

$$E = 4.4 \cdot \sqrt{L} \qquad (1)$$

where:
E – depth of Epimilion [m],
L – length of the wind run-up [km].

The calculations assumed the observed division of the lake into NE and SW where at traverse of the lake in between control points 25 and 31 (Figure 1) the wind directions changed to opposite ones. The calculations gave a depth of Epimilion equal to 1.76 m (NE) and 1.55 m (SW). These calculated results, especially for NE part of the lake, were very close to measured values in September 2016. Based on the consistency between the measured and calculated thermocline depths, it was assumed that the surveyed reservoir should well reflect the phenomena occurring also in larger water reservoirs.

5. Statistical results of relationships between parameters of sonar echoes

The coefficient of determination R^2 was determined for simple formulas only. It was noted that for polynominal functions the values of determination coefficient R^2 were higher for 0.15. Another functions were not considered due to more complicated shape of approximation line or surface. Most relationships were statistically significant (number of samples were from minimal 993 for the single part of the lake to 7,528 for the whole lake). The approximation line courses indicated no relationship between D_1, E_1, E_2 and PV. The PV parameter maintained no significant changes with changes in the values of D_1, E_1 or E_2. There was a noticeable relationship between changes in the values of E_1 and E_2 with changes in the depth D_1. For the relationship between E_1 and D_1 the correlation coefficient r_s was from 0.44 to 0.68 (median equal 0.54) and the coefficient of determination R^2 from 0.27 to 0.61. For the relationship between E_2 and D_1 the correlation coefficient r_s was from 0.16 to 0.51 and the coefficient of determination from 0.28 to 0.35. The exception was NNE part of the lake where the correlation coefficient r_s and determination R^2 coefficient were very low and the results were statistically insignificant with 3405 samples. In both cases (D_1–E_1 and D_1–E_2) the values increased proportionally until reaching a maximum for the depth D_1 equal to 1.10 meters and then assumed slightly variable values with increasing depth. Statistical coefficients were very high only for relationships between E_2 and E_1 (correlation coefficient r_s from 0.73 to 0.97 and determination coefficient from 0.53 to 0.95).

6. Discussion of results for control points

For most analyses, the control points were used, where D_2 and D_3 results were obtained by means of the pole measurements. For these 27 points, statistical analysis of relationships between following 16 factors was performed: depth of water column measured by the sonar D_1, power of initial part of a first reflected echo E_1, total power of a second echo E_2, peak value of a first echo *PV*, number of echoes reflected from a bottom and registered by the sonar N_e, height of *Myriophyllum* algae H_a, distance to closest shoreline d_s, hardness of higher part of soft bottom layer by the stick, thickness of higher part of soft bottom layer by the stick (D_2–D_1), depth, at which the existence of ground resistance was first observed by measure the pole D_2, depth, at which the limit of the possibility of further driving the measuring stick into the bottom of the water reservoir was observed D_3, hardness of lower part of soft bottom layer by the stick, thickness of lower part of soft bottom layer by the stick, average hardness of both layers, total thickness of soft bottom layer (D_3–D_2) and average hardness multiplied by total thickness of soft and hard bottom layer (D_3–D_1). The number of samples for the whole lake and its parts was presented in Table 2.

The best results in all areas were obtained by the E_1–E_2 relationship, where the correlation coefficient r_s for the whole lake and its four halves was 0.76-0.91 and was statistically significant. For the lake quarters, the correlation coefficient r_s was 0.73–0.95 and was statistically insignificant only for part E (9 samples) and part W (6 samples).

Good statistical results were obtained for the relationships between N_e, H_a, d_s, hardness of higher and lower soft bottom layers, D_2 and D_3, where the median absolute value of the correlation coefficient r_s was 0.71 and the criterion of statistical significance ($p<0.001$) was met in 29 cases out of 108 analysed relationships. In the remaining cases, in most cases $p<0.01$. Comparable to the above were the results of the relationships between D_1 –D_2 and E_1–D_2. The median absolute value of the correlation coefficients r_s for the relationships D_1 and D_2 was 0.63 and the criterion of statistical significance ($p<0.001$) was met in three cases out of nine analysed relationships. The median absolute value of the correlation coefficients r_s for the relationships E_1 and D_2 was 0.68 and the criterion of statistical significance ($p<0.001$) was met in two cases out of nine analysed relationships.

Table 2. The number of available samples of measured data by pole for the whole lake and its parts

Part of lake	Whole lake	NE	SW	NW	SE	N	E	S	W
Number of samples	27	17	16	12	15	9	9	12	6

Worse statistical results were obtained for the dependencies between D_1–D_3, E_1–D_3, and D_1–E_1. The median absolute value of the correlation coefficients r_s for the dependencies D_1–D_3 was 0.37, where the criterion of statistical significance ($p<0.001$) was not met. Similarly, the median absolute value of the correlation coefficients r_s for the dependencies E_1–D_3 was 0.44, where the criterion of statistical significance ($p<0.001$) was also not met. The median absolute value of the correlation coefficients r_s for the D_1–E_1 dependence was 0.46, where the criterion of statistical significance ($p<0.001$) was also not met. The median correlation coefficients r_s between D_1–E_1 for the full data series was 0.54 and for the reduced series for control points only was 0.46. The results were therefore

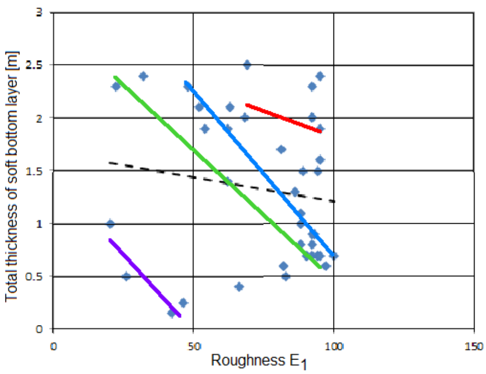

Figure 11. Relationships between roughness E_1 and total thickness of soft bottom layer: dash line – trendline for all control points, magenta line – control points adjacent to the shoreline, green line – control points moderately far from the shoreline, blue line – control points at the central part of the reservoir, mostly South from the slope demarcation line, red line – control points at the central part of the reservoir, mostly North from the slope demarcation line

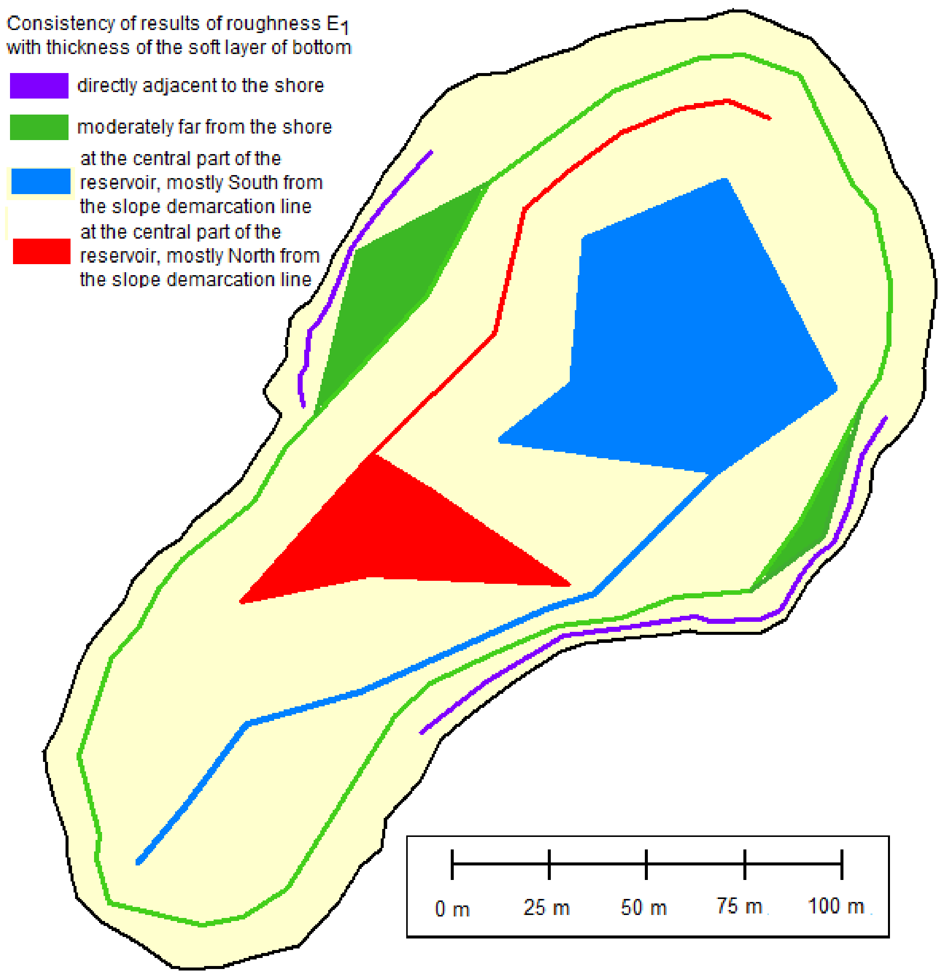

Figure 12. Geographical distribution of consistency between roughness E_1 and thickness of soft bottom layer

comparable and it can be assumed that they did not depend on the number of samples.

The 3-dimensional relationships for D_2 and D_3 that were dependent on D_1 and E_1 were also determined. The dependencies were approximated using a simple formula (without polynomial functions) where for D_2 the coefficient of determination R^2 was 0.59 and for D_3 it was 0.18. The 3-dimensional approximation for D_2 and D_3 dependent on H_a and d_s obtained using simple formulas (without polynomial functions) provided the coefficient of determination R^2 equal to 0.39 for D_1, 0.74 for D_2 and 0.73 for D_3. It follows from the above that the approximation of individual depths D_1, D_2 and D_3 using H_a and d_s provides much higher precision than using D_1 and E_1.

It was noted that the relationships analysed for 40 control points between depth D_1 and total thickness of soft bottom layer (Figure 11), roughness E_1 and total thickness of soft bottom layer (Figure 13), and depth D_3 and total thickness of soft bottom layer (Figure 15) have a low coefficient of determination. It was found that a much higher coefficient of determination occurs for these relationships after taking into account the distance from the coastline (Figures 11–16). For example, for the relationship

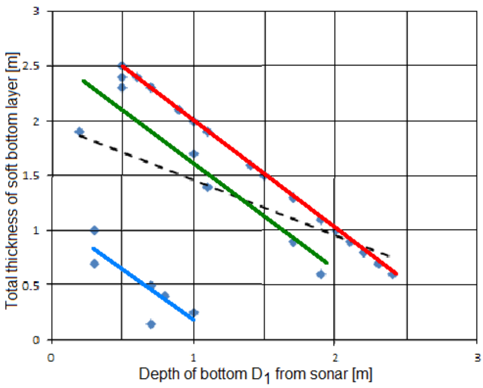

Figure 13. Relationships between depth of bottom from sonar D_1 and total thickness of soft bottom layer: dash line – trendline for all control points, blue line – trendline for control points close to shoreline, green line – trendline for control points away from shoreline, red line – trendline for most distant control points, close to the centre of the reservoir

E_1 with total thickness of the soft bottom layer for all samples, the coefficient of determination R^2 was 0.023 (dashed line in Figure 11). For the separated groups (Figure 12), the values reached were 0.64–0.82. Similarly, for the relationship D_1 with the total thickness of the soft bottom layer for all samples, the coefficient of determination was 0.24 (dashed line in Figure 13). For the separated groups (Figure 14), the values reached were 0.69–1.0. It follows from the above that taking into account a larger number of factors (driving factors), i.e. increasing the number of dimensions of the occurring relationships, increases the precision of the presented relationships, which is expressed by higher values of the determination coefficient R^2.

The relationships between D_1, D_2 and D_3 for the entire water reservoir (Figure 15) had low coefficients of determination (median 0.32). In case the area was divided into north-eastern and south-western part, and shallow-water and deep-water (Figure 16), the above relationships (Figures 17-20) obtain a much higher coefficient of determination (median 0.79). It follows from the above that taking into account a larger number of factors, i.e. increasing the number of dimensions of the occurring relationships, increases the precision of the results, which is expressed by higher values of the coefficient of determination R^2.

Statistical analysis shows that for determining depths D_2 and D_3 the most reliable are depths D_1, roughness E_1, distance to shoreline d_s and algae height H_a. However, only D_1 and E_1 can be recorded by sonar in an amount that ensures statistical significance ($p<0.001$, or $p<0.01$). Algae height H_a depends on the season and intensity of plant mass production, so this indicator will not be universal. Distance to shoreline d_s seems to be a property specific to individual water bodies. It was therefore also assumed that it will not be a universal indicator.

Taking the above into account, the depth D_1 and roughness E_1 were used for further studies. Data series for 27 or 40 measurement points were used. The approximated curves were determined for data pairs D_1–D_2, D_1–D_3,

Table 3. Volumes in between various surfaces numerical models of the reservoir

No.	Surfaces of numerical models	Total volume between surfaces [cubic meters]	Difference [%]
1	D_0, D_1 (from sonar)	31,817	2.9
2	D_0, D_1* (as function of E_1)	30,907	
3	D_0, D_2 (as function of D_1)	46,608	0.02
4	D_0, D_2 (as function of E_1)	46,597	
5	D_0, D_3 (as function of D_1)	69,061	6.3
6	D_0, D_3 (as function of E_1)	73,730	
7	D_1 (from sonar), D_2 (as function of D_1)	14,790	1.7–5 7
8	D_1 (from sonar), D_2 (as function of E_1)	15,046	
9	D_1* (as function of E_1), D_2 (as function of E_1)	15,691	
10	D_2 (as function of D_1), D_3 (as function of D_1)	24,022	11.5
11	D_2 (as function of E_1), D_3 (as function of E_1)	27,133	

* values of D_1 based on E_1 values were calculated for all (40) control points

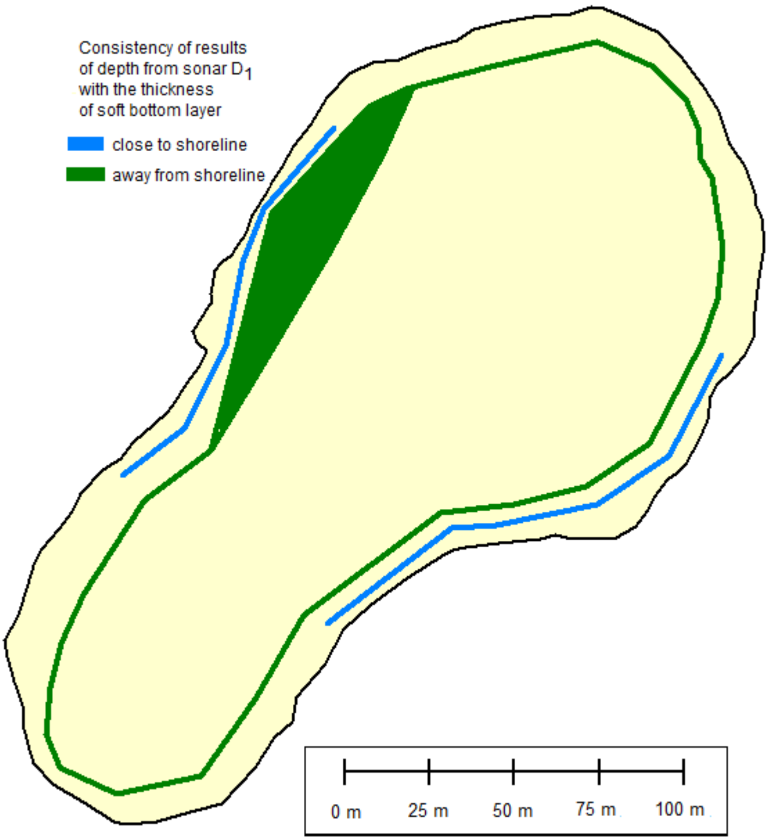

Figure 14. Geographical distribution of consistency between depth of bottom from sonar D_1 and thickness of soft bottom layer

E_1–D_1, E_1–D_2 and E_1–D_3 for the entire lake, parts of the NE, SW, NW, SE lake halves and parts of the N, E, S, W lake quarters. It was assumed that each of the parts so determined had the same weight. The median graphs of individual dependencies were determined and thus the mathematical dependency defined by the formula was determined. The graphs for the individual parts of the lake were very consistent. In the case of the D_1–D_2 relationship, the approximated curves for the S, W and SE parts of the lake were mutually consistent and achieved slightly higher D_2 values than the other lines. In the case of the D_1–D_3 relationship, deviations occurred for the approximated curves for the S and SW parts of the lake. For the E_1–D_2 and E_1–D_3 relationships, the approximated curves were consistent except for the

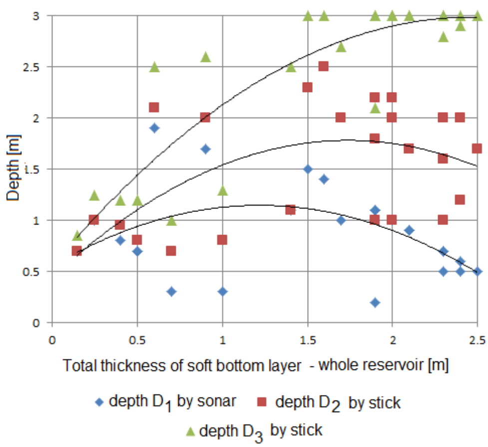

Figure 15. General relationships between value of D_1, D_2, D_3 and total thickness of soft bottom layer in the specific areas of the reservoir

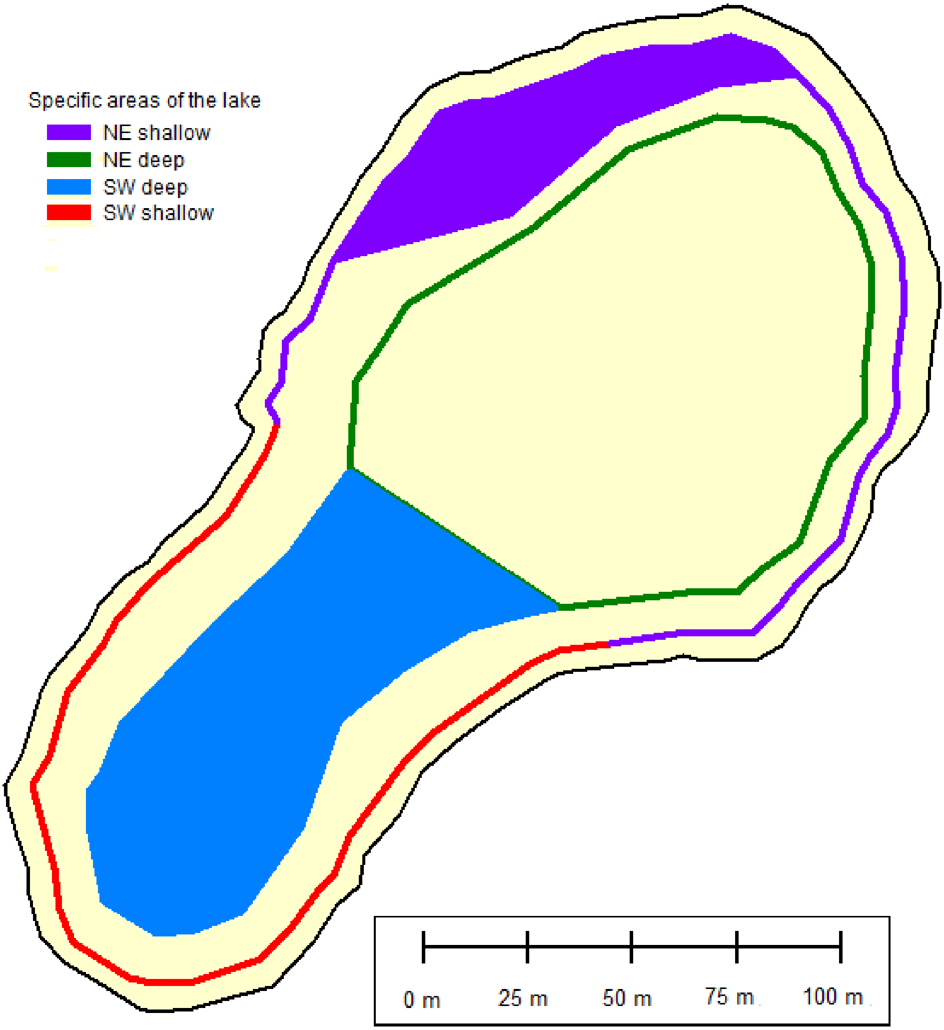

Figure 16. Geographical distribution of consistency between depth of bottom from sonar D_1 and thickness of soft bottom layer

E part, which achieved lower values than the other lines.

The formulas obtained on the basis of approximation for the dependencies D_1–D_2, D_1–D_3, E_1–D_1, E_1–D_2 and E_1–D_3 were used to develop numerical models of surfaces D_1, D_2, D_3 for sets of 7528 pings for input data D_1 and E_2. In order to enable the calculation of all volumes limited by surfaces D_1, D_2 and D_3 based on input data D_1 or E_1, the additional file was developed for the set of 7,528 pings with zero depth D_0, which was to present the lake surface. Due to the lack of measurements at the shoreline, it was assumed that the values of all depths D_0, D_1, D_2 and D_3 equal at shoreline zero meters. The obtained data files were used in the Global Mapper software to calculate the volume between individual surfaces. The calculation results were presented in Table 3.

The volumes of reservoir between the individual surfaces of the numerical models for the input data D_1 from the sonar, D_1 from E_1 and

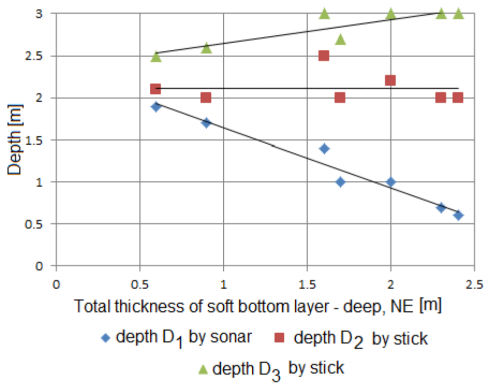

Figure 17. Relationships between value of D_1, D_2, D_3 and total thickness of soft bottom layer specified for area far away from shoreline in the NE part of the reservoir

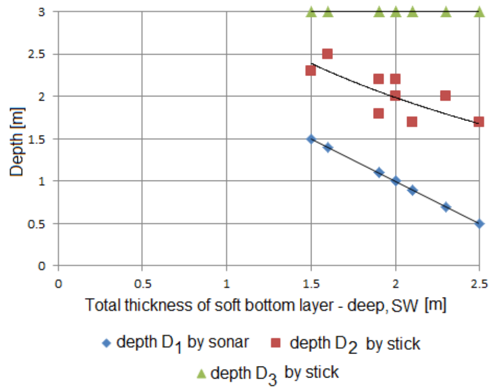

Figure 18. Relationships between value of D_1, D_2, D_3 and total thickness of soft bottom layer specified for area far away from shoreline in the SW part of the reservoir

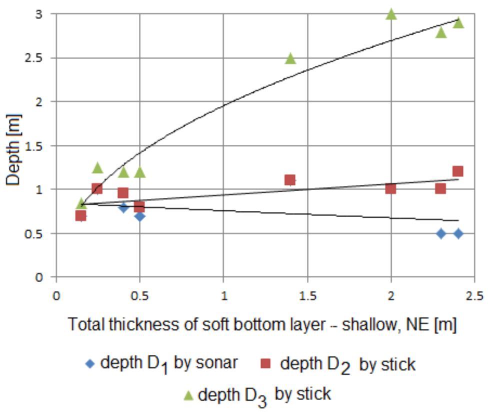

Figure 19. Relationships between value of D_1, D_2, D_3 and total thickness of soft bottom layer specified for area close to the shoreline in the NE part of the reservoir

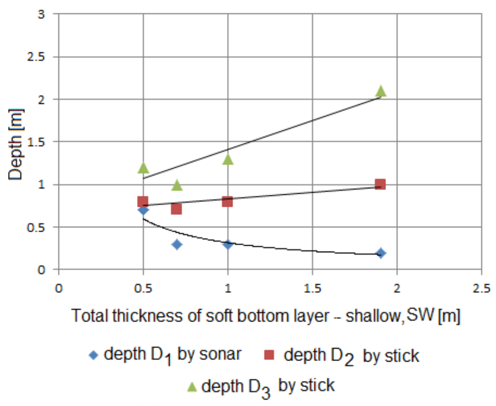

Figure 20. Relationships between value of D_1, D_2, D_3 and total thickness of soft bottom layer specified for area close to the shoreline in the SW part of the reservoir

E_1 from the sonar for the output models D_1 and D_2 are very similar. The difference in between the various input data used did not exceed 6.3%. The difference in between the surfaces of the numerical models for D_2 and D_3 obtained on the basis of the input data D_1 and E_1 was twice as high and amounted to 11.5%. It should be noted that the volume important for environmental protection purposes between the numerical surfaces D_1 and D_2 calculated using three different methods was very similar, within the difference range of 1.7–5.7%. The above results indicate that each of the above methods using single beam echo sounder (sonar) can be used to assess the scope of work and the costs of required restoration measures by removal of colloid suspension layer.

7. Summary and conclusions

In the work the muddy bottom of the water reservoir was mapped. The goal was to achieve numerical models of sediment structures under the bottom surface of a water reservoir with relatively soft ooze-muddy sediments using the recorded parameters of the first and second sonar echoes. As a result of the studies, three reference surfaces were determined: the bottom depths for initial top surface of the colloidal state (ooze) layer D_1, the top surface of the dense muddy bottom D_2 and the surface of solid bottom D_3 under the muddy layer. For this purpose, 21,858 pings were recorded, of which 7,528 pings were analysed (1 ping per 3.8 sq. m of the lake). For this data, the sonar screen image was additionally analysed to determine the number of echoes returned and the height of the *Myriophyllum* algae. This data allowed for the determination of information on the water column and the surface of the lake bottom. In order to determine the structure of sediments under the surface of the bottom of the water reservoir, the pole measurements were used for the 40 or 27 control points. Based on the data from the control points, 78 relationships in between 16 factors were analysed.

Based on the evaluation of the correlation coefficient r_s, the statistical significance coefficient p and the coefficient of determination R^2, it was determined that the most reliable input data to the numerical models were height of algae H_a and/or distance to shoreline d_s. However, they were not available using data recorded by the sonar. For the above reason, they were not considered further. Other input data to the numerical models were depth D_1 and/or roughness E_1. They were recorded by the sonar. For this reason, they were subjected to further studies.

The calculated volumes of reservoir between the individual surfaces of the numerical models for input data from single beam echo sounder (sonar) were very similar. The difference of volumes in between the surfaces of numerical models D_2 and D_3 was 11.5%. Considering that the numerical models for D_2 and D_3 were not obtained on the basis of direct measurements with the single beam echo sounder (sonar), the obtained results should be considered as very similar. The volume between the numerical surfaces D_1 and D_2, significant for environmental protection purposes, calculated using three different methods was very similar, within the discrepancy range of 1.7–5.7%. The above results indicate that each of the above methods using a single beam echo sounder (sonar) can be used to assess the scope of work and costs of required restoration measures by removal of colloid suspension layer.

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