

Research Article

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Using the geodetic and hydroacoustic measurements to investigate the bathymetric and morphometric parameters of Lake Hańcza (Poland)

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Abstract: Most of the inland lakes do not have up-to-date bathymetry. However, a significant progress in surveying technologies creates a possibility to quickly and accurately describe the underwater environment. Modern geodetic and global positioning techniques integrated with hydroacoustic systems provide a great opportunity to study the bottom shape with high resolution. Our study presents a reliable methodology for investigation of bathymetry and morphometric parameters with the use of GNSS positioning techniques and single beam echosounder. The research was implemented on the deepest, glacial reservoir in the central part of European Depression - Lake Hańcza. Direct hydroacoustic and geodetic measurements completed by sediment study were conducted by the authors in 2010-2013. After performing a field survey the Digital Elevation Model was constructed and the new bathymetric map and morphometric card were elaborated. The maximum depth was confirmed to be 105.55 m. The final conclusions show that the available bathymetric data and morphometric parameters of lakes are highly dependent on the research methodology used, the precision and accuracy of measurement techniques, proper water level determination, digital elevation model and bathymetric map elaboration processes.

Keywords: bathymetry; GIS; GNSS; Lake Hańcza; morphometry; SBES

1 Introduction

Water environment is a complex phenomenon, dynamic in both space and time. Understanding the processes occurring in aquatic environment requires monitoring of changes over time. Due to its complexity, water environment is difficult to model and describe. Over the years different approaches have been employed to accurately describe the shape of the lake basin. They involve application of specified procedures, such as a sensor, instrument, algorithm or process chain. These differences in methodology can be an important issue in the interpretation of the environmental changes.

The big progress in surveying technology has had a strong impact on the data acquisition. Modern techniques introduce a possibility to quickly and accurately describe the Earth environment. The growing popularity of aerial photography, satellite data, radar imagery data and high resolution sensors (single/multibeam sonars and laser scanners) require appropriate methodology for data collecting, spatial processing, storing, analyzing and visualizing.

The most commonly used bathymetric map is mainly a topographic map of the lake bottom that shows depth contours within the lake basin. Almost 40% of the world's largest lakes have not yet been studied. The same applies to smaller inland reservoirs. Existing analogue maps do not present up-to-date bottom surface. Therefore, it is very important to explore their bottom shape and create accurate bathymetric charts and digital bottom visualizations.

Bathymetry and especially lake morphometric parameters are widely used in limnology, hydrology, hydrobiology, fisheries, water biology, etc. [1]. The reliability of the morphometric data highly depends on the accuracy and precision of bathymetric maps, which in turn depends on the accuracy of the hydrographic surveys [2]. The general idea of bathymetric surveys has not changed for centuries but the relevant technology and instrumentation are constantly developing. Today high quality bathymetric data are being acquired in inland shallow water using high frequency single or multibeam echo sounders, precise global positioning systems, airborne laser scanning, side scan

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sonars, sub bottom profilers and multi parameter sensors. The Global Navigation Satellite Systems (GNSS) RTK positioning and new multi-station GNSS precise solutions provide one-centimetre horizontal accuracy [3]. The empirical experiments indicate that even cost-effective DGNSS measurements of DEM give an accuracy sufficient in most GIS projects [4]. According to the International Hydrographic Organization (IHO) Standards for Hydrographic Surveys, where the horizontal accuracy for Special Order reservoirs is 2 m, the achieved position/depth accuracy is adequate for the majority of bathymetric surveying [5]. The accuracy of depth measurements ensured with the use of a properly-calibrated Single Beam Echo Sounder (SBES) is usually a few centimeters, depending on the distance from the transducer to the bottom.

Raw data are stored in databases, processed by modern algorithms and shared using novel visualization techniques. They give information about bathymetry, geomorphology and lake floor geologic processes [6].

The authors describe a reliable methodology for investigation of bathymetry and morphometric parameters of inland reservoirs with the use of historical data, modern integrated GNSS and SBES techniques. The proposed methodology was implemented on the deepest, glacial reservoir in the central part of European Depression - Lake Hańcza.

2 Study area

Lake Hańcza is a unique, oligo-mesotrophic lake in the north-eastern part of Poland in the Suwałki Landscape Park. It is the deepest inland reservoir, not only in Poland but also in the central part of the European Depression. In the literature there are several studies presenting its morphometry, maximum depth and the bottom shape. Many different approaches have been applied to explore this issue. The first depth survey, reported by Śledziński in 1927, was done directly from an ice platform [7]. The maximum investigated depth was described as 104.5 m. According to the first bathymetric measurements covering the whole lake taken in July 1930 by Rühle, the maximum depth was 108 m (referenced to the water level of 227.2 m above sea level) [8]. Similar information has been included in Stangenberg's publications. In 1936 he estimated the depth of Lake Hańcza at 108.5 m and the surface of 305.84 ha [9, 10].

The existing analogue bathymetric plan of Lake Hańcza has been developed by the Inland Fisheries Institute in Olsztyn on the basis of both historical works by Rühle and Stangenberg. The morphometric card elabo-

rated by the Institute includes the maximum depth of 108.5 m and the surface of 311.4 ha. The calculation of the water level above the sea at 229 m differs from the information given by Rühle by as much as 1.8 m.

Another report about the maximum depth of Lake Hańcza was described by Choiński and Skowron in 1998. Bathymetric survey was performed in the central, deepest region with the use of YE 43 echo depth finder and hand lead line. The maximum measured depth was 106.1 m reduced to average multi-annual water level of 227.45 m above sea level [11].

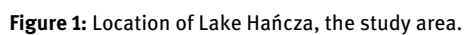
In the years 2000-2007 the scientific team: Jozsa, Tatrai, Gyore and Kozłowski conducted a hydroacoustic survey with the use of Biosonics DT400 and SIMRAD EK60 equipment [12]. They achieved the depth of 112 m, which was four meters deeper than the survey in 1930.

Generally, bibliography gives different values of Lake Hańcza maximum depth (104.5 - 112 m, Table 1). In most cases, the value of 108.5 m given by the Inland Fisheries Institute in Olsztyn is quoted. To clarify these issues a new methodology of integrated geodetic/satellite and precise hydroacoustic measurements has been proposed and conducted.

3 Methodology

The proposed reliable methodology for bathymetry and morphometry investigation starts from a thorough analysis of historical reports and plans. The next, practical part of the hydrographic measurements should be divided into three basic stages. The first includes fundamental bathymetric measurements of the whole lake using integrated GNSS and hydroacoustic systems. Subsequently, a geodatabase should be created and then the deepest region needs to be carefully explored. To verify the maximum depth and precisely calculate the water level above the sea, geodetic and hydroacoustic surveys should be conducted directly from the ice platform. The authors suggest using both measurement techniques, namely high frequency single beam echo sounder and calibrated wire sounding machine. The final stage of the field studies should provide information on the lake bottom contemporary slack-structure sediments based on direct *in-situ* probes confirmed by double frequency echo sounder echograms. Finally, the collected high quality raw data makes it possible to elaborate a reliable bathymetric map and calculate morphometric parameters.

To achieve a high accuracy of depth measurements using an echo sounder, the sound velocity in a water column



must be precisely determined. The sound velocity varies with the density and elastic properties of the water. These properties are primarily a function of the water temperature and its suspended or dissolved contents (i.e. salinity). Due to these effects, the velocity can range from 1400 to 1500 m s⁻¹. Most lakes can exhibit large variations in temperature with depth and the velocity of sound wave will usually not be constant over the distance from the boat's transducer to the bottom and back. For this reason, the determination of the sound velocity is the most critical factor in hydroacoustic depth measurements¹. For example, winter water temperature in Lake Hańcza varies from about 0°C under the ice to 3.30°C at the depth of 100 m. In summer the temperatures range respectively from 26°C to 4.00°C [13, 14].

The proposed technology of using a bathymetric survey to precisely examine the lake bottom is based on GNSS techniques and single beam echo sounders [15]. The navigation of a small hydrographic boat along the predefined profiles made it possible to conduct a hydroacoustic survey, examine the bottom shape, compute water volume, calculate morphometric data and elaborate a bathymetric chart. The Integrated Bathymetric System basically consists of: the Real Time Kinematic (RTK) or Differential Global Navigation Satellite System (DGNSS), the hydroacoustic bottom detection equipment and special GNSS and GIS software. The estimated horizontal accuracy of carrier phase kinematic positioning with the use of professional geodetic receivers is about 0.05 m and 0.2 – 0.5 m using Differential GNSS navigation.

A high frequency, single beam digital hydrographic echo sounder is the most precise and accurate hydrographic SBES equipment for reliable depth measurements. Properly calibrated 200 kHz frequency equipment calculates depths with a centimeter accuracy in shallow lakes. Dual channel/frequency transducers (38 and 200 kHz) should be used for bottom structure analysis. The higher frequency is used to determine the first reflected bottom (often a soft bottom, the upper layer of sediment). The lower frequency is usually used to study the structure and evaluate the thickness of the sediment. In bathymetric measurements, the knowledge of sound speed in water is crucial for the accuracy of depth calculation. The conductivity, temperature, depth sonde (CTD) or Sound Velocity Profiler (SVP) can provide water quality sampling and information on sound speed in water.

The accuracy of water level determination has a strong impact on the final bathymetric and morphometric data [16]. During measurements, the reported maximum depth of the lake must be referenced to the common level. Water level in Polish lakes varies in time in line with seasonal and multi-annual changes. One distinct spring maximum usually occurs in the period between April and May. To calculate the final water level on a given measurement stage, the data on the height of the GNSS antenna positioned on the boat during hydroacoustic sounding computed in kinematic On The Fly (OTF) GNSS post-processing mode and static measurements on the ice platform should be considered. In order to obtain the normal height above sea level (Kronsztadt'86), all measured points which have ellipsoidal heights should be reduced to quasi-geoid level separately for each of the proposed survey stages. Additionally, the water levels based on GNSS observations must be compared to local gauge readings. Figure 2 presents a flowchart describing the complete methodology proposed by the authors for Lake Hańcza reliable bathymetry investigation.

4 Measurements

The universal methodology of acquiring reliable bathymetric information was implemented during Lake Hańcza research project. All stages of research in 2010-2013 have been prepared and conducted by the authors. Before the start of the practical procedures, a thorough historical data investigation was done. Then the sounding profiles were planned on the background of the lake coastline based on satellite imagery and aerial photos. The practical hydroacoustic part of the authors' research was carried out in a three-step process of integrated GNSS and SBES surveys. At the end of the experimental part of the study water level examination and bottom sediment investigation were conducted.

4.1 Water temperature

The first bathymetric measurements were performed in May 2010 (May 18-19, 2010). The hydrographic SBES equipment included two single beam digital hydrographic echo sounders: a Simrad EA501 P (200 kHz) and a Reson Navisound 515 (38/200 kHz dual frequency transducer). Additionally, a YSI 600R sonde for water quality sampling was used.

¹ International Hydrographic Organization IHO, Manual on Hydrography C-13. International Hydrographic Bureau, Monaco, 2005.

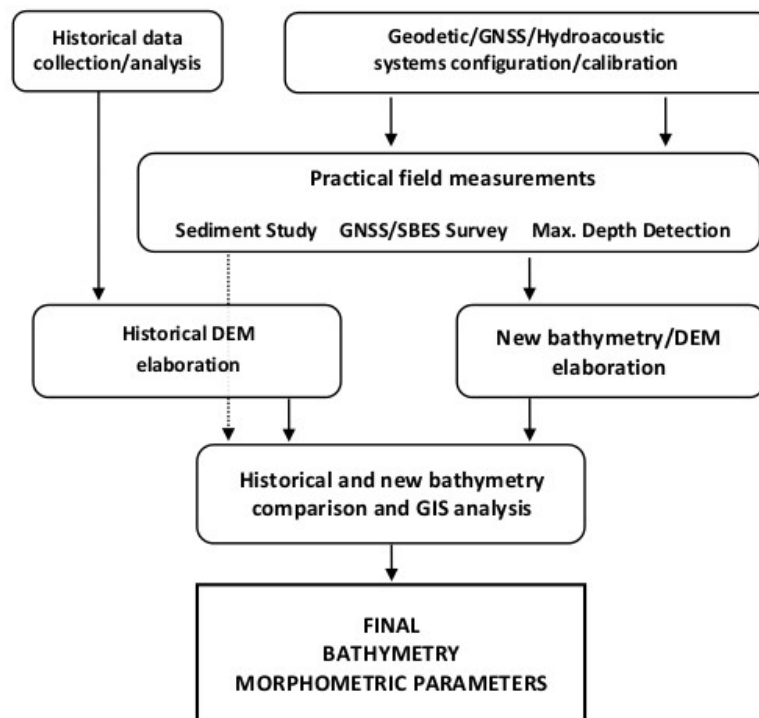


Figure 2: Flowchart of the adopted methodology.

Prior to hydrographic sounding, the echo sounders were calibrated. The YSI 600R CTD sonde was used to determine the temperature, conductivity and finally precise sound speed profile of the water column. The speed of sound in the water was estimated by YSI 2SS software using the Clay and Medwin formula [17]. The sound speed value from 0 to 60 meters was between 1458 and 1422 m s⁻¹. The water temperature ranged from 13.12°C to 4.27°C depending on the depth (see Figure 3). An average speed of sound - 1430 m s⁻¹ was entered directly into the echo sounder before data acquisition. The SBES was controlled by conducting a bar-check calibration. The bar-check procedure was also used to estimate depth corrections to ensure accurate measurements at the level of centimeters. The observed depths were mathematically corrected between their closest range of calibration data following the survey during the post-processing phase². During the first stage of the project, the central deepest area of Lake Hańcza was investigated.

4.2 Maximum depths region investigation

The second part of the work was continued on March 12, 2011. The surveys were done in the deepest region of the lake. The area of interest was determined through the bottom elevation model elaborated after the first stage. A depth study was carried out at the thirty locations situated at the deepest profiles on the bottom. The selected points were spaced 10 meters apart. The classical geodetic and bathymetric measurements were done directly from the ice platform to confirm the maximum depth. The hydroacoustic measurements were performed using Simrad EA501 P and Reson Navisound 515 echo sounders. To calibrate bathymetric equipment, the water parameters were measured using YSI 600R CTD sonde. The water temperature varied from 0.86°C under the ice to 3.30°C at a depth of 100 m (see Figure 3).

The value of sound speed was between 1406 and 1418 m s⁻¹. A sonar transducer was immersed to a depth of 1 m to avoid the influence of extremely cold water directly under a sheet of ice. Before data acquisition, the speed of sound in water was set into the echo sounder at 1418 m s⁻¹.

To confirm hydroacoustic measurements, a manual survey from the ice platform was made. The calibrated wire sounding machine was used to measure the maximum depth at the same points as the hydroacoustic work. The depth-measuring equipment consists of stranded wire

² US Army Corps of Engineers, Hydrographic Surveying, Engineering and Design, Manual EM 1110-2-1003, Washington, 2003.

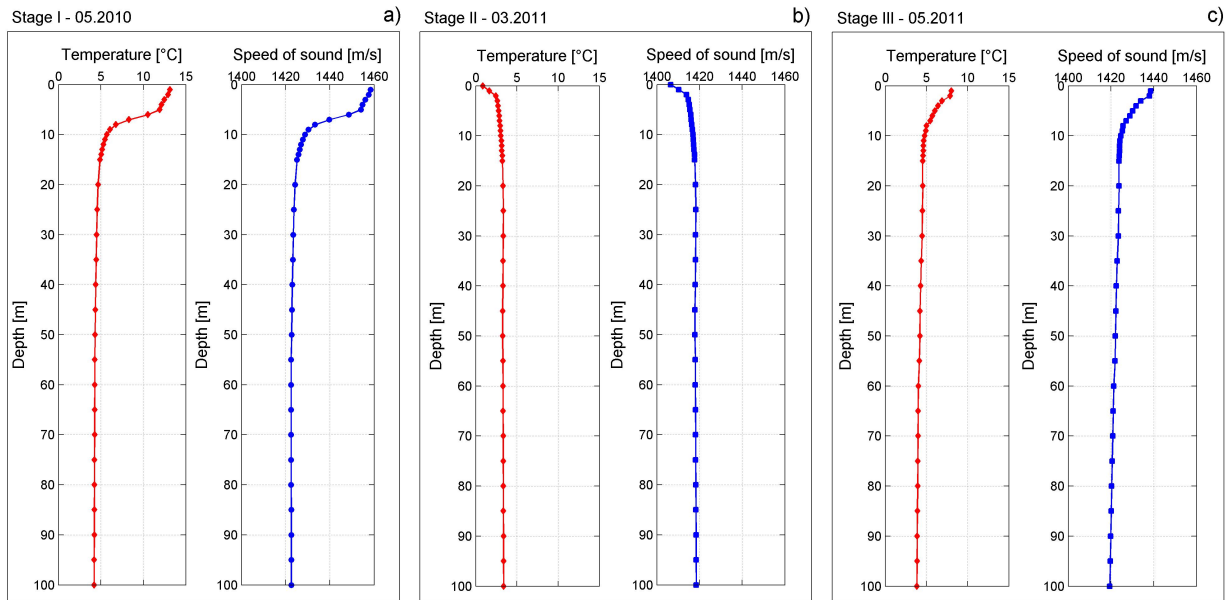


Figure 3: Water temperature distribution: Stage I 05.2010 a), Stage II 03.2011 b), Stage III 05.2011 c).

with marked distances (calibrated by geodetic techniques) wound on the reel and a stainless steel plate attached to the end of the wire.

The depths of 30 positions were determined using three independent systems. The results were very coherent. The maximum difference between analog and hydroacoustic measurements was 5 cm. The maximum depth achieved was 105.70 m in the central region of selected points area (water surface at 227.60 m above sea level).

4.3 Bathymetric survey

The last depth data acquisition phase was conducted in May 2011 (May 6-8, 2011). The bathymetric surveys were conducted using single beam hydroacoustic sounding and the RTK/GNSS satellite positioning technique. The calibration procedure was similar to that carried out during the first and second stages. The sound speed in the water column varied between 1438 and 1421 m s^{-1} . The water temperature ranged from 8.00°C under the water surface to 4.00°C at a depth of 100 m (Figure 3). An average speed of 1422 m s^{-1} was entered directly into the echo sounder before data acquisition. The raw data were then corrected according to the bar-check procedure. The old Rühle sounding points and the new bathymetric survey stages are presented in Figure 4.

4.4 Water level examination

The water level of Lake Hańcza varies according to seasonal and multi-annual changes. The maximum variability of average monthly water level in the period of 1961-2000 is 0.25 m (in April). The mean multi-annual amplitudes were 0.59 (1971-1980), 0.56 m (1961-2000) and 0.53 m (1961-2005) [18, 19]. In 1930, Rühle observed up to 0.50 m in monthly water changes [8]. The average multi-annual Lake Hańcza water level is periodically calculated and reported. The results of the analysis of the average water level in the years 1960-2004 report 227.44 m above sea level [20]. Further studies show the average water level in the years 1961-2006 at 227.45 m [21]. Average long-term water level from the years 1969-2012 is 227.46 m above Kronsztadt'60. The calculation was made by Institute of Meteorology and Water Management (based on Wróbel water level gauging site data).

The water level during the Lake Hańcza research was changing slightly over each of the three stages of bathymetric and geodetic surveys (decimeter changes). The final water levels were computed in kinematic OTF GNSS post-processing mode and static measurements on the ice platform. GNSS surveys were done using the POZGEO service according to three ASG-EUPOS reference stations (Active Geodetic Network). All calculations were reduced to Kronsztadt'86 (vertical map datum in Poland – normal heights above sea level) and confirmed with gauge read-

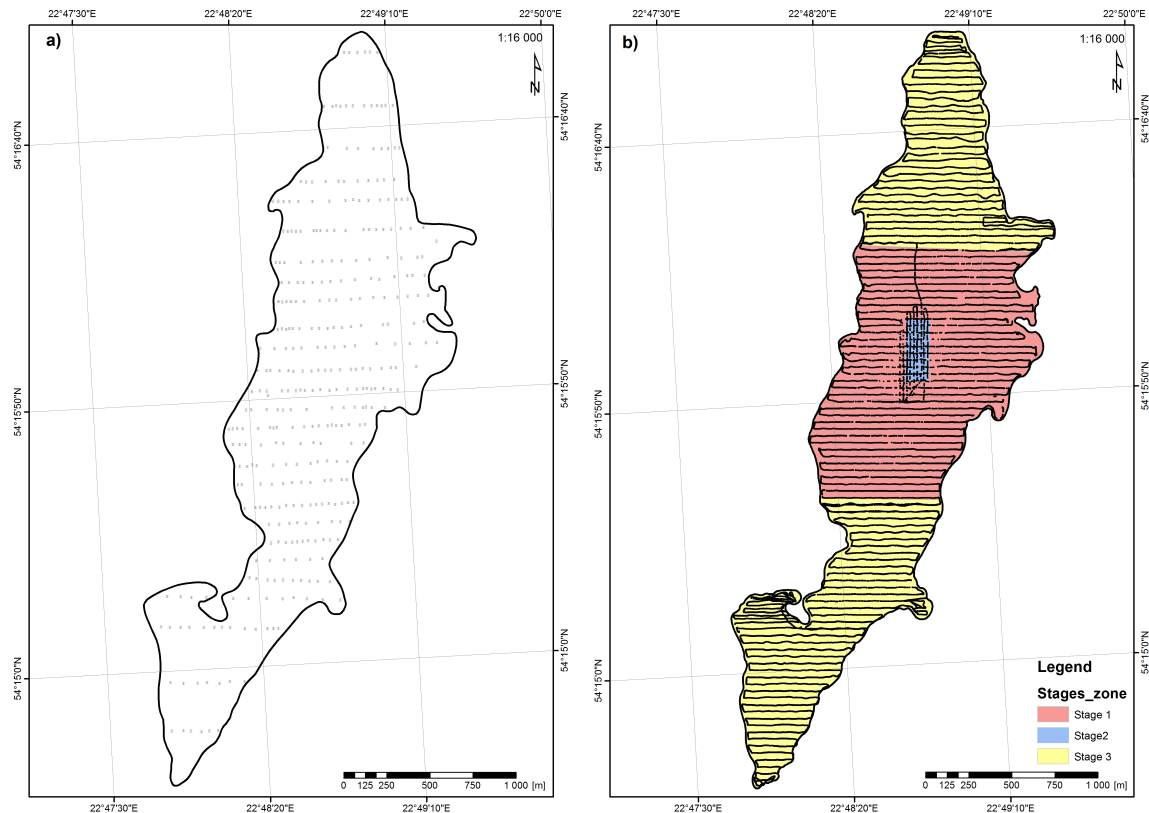


Figure 4: Old Rühle soundings (a) and new survey stages (b).

ings in Wróbel. Results show differences ranging between 1 - 3 cm. The results are presented in Table 1.

4.5 Bottom sediment study

The final part of the field investigation provides information on the lake bottom sediment. Previous Rühle work described the bottom in the deepest region of the lake as being hard with sand and gravel [8]. A deep analysis of the high and low frequencies echograms from 2010-2011 SBES surveys show in many places up to 3 meters' layer of probably homogeneous organic sediment with a thin upper layer of loose structure. To confirm this hypothesis a DEM was used to find out the location of sampling points for direct sediment inventory. Sediment studies were performed in 2013 in 30 previously designed main points on the longitudinal and transverse cross-section of the lake. Sediment samples were collected using Kajak-type gravity core sampler with an internal diameter of 52 mm. Macroscopic analyses of obtained undisturbed sediment cores (thickness of about 40-50 cm) were performed by extracting individual layers with an accuracy of 1 cm. These experiments pro-

vide information on the lake bottom contemporary slack-structure sediments based on direct *in-situ* probes.

5 Results

The new methodology for acquiring reliable bathymetric information was implemented during Lake Hańcza research project. The new collected bathymetric raw data were processed and filtered using the software called Echo Converter, Echo View (developed by the authors) and commercial GIS packet ESRI ArcMap, version 10.0. Verified data were adjusted to the common water level and converted to the average multi-annual water level (227.46 m above sea level, 1969-2012, Table 1). The BLH geodetic coordinates (Latitude, Longitude, Ellipsoidal Height) were transformed into a projected coordinate system (ETRS 1989 Poland CS 2000 Zone 8) and converted into multipoint feature class. All measured points were used for creating the Digital Elevation Model (DEM) of the Lake Hańcza bottom.

Table 1: Maximum depths and normal heights above sea level in particular survey stages.

Stage/Data	Year	Water Level [m]	Maximum depth [m]
Śledziński	1927	-	104.5
Rühle	1930	227.2	108
Stangenberg	1936	-	108.5
Inland Fisheries Institute in Olsztyn	1966	229	108.5
Jozsa, Tatrai, Gyore and Kozłowski	2007	-	112
Choiński & Skowron	1998	227.45	106.1
Popielarczyk & Templin	2010-2011	227.45	105.55

5.1 Bathymetric measurements results

The Lake Hańcza bathymetric map was elaborated on the basis of Digital Elevation Model, which is a continuous representation of the ground. DEM can represent many phenomena, and as such is used in many various application domains [22–25]. The DEMs vary, depending on their purpose, the quality of data sources or interpolation algorithms, the experience of the operators, etc. In the literature, many studies have been done to find the optimal method to extract the lake morphometry from DEMs [26, 27]. Today, the major problem with morphometric results is the absence of standards for extracting descriptive measures (“parameters”) and surface features (“objects”) from DEMs [28]. The parameters for Lake Hańcza were calculated using the methods and definitions described by Hutchinson and Wetzel [29, 30].

The new bathymetric map, elaborated on the basis of DEM was used to estimate Lake Hańcza morphometric parameters (Figure 5).

The following parameters describing Lake Hańcza were elaborated and then analyzed: lake area (km^2), shoreline length (Ls), maximum lake length (Lmax), volume (V), maximum and mean width (Bmax, Bmin, respectively), maximum and mean depth (Dmax, Dmin, respectively), relative depth (Zr), shore development index (Ld1), mean aspect. Actual morphometry parameters are shown in Table 2.

5.2 Historical data analysis

Historical reports and plans were used to elaborate DEMs and digitize old bathymetric maps. Both historical and new DEMs/bathymetric maps were compared and analyzed in order to evaluate changes in Lake Hańcza morphometry. Additionally the authors sought to confirm

these results by the study of sediments. The analysis of historical and new bathymetry was carried out with DEM created using GRID representation. All steps were performed with ESRI ArcMap, version 10.0.

Contour lines derived from the old bathymetric charts are often the only available data source to compute a DEM. The transformation of these contour lines into a DEM involves digitizing, sampling and interpolation. The process of Lake Hańcza map digitalization was done with on-screen functions from the ESRI ArcGIS software. The hydrographic survey soundings collected in 1930 by Professor Rühle and the Inland Fisheries Institute in Olsztyn bathymetric plan from 1966 were processed³. The feature classes, representing contour and shoreline, were extracted from historical bathymetric data and plans.

Interpolation functions were used to produce a continuous surface of data representing the bathymetry of the Lake Hańcza for each year: 1932, 1966 and 2011. Contours, depth ranges, volumetric and area calculations were derived from a DEM grid. The grid was created using a spatial resolution of five meters. This interpolation method was designed for the elaboration of hydrologically-correct digital elevation models. It is based on the ANUDEM software developed by Hutchinson [31]. The contour lines were edited to improve accuracy and to smooth the lines. Then the contours were converted to polygon feature classes and attributed to show 10-m depth ranges across the lake. The DEMs and numerical representation of contours generated from the historical and newly-obtained data were used to calculate the surface area, water volumes and other morphometric parameters. Finally, a comparison between DEMs built from data collected using different measure-

³ Inland Fisheries Institute in Olsztyn, Bathymetric plan of Lake Hańcza. Olsztyn, 1966.

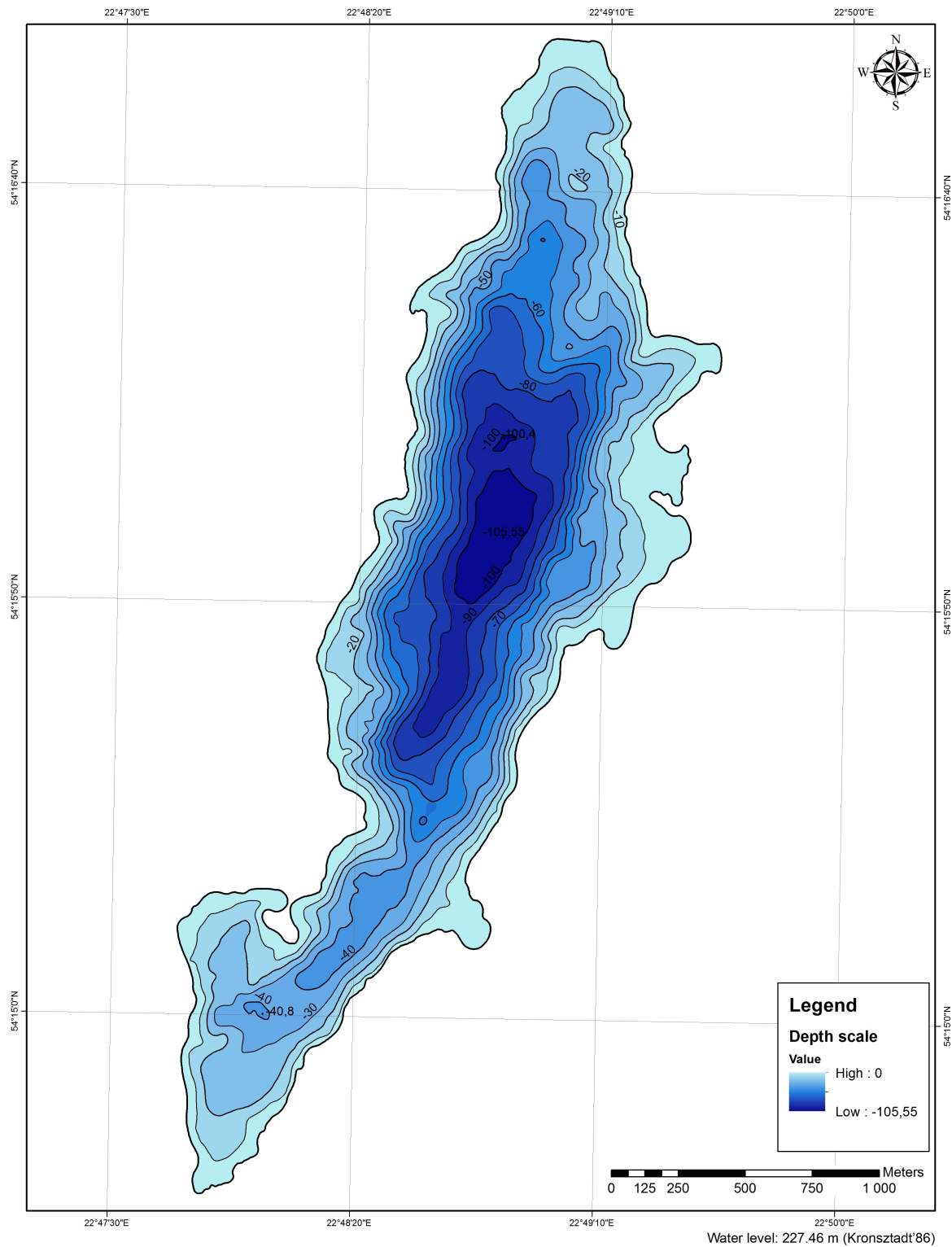


Figure 5: The new bathymetric map of Lake Hańcza.

ment techniques was conducted. The bathymetric maps of Lake Hańcza are shown with 10-m contour intervals (Figure 6).

5.3 Bottom sediment study results

Macroscopic analysis indicates the presence of different structures of bottom sediments. Gravel and stones were found only in the areas where the bottom was sloping. It was not possible to collect a small fraction layer using a gravity pipe sampler. However, in most of the points on the bottom the organic layer of sediment was present. This layer was determined as detritus gyttja with a thickness of up to 30 cm, depending on the sampling site. The greatest thickness of this layer was found on the northern and southern edge of the main lake trim (points 7 and 11 at depths of 98 and 65 m respectively). The least of such deposits on the longitudinal and transverse transect were found in coastal and offshore locations.

Under the layer of organic deposits, a more concise carbonate gyttjas were observed, usually reaching the end of the core (0.4–0.5 m). In shallower areas, especially in the north and south end of the lake they formed a thin, several-centimetre layer and passed in sand gyttjas, graphite silts, or sand. However, sand admixtures and interbeddings were also found in a few deeper positions (7,17). Also sediments collected from the deepest part of the lake bottom were characterized by a heterogeneous structure, where the organic gyttja layer (thickness of 0.2 m) was supported with sandy tracks (0.1 m). At the deepest part of the sediment core, organic, carbonate and sand laminations were observed, forming clear sections with the thickness of 1–2 cm.

The spatial structure of the surface layers of Lake Hańcza sediments is heterogeneous with a tendency to increase the thickness of the organic formations along with the depth of sampling locations. Such formations are however, disordered locally with the presence of minerals interbeddings.

6 Discussion

6.1 Bathymetry analysis

Both Professor Rühle (1932) and the Inland Fisheries Institute in Olsztyn (1966) list values for morphometric param-

eters, but it is not certain what the exact level of the water was during their historical soundings. The Rühle study reports that depth measurements were collected with a lake elevation of 227.2 m. However, the Institute morphometric card attached to bathymetric plan from 1966 reports that the lake water level was 229 m above sea level (Table 1). Additionally they did not explain their methodology for determining the lake length, centerline lengths or widths. Nevertheless, most of their values are surprisingly similar to the ones presented by the authors, despite the low number of sounding measurements and the simple techniques used to develop the bathymetry and morphometric values (Table 3).

Visual inspection of the DEMs (Figure 6) reveals deficiencies in the 1932 and 1966 bottom models. The 2011 DEM produces a sharp image that clearly defines the shape of the bottom, whereas 1960 and 1933 models, having the same general structure, show many local variations. This makes the image attributes more diffuse (slope, aspect area). Although the general bottom shapes are quite similar, the lack of sampling points has significant impact especially on the area with various bottom shape. Such areas differ considerably between the three models.

The impact of data acquisition methodology on model accuracy was investigated by comparing the 2011 model with 1932 and 1966 models. A cell by cell comparison of DEMs with the same resolution was employed. The reference 2011 DEM was compared with both 1966 and 1932 models (Figure 8). The range of 2011–1932 differences (mean 2.3 m, standard deviation 7.0 m) is greater than 2011–1966 (mean 0.7 m, standard deviation 3.9 m). Maximum differences between the models are visible in steep areas with various bottom relief. The highest and the lowest value of the difference were seen on the underwater slope and on a flat area, respectively. Compared to the reference DEM, the 1932 model does not show any correlation between the depth and observed differences. The changes are evenly distributed throughout the area. Comparing 2011 and 1966, it can be seen that there is a reasonable agreement between the two models for relatively flat area (northern and southern part of the lake). The bigger differences are concentrated in the central, narrow and deepest part of the lake.

The presented results confirm that data acquisition methodology has strong impact on the final DEM quality. Accuracy and reliability of raw measurement data significantly affect the bathymetry and morphometric parameters and can be a very important issue in the interpretation of the environmental changes.

Table 2: Lake Hańcza morphometric parameters – 2011.

Izobaths (m)	Isobath surface (m ²)	Surface area between isobaths (m ²)	(%)	Volume (m ³)	Volume between isobaths (m ³)	(%)
0 0-5	3035581	365007	12,0	118647998	14079083	11,9
5 05/10/15	2670574	195591	6,4	104568916	12855070	10,8
10 10-15	2474982	198738	6,5	91713846	11886810	10,0
15 15-20	2276244	225931	7,4	79827036	10827037	9,1
20 20-25	2050314	246516	8,1	68999999	9629920	8,1
25 25-30	1803798	203548	6,7	59370078	8469807	7,1
30 30-35	1600250	164430	5,4	50900272	7607859	6,4
35 35-40	1435819	177649	5,9	43292412	6744522	5,7
40 40-45	1258171	197022	6,5	36547890	5749471	4,8
45 45-50	1061148	101154	3,3	30798419	5039213	4,2
50 50-55	959994	90037	3,0	25759206	4576824	3,9
55 55-60	869958	104746	3,5	21182383	4075267	3,4
60 60-65	765212	79919	2,6	17107116	3623394	3,1
65 65-70	685293	80688	2,7	13483721	3227360	2,7
70 70-75	604605	88814	2,9	10256361	2811083	2,4
75 75-80	515791	96954	3,2	7445278	2339275	2,0
80 80-85	418837	96763	3,2	5106003	1845135	1,6
85 85-90	322074	85754	2,8	3260868	1382383	1,2
90 90-95	236320	76169	2,5	1878486	992100	0,8
95 95-100	160151	76581	2,5	886386	598293	0,5
100 100-105	83571	64213	2,1	288093	280991	0,2
105 105-106	19357	19357	0,6	7102	7102	0,0

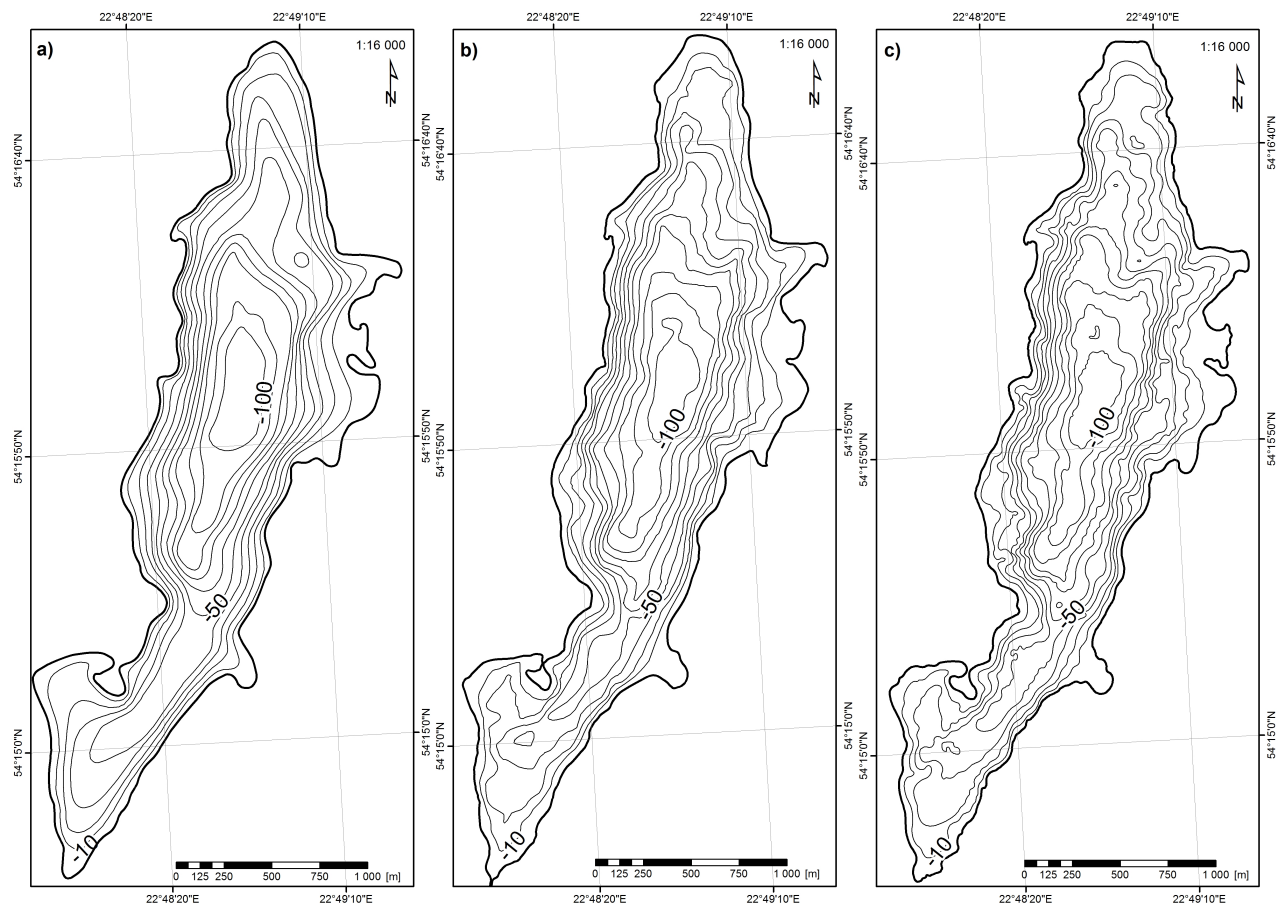


Figure 6: Bathymetric maps of Lake Hańcza: 1932 a), 1966 b), 2011 c).

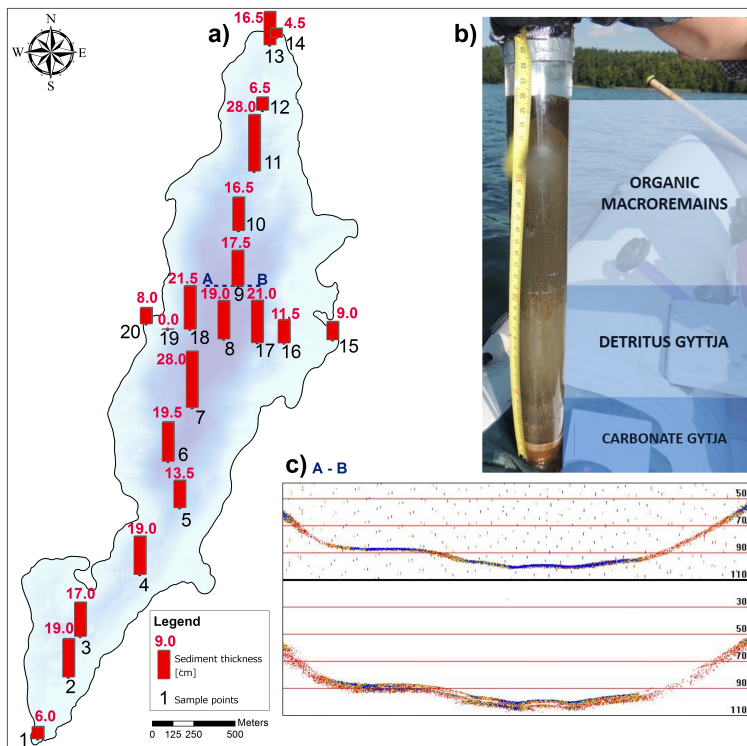


Figure 7: Spatial distribution of loose-structure organic sediments in Lake Hańcza a), in situ probe, sample point No. 10 b), dual frequency echogram c).

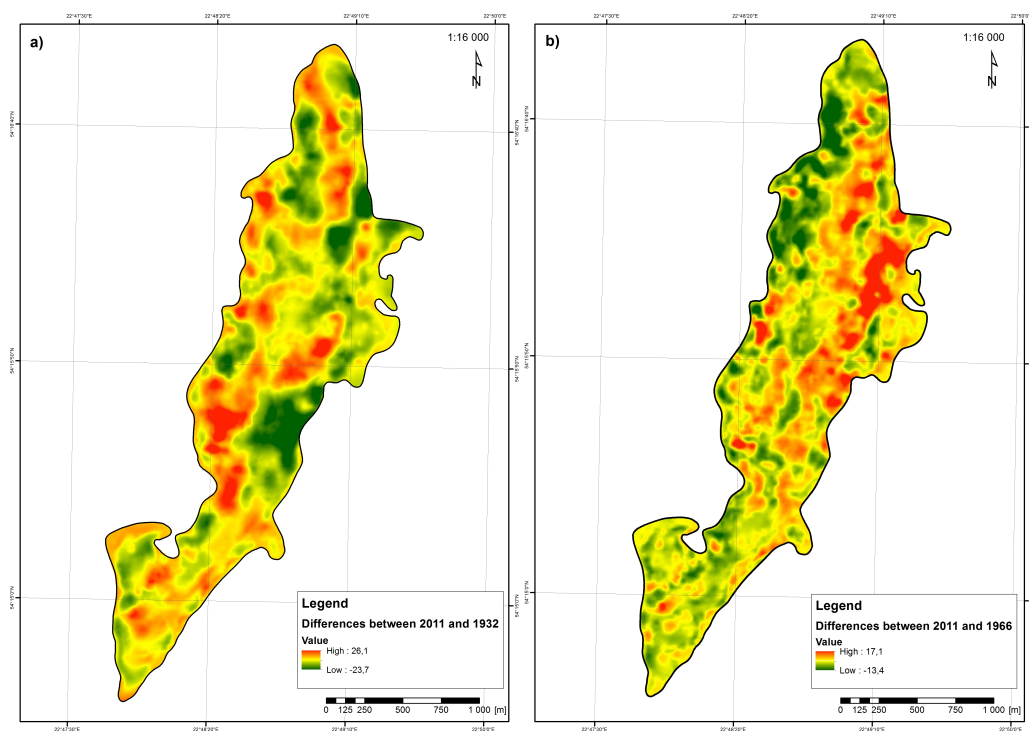


Figure 8: Subtraction of bathymetric maps: 2011-1932 a), 2011-1966 b).

6.2 Morphometry analysis

The study of differences between morphometric parameters from the new and previous survey has caused some problems in the interpretation of results. The DEM quality is basically a function of the accuracy of individual survey points (GNSS positioning and depth measurements), the field measurements strategy and the method of interpolation. The methodology implemented by the authors, new techniques of spatial data acquisition and raw data elaboration give large data sets with high accuracy (5-10 cm horizontal and 5 cm depth detection accuracy).

The historical soundings were done with the use of traditional techniques which were not as precise as the new ones. What follows is that not only time-dependent bottom changes, but also a difference in the accuracy of measuring equipment is evident in the presented results. Additionally, the water levels during historical soundings were not clearly specified. This made it difficult to accurately compare the new bathymetric results with historical data and draw conclusions about sedimentation rates, shoreline development, etc.

The new morphometric and bathymetric parameters of Lake Hańcza were elaborated and compared with the historical data (Table 3). The analysis of the 1932, 1966 and 2011 survey suggests that over 80 years the surface area of Hańcza Lake has changed from 296.3 ha to 303.6 ha. It shows that the area parameter at first increased by 15.1 ha and then decreased by 7.3 ha. The length of the lake decreased by 10 m in 1966, but is similar to 2011. The maximum width has not changed significantly, but in 2011 it increased by 5 m. The biggest changes took place in the mean width of the lake. It varied in value from 653 m to 688 m and then to 669 m. These changes were reflected in the development of the shoreline parameter $Ld1$ (respectively 2.08, 1.88, 2.04). It was reduced by 9.6% in 1966, although the new survey showed a similar value of $Ld1$.

The measurement techniques and computation methods utilized in the 2011 survey differ from those employed in the previous surveys. When comparing the area-capacity between the historical and the new hydrographic survey, the new calculation of maximum lake length (L_{max}) - 4,536 m will probably serve as more accurate for future work. The analysis of volume and depth showed the reduced capacity of the lake. The maximum depth of the lake was reduced from 108 m, 108.5 m and 106.1 m to 105.55 m. The depth is directly connected with the real water levels: 227.2 m, 229 m, 227.45 m and 227.46 m respectively.

The results from 1932 and 2011 are surprisingly similar, despite the rudimentary techniques used to develop

the morphometric parameters in 1932. It suggests that the differences were rather an effect of imperfections in the method of depth measurements (especially positioning), bathymetry elaboration and morphometric parameters calculation rather than significant changes in the lake morphology.

6.3 Bottom sediment analysis and environmental aspects

The above hypothesis was also confirmed by the contemporary analysis of sediments. The historical study made by Rühle indicates that in the central deepest area the bottom mineral content was predominantly made of sand and gravel. The results of the authors' research indicate the occurrence of a loose layer of organic sediment – a dozen or so cm on average. Under a layer of detritus the light-colored carbonate gyttjas with interbeds of mineral and organic material were detected. In the study of 1932 this layer was probably identified as the sandy bottom of the lake.

An average sedimentation rate of carbonate or detritus gyttjas in Polish lakes' profiles was estimated of 1-2 mm per year [32–34]. It can be assumed that sedimentation rate in the last decades has been increasing as a result of anthropogenic changes in catchment areas and accelerated eutrophication processes. However, the thickness of the sediment layer identified after more than 80 years corresponds well with the above assumptions. Contemporary environmental studies [35, 36] did not confirm the prevalence of suspended matter sources silting the lake bottom and consequently a rapid increase in the rate of sediment deposition is unlikely.

7 Conclusion

The main objective of the present work was to describe a simple but reliable and accurate methodology of bottom shape investigation of inland reservoirs. The proposed technology uses modern, integrated satellite positioning (GNSS) and hydroacoustic (SBES) techniques. The presented methodology also includes a historical bathymetric data analysis and a contemporary study of bottom sediments. The proposed lake floor topography investigation process was implemented during bathymetric measurements of the deepest lake of the Polish Lowland - Lake Hańcza.

The authors' research includes a careful study and analysis of the historical bathymetry, integrated GNSS and

Table 3: Changes of the morphometric parameters of Lake Hańcza in 1932, 1966 and 2011.

Year	1932	1966	2011
Source	Rühle	Inland Fisheries Institute in Olsztyn after Rühle & Stangenberg	Popielarczyk, Templin & Łopata
Maximum lake length (L_{max})(m)	4 535	4 525	4 536
Maximum width (B_{max}) (m)	1 175	1 175	1 180
Mean width (B_{min}) (m)	653	688	669
Area (ha)	296,3	311,4	303,6
Shoreline length (m)	12 700	11 750	12 599
Shore Development Index L_{dl}	2,08	1,88	2,04
Volume (thousands m ³)	124 400	120 364	118 648
Maximum depth (D_{max}) (m)	108,0	108,5	105,55
Mean depth (D_{min}) (m)	42,0	38,7	39,1
Relative depth (Z_r) (m)	0,0630	0,0616	0,0606
Mean aspect	12°3'	-	12°9'

hydroacoustic measurements, a maximum depth investigation, a DEMs and bathymetric maps elaboration, a morphometric parameters calculation and a bottom sediment study. As a result of the newest bathymetric survey performed in 2010 and 2011, a digital elevation model of the bottom was elaborated and finally the accurate maximum depth result was determined to be 105.55 m with the water elevation above the sea at 227.46 m. The maximum depth was investigated and confirmed with the use of three independent systems: Reson NS 515 200/33 kHz dual frequency SBES, Simrad EA 5011P 200 kHz SBES and manual sounding using stranded wire machine. Taking into account similar results of the maximum depth investigation conducted by Choiński and Skowron in 1997 (106.1 m, the water level 227.45 m) and bottom sediment study results we can conclude that the other, different values of the maximum depth served in the bibliography, result from imperfect measurement methods and inconsistencies in the reduction of the measured depth to the average water level.

Nowadays most of research activity shifts from the representation of the form of the Earth's surface to the analysis of the processes that define its dynamics. The spatial analysis presented in the article utilize historical data and require taking into account specific procedures, such as a measurement sensor, instruments, algorithms or process chain.

An important element of the methodology proposed by the authors is a thorough analysis of archival materials. Source data, historical bathymetric plans and morphometric parameters, technical reports and bibliography help scientists to analyze bottom changes over the last few decades. In the case of Lake Hańcza the first historical and the new bathymetry parameters have shown that the

new digital elevation model of the bottom is slightly higher than the Rühle data. Taking into consideration the water levels, the maximum depth between 1932 and 2011 differs by 2.7 m. On the basis of the authors' study the bottom sediments in the deepest area were characterized by the presence of only a thin (0.2 m) layer of loose, slimy texture, supported by a concise gyttja formations. Rühle described the bottom in 1930 in the central region of the lake as being hard with sand and gravel but the new bathymetry echograms (200/33kHz frequencies) and direct inventory show up to a 30-cm layer of soft, organic sediment on the bottom. The rate of growth at 2-3 mm/yr over the 80 years that have elapsed since the date of the first Rühle bathymetric measurements could result in shallowing the lake basin by an average of 0.2 m. The authors' investigation shows that the difference in the maximum depth of Lake Hańcza which was observed between the historical and contemporary measurements (2.7 m) cannot be due to the deposition of organic matter on the bottom.

To monitor bathymetry, morphometric parameters and changes in the shape of lake bottom, bathymetric surveys can be performed periodically (for example every ten years), using the same methodology and modern measurement techniques that have been presented by the authors. The differences between the digital elevation models and morphometric data depending on the elapsed time may help to identify any physical changes in inland lakes occurring over decades.

The authors demonstrate that the dynamic growth of global satellite positioning systems, geodesy, laser scanning, aerial photography, hydroacoustic techniques, remote sensing and GIS technologies provide a great opportunity to study the underwater environment. The col-

lected bathymetric data and bottom sediment study results are used not only for the creation of bathymetric maps and digital elevation models, but also for morphometric studies and research in hydrobiology, limnology, fisheries and other environmental research. For example, the new Lake Hańcza morphometry has been used to investigate changes in the spatial distribution of phosphorus and nitrogen (P, N) [36].

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