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Hydrographic Surveying of the Steppe Lake Neusiedl – Mapping the Lake Bed Topography and the Mud Layer

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Keywords: hydrographic surveying, sub-bottom-profiling, side scan sonar, Lake Neusiedl, mud layer

Summary: To ensure the various functions of the Lake Neusiedl, commercial as well as ecological, in the future a sound management of the water, the mud and the reed belt is required. Management needs concise data to assess the risks and vulnerability. In order to build on previous investigations, to observe changes, and to create a high resolution digital terrain model (DTM) of the lake bed, a comprehensive survey of the lake bottom and the mud layer was initiated. Hydrographic surveying methods based on acoustic echo sounding techniques provide the back bone of topographic data generation of the lake bottom and the mud layer. The acoustic echo sounding system consists of side scan sonars, single beam sounders and a sediment profiler. Shallow lakes with a composition of thick mud layers compared to the water depth are a challenge for these systems. Transects were measured in a regular grid by boat. To verify the echo sounding measurements, to obtain data in areas with a water depth lower than 50 cm (where echo sounding is not applicable), and to provide data for the transition zone between the water body and the reed belt, a combination of soil physical sensors in a measuring system was introduced. The single-point measurement system consists of a capacitive sensor and a cone penetrometer. At selected points soil cores were taken as an additional reference. A global navigation satellite system (GNSS) for real-time kinematic (RTK) positioning of dynamic, precise vertical point-measurements was utilized for the exact positioning of all measurements.

Cross-correlation of the dataset enabled the identification of outliers and systematic errors, hence the provision of the dataset with high quality. This spatial data is now available with an overall accuracy of better than ± 10 cm to generate DTMs of the lake bottom and the mud layer.

Zusammenfassung: *Hydrographie des Steppensees Neusiedler See – Vermessung des Seebodens und der Schlammschicht.* Damit der Neusiedler See als besonders schützenswertes Ökosystem sowohl in seiner ökologischen Funktionsfähigkeit aber auch in seiner ökonomischen Funktion erhalten bleibt, ist eine genaue Kenntnis der Wasserfläche, des Schlammkörpers und des angrenzenden Schilfgürtels von Nutzen. Daher wurde eine topografische Aufnahme des Seebodens und der Verteilung und Mächtigkeit des darin abgesetzten Schlamms initiiert. Durch den Vergleich mit vorangegangen Vermessungen können so auch Veränderungen aufgezeigt werden. Die hydrographische Vermessung basierend auf Echolotmessungen mit Einzelstrahl-Echolot, Sub-Bottom-Profiler und Seitensichtsonar stellt die Basis für die Generierung von Seeboden und Schlammoberflächenmodellen dar. Zur Validierung der Echolot-Schallausbreitungswerte für Schlamm und zur Erfassung der Seichtwasserflächen im Uferbereich (Übergang von der Wasserfläche zum Schilfgürtel) wurden zusätzlich Einzelpunktmessungen mit einem adaptierten bodenphysikalischen Messsystem durchgeführt. Dieses Messsystem basiert auf zwei gebräuchlichen Sensoren, einem kapazitiven Sensor und einem Penetrometer, welche mit einem RTK-GNSS georeferenzierte Vertikalprofile von der Wasser-Schlamm Seebodensedimentschichtung liefern. Die Referenzmessungen dienen zur Eliminierung von Ausreißern und systematischen Fehlern der Echolotmessungen. Damit wurde als Ergebnis ein hochwertiger Datensatz mit einer Genauigkeit von besser als ± 10 cm zur Generierung Digitaler Geländemodelle (DGM) der Schlammoberfläche und des Seebodens und somit zur Bestimmung der Schlammverteilung erstellt.

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1 Introduction

Shallow endorheic lakes, like Lake Neusiedl (Hungarian: Fertö), are particularly vulnerable to changes in climate parameters. An increase of the air temperature because of global climate change would have a considerable impact on the water balance of Lake Neusiedl. Extreme water levels will cause significant changes in the expanse of the water surface, causing multiple consequences for the lake's eco-system, agriculture and local tourism (Soja et al. 2013, EuLakes vol. 2 2013: 44ff.).

Another important factor for a reduction of water volume of the lake is the accumulation of unconsolidated sediments (mud) in the lake basin. It is enhancing due to a shift of wind-driven sediments, which are accumulated in the surrounding reed belt (Bácsatyai et al. 1997).

To carry out investigations on present vulnerabilities and risk assessment, and for the improvement of lake water management issues it is necessary to develop realistic water level scenarios (Schönerklee et al. 2006: 45ff.). In 2011 a cooperative project between Hungary and Austria was initiated in order to provide a homogeneous topographic data base of the Lake Neusiedl basin and the Hanság-Channel also including the investigation of the huge, stratified mud body of the lake (GeNeSee 2011).

Hydrographic surveying methods based on acoustic echo sounding techniques were chosen to provide the topographic data of the lake bottom and of the mud layer, particularly with regard to generate high resolution digital terrain models (DTMs) of the lake bed.

Applying acoustic echo sounding techniques for detecting the acquisition of mud in shallow waters, like lakes and estuaries, is highly demanding due to the presence of unconsolidated material suspended in the water column. The distortion of the acoustic signals in unconsolidated fine grained sediments (mud) may result in an erroneous detection of the lake bed sediment structure (Buchanan 2005, Schrottke et al. 2006, Missiaen et al. 2008). To deal with those misleading acoustic parameters at Lake Neusiedl with a stratified mud body of up to 2 m, additional tools for the provision of density information are required.

The aim of this paper is to describe the acquisition of highly accurate lake bed data for generating DTMs of Lake Neusiedl with special regard to the distortion of acoustic signals in the mud body. The aim is reached by the application of a high frequency echo sounder, a parametric sub-bottom profiler, side scan sonars, and measurements with soil physical sensors for the detailed interpretation of the sediment structure.

2 Site Description

Lake Neusiedl is the westernmost steppe lake in Europe located in the western part of the Little Hungarian Plain (Fig. 1). The lake basin covers a total area of 321 km^2 at the boundary line of 116.50 m above sea level, of which 233 km^2 are on the Austrian and 88 km^2 on the Hungarian territory (Bácsatyai et al. 1997). The open water body of Lake Neusiedl has a total area of about 143 km^2 and is surrounded by an extensive reed belt of about 178 km^2 (Schmidt & Csaplovics 2011), which is the second largest connected reed belt in Europe. The lake is quite shallow with a huge stratified mud body consisting mainly of fine sediments. On the Austrian territory the mud volume has almost doubled during the period from 1963 – 1988, from 75 Mio. m^3 to 150 Mio. m^3 (Csaplovics 1998: 58, Bácsatyai et al. 1997: 41). These values provide only an order of magnitude of the increase, because the data acquisition methods and the amount of surveyed data in the years 1963 and 1988 are not directly comparable.

The water balance of the lake is dominated by precipitation and evaporation, and just minor inflow of the river Wulka and even less inflow (~ 2%) origins from ground water springs. 80% of the water gain originate from precipitation and 90% of the water loss is due to evaporation, which is the predominant factor concerning the water balance. Groundwater level changes due to extensive agriculture have no significant impact on the lake water level. Indirect connection is given by the climate, which affects both water bodies in a significant way (Schönerklee et al. 2006: 54 ff.). Variations in sunshine duration, mean air temperature, precipitation and other meteorological components cause significant changes in evaporation. The change of air temperature of +0.7 °C in the period of 1991 – 2004 compared to 1961 – 1990 induced a rise in evaporation of nearly 10%. Since 1740, the lake has dried out four times. The last vanishing was from 1864 to 1870 (Nationalpark Neusiedler See – Seewinkel 2012, Loiskandl et al. 2012). The Lake Neusiedl has no natural outflow. At the end of the 19th century, an artificial channel for excess water drainage was constructed. A weir at the main regulation channel Hanság regulates nowadays the lake water level according to operation rules and supervised by an Austro-Hungarian committee for water bodies. The weir can only prevent flooding, drainage of excess water, but not raise the lake water level, thus the lake water level is predominated by precipitation and evaporation (Eitzinger et al. 2009).

3 Methodology

The core of the applied hydrographic measurement system is based on different acoustic sensors for depth measurement and image acquisition of the lake bed (3.2, 3.3 & 3.4), combined GNSS/IMU components to determine ships position and attitude and a hydrographic data acquisition, navigation and processing software package to plan, manage and synchronize all different sensor measurements (3.1). Fig. 1 gives an overview of the system of the survey vessel.

Subsequently, the application of a soil physical sensor system delivers precise height information of the mud layer and the sediment structure at 61 individual reference points, thus enabling the determination of proper sound velocity parameter for processing the sub-bottom echo soundings of the entire lake.

3.1 *Positioning and Navigation Data*

Positioning and navigational data are needed for determining the correct geographic coordinates of the depth measurements (depth soundings) and for navigational purposes of the survey boat.

The geographical situation of the lake in an open plain and the nearly constant appearance of wind causes waves on the lake surface, and a water level rise at one lake side and a drop at the other, with a period of minutes or even hours, called a *wind tide* or a *seiche*. In March 2013, strong north-westerly winds sustaining over many hours caused a water level difference between Breitenbrunn (NW-end) and Apetlon (SE) up to 90 cm (Geschnatter 2013).

As waves cause heavy motions of the survey vessel in all six parameters (fore-aft, lateral, vertical, roll, pitch, and yaw), the accurate determination of position and attitude parameters are crucial for the quality of the final lake bed coordinates, i.e. for the vertical component.

This could be achieved with the integration of satellite based positioning (GNSS) and high quality inertial measurement system (IMS) based on fibre optic gyroscope.

A RTK-GNSS system was used to provide real-time 3D-position data with an accuracy of ± 3 cm and a data rate of 10 Hz. Permanent GNSS base stations distributed on three places around the lake delivered the necessary RTK-GNSS correction data. The transmission from GNSS reference station to GNSS rover was realized with UHF radio modem “Satelline Easy Pro”, which offers different setup possibilities, to fulfil the Hungarian as well as the Austrian telecommunication regulations.

Remark: The use of UMTS modems for receiving real-time correction data for precise VRS-GNSS positioning failed due to bad UMTS coverage at the border region (Austria-Hungary) (Heine et al. 2013).

A 6-parameter motion sensor IXBLUE/IXSEA Octans was used to provide highly accurate true heading, motion, speed, and acceleration data. This inertial measurement unit (IMU) consists of gyrocompass and motion sensor, and delivers attitude information with an accuracy of 0.1° on heading and 0.01° on roll and pitch.

On the survey vessel, the transducers of the acoustic system were placed on the outside of the hull; situated at the starboard bow, the starboard beam, the port bow, and the port beam (Fig. 1b). The GNSS-antenna and the IMU where placed amidships. The offsets (lever arm), between all sensors, were defined by an X, Y, and Z offset from the GPS antenna as the origin for all measurements.

The integration of the GNSS/IMU measurements and lever arm information for the determination of position and attitude for each transducer, and finally the calculation of the lake bottom coordinates based on the acoustic measurements were realized by the use of the hydrographic data acquisition, navigation and processing software package QINSy (quality integrated navigation system) (QINSy 2014).

ETRS89 was selected to be the homogeneous coordinate reference system for all geodetic measurements on the lake within the GeNeSee project, whereas UTM33N is the commonly used cartographic projection. Transformation to the national horizontal and vertical geodetic datum can be done using transformation parameters and geoid data provided by the respective national mapping agencies.

3.2 *Acoustic System: Single Beam Echo Sounder (SBES)*

High frequency single beam echo sounder (Simrad 710-36) with a narrow 2.8 degree beam was used for detailed mapping of the water depth. Its high frequency of 710 kHz allows using a short pulse length providing fine range resolution. In areas with soft bottoms, it will detect the upper limit of mud.

Furthermore the nominal depth range minimum of 0.1 m allows carrying out detailed measurements of the very shallow shore zones.

3.3 *Acoustic System: Parametric Sub Bottom Profiler (SBP)*

Sediment profilers, also known as sub bottom profilers (SBP), are structurally similar to single-beam sounders, but working at lower frequencies and thus gathering vertical cross-sections of the inner sedimentary sea bed structure (Lurton 2002). Parametric echo sounders are based on the concept of non-linear generation of acoustic waves. During simultaneous transmission of two signals of slightly different high frequencies at high sound pressure, a new frequency arise, with a frequency equal to the difference between the two primary frequencies. The resulting low frequency signal allows a better bottom penetration and a high vertical resolution.

For determining the sediment layers in Lake Neusiedl an Innomar SES 2000 parametric sub bottom profiler was used. The device generates a low frequency between 4 kHz and 12 kHz based on primary frequencies of around 100 kHz. The system is able to achieve a resolution of about 5 cm, an accuracy of ± 2 cm + 0.02% of the water depth for the 100 kHz frequency, and about ± 4 cm + 0.02% of the water depth for the chosen low frequency of 10 kHz (Innomar 2005). This requires detailed information about the sound velocity for the penetration material, which ranges between 1450 m/s and 1900 m/s for saturated sediments (Santamarina et al. 2005).

3.4 *Acoustic System: Side Scan Sonar (SSS)*

Several projects at estuaries and shallow coastal zones have shown that side scan sonar in combination with results of sub-bottom profiling and bathymetry provides more details of the sedimentation process itself and verifies the classification (Nitsche et al. 2004, Schrottke et al. 2006).

200 kHz high-resolution side looking sonar for shallow water surveying were used for mapping the morphology of the lake bed. Two transducers (Simrad 200 kHz – 0.5° x 49°) were mounted at the port bow and the starboard bow respectively, looking athwart ships. The side scan sonar images have a pixel resolution of 10 cm and are displayed as monochrome images (Fig. 2). The grey scale variations represent "backscatter" energy received from the lake bed, with strong backscatter producing lighter tones and weak backscatter producing darker hues. This variation is caused by a complex range of factors, such as lake floor slope, topographic variability, grazing angle of insonification (geometry of the sensor-target system), physical characteristics of the target surface, e.g. surface roughness, and the variations in sediment composition (Ulrick 1983).

3.5 *Combination of Soil Physical Sensors in a Measuring System (CSPS)*

A complementary methodology of single-point measurements with a soil physical approach was used to support acoustic techniques for mud layer and lake bed mapping (Kogelbauer et al. 2013). The designed system combines two commonly applied soil physical measurement techniques and provides reproducible physical values joined with a RTK-GNSS for dynamic, horizontal and vertical point positioning (Fig. 1c). The designed system enables the delineation of water, mud, and lake bed sediment layers. It utilizes three main components: 1.) a capacitive sensor (Hydra Probe, Stevens Water Monitoring System) to determine the water content in soft mud and a modified cone penetrometer (Eijkelkamp) to measure penetration resistance in compact mud layers and shallow lake bed sediments, 2.) the data acquisition system using a data logger (CRX23, Campbell) to process data from the sensors and a GNSS RTK, and 3.) developed C# based software for synchronizing sensor data and GNSS position.

The designed system is based on well-known and commonly applied sensors that provide physical values for comparative purpose. Moreover, it supports non-destructive in-situ measurements without cost and time consuming sampling effort. The synchronization with a RTK-GNSS enables rapid dynamic vertical measurements with highly accurate positioning. Thus, this non-acoustic system provides valuable ground truth information for the echo sounding layer delineation.

The Hydra Probe is based on frequency domain reflectometry (FDR) at 50 MHz and indirectly indicates volumetric water content θ ($m^3 \cdot m^{-3}$) by measuring the relative dielectric permittivity ε_r. The dielectric permittivity ε_r enables the layer delineation of the water-mud interface by its significant difference, with ε_r in air (1), Lake Neusiedl water (70 – 80), and solid particles (4 – 7). It was correlated to the water content by a site-specific laboratory calibration, which accounted for the variation of mud composition throughout the lake. The data pairs of ε_r with θ were fitted to a third degree polynomial ($R^2 = 0.9877$) (1) (D'Amboise 2012).The Hydra Probe measurement error of ε_r was ± 1.5%.

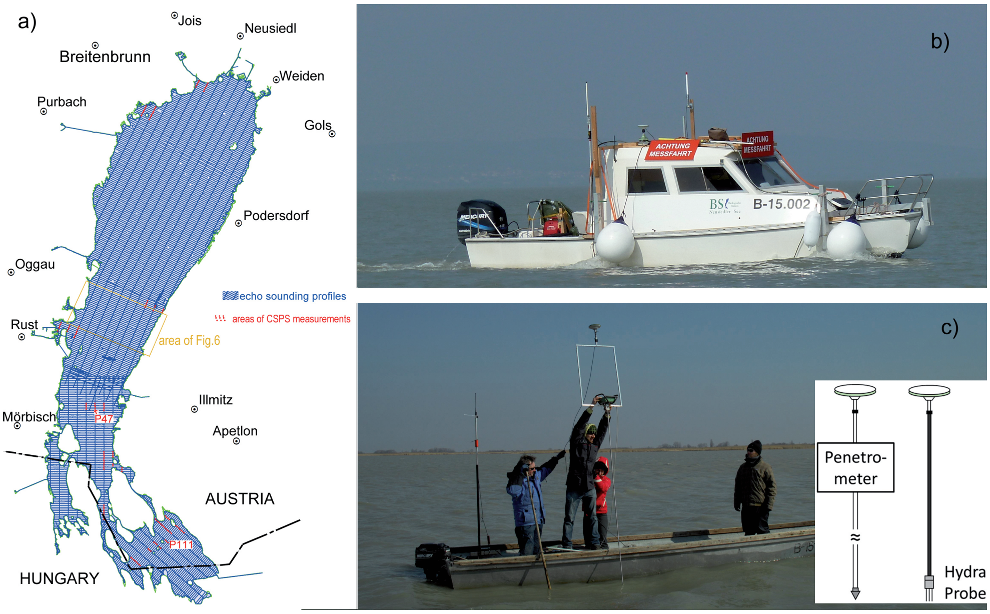


Fig. 1: a) Echo sounding profiles and distribution of calibration points, b) survey vessel, c) mud layer measurement with soil physical sensors system, i.e. penetrometer.

$$\theta = -0.087968 + 0.027307\,\varepsilon_r - 0.000356\,\varepsilon_r^2 + 2.34 \times 10^{-6}\,\varepsilon_r^3 \quad (1)$$

The cone penetrometer, the second sensor, measures the penetration resistance PR_x (MPa), which is the force required to push forward the cone penetrometer through the soil (Bradford 1986). The laboratory calibration of the cone penetrometer related the output voltage y (mV) from the penetrometer's force transducer with the applied weight. Hereby, a linear relation was obtained (2) with the base voltage y_0 (mV) and the cross sectional area of the cone $A_{p,x}$ (cm^2) (Kogelbauer et al. 2013). Another factor for the probing rod weight $R_{p,x}$ was added. The conversion from mV to MPa was as proposed by Bradford (1986), where also the factor 0.09807 arises.

$$PR_x=((y-y_0+R_{p,x})/(29.82*A_{p,x}))*0.09807 \quad (2)$$

4 Survey and Data Collection

4.1 *General Echo Sounding Survey Setup*

The echo sounding measurements were realized along transects. The sounding lines run perpendicular to the assumed centre line of the lake bed, with a line spacing of 100 m. For quality control, lines of 500 m spacing running parallel to the lake bed centre were defined. Mistakes and gross errors as well as systematic errors are able to be detected at the intersection point of the transect lines.

Furthermore, surveying lines running parallel to the shore line had been defined to enable a comprehensive mapping of the shore zone by means of the side scan sonar.

The sounding lines and actual vessel position and vessel heading were visualized together at a navigation screen for the helmsman to steer a correct and steady course.

Sound velocity profiles (SVP) were measured frequently to correctly produce echo sounding depth measurements. Presence of unconsolidated material suspended in the water column affects the speed of sound propagation. Changing suspension situations due to swirl up of fine bottom sediments caused by waves, as well as the significant variations in water temperature during the survey (28 °C in August, 4 °C in November) requires sound velocity correction of the soundings, even for shallow water depths.

4.2 *Set-up and Measurement Procedure of the CSPS*

The Hydra Probe and the cone penetrometer were modified to enable measurements at the lake. For this application the Hydra Probe was mounted on a telescope rod with a GNSS antenna mounted on top. The modifications of the cone penetrometer were the direct connection of the strain gauge to the datalogger and the extension of the probing rod. The probing rod length of up to 5 m depended on the water depth and the possible penetration depth. The GNSS antenna was fixed on a frame at the penetrometer aligned with the penetrometer's cone tip. The detection of shallow layers with the penetrometer setup was restricted by factors such as the rod length, the lateral bending resistance of the rods determined by the rods' diameter, and muscular strength of the person in charge (Kogelbauer et al. 2013).

The designed system (CSPS, combination of soil physical sensors) was applied at the open water area for referencing echo sounding, at shallow water areas below 0.5 m to describe the shore line topography, and at the reed belt areas. The measurement procedure was similarly conducted at all sites using the sensors consecutively at the same site to create an instantaneously vertical profile in the soft mud and the consolidated lake bed sediments. The Hydra Probe measurement starts at the water surface, with the sensor head and its tines still in the air. After a few seconds the sensor is slowly inserted in the water and continuously submerged until no further penetration of the sensor is possible due to compacted mud. The penetrometer measurement starts at the mud layer, when first minimal pressure resistance is detected. The sensor is slowly submerged until the consolidated lake bottom. The pressure resistance rapidly increases when reaching more compacted mud and the shallow, consolidated lake bed sediments. Each sensor measurement was repeated at least three times for the same area to consider local variability of the mud layer structure. At the open water surface the measurements were taken at predefined echo sounding reference points, using a small boat tied up by stakes. At the shore zone the measurements were taken along a short transect, starting with a point in the reed, going on at the transition from the reed to the open water surface, and then at the open water. This enables a description of the lake bed topography at the transition from the reed to the open water.

Mud cores were collected at some of the predefined echo sounding reference using a hand core sampler with polycarbonate core barrel. These samples had been analysed qualitatively (colour, roots) and quantitatively (particle size distribution, total and inorganic carbon, total nitrogen, pH, electrical conductivity, mineralogy) for the calibration of the CSPS sensors. In Tab. 1 the particle size distribution of the mud core samples of two reference points are listed. The percent by weight are given for the sand fraction S (from 2 mm to 0.063 mm), silt fraction U (from 0.063 mm to 0.002 mm), and clay fraction C (below 0.002 mm). The samples generally show high content of silt (0.002 mm to 0.05 mm) and clay (below 0.002 mm).

5 Results

The echo sounding campaigns resulted in a total of 2,000 km of transect measurements for SSS, SBES and SBP respectively. Approximately 4100 CSPS measurements are available for calibration purposes, complementing shallow areas (water depths below 50 cm) and shore line sediment layer composition and shore line morphology. More than 550 CSPS measurements are located at ten test areas of different mud accumulation, distributed over the lake area (Fig.1a), to account the distortion of acoustic signals.

According to the measuring campaigns the results can be classified as:

SSS morphological information

Georeferenced side scan sonar (SSS) images: About 4000 SSS images were georeferenced using accurate positioning and attitude information from the RTK-GPS and IMU sensors. Due to a medium water depth of 1.4 m,

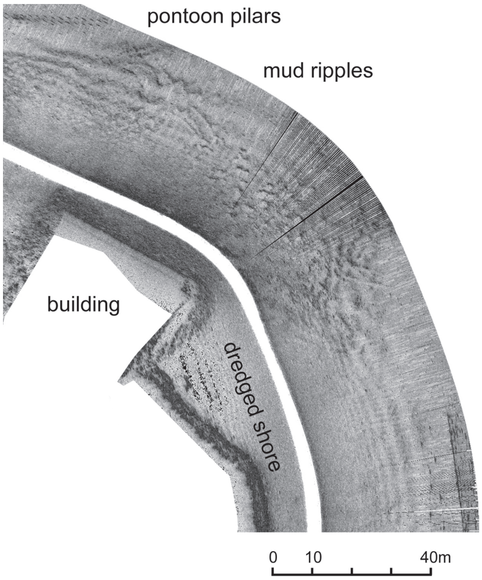


Fig. 2: Side scan sonar image showing mud ripples and man-made structures.

Tab. 1: Particle size distribution of the core samples at the reference points P47 and P111 (masl = metres above sea level).

	Elevation (masl)		p(S) (%)	p(U) (%)	p(C) (%)
P47	113.40	113.56	5.6	54.6	39.8
	113.56	113.64	1.6	45.1	53.3
	113.64	113.72	2.2	41.9	55.9
P111	114.19	114.23	1.4	47.1	51.5
	114.23	114.28	4.1	44.5	51.4

the suitable sonar image strip width is limited to approximately 30 m. Information about the transition zone from the lake bottom to the reed area as well as manmade structures, pontoon pillars, dredged harbours etc., and mud surface morphology is given in detail. The main differences in the side scan backscatter of the mud surface represent erosional, depositional and dynamic environments (Fig. 2).

High frequency echo sounding depth measurements of the mud surface layer

2,000 km of echo sounding depth measurements surveyed with high frequency sensors of 710 kHz and 100 kHz, and at low frequency of 10 kHz are available. The high frequency data show clearly a distinct reflection at the water-mud interface and enables the calculation of an accurate mud surface layer (Fig. 3).

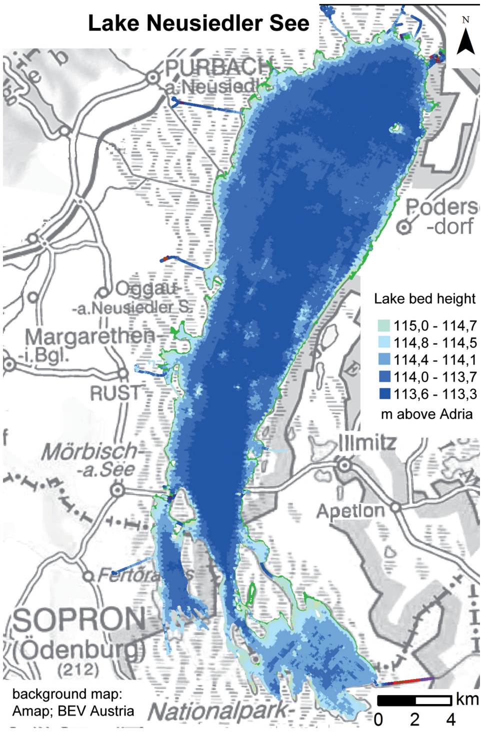
CSPS data and 10 kHz Sub Bottom Profiler data for mud thickness determination

The 10 kHz frequency is penetrating well the sediments and displays also significant reflections of layers deeper in the subsoil.

For the interpretation and correct layer detection of the 10 kHz sub bottom data, it was necessary to apply proper sound velocities not only for the water column, but also for the mud layer and for the subsoil. This could be achieved by integrating CSPS measurements in the sub-bottom data processing. 61 reference points within ten zones of different mud accumulation were compared. All reference points (CSPS measurements) were placed at intersections of at least two echo-sounding transects.

The comparison shows, that the first reflection displayed in the echogram is approximately at the same height as the Hydra Probe delineates the water-mud interface by a sudden decline to smaller volumetric water content θ ($m^3 \cdot m^{-3}$). The second reflection representing the interface between mud and the cohesive lake bed sediment is corresponding to the first significant pressure resistance peak detected by the cone penetrometer.

The acoustic sound velocity for the sub bottom layer detection was adapted until the echo sounding layers fitted with the CSPS layer delineation. After that, in spite of small differences, the hydro acoustic sub bottom data is providing reasonably good lake bed sediment structure information of Lake Neusiedl. As an example, reference points at two representative sites with different sediment layer composition (P47 high mud accumulation and P111 low mud accumulation), are shown in Figs. 4 and 5.



background map: Amap; BEV Austria

Fig. 3: Topography of the lake bed (mud surface).

The CSPS measurements, left part in Figs. 4 and 5, of the Hydra Probe in water at almost constant θ of about 0.95 is interrupted by a sudden decline in θ to about 0.80 indicating the water-mud interface. The submersion end of the Hydra Probe sensor coincides with the point of detecting significant pressure resistance PR, consequently a continuous vertical mud-sediment profiling is gained with both sensors (Kogelbauer et al. 2013). In detail, the Hydra Probe measurements (ID47 and ID50; top blue scale) in Fig. 4 show a clear water-mud layer transition at 113.85 masl, where the vol. water content θ suddenly decreases below 0.95. The penetrometer measurements (ID51 and ID53; bottom black scale) at point P47 detect two shallow top layers, which are also recorded by the echo sounder. The lake bottom is the significant penetration resistance peak of 1.2 MPa at 112.95 masl. The first penetration resistance peak at 0.6 MPa indicates already compacted mud. Thus the mud layer is about 0.9 m thick, ranging from the water-mud interface at 113.85 masl to the lake bottom at 112.95 masl, with an increasing degree of consolidation starting at 113.21 masl.

In contrast to a distinct mud layer at point P47, point P111 (Fig. 5) shows almost no mud layer and a highly consolidated lake bottom in the CSPS profile as well as in the echogram. The Hydra Probe measurements (ID4 and ID5) indicate only a very thin mud layer of about 8 cm at the water-mud interface height of 114.30 masl. The penetration resistance (ID7 and ID8) of the penetrometer rapidly increases indicating a highly consolidated layer that prevents further penetration. A high degree of consolidation is also indicated by the intensive red colour of the interfaces in the echogram.

The challenge for the establishment of a concise spatial dataset was the combination of SBES, SBP and CSPS in an optimum way to achieve the highest possible accuracy. Each dataset passed an individual quality check, based on classical statistics, removal of outliers, noise, and averages of repeated measurements. These datasets were then cross-referenced at approximately 61 calibration points, utilizing an interactive software tool, originally designed and programmed for the CSPS data smoothing and measurement analyses. In a further step cross referencing was performed using nearest neighbours of SBES and high frequency SBP data points. Hence, for each calibration point mud layer surface heights and thickness were obtained. Finally distortion factors for low frequency SBP readings were inversely calculated by comparing

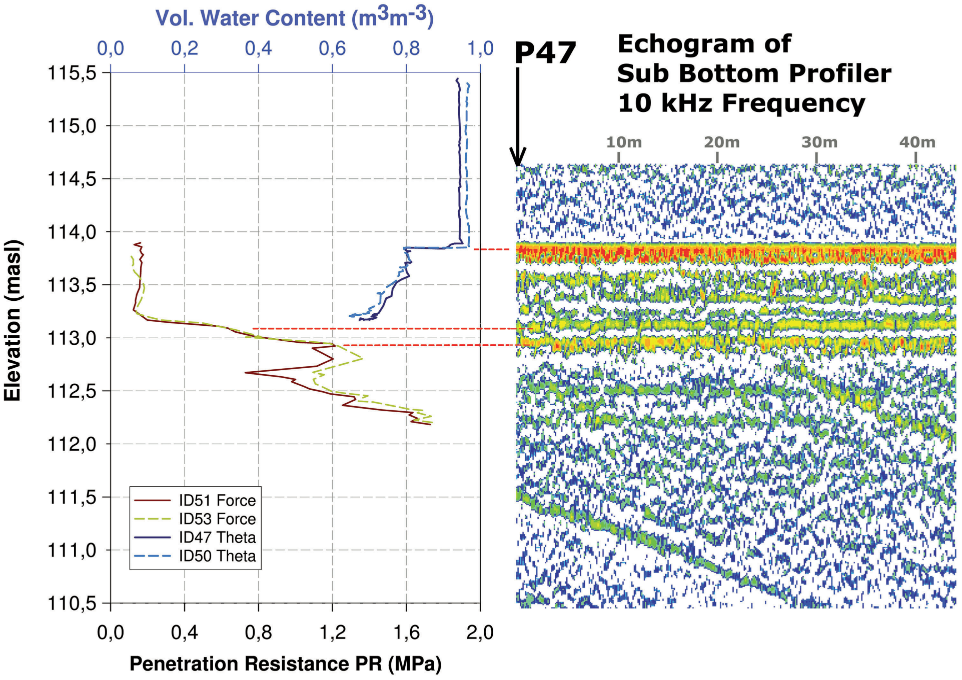


Fig. 4: Example of the layer validation by comparing the SBP echogram sequence (right) with the CSPS (left) at the reference point P47. The layering in the echogram coincides reasonably well with the CSPS interfaces. Strong reflections due to high impedance contrast indicated interfaces visualized by red-yellow.

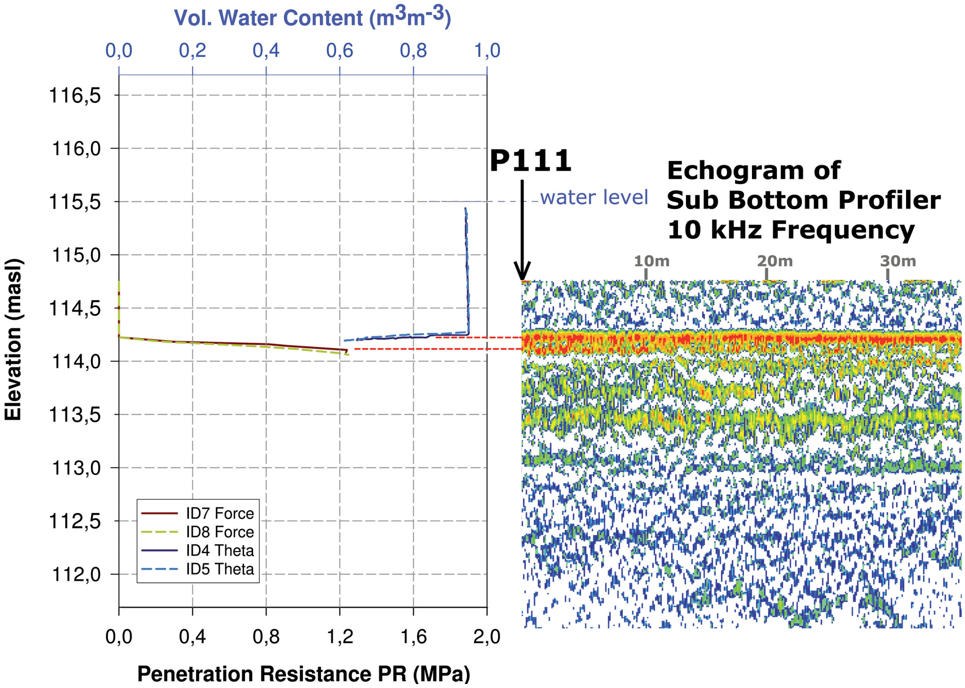


Fig. 5: Second example of layer validation at point P111 comparing the SBP echogram sequence (right) with the CSPS (left) showing little mud accumulation and a consolidated shallow lake bed.

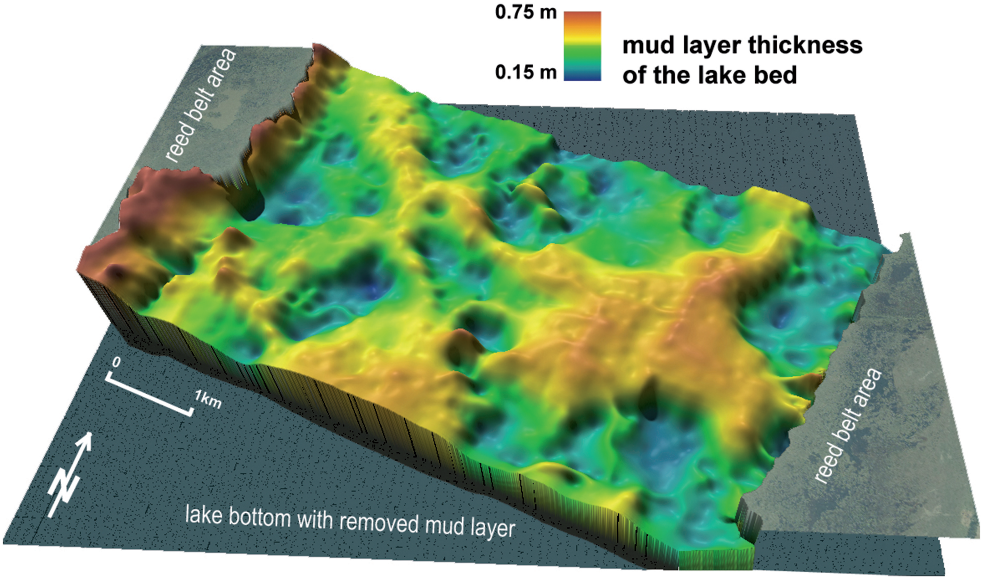


Fig. 6: Mud layer distribution and thickness at the central part of Lake Neusiedl, vertical exaggeration factor = 200.

the CSPS thickness and the SBP raw data. Thus the SBP data post processing was able to deliver a layer of consolidated sediments of the lake bottom within an accuracy of ± 5 cm. The difference between both layers is a good indicator for thickness and distribution of the mud layer of Lake Neusiedl (Fig. 6).

6 Discussion and Outlook

It could be proven that for the conditions of a shallow lake the water-mud interface can be reliably detected with SBES, SBP and CSPS. The results showed a very good agreement of these methods in the detection of the mud surface. The used SBP delivered suitable sediment layer images up to several metres. For an exact determination of the thickness of the mud layer, the distortion of the acoustic system could be calibrated with the readings of the CSPS. Repetitions of CSPS profile measurements proofed the reproducibility of data and reliability of the concept. Moreover, physical profile values are providing a continuous description of the depth of the sediment layer compositions.

Cross-referencing ensured the compensation of systematic errors of the echo sounding systems due to the density differences of water and mud layer. This procedure enabled the calculation of spatially distributed interface heights of high quality.

SSS images provide additional information for generating the shore line for the digital terrain model. The information about the shore line sediment layer composition and morphology is delineated from CSPS measurements at the transition zone from the open water body to the reed area.

The final result is a topographic dataset of the lake bottom and the mud layer, allowing generating high resolution digital terrain models (DTMs) of the lake.

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