GROUND-PENETRATING RADAR (GPR) SCREENING IN SHALLOW ENGURE AND PAPE LAGOON LAKES

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Abstract

Geophysical studies in mapping and screening applications are widely applied for archaeological, environmental, geological, hydrological and many other applications. Ground-penetrating radar (GPR) is one of methods from geophysical toolbox that is also called a ground-probing radar, subsurface radar, surface-penetrating radar and ‘georadar’ or impulse radar – it is a non-invasive and non-destructive technique. Pulsed electromagnetic signal is recording the reflected energy and scattering from subsurface objects. Studies were performed in former Littorina Sea lagoons that became lakes after the further Limnea Sea stage in the Baltic Sea established with comparatively lower absolute sea level that is close to present day situation. Characterization of sediments as well as full sediment core description for comparison with GPR signals were performed. Major results show that GPR as non-destructive method in combination with geological coring followed by laboratory analysis of sediment properties can be successfully used to describe layering conditions, topography and depth of shallow lakes. Although there are some limitations regarding the electromagnetic (EM) noise and similar EM properties of analysed sediments, proper treatment of data gives complementary insight thus diminishing the necessity of dense coring network establishments in analysed areas of lakes. The aim of this screening study is to analyse potential advantages of GPR use for mapping sediments and topography of sandy bottom in shallow lagoon lakes as well as pinpoint problems during field and cameral works considering electromagnetic, geological and topographical disturbances.

Key words: ground-penetrating radar (GPR), benthic sediments, lagoon lakes, geophysics.

Introduction

Characterization of various environments (e.g., glacial, fluvial, aeolian or lacustrine) is influenced by obstacles of previous geological environment such as accumulation and erosion processes. The influence of these processes is mostly recorded in sedimentary architecture (Slowik, 2014). Geophysical methods might be useful tools for studies of internal structures as well as obtaining information about relief forms and their historical evolution. Nowadays geophysical data is becoming a primary source for such information versus traditional methods (e.g., coring and trenching) (van Dam, 2000; van Dam, 2012). In a variety of archaeological, environmental, engineering, geological, and hydrological applications, ground-penetrating radar (GPR) has become a popular geophysical tool with which to image the shallow subsurface (Bristow & Jol, 2003; Daniels, 2004; Jol, 2009).

In principle, GPR emits a pulsed electromagnetic signal and records the energy reflected and scattered at subsurface structures and objects. Data can be processed in a similar way to reflection seismic studies for obtaining a relatively structural image of the subsurface. GPR is a non-invasive and non-destructive geophysical technique that detects electromagnetic discontinuities in the shallow subsurface (< 50 m) (Neal, 2004). Despite some difficulties, GPR surveys are widely used in different scientific and applied fields: geosciences, structural and health monitoring, archaeology, forensic, exploration and mining, sedimentology (Ansellmetti *et al.*, 2004). A key step in processing acquired data sets is the use of an appropriate migration scheme moving dipping reflections to their real position, eliminating electromagnetic (EM) noise, crossing and diffraction events resulting from point reflectors (Yilmaz & Doherty, 2001). During complex structural settings, the migration itself becomes an essential processing step for imaging subsurface structures and, thus, is a prerequisite for a relevant interpretation of GPR information. Despite all positive applications provided by GPR and diminishing technological weaknesses, it is still a research technique that can be called as the ‘state-of-the-practice’ rather than ‘state-of-the-art’ - it is developing and geophysicists are still elaborating the organisation of the multitude of parameters to enhance data quality and elaborating interpretation by improving technological tools (Parker *et al.*, 2010). The shallow water environment creates operational problems with geophysical surveying in general matter as was pinpointed already by Dobinson *et al.*, 1990. Case studies onshore as well as offshore by using GPR methods in combination with offshore high-resolution reflection seismic methods have been used for sedimentological analysis, e.g., Geneva Bay area (Switzerland) (Ansellmetti *et al.*, 2004; Beres *et al.*, 2006). GPR allows the imaging of sedimentary structures with some exceptions in the shallow sub-surface. It provides a near-continuous record both above and beneath the groundwater sometimes even impossible by using conventional techniques. Therefore, it is used in a variety of depositional environments: wetland (Comas *et al*., 2004; Sass *et al*., 2010), glaciofluvial (Asprion & Aigner, 1999), fluvial (Leclerc & Hickin, 1997; Vandenberghe & van Overmeeren, 1999; Hickin *et al*., 2009; Słowik, 2012), aeolian (Tatum & Francke, 2012), glacial (Sadura *et al*., 2006), and finally technogenic (Blumberg *et al*., 2004; Słowik, 2011). Fluvial and wetland environments are most challenging for geophysical surveys in general due to high groundwater level standings and presence of clay and organic. These have properties of relatively low EM wave (Neal, 2004). Groundwater saturation and porosity are important factors causing GPR reflections. By the increase of moisture, the effect of free water in sediments affects GPR reflections (van Dam & Schlager, 2000; Koh, 2012). Sediments with significant admixture of clay give attenuation of the GPR signal (van Heteren *et al*., 1998; Bano *et al*., 2000). EM wave propagation has been detected also in Sass *et al*., 2010. Studies reveal that 2 m penetration in clayey sediments might be doable (Barone *et al*., 2013) hence are marked significantly lower than in unsaturated sands and gravels (Jol & Smith, 1995). Depth range and resolution of GPR surveys are dependent on antennae frequency (Neal 2004), hydrogeology (Boll *et al*., 1996; Steelman & Endres, 2010; Koh, 2012; Barone *et al*., 2013), climate conditions (Lunt *et al*., 2005; Tran *et al*., 2012).

In Latvia, scientific studies by using GPR have been performed mostly for peat properties and mapping studies as well as hydrological applications (Karuss & Berzins, 2014; Karuss, 2015).

The aim of this screening study is to analyse potential advantages of GPR use for mapping sediments and topography of sandy bottom in shallow lagoon lakes as well as pinpoint problems during field and cameral works considering electromagnetic, geological and topographical disturbances. GPR data in joint analysis with coring and laboratory information from experimental screening case studies in Engure and Pape lakes elaborate understanding of geophysical screening potential for mapping applications in shallow partly overgrown lagoon lakes.

Materials and Methods

Screening case study lakes and their geological description

Engure and Pape Lakes (Fig. 1) are relatively large and shallow lakes in Coastal Lowland developed during Littorina Sea stage and are separated (from the Gulf of Riga and Baltic Sea, respectively) by 1.5 to 2.5 km wide dune strips. At present, the Engure Lake depth

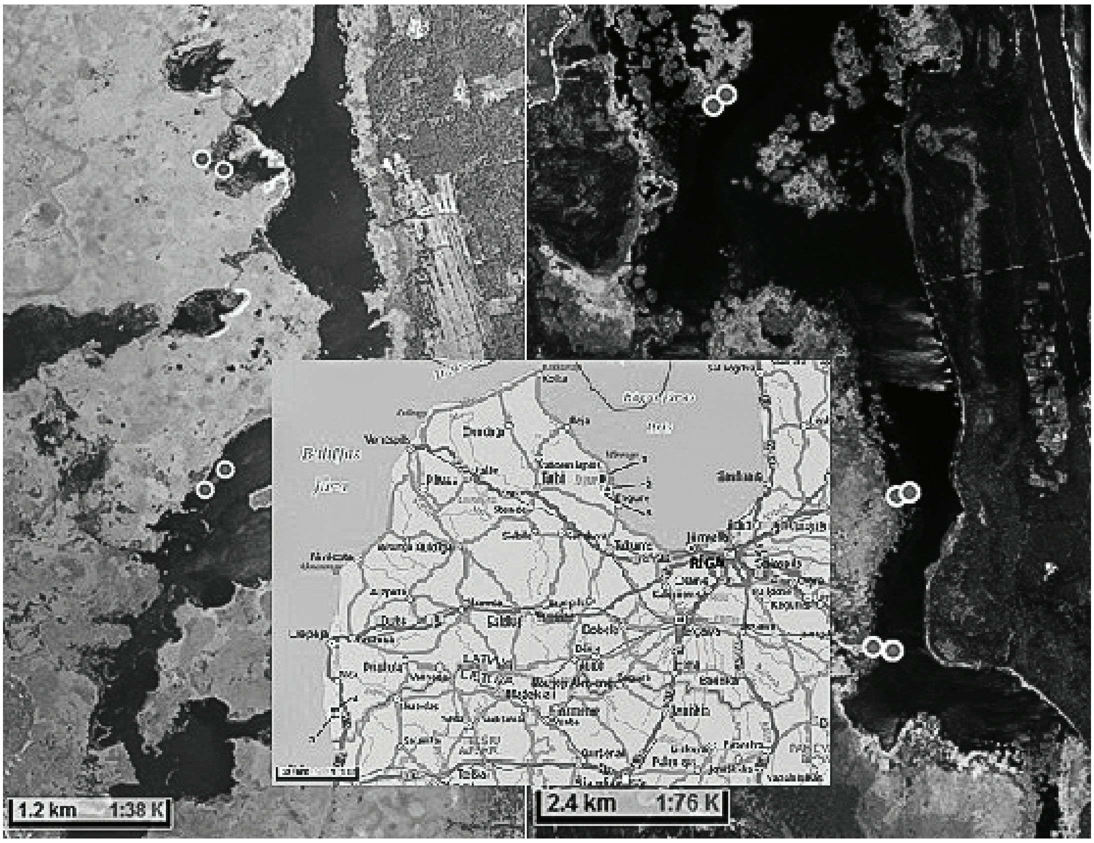

Figure 1. Location of sediment sampling and geophysical profiling sites in Pape (A) and Engure Lakes (B).

does not exceed 2 m and the Pape - 1 m (Eberhards *et al*., 2000), with an average depth of only 0.40 m for Engure and even less for Pape where depending on season the lake almost disappears (Prieditis, 2002). Banks of flat, open coastal landscape dominate, coasts of both lakes in several places are grazed and are severely overgrown. Sediment samples of various types were derived from both shallow overgrowing freshwater lakes containing rich organic sediment layers, located in Engure and Rucava Districts, in Latvia (Figure 1).

Sediment sampling cores in lakes were carried out in certain points selected according to the established network and coupled with geophysical study profiles (Fig. 2-5). Texture analysis, elemental and moisture content, loss of ignition, pH, conductivity were determined and are given in Table 1-3. Mostly organic material, mud and gyttja (sapropel) are covering mineral soil layer which is mostly sand, gravelly sand and rarely glacial till.

Coring of sediments was done using a Russian-type peat sampler equipped with a 1.0 m long (d=5 cm) camera. Every cored sample was put into a non-transparent air-tight plastic bucket with a lid and stored at constant temperature (+4 ºC) to achieve *in situ* conditions during the storage. Sediment core was

Table 1

Description of sediment profiles pH, ash, dry matter content in studied lakes (Engure, Pape)

Sample No.	Depth, m	pH	Content of organic matter, %	Content of carbonates, %	Ash, %	Moisture, %	Content of dry matter, %
Engure Lake							
1	1.33-1.50	6.74	17.08	1.65	84.58	78.99	21.01
	2.00-2.10	6.84	26.98	0.69	73.71	80.04	19.96
	2.35-2.50	8.5	10.53	8.53	98.00	76.42	23.58
2	1.50-1.60	7.15	34.06	0.19	66.14	91.76	8.24
3	2.60-2.70	6.65	3.61	0.12	96.51	45.16	54.84
Pape Lake							
4	1.50-1.60	6.65	15.58	0.14	84.56	82.68	17.32
	2.80-2.90	6.81	12.94	0.10	87.17	73.46	26.54
5	1.50-1.65	6.45	14.95	0.08	85.13	83.38	16.62
	2.50-2.60	6.91	17.02	0.20	83.18	82.58	17.42

Table 2

Lithology of Engure Lake sediments

Engure Lake								
	Coring coordinates	57°27’39,49” N 23°09’19,16” E			57°22’56,55” N 23°13’10,55” E			57°21’07,24” N 23°12’31,40” E
No.	**Depth, m**	**Lithology of sediments**	**No.**	**Depth, m**	**Lithology of sediments**	**No.**	**Depth, m**	**Lithology of sediments**
1	0-0.7	Water	2	0-0.9	Water	3	0-2.2	Water
	0.7-0.95	Mud		0.9-1.2	Mud		2.2-2.25	Mud
	0.95-1.85	Sapropel		1.2-1.8	Mud/sapropel		2.25-2.45	Peat
	1.85-2.1	Peat		1.8-2.3	Sapropel		2.45-2.5	Sapropel
	2.1-2.20	Sandy sapropel		2.3-2.6	Sand		2.5-2.6	Sapropel
	2.20-2.25	Sand with shells		2.6-2.75	Sand with shells		2.6-2.7	Sand
	2.25-2.30	Peat		2.75-2.85	Sand			
	2.30-2.35	Sand						

Table 3

Lithology of Pape lake sediments

Pape lake					
	Coring coordinates	56°20’56,20” N 21°04’28,11” E			56°18’55,26” N 21°04’45,17” E
No.	**Depth, m**	**Lithology of sediments**	**No.**	**Depth, m**	**Lithology of sediments**
4	0-0.73	Water	5	0-0.6	Water
	0.73-1.15	Reed roots with partly decomposed mud		0.6-1.25	Reed roots with partly decomposed mud
	1.15-1.35	Mud		1.25-1.62	Mud with reed roots
	1.35-3.00	Sapropel		1.62-2.5	Mud/sapropel with reed roots
	3.00-3.25	Sapropel with organic material		2.5-3.3	Sapropel
	3.25-3.5	Sandy sapropel		3.3-3.45	Sandy sapropel

characterised by type of sediments. Loss on ignition (LOI), pH and metal content analyses has been done for samples of sediments (Heiri *et al*., 2001)

GPR studies

The theoretical background to the GPR technique and the practical methodology of data collection are comprehensively described in the current literature (Davis & Annan, 1989; Reynolds, 1997; Neal & Roberts, 2000). The Zond-12e GPR Advanced equipped with shielded 500 MHz antenna, manufactured in Latvia by Radar Systems was used for the measurements. In Engure Lake, transects with length ~200 m were scanned, but in Pape Lake ~500 m. After test runs for better results there was decided to use dielectric permittivity – 81 with scanning rate – 512 samples per trace. Sounding (time) range was used 300 ns, which is equally 5.00 m in nature with used dielectric permittivity. Also, strong high-pass filter was applied for soundings.

Results and Discussion

GPR like other geophysical method characterises the subsurface and can identify inhomogeneous features or objects that differ from homogenous material. Identification of these anomalies is often the objective of a geophysical survey or buried target identification (Robinson *et al*., 2008; Kearey *et al*., 2002). The use of geophysical methods on water bodies is slightly different to terrestrial as the freshwater is chemically less variable in axial and planar directions than soil. Water bodies and their chemical composition are changing faster over shorter periods of time in comparison to soil (Parker *et al*., 2010). Objects can be identified when a contrast is sufficiently large to alter the geophysical signals of the subsurface. GPR survey success is dependent on complexity of soil or water body and differences of physical and chemical properties of material; also complexity of structures and textures influences interpretation quality (Parker *et al*., 2010). Lagoon lakes in this case can provide even more complexities, e.g., conductivity and suspended matter in water masses have certain EM noise effects creating additional wave propagation and reflection that leads to difficulties within interpretation works. The main reason is that fresh and saltwater have similar dielectric properties (about 80 each) and radar velocities (freshwater has 0.033m ns^{-1}, saltwater – 0.01m ns^{-1}); however, both mentioned have very incompatible conductivity parameters (freshwater has

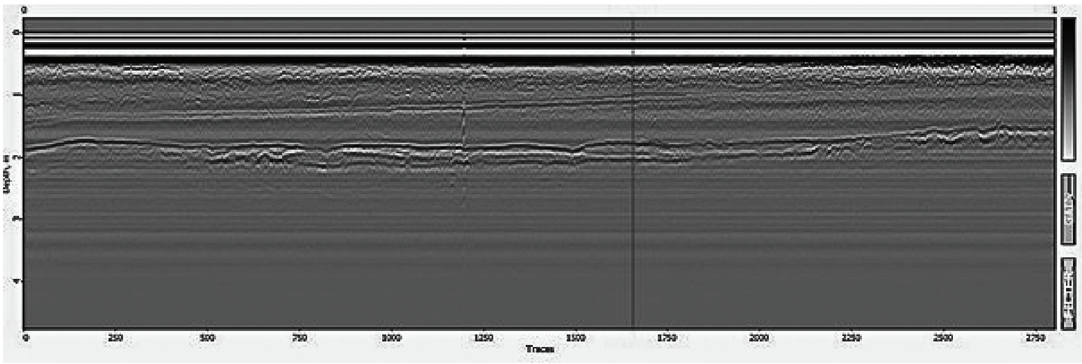

Figure 2. Scanned transect with GPR in Engure Lake (No.1).

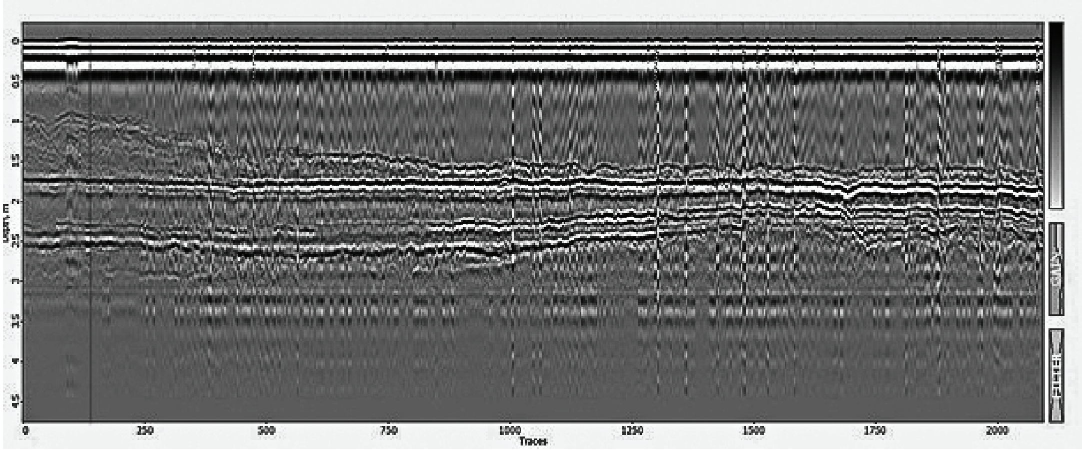

Figure 3. Scanned transect with GPR in Engure Lake (No.2).

0.5 mS m^{-1}, saltwater even up to 30 000 mS m^{-1}). All radar signals in such water bodies are simply soaked up. Nevertheless, in majority of freshwaters GPR response is good enough to operate with radar signal and discover layers and buried objects (Ruffell, 2006).

Studied lagoon lakes are shallow with several sediment layers with slight differences between Engure and Pape Lakes (Table 2, 3). High content of mineral compounds (also clays) and minor differences among layers in Pape Lake (Table 1) causes problem to analyse and even see the GPR signal. Most of the signal dissipates in sediments and deeper layers cannot be seen (Fig. 5, 6). Problems of permittivity in that kind of material correspond to results in literature, where is suggested that GPR is not a viable choice for surveying in clay rich areas where 5 – 10% clay content can reduce penetration depth to less than 1m (Parker *et al*., 2010; Karušs *et al*., 2012).

In GPR profiles with horizontal lines, sub-surfaces of sediments detected with GPR and confirmed by coring (vertical line) simultaneously are marked. For example, in Engure Lake (Fig. 2, 3, 4) easily can be

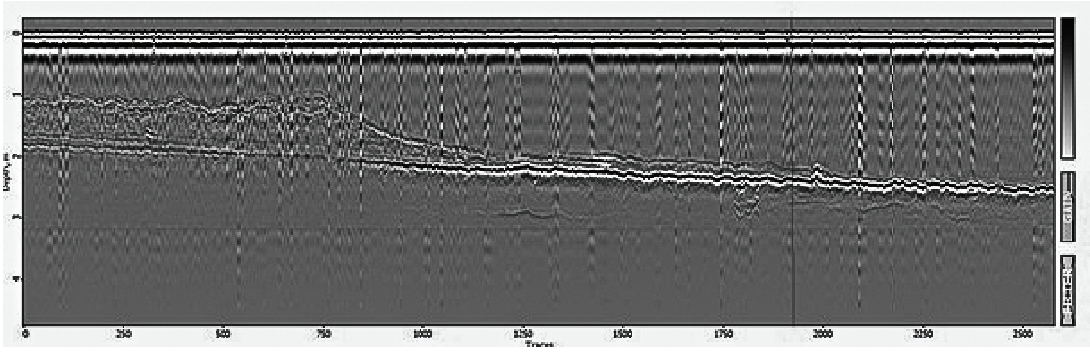

Figure 4. Scanned transect with GPR in Engure Lake (No.3).

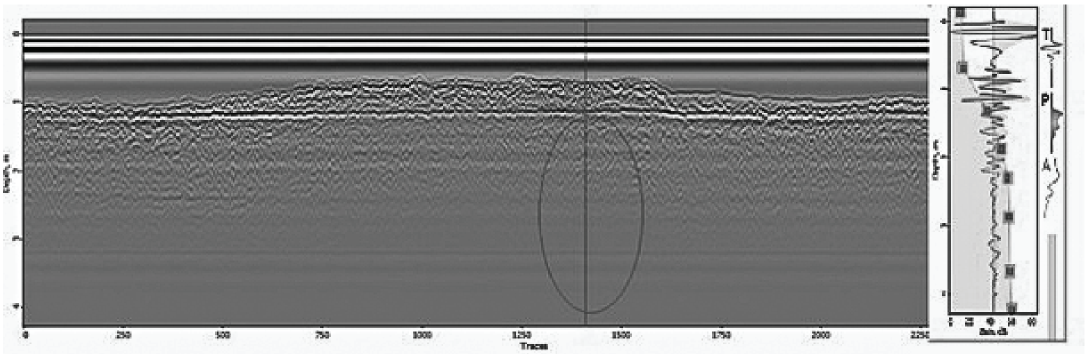

Figure 5. Scanned transect with GPR in Pape Lake (No.4).

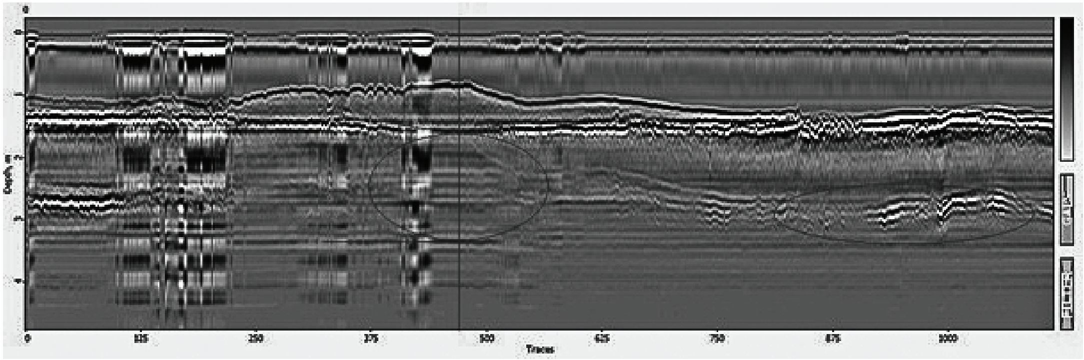

Figure 6. Scanned transect with GPR in Pape Lake (No.5).

distinguished upper sedimentary layers, but problems appear with detection of deeper layers. One of key problems is too slight difference among sediments (high homogeneity) of metal content as well as relatively uniform sediment composition. Sandy bottom clearly can be identified only in GPR profile 3 (Fig. 4) in Engure Lake where noticeable differences between sub-surface and upper (Holocene) sediments are detected. Other factor are differences of EM wave propagation among sediment layers, respectively, propagation speed in peat is significantly faster than in gyttja (sapropel) with high clay content above the peat layer. In the theory of EM wave propagation it is known that if bottom layer dielectric permeability is greater than the divisional layer complex dielectric permeability of the environment, the reflected GPR signal will have the opposite phase of the emitted signal (Reynolds, 1997). Due to differences of sediment permittivity ε in comparison to water, there can be slight offset of total depth of deeper sediment layers which can be corrected with adjusted ε or by linking with coring data.

In studied GPR profiles, there are different kinds of disturbances and reflections. For example, noise level and several disturbances can originate from air bubbles in water (boat engine, waves) (Fig. 2, 3, 6). In edges of GPR profile 5 (ellipse in right side) (Fig. 6), there is a strong reflection from upper layers bothering analysis of bottom layers. On the one hand, it is possible to partly identify the bottom layer with sand, but on the other hand, the middle part of sediments (homogenous sapropel layers with high content of reed roots) cannot be analysed even with inequalities of raw data straight form radar. There are differences in GPR profile 4 (Fig. 5.), where slight transition (high homogeneity) of sediments allow us to identify only the upper layer of sediments (marked with lines), but the gain profile (right side of Fig. 5) shows small differences of EM wave reflection in deeper layers (with ellipse marked deeper layers), regarding to composition of sandy sapropel (3.25-3.5 m).

Conclusions

The screening studies in Engure and Pape Lakes have shown that despite technical difficulties of GPR use in field environment on water bodies and complicated procedures of EM noise reduction, the research work can be performed in optimized mode if coupled with coring and laboratory analyses. Crucial aspects in gaining success are careful preliminary study of available geological and paleogeographical information, experience of the personnel in field work, good establishment of GPR profiles and coring points, careful interpretation of gained data as well as appropriate preparation of set of recommendations for further works if more detailed study is needed. Hereby GPR profiles have shown main topography features, approximate boundaries between various stratigraphic and lithological complexes and helped significantly reduce the number of coring points in study and simultaneously keep the quality of dataset.

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