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ADVANCED ASSESSMENT OF SEDIMENT CHARACTERISTICS BASED ON RHEOLOGICAL AND HYDRO-ACOUSTIC MEASUREMENTS IN A BRAZILIAN RESERVOIR

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ABSTRACT

Reservoir siltation threatens the operation and ecological state of many reservoirs worldwide. Due to land use change and more frequent erosive rain events expected in the future, the sediment load to reservoirs is likely to increase. Sediment accumulation in reservoirs and related problems cause already more than 20 billion USD of follow-up costs per year globally. In many cases, the siltation rate, the type of sediment and the spatial distribution within the reservoir are unknown. This makes an appropriate management of the reservoir impossible. Independent of the use of, e.g. hydropower generation or drinking water supply, the exact storage capacity, surface-volume curve, predicted future scenarios as well as the sediment distribution in the reservoir represent crucial information. In order to obtain this type of information for reservoirs, especially if no or little historic information is available, we developed a methodology to assess the existing sediment magnitude as well as the type of sediment. We combined a dual-frequency hydro-acoustic (38 & 200 kHz) sediment classification approach with rheological measurements using a dynamic penetrometer. The measurements were conducted on a medium-sized Brazilian reservoir with a maximum depth of 17 m, which is used for drinking water supply. A set of significant correlations between acoustic backscatter parameters and physical sediment properties (undrained shear strength and cone penetration resistance) allow for a detailed characterization of the sediment composition (grain size, density). The acoustic “hardness” of the sediment reached a Pearson correlation coefficient of $R = 0.7$ with the cone penetration resistance obtained from the penetrometer. In addition, the sediment magnitude was derived. The use of the penetrometer for ground truthing helped to identify the influence of gas voids in the sediment, which strongly changes the acoustic response. Based on the regressions between hydro-acoustic and physical/rheological parameters, the local characteristics were extrapolated over the reservoir surface by conducting hydro-acoustic surveys. Next to the assessment of the lake bed type, a precise estimation of the sediment mass can be performed. Therefore, the developed methodology produces essential information for the management of reservoirs, including the planning of measures like dredging or a life-time assessment of the usable reservoir volume.

Keywords: sediment, GraviProbe, siltation, reservoir, hydro-acoustic

1 INTRODUCTION

Sediment transport and accumulation in and to reservoirs, harbors, waterways as well as rivers, and related technical and environmental problems already cause global follow-up costs of tens of billions of dollars. Next to the costs for operators and the society, disturbed sediment regimes may have severe impacts on the ecological state of water bodies. Due to generally high trapping efficiencies and siltation as well as a high economic importance, multipurpose reservoirs have been in the focus of sediment research for decades (Mahmood 1987; Basson 2009; Schleiss et al. 2016). Future intensification of land use changes in the catchments and more frequent erosive rain events in many places of the world may lead to augmented sediment loads to reservoirs (Gellis et al. 2006) increasing the pressure on sediment and reservoir management (Schleiss et al. 2016). Especially under changing climatic conditions, knowledge about the original and actual exact storage capacity, siltation rate and sediment quality is of critical importance for an adapted reservoir management. Predicted future sedimentation scenarios as well as the actual sediment distribution in the reservoir represent crucial information. One essential part of a good management is sediment monitoring within the existing waterbody as a basis of decisions made by the operator or the authorities.

In-situ lake bed investigations are usually difficult, expensive and can only cover small areas. Hydro-acoustic sediment detection methods show promising results for extensive lake bed classification and sediment magnitude assessment (Harris et al. 2008; Hilgert and Fuchs 2015; Hilgert et al. 2016); however, they are strongly impaired by the presence of free gas in the sediment and they rely on ground truthing information, mostly obtained by sediment sampling. In order to acquire fast and accurate sediment information so-called portable free-fall penetrometers (PFFP) were developed (True 1975; Beard 1981; Stoll 2006; Osler et al. 2006; Stark and Kopf 2011; Seifert and Kopf 2012; Albatal and Stark 2017). Most of the published work was done in marine environments, and only a few examples like Corella et al. 2014 report about freshwater applications. Until now, we are not aware of any published PFFP application in freshwater reservoirs. However, we are convinced that modern PFFP can provide highly valuable information for dam operators. Therefore, we aimed in this study to investigate if the commercial system GraviProbe (dotOcean) can be used to assess the sediment magnitude in reservoirs and also create information about the sediment composition and rheological sediment features serving as ground truthing for a parallel hydro-acoustic sediment assessment. The hydro-acoustic lake bed classification could be used to regionalize this information and create valuable physical sediment maps. However, fluid mud and more consolidated fine sediment often is a challenging substrate for hydro-acoustic lake bed classification. P-wave velocity changes are only a crude measure for detection of the density of sediment volumes (Seifert and Kopf 2012) and especially in organic-rich sediments, free gas can strongly impair the results of sediment magnitude detection as well as sediment classification (Anderson and Martinez 2015; Naudts et al. 2008). In order to create sediment information for reservoirs, especially if no or little historic information is available, we developed a methodology to assess the existing sediment magnitude as well as the type of sediment (granulometry, organic content and wet bulk density). We combined a dual-frequency hydro-acoustic (38 & 200 kHz) sediment classification approach with rheological measurements using the GraviProbe (GP).

The Passaúna reservoir in South Brazil at the border of the metropolitan area of Curitiba is one example of water supply reservoirs of crucial importance to the population and at the same time of a mostly unknown siltation rate. In order to validate the sediment magnitude and relevant physical properties obtained from hydro-acoustic measurements, a free-fall penetrometer (GraviProbe) was deployed 85 times at 28 locations. At all locations, sediment cores or grab samples were taken as ground truthing references. Sediment samples were investigated for grain size distribution, wet bulk density, phosphorus content and loss on ignition. The GP-determined sediment magnitudes ranged from 0.34 m to 1.46 m. A set of significant correlations between acoustic backscatter parameters and physical sediment properties (undrained shear strength and cone penetration resistance) allow for a detailed characterization of the sediment composition (grain size, density) and an empiric model-based spatial interpolation.

2 STUDY AREA

The Passaúna reservoir is located between the parallels 25°15'-25°35'S and meridians 49°25'-49°20'W in southern Brazil in the state of Paraná. It is part of the municipalities of Curitiba, Araucaria, Campo Largo, Campo Magro, and Almirante Tamandaré and is a sub-basin of the Iguaçu River. The sub-basin upstream of the dam has an area of 153 km² (Saunitti et al. 2004). The Passaúna reservoir started operation in 1989. It has an average depth of 9 m and reaches depths of up to 17.2 m. The reservoir is 11 km long. The entrance of the reservoir is a divided water body which is connected to the main body via a channel only (Figure 1). This inlet zone acts as a shallow pre-dam area with low flow velocities. By former hydro-acoustic investigations, the amount of accumulated sediment was assessed to be in the range of 3.7 million m³ (unpublished data). The reservoir with its volume of 66 million m³ supplies about 22% of the population of the metropolitan region of Curitiba. It is located within the Passaúna Environmental Protection Area (APA Passaúna), which was created two years after the reservoir's construction. The APA has an area of 16,000 ha and extends from the upstream parts of Passaúna River to the reservoir. The substrate in the catchment consists of metamorphic and igneous rocks of the Proterozoic basement, dikes of Mesozoic age, sediments of the Curitiba Basin and Quaternary deposits. In its geomorphological aspects, it is heterogeneous, with strong wavy relief formed by hills, altimetry ranging from 875 masl to 1050 masl (Saunitti 2003).

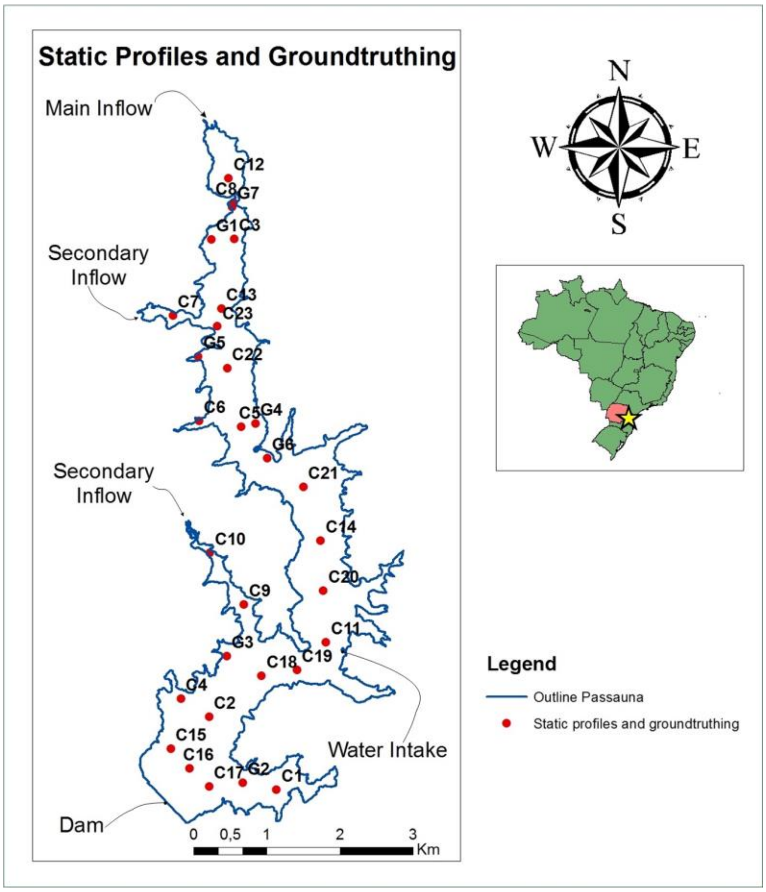

Figure 1. Passaúna reservoir with sediment sampling locations (C = cores; G = grabs).

3 METHODOLOGY

In order to validate the sediment magnitude and relevant physical properties obtained from hydro-acoustic measurements, a free-fall penetrometer (GraviProbe) was deployed 87 times at 28 locations. At all locations, sediment cores or grab samples were taken as ground truthing references. Sediment samples were investigated for grain size distribution, wet bulk density and loss on ignition. Additionally, the sediment was ensonified by a single beam echo sounder with a 200 and a 38 kHz frequency. In order to transfer the derived results to an increased area, the correlations found between rheological and acoustic parameters will be applied to a driven acoustic transect.

Hydro-acoustic Measurements

Ensonification of the sediment with the echo sounder was carried out before disturbing the sediment by sampling or using the GP. The configuration of the EA 400 echo sounder is given in Table 1; it is based on the results obtained by Hilgert et al. 2016. Each location was ensonified for a minimum of 300 pings. Bottom detection was carried out using the Sonar5-Pro bottom detection tool (Balk et al. 2011). The threshold for bottom detection was set to -36 dB to detect the sediment water interface. Based on Burczynski 1999, the signal of each echo is divided into two parts (AttSv1 and DecSv1). The first part covers the attack phase (duration: one pulse length below bottom detection) and the second part the decay phase (duration: three pulse lengths from the end of the attack phase). AttSv1, which is created during the attack phase, is mainly caused by the bottom surface; the energy of this part of the echo can be used as a measure of acoustic hardness or reflectivity. The part of the echo created during the decay phase (DecSv1) is caused by diffuse volume backscattering from the sediment. The energy of this part of the echo is generally described as acoustic roughness (Burczynski 1999). Additionally, derived from the 'first echo division method' the "AttackSv1/DecaySv1-value" and the "AttDecSv1" value, representing the energy of the entire first bottom echo, were exported. By averaging a minimum of 300 pings and selecting the strongest backscatter value, the "Max_Avg_Sv" value was calculated. Without averaging the echo envelopes, the maximum backscatter value was extracted from all 300 pings for the Max_Sv value. Based on the individual Max_Sv values of all 300 envelopes, the Avg_Max_Sv was calculated.

Table 1. Overview of the EA 400 echo sounder configuration.

Frequency	Opening angle (longitudinal)	Opening angle (transverse)	Pulse length (ms)	Power input (W)
200 kHz	7°	7°	0.128	100
38 kHz	13°	21°	0.512	100

Sediment Sampling
Twenty-three sediment cores were taken using an elongated (80 cm) Uwitec Mondsee gravity corer with an inner diameter of 8.9 cm. In addition to the cores, seven grab samples were taken (Figure 1). The sample material was stored in Whirl Paks® (Nasco) sampling bags of two liters volume until analysis. Sediment samples from both coring and grabbing were analyzed for granulometry, loss on ignition (LOI) (Heiri et al. 2001) representing the organic content and wet bulk density (WBD; cores only) (Harris et al. 2008). Granulometry was assessed by wet sieving of the samples (DIN 52098:2005-06), as the use of water guarantees that agglomerates disaggregate and the particles are classified as the correct grain size. To obtain five classes of grain size, sieves with mesh widths of 2 mm, 500 µm, 250 µm, and 63 µm were used. The LOI was measured according to DIN EN 15169:2007.
Around 2 g of each sample were filled into ceramic pots and weighed on a high-precision scale. They were then dried for 12 h at 105°C, cooled to room temperature in a desiccator, and weighed again. The samples were then burnt for two hours in a muffle furnace at 550°C, cooled down, and weighed again to determine the LOI. As the sediment structure of the inner core is assumed not to be disturbed during the penetration of the corer, the wet bulk density can be determined. A sharp-edged cylinder of fixed volume (17.6 cm^3) was used to cut material out of the undisturbed inner core sample. From the weight of the fresh core material and the volume of the cylinder, the wet bulk density of the sediment was calculated.

GraviProbe Measurements
The GraviProbe gathers data about underwater sediment layers during intrusion. It accelerates during the free fall and penetrates fluid and consolidated sediment layers. The data measured by on-board accelerometers, inclinometers and pressure sensors is feeding a dynamical model which determines the geotechnical parameters (cone penetration resistance (CPR), undrained shear strength (USS), depth) of the intruded sediment (Table 2). At each location, the GP was deployed three times in order to receive more robust rheological results. The boat was shifted slightly along the anchor ropes to avoid hitting the spot of the previous sampling. To allow for a constant friction of the rope while the GP is in free fall, a weight on the rope was lowered to the sea bed before releasing the GP. In that manner, only the rope from the ground to the GP at the surface needs to pass through the water column without pulling extra rope behind it.
In order to compare the GP parameters to the hydro-acoustic and sediment parameters, the geotechnical parameters were analyzed in Mathworks MatLab (R2016b) and single values were derived from the penetration curves. The bottom pick and the maximum penetration depth were automatically detected and used for calculation of the penetration depth in the sediment. Additionally, the maximum CPR and maximum USS as well as the ratio of penetration depth to CPR were calculated. The detected depth of the sediment water interface (bottom pick) was used to vertically align all three GP measurements at one location. The profiles were shifted so that the sediment water interface was at the same vertical position. If one of the three runs showed exceptional or illogical results, the corresponding data was discarded and the mean value of only two resulting runs was used.

Table 2. Hardware characteristics of the GraviProbe 2.0.

Characteristics	Value
Depth	3.5 to 35 bar
Dynamic Cone Penetration Resistance	0 – 1000 kPa
Dynamic Undrained Shear Strength	0 – 10 kPa
Maximum Impact	0 – 70 G
Acquisition	5120 Hz Sample Rate
Size	Ø 50mm – L: 960mm – Weight: 8 kg

4 RESULTS AND DISCUSSION

Sediment Composition

The sampling locations ranged from water depths of 2.03 m to a maximum of 14.16 m. Wet bulk density in the core samples had a minimum of 0.7 g cm^{-3} and a maximum of 1.58 g cm^{-3} while the mean value was 1.12 g cm^{-3}. The share of sediment particles smaller than 63 µm in core and grab samples reached from 34.2% to 99.9%, the mean value was 89.8%. LOI was determined between a minimum of 8.4% and a maximum of 51% with a mean of 17%.

Rheological Sediment Properties

In-situ rheological surveys showed distinct differences in the sediment of the Passaúna reservoir. Penetration depth and CPR varied clearly between the measurement locations (Figure 4). The penetration of the GP ranged from 0.29 m to 1.45 m. Within the 28 locations of GP measurements and 85 single measurements, the standard deviation between the runs at each location ranged from 0.01 m to 0.35 m with a mean value of 0.12 cm. Figure 2 (right), shows the CPR over depth of two measurement runs at the location of core 1. The graph illustrates that not only the CPR value is rather consistent between the two runs, but also the course of the line. High and low peaks are well reproduced.

Deepest penetrations were measured in the shallow inflow area of the Passaúna river at the northern end of the reservoir as well as in the southern central part of the reservoir. The penetration depth fits to the expectation of local sediment accumulation rates. For instance, downstream of the fast-flowing part between the buffer area and the main reservoir, where higher flow velocities are likely to prevent finer particles from settling and reducing the overall accumulation rate, the penetration only reached between 0.29 and 0.61 m. At the location of core 17 in the southern part of the reservoir, the core shows 60% of coarse material (> 63 µm) and little sediment overlay. Here, the measured penetration depth reached 0.47-0.66 m. High penetration depths are reached in the direct inflow area where fresh soft material settles due to strongly reduced flow velocities. Likewise, in the deeper central part of the Passaúna reservoir, fine material from internal production and from density currents settles and creates a soft overlay (> 95% silt and clay fraction), which can easily be penetrated (Figure 4). As expected, the CPR showed a contrary behavior. The locations with deep penetration of the GP had low CPR values and vice versa. Even though the sediment composition in terms of grain size did not show a high spatial variability, the GP revealed distinct behavior of the sediment at the tested locations (Figure 3). Nine out of 14 samples with a silt and clay fraction of more than 80% showed very low CPR values in the range of 115 to 186 kPa. The remaining samples reached CPR values of up to 346 kPa illustrating that independent of the grain size distribution, the CPR can vary considerably due to the consolidation state of the sediment. However, Figure 3 shows a clear correlation ($R = -0.65$; $p = 0.05$, $n = 18$) between the share of particle fraction <63 µm and the CPR. Higher shares of sand increase the CPR. This effect can be seen already from a fine and medium sand share of 10% and higher. The correlation between the WBD and the CPR is clearly lower with a Pearson R value of 0.36 ($p = 0.05$, $n = 12$). WBD values close to 1.0 or lower indicate the presence of gas voids in the sediment matrix. Sediment as well as GP data has been tested for normal distribution using ANOVA ($p = 0.05$, $n = 28$) in OriginPro 2018b.

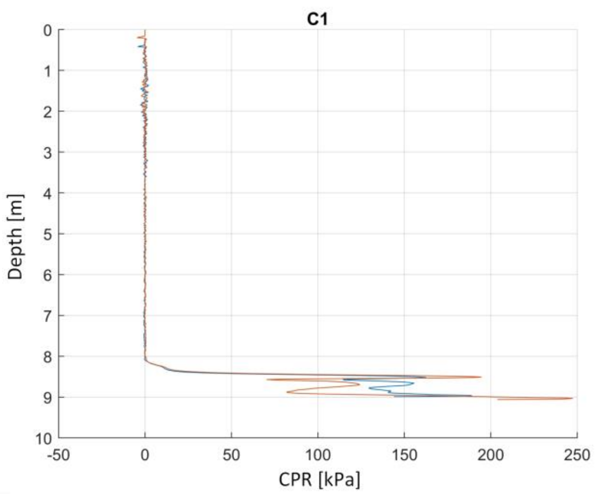

Figure 2. GraviProbe after penetration of a cohesive fine-grained sediment layer (left). Adjusted CPR depth profiles (right).

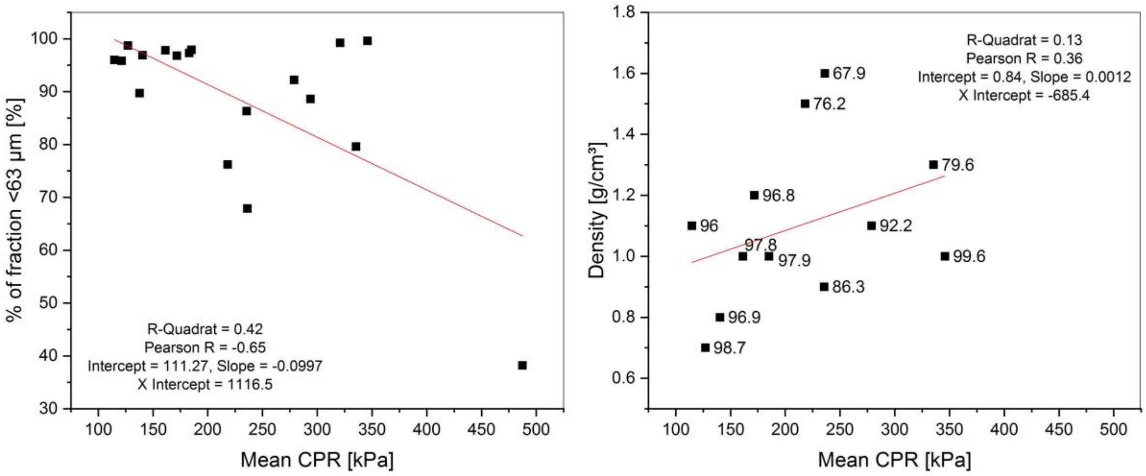

Figure 3. Share of sediment fraction smaller than 63 µm [%] over the mean CPR [kPa] (left); density of the core samples over the mean CPR [kPa], numbers show the percentage of sediment fraction smaller than 63 µm [%] (right).

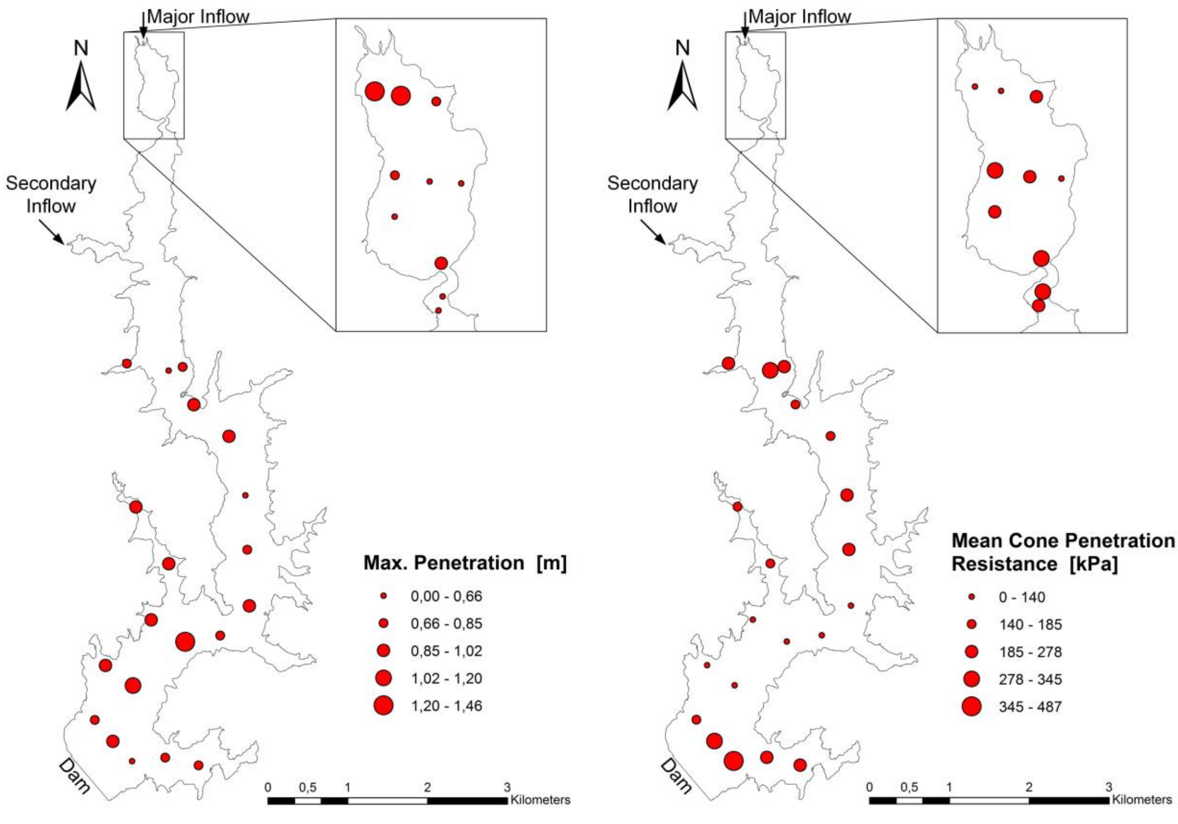

Figure 4. Maximum penetration (left) and Mean CPR (right) measurement results in the Passaúna reservoir.

Acoustic Sediment Properties

From the static ensonification, a set of backscatter values was derived. An overview of the data is given in Table 1. The obtained values were correlated with the rheological values obtained from the GP measurements. Pearson correlation coefficients are given in Table 4. A two-sided significance test was used, and significant correlations are given on a basis of a 0.05 significance level. Significant correlations are marked in red (Table 1). The 38 kHz frequency was not able to produce backscatter information significantly correlating with the GP information. It was shown before that the 38 kHz frequency with the same configuration correlated very well with sediment properties like WBD, LOI, particle share < 63 µm as well as total carbon. Even significant correlations with iron and manganese content were found (Hilgert et al. 2016). In

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this study, the mean and maximum CPR, which are closely related to the density and compactness of the sediment, showed a trend in relation to the 38 kHz parameters, however no significant correlation. This might be due to the lower vertical resolution of the 38 kHz frequency and to the interference with free gas in the deeper layers of the sediment. Hilgert et al. 2016 found very high correlations between the 38 kHz AttSv1 value and sediment properties like density (r =-0.92) and DecSv1 with % < 63 µm (r = 0.95). These results cannot be reproduced in this study. Due to large amounts of gas liberated during penetration of the GP and core sampling, it can be assumed that the gas interferes strongly with the 38 kHz in the deeper sediment layers (> 30 cm below sediment water interface). In the sediment cores, only little to no gas was found in the upper 20 cm of the cores. The larger part of the echo reflected or scattered by the upper part of the sediment in comparison to the 38 kHz could explain why the 200 kHz is able to create the better correlations with the sediment properties as well as with the GP parameters.

Table 3. Overview of the hydro-acoustic backscatter data.

	kHz	Mean [dB]	Min. [dB]	Max. [dB]	kHz	Mean [dB]	Min. [dB]	Max. [dB]
AttSv1		-10.4	-19.2	-6.8		-20	-33	-12.6
DecSv1		-22.9	-37.7	-16		-20.6	-32.6	-15.1
AttDecSv1		-14.9	-23.3	-11.8		-18.6	-27.1	-15.3
Att/DecSv1	**38**	0.5	0.2	1.1	**200**	1.1	0.5	2.1
Max_Avg_Sv		-12.5	-42.5	-4.4		-15.3	-24.6	-9.9
Max_Sv		-1.1	-10.3	4		-3.4	-9	0.8
Avg_Max_Sv		-6.2	-16.2	-2.5		-9.6	-15.7	-6.6

Table 4. Pearson correlation coefficients of hydro-acoustic and rheological sediment parameters. Significant correlations are marked in red (p = 0.05, n = 28).

38 kHz	**AttSv1**	**DecSv1**	**AttDecSv1**	**Att/DecSv1**	**Max_Avg_Sv**	**Max_Sv**	**Avg_Max_Sv**
Max. Penetration	0.15	0.20	0.20	0.10	-0.41	0.13	-0.24
PendDepth_CPR	0.12	0.30	0.21	0.23	-0.36	0.14	-0.10
Mean CPR	-0.06	-0.26	-0.20	-0.31	0.45	-0.31	-0.03
Max. CPR	-0.39	-0.29	-0.46	-0.01	0.35	-0.41	-0.25
Max. USS	-0.29	-0.24	-0.34	-0.04	0.21	-0.31	-0.19

200 kHz	**AttSv1**	**DecSv1**	**AttDecSv1**	**Att/DecSv1**	**Max_Avg_Sv**	**Max_Sv**	**Avg_Max_Sv**
Max. Penetration	-0.45	0.06	-0.15	0.41	-0.61	-0.19	-0.22
PendDepth_CPR	-0.47	0.14	-0.14	0.42	-0.59	-0.16	-0.25
Mean CPR	0.57	0.13	0.41	-0.37	0.79	0.39	0.51
Max. CPR	0.7	-0.02	0.26	-0.42	0.64	0.16	0.35
Max. USS	0.58	0.01	0.39	-0.42	0.56	0.27	0.48

Based on the best-performing regression model of Max CPR and AttSv1 with a Pearson coefficient of 0.7 (Table 4), the following linear function was derived:

$$Max\ CPR = 623.1 + 14.8X \qquad [1]$$

This function was used to calculate max. CPR values along a driven transect of hydro-acoustic measurements (Figure 5). The results show a gradient from the shallower northern part with higher CPR values towards lower values in the middle section of the reservoir, where depths reach around 9 to 12 meters. The southern and deepest part shows CPR values below 231 kPa, indicating the accumulation of soft sediment. In the enlarged part of Figure 5, the accumulation of soft sediment in the depressions and harder sediments or former soil on the slopes is evident. The longitudinal gradient of the derived CPR corresponds to the measured wet bulk density, which reaches 1.21.3 g/m^3 in the northern part, and only 0.81.0 g/m^3 in the southern area of the reservoir, due to larger amounts of free gas in the sediment matrix.

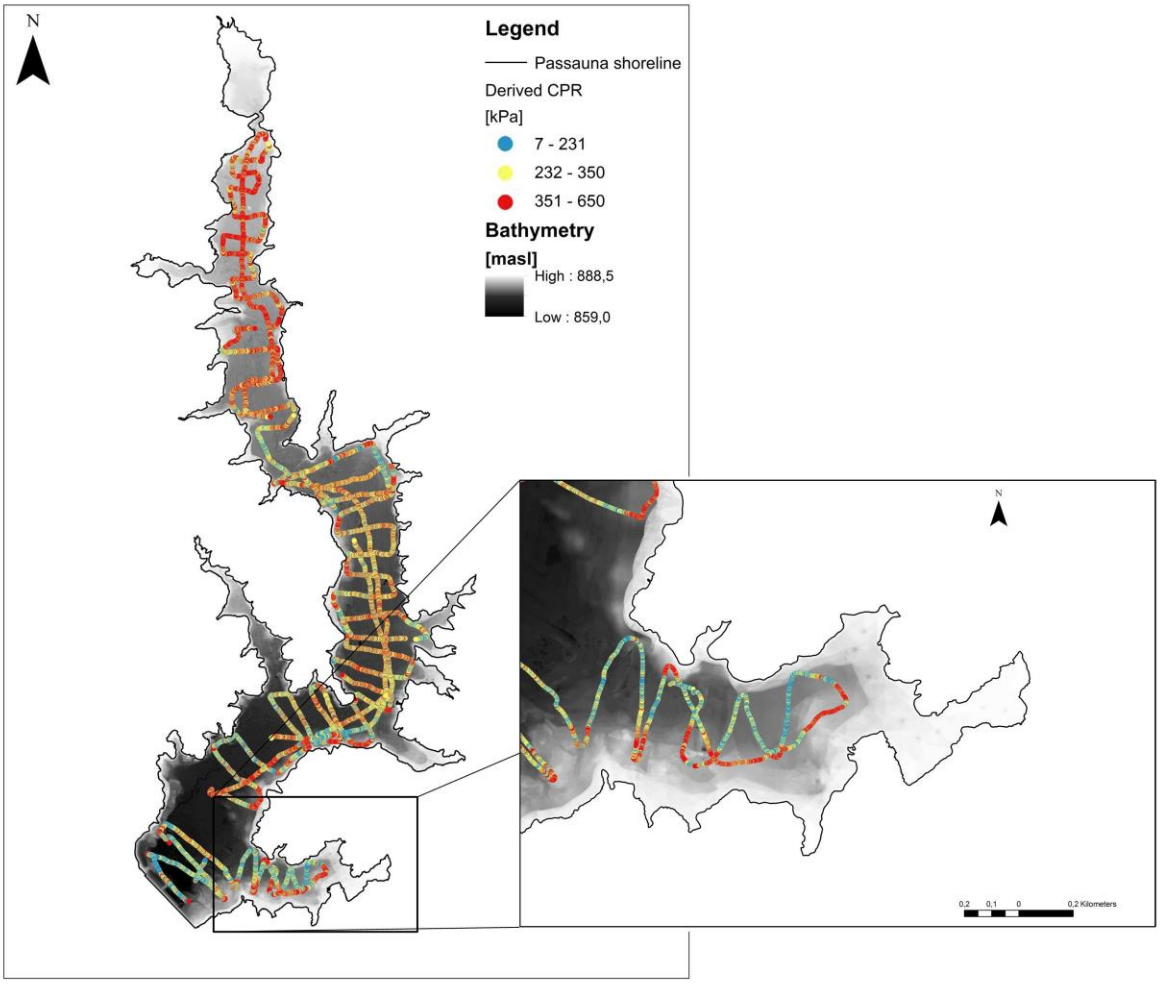

Figure 5. Calculated max. CPR values in three classes along a hydro-acoustic measurement transect at Passaúna reservoir. The black-white background shows a high resolution bathymetry of the reservoir.

5 CONCLUSIONS

The GraviProbe was used for the fast and easy detection of rheological sediment properties in order to support ground truthing information for acoustic lake bed classification. Sediment properties may change over small distances or can feature local changes like stones or trees. Therefore, multiple runs are recommended to prevent misinterpretation of single measurements and erroneous derivation of empirical models. The GP data could be correlated to physical sediment properties like WBD and silt and clay share. Moreover, besides the penetration depth, all rheological parameters correlated significantly with the AttSv1 and Max_Avg_Sv value of the 200 kHz frequency. The 38 kHz frequency was, most likely due to the interference with deeper gas layers, not able to reproduce physical or rheological sediment features. The empirical model based on the AttSv1-CPR correlation was exemplarily used to create a map of sediment features along the driven lines.
In future research, the GP probe will be used in higher spatial density to create a better understanding of local sediment property changes. Additionally, we will test the combination of the GP and acoustic parameters in water body with a more diverse sediment composition to increase the gradient of grain size. It will also be investigated in more detail how well the upper 200 kHz reflector correlates to the top mud detection of the GraviProbe and if the 38 kHz lower reflector can be related to a strength interface inside the mud layer. A new important goal is to test the capability of the GP to infer gas volumes within very fine grained sediment volumes.

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