E-proceedings of the 38th IAHR World Congress
September 1-6, 2019, Panama City, Panama
doi:10.3850/38WC092019-0549

DERIVATION OF A HYDRO-ACOUSTIC SEDIMENT CLASSIFICATION METHODOLOGY FROM AN EXTENSIVE DATASET OF SIX RESERVOIRS

KLAJDI SOTIRI[1], STEPHAN HILGERT[1] & STEPHAN FUCHS[1]

[1] Karlsruhe Institute of Technology, Institute for Water and River Basin Management, Department of Aquatic Environmental Engineering, Karlsruhe, Germany
klajdi.sotiri@kit.edu; stephan.hilgert@kit.edu; stephan.fuchs@kit.edu

ABSTRACT

The most direct impact of dam construction is disruption of riverine systems and their biochemical cycles. A common byproduct of this disruption is the accumulation of sediments upstream of the dam. The accumulated sediment is often rich in nutrients, organic matter and sometimes pollutants. The increased concentration of these components in the sediment has a direct influence on the water quality of the reservoir thus, the reservoir management. Consequently the necessity emerges, not only to collect data about the amount but also about the quality of accumulated sediment. In many cases the limiting factor for traditional lakebed single point sampling is the extensive area of the impoundments, as high costs are generated. We implemented a coupled approach of sediment point measurements (core and grab sampling) with hydro-acoustic sediment parameters, in order to map sediment characteristics. Six different reservoirs (Vossoroca, Capivari, Passauna Reservoirs in Brazil, Urft- and Große Dhünn- (GDTS) Reservoir in Germany and Phalaborwa Barrage in South Africa) were investigated between 2011 and 2018. These reservoirs are located in different geographic and climatic zones and are characterized by different watershed land use, morphometry and purposes. The siltation rate varies strongly from nearly no accumulated sediment to extreme storage capacity loss. For the hydro-acoustic survey a single beam echo-sounder (EA 400, Kongsberg) with two frequencies (200 & 38 kHz) was used. Over 70 sediment core samples and 30 sediment grab samples were taken as groundtruthing for the hydro-acoustic measurements. Significant correlations were observed between geo-chemical parameters (LOI 550°C) as well as physical parameters (grain size distribution and density) with a selection of hydro-acoustic parameters. All six reservoirs were covered with dense measurement transects allowing for a sediment classification of the entire lakebed surface. Regression analyses were performed for the derivation of empiric models. By applying the models to the obtained hydro-acoustic spatial information, the detailed type of lakebed was derived. The results show that the method is transferable, independent from the location, catchment properties, morphology and trophic state of the waterbody. Within certain ranges of uncertainty, the acoustic classification can be used to create maps of sediment types. These serve as a basis for any type of sediment related measure to be implemented e.g. dredging.

Keywords: reservoir, sedimentation, sediment classification, sediment properties, hydro-acoustics

1 INTRODUCTION

Certainly dams provide an important boost for the social and economic development, nevertheless the environmental impact on the area and the entire river catchment where they are built is considerable. By impounding rivers, biogeochemical cycles are disrupted. One significant aspect of river continuum disruption by dams is sedimentation. The suspended solids transported by the river settle when reaching the reservoir.

In this study a coupled approach of echosounding-ground truthing was used in order to optimally perform a lakebed classification. The focus was mainly on the physical parameters like grainsize distribution and wet bulk density (WBD) but also chemical parameter as loss on ignition at 550°C (LOI 550°C) were investigated. Important was to classify the lakebed material but also to detect potential greenhouse gas hotspots in the reservoir (Ostrovsky et al. 2008).

The aim of the study is to create a robust lakebed classification methodology in base of a large dataset. Knowing the exact composition of the lakebed is extremely helpful for managing the sediment. In dredging activities, information about the thickness and the type of material is essential for the better planning and resources efficiency.

2 METHODS AND MATERIALS

Six different reservoirs (Vossoroca, Capivari, Passauna in the south-east of Brazil, Phalaborwa in north-east South Africa and Urfttalsperre and Große Dhünntalsperre pre-dam in West Germany) were investigated between 2011 and 2018. For the development of a sediment classification method, data collected in the six reservoirs were used. The integration of static profiles from the six water bodies in one dataset, made it possible to cover a high range of values for different sediment types.

Initially static profiles were recorded with the echo-sounder in predefined positions, properly distributed in terms of depth and surface area. In parallel in all reservoirs sediment samples were collected at the same spots. From the static profiles, acoustic parameters were derived and a relation between the sediment physical-chemical parameters and the acoustic parameters was found. The results from the static profiles were then extrapolated and used to create a bottom classification map of reservoirs in terms of sediment accumulation, sediment characteristics and gas detection (Hilgert et al. 2016; Anderson, Michael A. and Pacheco 2011; Anderson, John T. et al. 2008).Regarding the equipment, a single beam echosounder (EA400) (SBES) from Kongsberg was used, with two different primary frequencies of 200 and 38 kHz. Groundtruthing was achieved with an Uwitec core sampling device (Niederreiter R 2012) and a regular grab sampler.

The reservoirs cover a wide range of depth, surface or age. The use of the water is also differing for each case (drinking water, electricity or process water). The main characteristics of the water bodies are presented in a summarized format in Table 1.

Table 1. Characteristics of the reservoirs

	Germany		S. Africa	Brazil		
	Große Dhünn Reservoir (pre-dam)	Urft Reservoir	Phalaborwa Reservoir	Passauna Reservoir	Vossoroca Reservoir	Capivari Reservoir
Maximum length	3.2 km	10 km	10 km	11 km	5.9 km	18 km
Maximum width	300 m	300 m	300 m	1.3 km	1 km	1.3 km
Average width	180 m	220 m	100 m	550 m	250 m	450 m
Maximum depth	27 m	48 m	8 m	16 m	17 m	45 m
Average depth	13 m	210 m	-	9 m	8 m	13.6 m
Surface area	0,6 km²	2.2 km²	1.4 km²	8.5 km²	5 km²	13.1 km²
Original Volume	7.5 hm³	45 hm³	-	71 hm³	33.6 hm³	178 hm³
Mean residence time	-	-	-	292 days	110 days	107 days
Catchment size	89 km²	374 km²	47.000 km²	150 km²	151 km²	1,200 km²
Complexity	15.5	10.1	14.8	7.3	11.5	10.2
Age	31 a	113 a	50 a	27 a	75 a	46 a
Use	Drinking water	Electricity production	Mining and drinking water	Drinking water	Electricity production	Electricity production

Hydro-acoustic survey and data post-processing

The EA400 system (Kongsberg Inc. 2006) is a linear single beam system with two primary frequencies, 200 and 38 kHz. The transducer was installed in an aluminum vessel with an incidence angle of 0°. The draught was set between 0-70 cm depending on the noise level and on the depth in the measuring area. The echosounder was connected with a Leica 1200 DGPS system for assuring cm-accuracy in positioning. Additionally CTD-profiles (CastAway®-CTD) were taken for sound speed corrections.

The measured profiles included (stable) static and moving (dynamic) profiles. During the static profiles the boat was stabilized with 3 anchors and the water column and sediment was ensonified for a minimum period of 40 seconds (ca. 400 pings) with different configurations (Table 2). The static profiles were recorded at each groundtruthing position before of the sediment sampling process, so that the information about undisturbed sediment layers could be acquired.

By increasing the pulse length, the sound wave penetration in the sediments increases. However increasing the pulse length is not always the better solution as the echogram resolution is decreasing significantly. The best configuration is a tradeoff between best penetration possible and minimal information loss due to the reduced vertical resolution. During driving, the EA 400 was set to an input power of 100 W, a pulse length of 0.256 ms for the 200 kHz frequency and 0.512 ms for the 38 kHz frequency. The driving speed was around 4 – 5 m/s in order to minimize the noise caused from the engine of the boat.

Table 2. Configurations of the echo-sounder

	200 kHz			38 kHz		
Configuration	*Pulse length [ms]*	*Pulse length [m]*	*Echo resolution [m]*	*Pulse length [ms]*	*Pulse length [m]*	*Echo resolution [m]*
A	0.064	0.096	0.012	0.256	0.384	0.048
B	0.128	0.192	0.024	0.512	0.768	0.096
C	0.256	0.384	0.048	1.024	1.536	0.192
D	0.512	0.768	0.096	2.048	3.072	0.384

For real time data recording, the EA400 software was used and the stored data was later processed in Sonar5Pro (Balk and Lindem 2014). For data visualization ArcMap 10.4 was used.

For sediment classification, acoustic parameters were calculated from the static profiles and related afterwards to the physical-chemical properties of the sediment.

For processing the hydro-acoustic signal the measured echo is divided in three phases (Burczynski J. 1999; Orlowski A. 1984).

- Phase 1 - Attack - from the moment the pulse reaches the bottom until the time when the bottom is reached by the back slope of the pulse. It has a duration of approximately one pulse length and it starts from the bottom detection point or water sediment interface.
- Phase 2 - Decay – starts from the end of the attack phase, a distance of one pulse length from water sediment interface, and lasts until the time when the front of the pulse reaches the boundary of the ideal beam pattern.(approximately 3 pulse lengths)
- Phase 3 - Release - lasting until the time when the pulse completely enters the bottom. In this study is not included as the calculated algebraic values are irrelevant.

Part of the backscattered sound is reflected again from the water surface in the sediment and results in a second delayed echo. Often the information of the second echo is also used for sediment classification, but not in our case (Ostrovsky and Tęgowski 2010; BioSonics Inc. 2008; Chivers 1990).

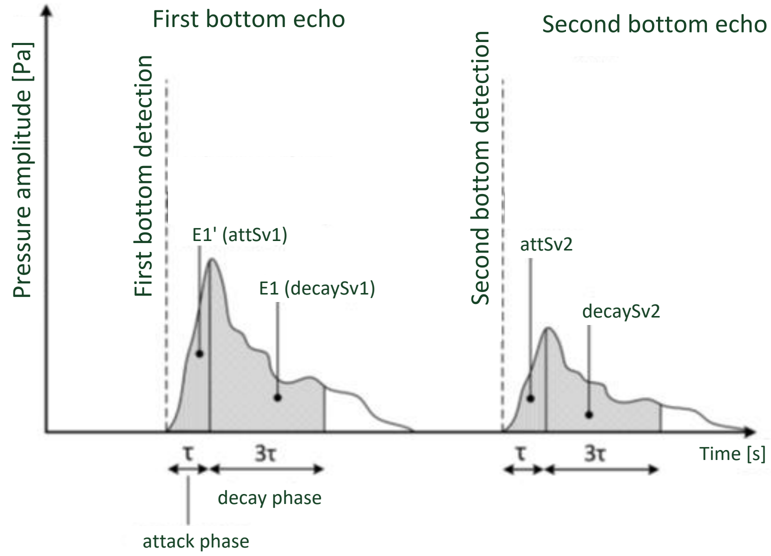


Figure 1. Echo division for calculation of acoustic parameters.

The terms attack and decay can be found often in literature as Hardness and Roughness respectively. They were initially introduced from Chivers 1990. The first part of the echo describes generally the surface of the sediments while the second part or decay phase depends more on the backscattering effect taking place in the sediments. As the backscattering effect is related mainly with the physical roughness of the sediment it is also called acoustical roughness. The attack phase is estimated by calculating the integral of the echo envelope of the first part of bottom echo (E1') and the decay phase is estimated by calculating the integral of the second part of first bottom echo (E1) (Orlowski A. 1984).

To transform in mathematical values the average volume backscattering strength during both attack and decay phase, the echo strengths (Sv1i) of each single sample belonging to that phase are converted into intensities, summarized, divided by the number of samples, and converted back into a dB value. The exact calculation of the parameters can be found in Hilgert et al(2016) and Balk et al. (2014). The values attSv1/decSv1 and attdecSv1 were also calculated. As explained in Tegowski (2005) these values can include important information of the lakebed composition.

The calculation of the input parameters was completed automatically with the Sonar5-Pro software, and the final data were analyzed using Matlab.

Groundtruthing

The gravity corer from Uwitech was used for groundtruthing. In some cases the hammer action was used in order to penetrate the sediment deeper for a better sediment sampling, especially in the positions where the sediment was dense or the sample was not long enough. The sampling tube was transparent PVC and the inside diameter of the tube was 86 mm. For all the tubes that were used, the length was 84 cm. (Niederreiter)

Apart from the visual assessment (color, texture, layering), density samples were also taken from each core. The sediment samples were afterwards wet sieved. For defining the granulometry, when it was possible 300 g material of each layer were sieved. The utilized sieves had the following mesh sizes: 2 mm, 500 µm, 250 µm, 125µm and 63 µm. After sieving, the samples were dried in 105°C for 24 hours. Then the dry mass of each sample was weighted and the granulometry was defined. For the core samples each layer was sieved separately. The fractions from each layer were summed up for each core determining the final grainsize distribution of the whole core.

For determining the WBD only the core samples were used. Visually it was assessed that the grab samples were highly disturbed and that the density measurements would not represent the real density of the sediments before sampling. For the cores it was assessed that the disturbance was minimal and the central part of the 9 cm core was intact. For sampling the material a cylinder with fixed volume of 17.6 cm^3 was used. The sampled material was weighted and the density was calculated.

3 RESULTS

Clustering

For the echograms of the static profiles with more than 400 pings, the acoustical parameters were calculated and then averaged in order to give only one set of parameters for each recorded profile. Each configuration was represented in one plot, making so the final number of plots to eight (four configurations for each of the two frequencies). As indicated in Hilgert et al (2016), configuration B is the best option as there is a satisfying penetration depth and the resolution of the echogram is still fine. Our findings also confirmed that 38 kHz in configuration B was also the best option and this is the only configuration that is presented.

The averaged echo for each static profile is visualized in coordinates AttSv1 vs DecSv1 (first part bottom energy reflectance versus second part). (Burzcynsky 1999, Orlowski 1984). The color of the point indicates the range of the finest fraction share. By plotting Attack versus Decay values, a clustering behavior of the points can be observed. The borders of the classes are chosen in an arbitrary way though. There is a clear border between the classes A-B, A-C and D, B-C and D. On the other hand, there is no clear border between C-D. The borders between these two classes were defined by the difference in physical properties as shown in Figure 3 but also from the amount of the finest fraction share in Figure 2.

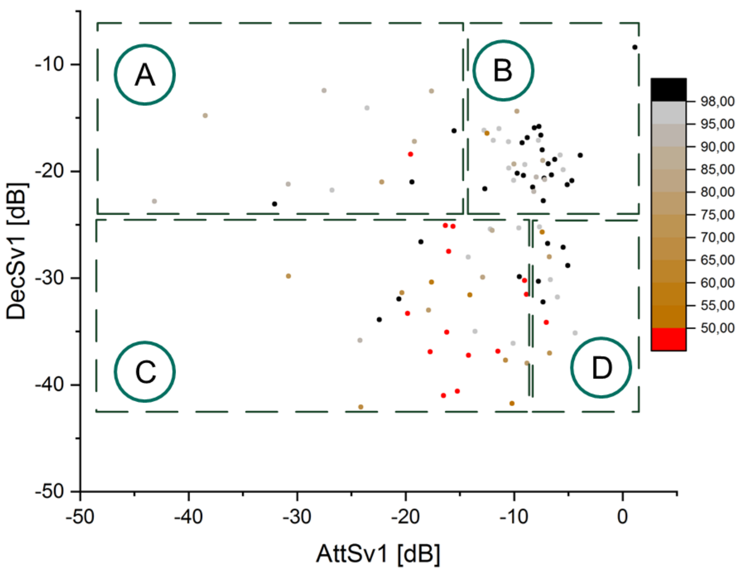


Figure 2. Scatterplot of AttSv1 vs. DecaySv1 and the derived classes.

The three investigated parameters for all sediment samples were wet bulk density, grainsize distribution and loss on ignition on 550°C. Core sampling was more accurate in regard to grab sampling as penetration depth can be higher and the very fine material was better sealed.

In order to have a better result visualization, the mean values of each parameter were calculated for each class. We tried to do the best representative sampling in terms of spatial distribution and zonation. This means that sediment samples were taken from each part of the reservoirs including here parts like side-arms, lacustrine area, transitional area and riverine zone.

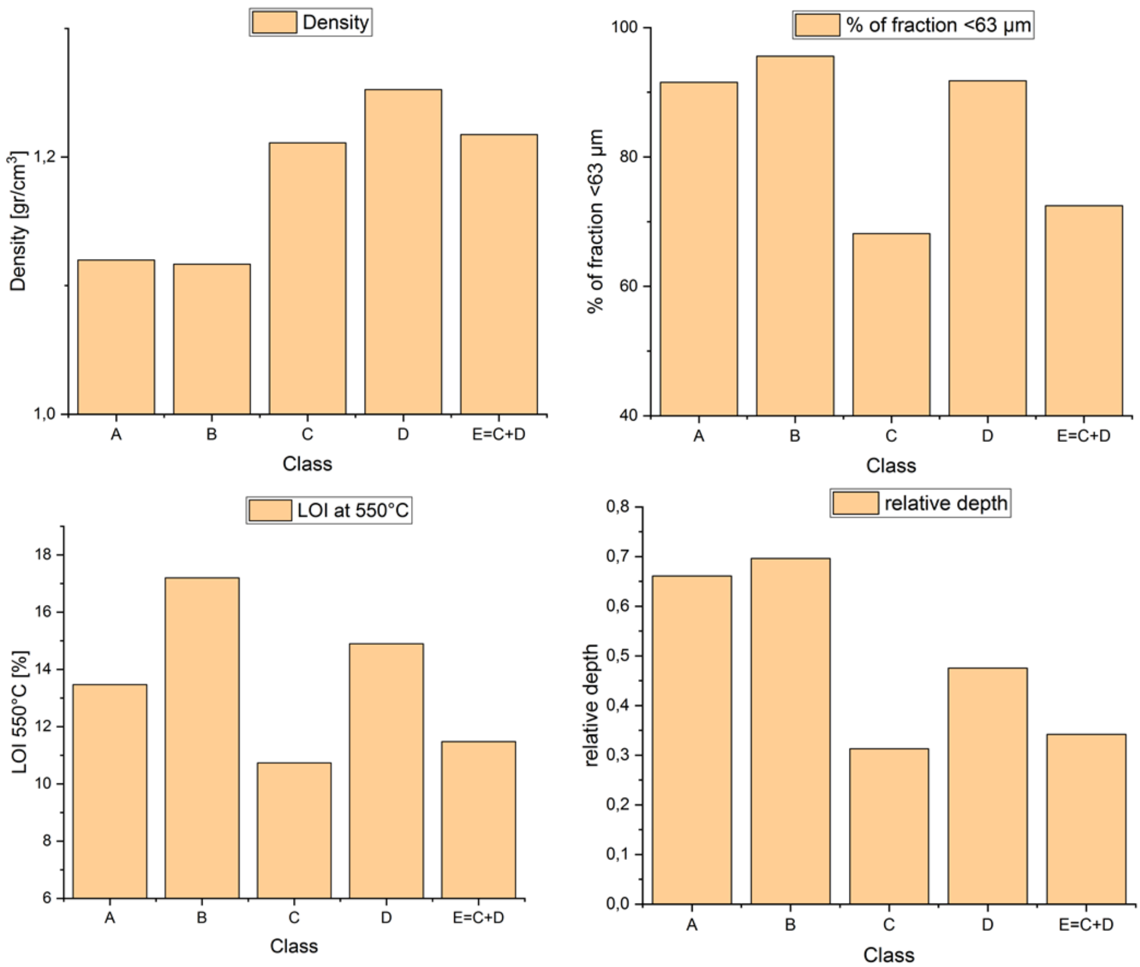


Figure 3. Physical characteristics of sediment for each class

For naming and describing the material of each group of points, the four investigated parameters were examined separately for each class.

Class A. There is relatively a low attack value and a high decay value, indicating that there is a thick layer of sediments and a layer of soft material, maybe even fluid, near the sediment-water interface (SWI). The results from the physical properties reinforce the hydro-acoustic findings. The material in this class has a relatively low density with more than 90% silt clay fraction. The LOI 550°C is also relatively low, showing that there is no high share of organic material which implies the absence of gas presence in the lakebed. This class of sediment is found more in the profundal zone of the reservoir.

Class B. the material from this class reflects strongly the soundwave both from the SWI (coherent reflection) and the deep layers (volume backscatter), suggesting that there is high gas concentration and a thick sediment layer. From the sediment analysis it could be derived that this class consists of unconsolidated material, with a 95% share of silt and clay, and also has low density (around 1.1 gr cm^{-3}). In contrast to Class A, here the LOI 550°C is also very high, emphasizing the hydro-acoustic results regarding the gassy sediment. This class is also characteristic of the deep areas of the reservoir where the most of siltation takes place.

Class C. The acoustic response form the sediment in class C is different from the two previous classes. The decaySv1 values (volume backscatter) are relatively low compared to the 2 previous classes, indicating the absence of sediment. The attackSv1 (coherent reflection) values have a wide range, suggesting the presence of all soft, hard or gassy top lakebed. From sediment physical properties it is obvious that the lakebed consists mainly of denser and coarser grained material compared to the two previous classes. The LOI 500°C results show also that the material is mainly mineral and the organic share is rather low. This type of material is found in the shallow parts of the reservoir and often near the shoreline. From the results it could be deducted that most of the times class C refers to pre-impoundment soil and sometimes to coarse sediment transported either as bedload or from density currents in high velocity flows in the vicinity of lacustrine zone.

Class D. As mentioned before, there is no clear acoustic boundary between Class C and D. Both Classes have a low volume backscatter, although class D represents the lakebed points with a higher coherent reflection compared to class C. The lakebed from this class is compacted fine grain material. On the other hand the LOI 550°C of the sampled material is relatively high compared to class C. By referring to the physical properties of the sediment, we could conclude that the lakebed represented from this class consists either form consolidated or from gassy material.

The above described classes were assigned to each point from the dynamic transects in each of the reservoirs. Figure 4a shows the distribution of the classes in the Passauna reservoir. The class C is systematically present near the shoreline and in the shallow part with high flow velocities while classes A and B are observed in the profundal zone. Class D is also present. It is visible in the shallow area near the dam (south part) and in some other shallow points near the shoreline.

Apart from the six examined reservoirs, the methodology was implemented in other water bodies (not only reservoir) for testing its transferability. One of these water bodies was also Lake Kinneret in Israel, as presented in Figure 4b. The results from Lake Kinneret showed a higher homogeneity of lakebed with only two classes present. In the shallow area of the reservoir the lakebed consists exclusively of coarse grained material classified as class C while, after the depth of 15 m until the deepest point the material of the lake is fine grained gassy material classified as B. The results were validated by four sediment cores as shown in Figure 4b by the crosses. At position 1 it was not possible to retrieve any sediment core as the material was too coarse (validated with divers), while at the other three positions (2,3 and 4) the material was homogene and consisted of almost 100% fine grained soft sediment.

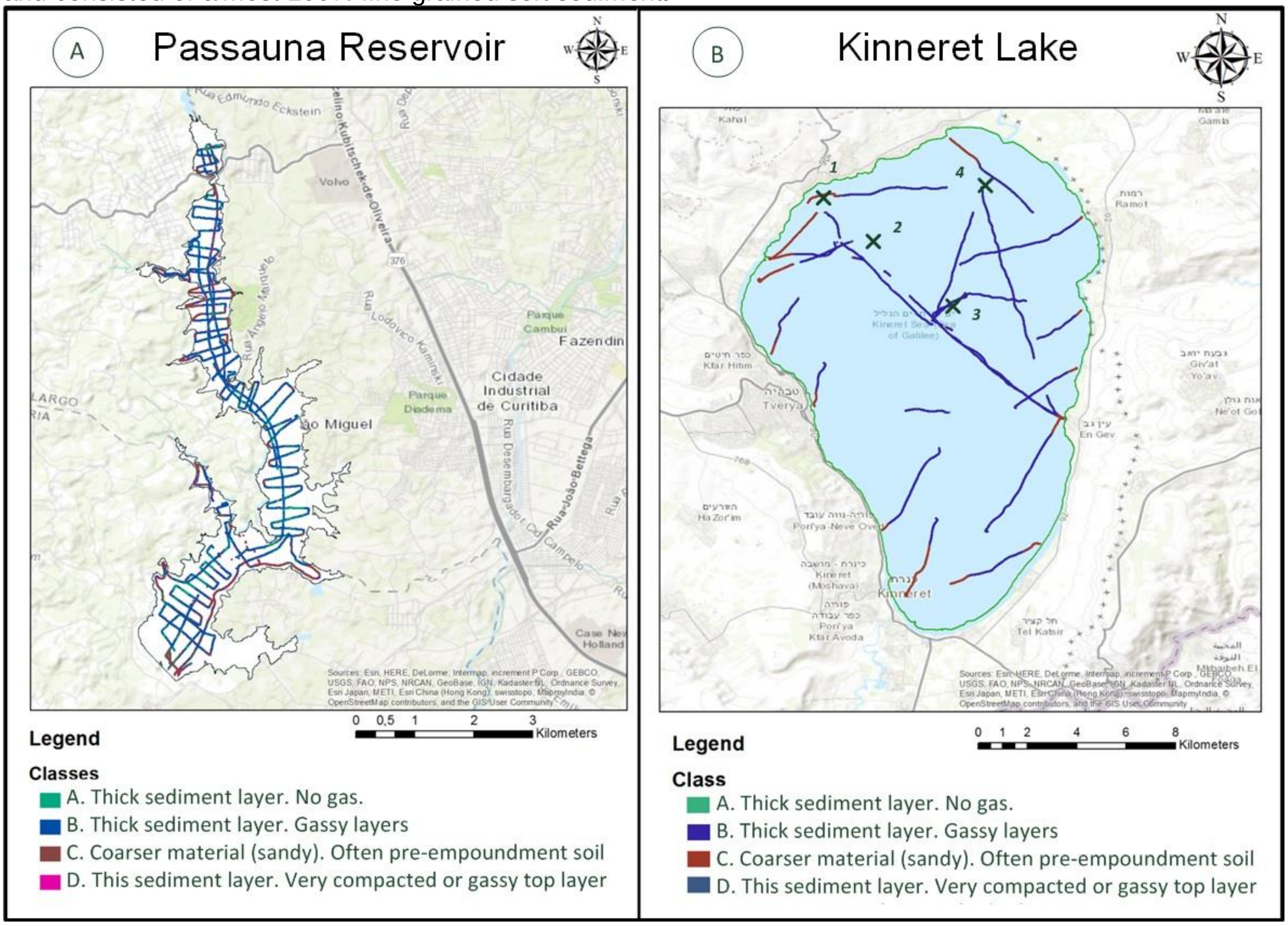
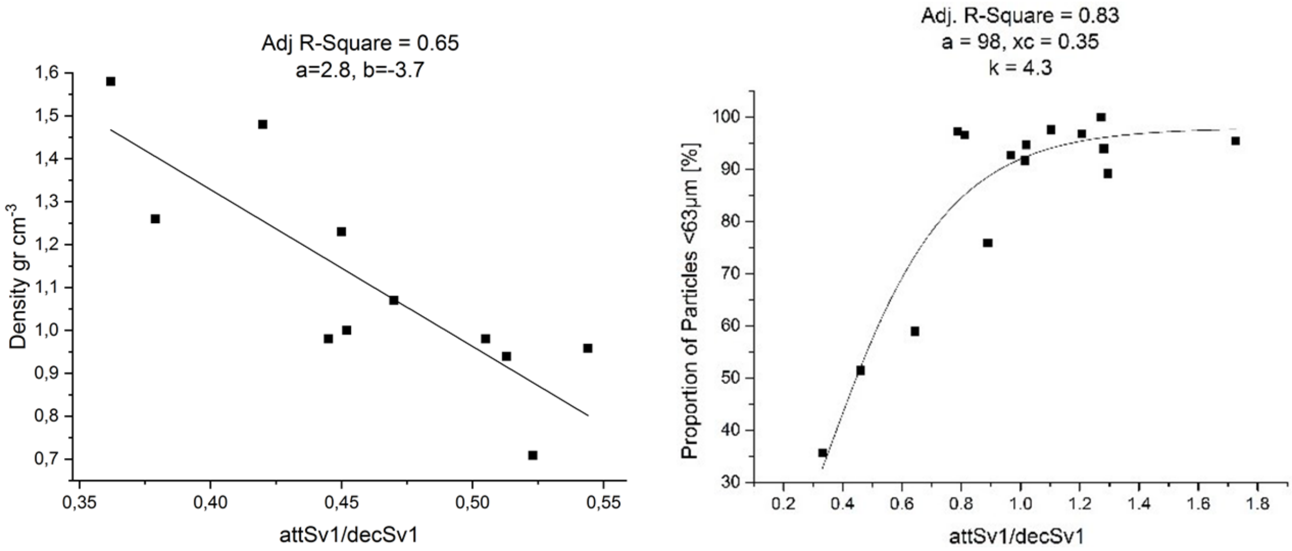


Figure 4a. Mapping of Passauna lakebed by implementation of the methodology in the dynamic transects.
Figure 4b. Mapping of Kinneret lakebed by implementation of the methodology in the dynamic transects of a new waterbody

Apart from clustering, another approach was used to classify the reservoir lakebeds. Statistical analysis was performed to check the correlation of all the physical parameters with the hydro-acoustic parameters. Regarding the whole dataset of 98 points, there was no significant correlation between the acoustic and physical parameters. However, when the reservoirs were analyzed separately, there were clear trends and significant correlations to be observed. For the most significant correlations, the respective linear or non-linear regression analysis was performed. Two of the better performing regression analyses are presented in Figure 5a and 5b for Passauna and Capivari. The best performing acoustic parameter in general is attSv1/decSv1.



(a) (b)

Figure 5a. Linear regression between attSV1/decSv1 and Density in gr cm^{-3} for Passauna reservoir
Figure 5b. Non-linear regression between attSV1/decSv1 and silt-clay fraction in % for Capivari reservoir

The function from the regression analysis was implemented to the acoustic parameters calculated from the dynamic profiles and the results were interpolated for creating a map of the physical parameter of interest. In Figure 6 the results from Capivari reservoir, regarding silt-clay fraction are presented. The results show the presence of fine grained material in the profundal zone, mainly in the center of the reservoir, and a coarser and heterogenic material in the lacustrine and transitional zone of the reservoir or in the side arms.

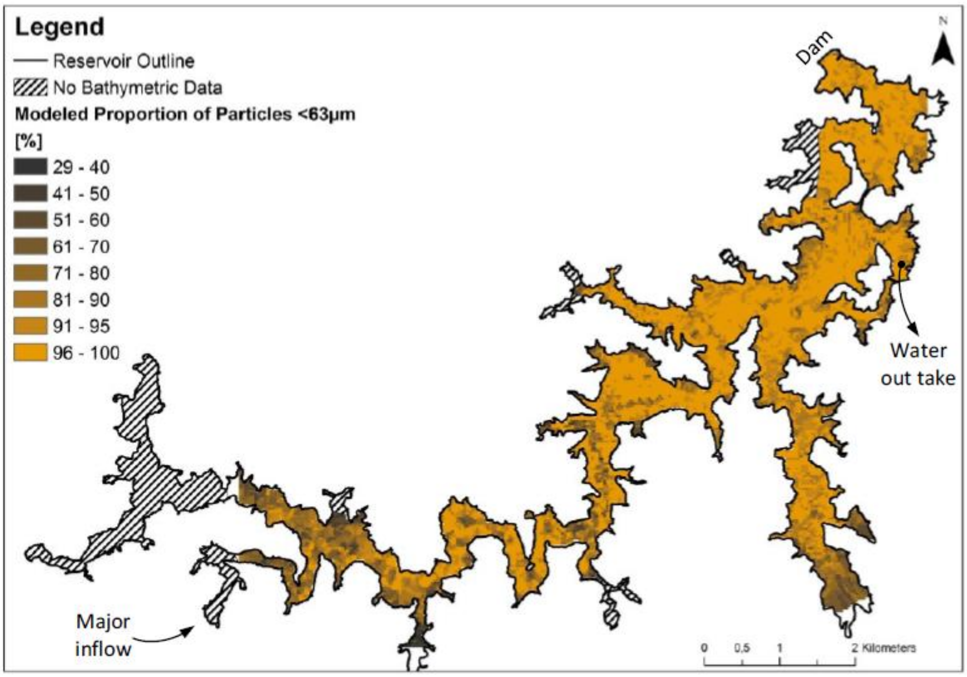


Figure 6. Modelled values of silt-clay fraction in Capivari reservoir (Hilgert 2014).

4 DISCUSION

In general the lakebed classification performed well in differing between areas with coarse or fine material. The methodology was implemented also to other reservoirs (Schwarzenbach reservoir) and it showed consistency. The methodology could be used with reliability in terms of detecting sediment hotspots. On the other side the method failed to differentiate between gassy and compact lakebed in class D. This is a major issue in all the echo sounding devices used for sediment classification and that is why the groundtruthing is always a necessity.

While the method managed to successfully detect a change in the material physical properties, it was not possible to quantify the change for the whole dataset. Gas plays a crucial role in this regard. As for class D, the gas content disturbs the echo reflection and creates artifacts that are misleading in terms of physical characteristics determination. For instance the reflection from a gassy fine grained material, which is rich in organic matter, could be similar with the reflectance of a compacted coarse mineral material. However as shown from the results quantification is still possible if the reservoirs are treated as separate cases

Regarding the classification technique, another issue is the arbitrary way of border definition. In addition, the K-MEANS clustering technique was also used to classify the points, resulting in the below plot (Figure 7). The results look similar regarding the differentiation between A-B, A-C, A-D, B-C, B-D but they look slightly different between C-D. For clustering with the K-MEANS technique we used only information about AttkSv1 and DecSv1 without including information about physical properties of the sediment. For this reason we decided to continue with the first clustering shown in the results. From both graphs (Figure 2 and Figure 7) it can be deducted that there is a clear boundary between high and low volume backscatter. This could be translated in muddy soft lakebed for high volume backscatter and coarse dense lakebed for low volume backscatter. As also shown from Tegowski (2005) the high DecSV1 are characteristics of areas in rich fine-sediment. For a better understanding of the reflected energy for each class, a representative echo amplitude is presented in Figure 8.

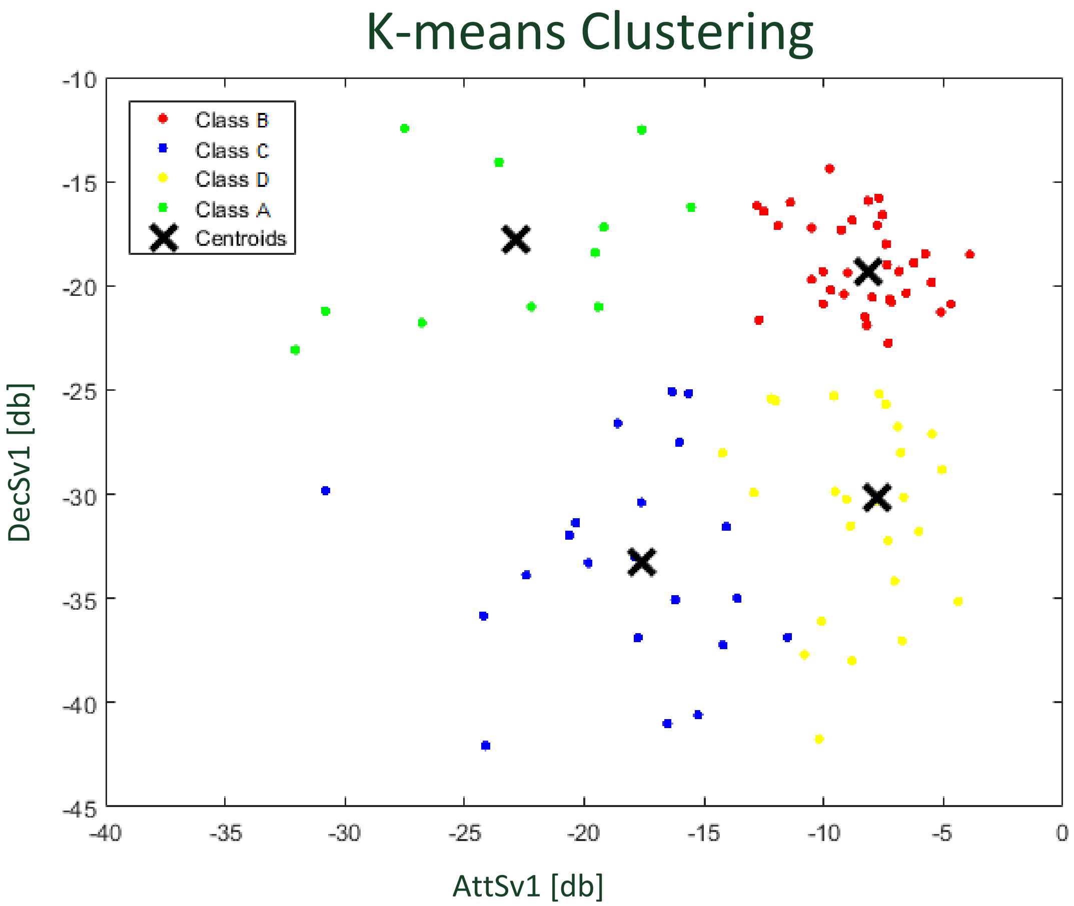


Figure 7. Classifying the points with K-MEANS clustering

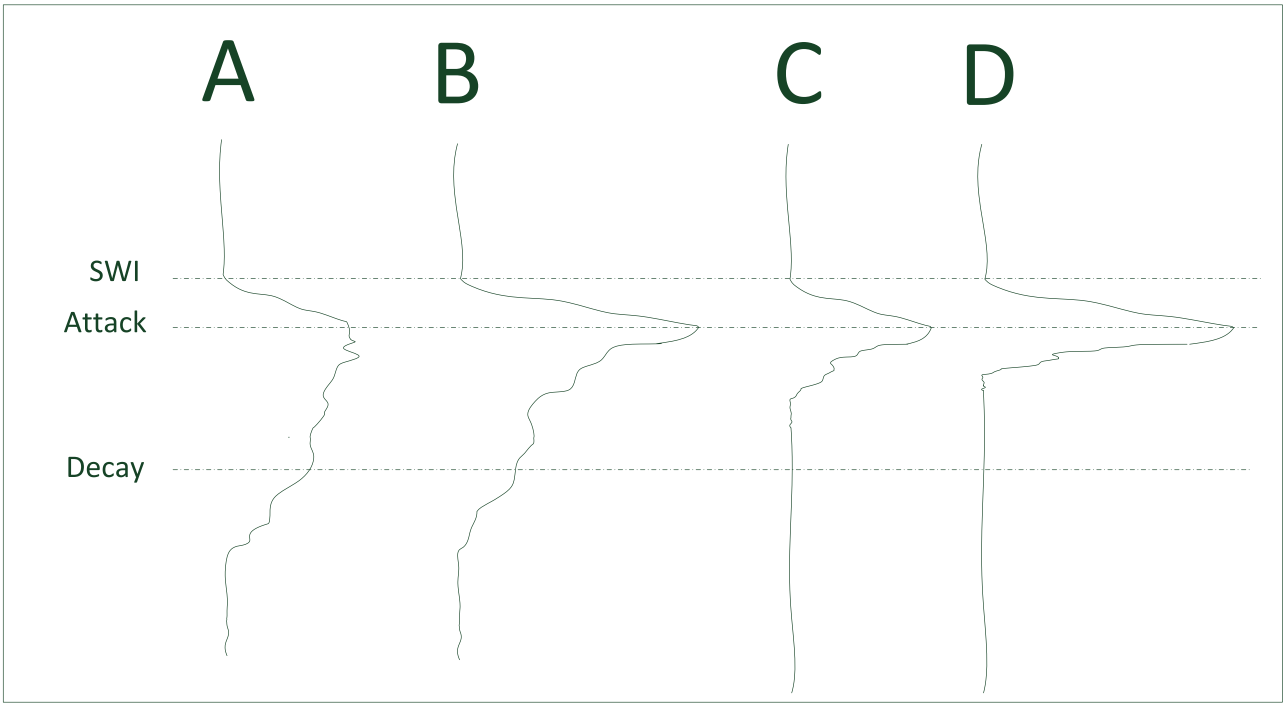


Figure 8. Visualization of exemplary echo-amplitude graphs for each class.

5 CONCLUSIONS

The technique shows reliable results for lakebed classification. It is possible to detect changes in the lakebed material from the acoustic response of the EA400.The extensive dataset of 98 points allowed for proper statistical analyses that lead to the above discussed results. The differentiation between soft gassy sediment and coarse lakebed were visible and decSv1 is the parameter better describing this differentiation. The attSv1 is also helpful for detecting gas voids in the sediment. The classification was used in other water bodies and showed reasonable results. It can be concluded that the technique has real potential for application in sediment management activities.

ACKNOWLEDGEMENTS

This research was funded by the Baden-Württemberg Stiftung (BWS), the German Academic Exchange Service (DAAD) within Project 57203877 and the German Federal Ministry of Education and Research within Grant 02WGR1431A and 02WGR1424C. We would like to cordially thank Sanepar and Wupperverband for logistical support and access to the PAssauna and Great Dhünn reservoir. We also thank the research team from DHS and DEA, UFPR and especially Prof. Tobias Bleninger, Prof. Cristovão Vicente Scapulatempo Fernandes and Mauricio B. Scheer from Sanepar team. Special thanks go to the staff of the laboratory and the technical staff of DHS, who supported our measurement campaigns. We also thank Dr. Ilia Ostrovsky with his team from the Kinneret Limnological Laboratory and Lepelle Northern Water for providing logistic support during Kinneret and Phalaborwa hydro-acoustic surveys.

REFERENCES

Anderson, John T., D. van Holliday, Rudy Kloser, Dave G. Reid, and Yvan Simard. 2008. *Acoustic seabed classification: Current practice and future directions*. ICES Journal of Marine Science 65 (6): 1004–11.

Anderson, Michael A., and Porfirio Pacheco. 2011. *Characterization of bottom sediments in lakes using hydroacoustic methods and comparison with laboratory measurements*. Water research 45 (15): 4399–4408.

Balk, H., and Lindem. 2014. *Sonar4 and Sonar5-Pro: Post processing systems. Operator manual version 6.0.3*. Norway. http://folk.uio.no/hbalk/sonar4_5/1_downloads/SonarX-Manual_v603-2014-12-30.pdf.

BioSonics Inc. 2008. *User Guide: Visual Bottom Typer 1.10.*

Burczynski J. 1999. *Bottom Classification.*

Chivers, R. C. 1990. *New acoustic processing for underway surveying*. Hydrogr. J. 56: 9–17.

Hilgert, Stephan. 2014. *Analysis of spatial and temporal heterogenities of methane emissions of reservoir by correlating hydro-acoustic with sediment parameters.* Doctoral Dissertation.

Hilgert, Stephan, Adrian Wagner, Lisa Kiemle, and Stephan Fuchs. 2016. *Investigation of echo sounding parameters for the characterisation of bottom sediments in a sub-tropical reservoir*. Advances in Oceanography and Limnology 7 (1).

Kongsberg Inc. 2006. *EA 400 Single beam hydrographic echo sounder*. https://www.km.kongsberg.com/ks/web/nokbg0397.nsf/AllWeb/5508DC01B38C35D2C12581B5004514C1/$file/160981_ea400_operator_manual.pdf?OpenElement.

Niederreiter R. 2012. *Uwitech sampling equipments*. www.uwitec.at/html/frame.html.

Orlowski A. 1984. *Application of multiple echoes energy measurement for evaluation of bottom type.* Oceanologia 19, 61-78." Oceanologia 19.

Ostrovsky, I., Daniel F. McGinnis, L. Lapidus, and W. Eckert. 2008. *Quantifying gas ebullition with echosounder: The role of methane transport by bubbles in a medium‐sized lake.* Limnology and Oceanography: Methods 6 (2): 105–18.

Ostrovsky, I., and Jarosław Tęgowski. 2010. *Hydroacoustic analysis of spatial and temporal variability of bottom sediment characteristics in Lake Kinneret in relation to water level fluctuation.* Geo-Marine Letters 30 (3-4): 261–69.

Tegowski J. 2005 *Acoustical classification of the bottom sediments in the southern Baltic Sea*. Quaternary International 130 (2005) 153–161

