

Full Length Research Paper

Estimation of suspended sediment concentration by acoustic equations for soil sediment

Ramazan Meral^{1*}, Andy Smerdon², Hasan Merdun³ and Ali Rıza Demirkıran⁴

¹Bingol University, Faculty of Agriculture, Department of Agricultural Structures and Irrigation, Bingol, 12000, Turkey.

²Aquatec Group Limited, Hartley Wintney Hampshire, RG27 8NY, UK.

³Kahramanmaraş Sutcu Imam University, Faculty of Agriculture, Department of Agricultural Engineering, Kahramanmaraş, 46060, Turkey.

⁴Kahramanmaraş Sutcu Imam University, Faculty of Agriculture, Department of Soil Science, Kahramanmaraş, 46060, Turkey.

Accepted 25 August, 2009

The acoustic backscattering systems, ABS, for sediment measurement are based on the determining of the backscattering and attenuation properties of the particles in suspension. The relevant acoustic quantities are the form function, f , which describes the backscattering characteristics, and the normalized total scattering cross-section, χ , which describes the attenuating characteristics of the particles in suspension. Formulations are required for these parameters of suspension sediment particles with size and acoustic frequency. Several studies have been conducted to determine the concentration of sediments such as glass spheres or sand. However, the acoustic properties of natural sediments vary and depend on many parameters such as particle size, shape, mineralogy and distribution of those parameters in sample. Therefore, this study was conducted to determine the possibility of soil sediment concentration with the f and χ equations, which were obtained for glass spheres and sandy sediments under laboratory and river conditions. The results show that the acoustic method, especially with glass scattering equation, works fairly well to calculate soil sediment for low concentration range at laboratory and river conditions.

Key words: Suspended sediment, acoustic, backscattering, attenuation, erosion, river.

INTRODUCTION

Acoustic sediment measurement method has been investigated and utilized successfully under different laboratory and field conditions by several investigators during the last few decades (Thorne and Hardcastle, 1997; Guerrero and Lamberti, 2008; Thorne and Hanes, 2002). The acoustic backscatter system, ABS, involves applying different high frequency sound beams through the water and a mathematical inversion to obtain particle size and concentration from the backscattered signal. The main process of this inversion is a description of the scattering and attenuation properties of the particles in suspension. While the form function, f , describes the backscattering characteristics, the normalized total scattering cross-

section, χ , describes the attenuation characteristics of the sediment particles. These many parameters are non-dimensional and based on the acoustic sphere scattering literature (Thorne and Meral, 2008)

Flamer (1962) studied sediment attenuation and the results were used by Sheng and Hay (1988) to define the sphere scattering approach using the f and χ parameters. They used a rigid mobile sphere model which compared with the measurements and they also formulated a simple heuristic expression which also provided good agreement with the data. Other investigators have adopted a similar approach (Thosteson and Hanes, 1988; Hay and Sheng, 1992; Crawford and Hay, 1993; Thorne et al., 1993; Schaafsma and Hay, 1997; Thorne and Buckingham 2004).

The acoustic properties of natural sediments vary and depend on parameters such as size, shape, mineralogy and distribution of those parameters in the sample.

*Corresponding author. E-mail: rmeral69@hotmail.com Tel: 90 5317909280.

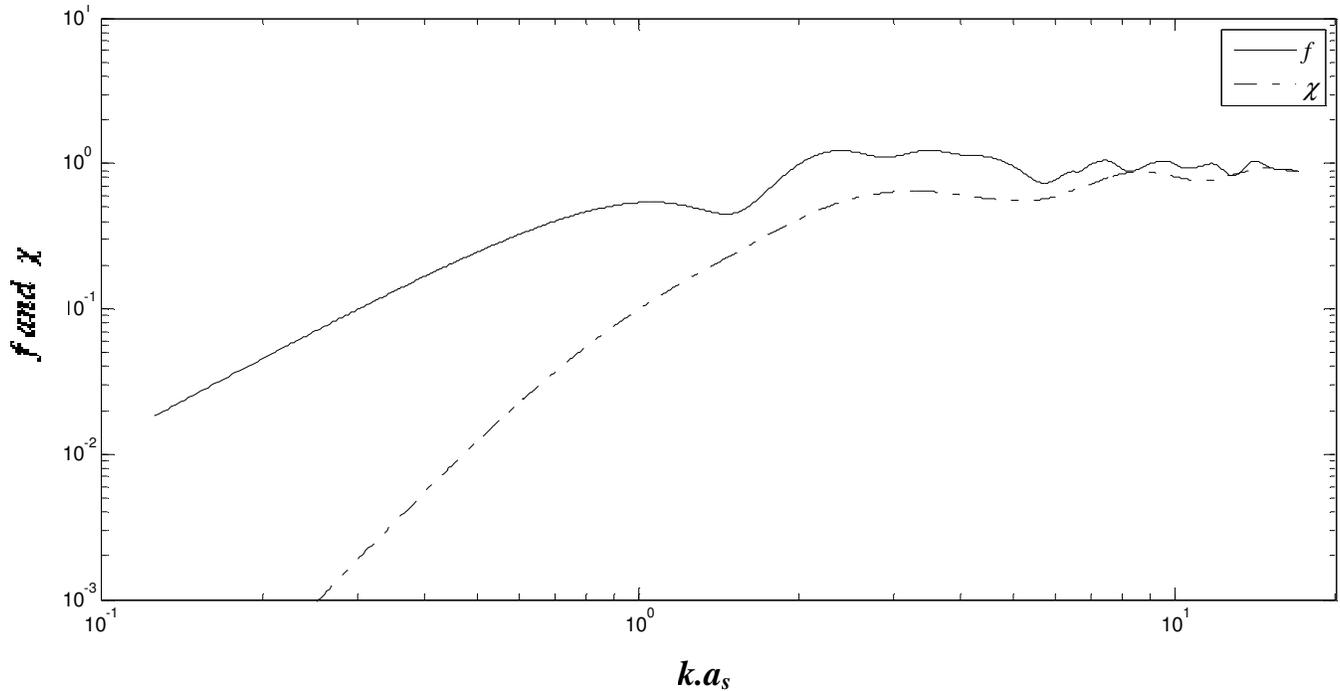


Figure 1. Form function and normalized total scattering cross-section for glass spheres.

Several studies have been conducted to determine the concentration of sediments such as glass spheres or sand. However, the approximated f and χ obtained for glass spheres or sand may lead to erroneous results if the natural sediment differs from the approximated sediment material properties (Thorne and Buckingham, 2004; Mouraenko, 2004). Therefore, the objective of this study is to determine the possibility of soil sediment concentration with the f and χ equations, which were obtained for glass spheres and sandy sediments.

MATERIALS AND METHODS

Theory

The portion of sound beam sent to water is reflected by sediment towards transducer depending upon sediment concentration, particle size, and sound frequency. The strength of the back-scattered signal can be converted to sediment concentration, M (Thosteson and Hanes 1988; Sheng and Hay, 1988; Thorne et al., 1993)

$$M = \left\{ \frac{V_{rms} \Psi r}{k_s k_t} \right\}^2 e^{4r(\alpha_w + \alpha_s)}, \quad k_s = \frac{f}{\sqrt{a_s \rho_s}},$$

$$\alpha_s = \frac{3\chi M}{4a_s \rho_s} \quad (1)$$

where, V_{rms} is the recorded voltage from the transducer, Ψ accounts for the departure from spherical spreading within the transducer nearfield, r is the range from the transceiver, k_t is

calibration constant, and k_s is a function of the scattering properties of the sediment. α_w is the water absorption and relatively straightforward and its dependence upon water temperature and salinity. α_s is the particle attenuation, a_s is the particle radius of the sediment, and ρ_s is the sediment grain density. The normalized total scattering cross section, χ , and the form function, f , can be determined for glass spheres or sandy sediment.

Glass scattering equation

The expression of the mean normalized scattering cross section and form function for glass spheres are given by

$$f = \frac{2}{x^2} \sum_{n=0}^{\infty} (2n+1)(-1)^n b_n \quad (2)$$

$$\chi = \frac{2}{x^2} \sum_{n=0}^{\infty} (2n+1) |b_n|^2 \quad (3)$$

where, $x = k \cdot a_s$; k is the wave number of the sound and equal to $2\pi/\lambda$, and λ is wavelength of the sound in water, b_n is a moderately complex function composed of spherical Bessel and Hankel functions of the first kind and their derivatives (Gaunard and Uberall 1983). Figure 1 presents f and χ calculated by Equations 2 and 3, for a suspension of glass spheres of uniform particle size (Betteridge et al., 2008).

Sand scattering equation

Thorne and Meral (2008) evaluated four decades of published data on the acoustic scattering properties of suspensions of sandy

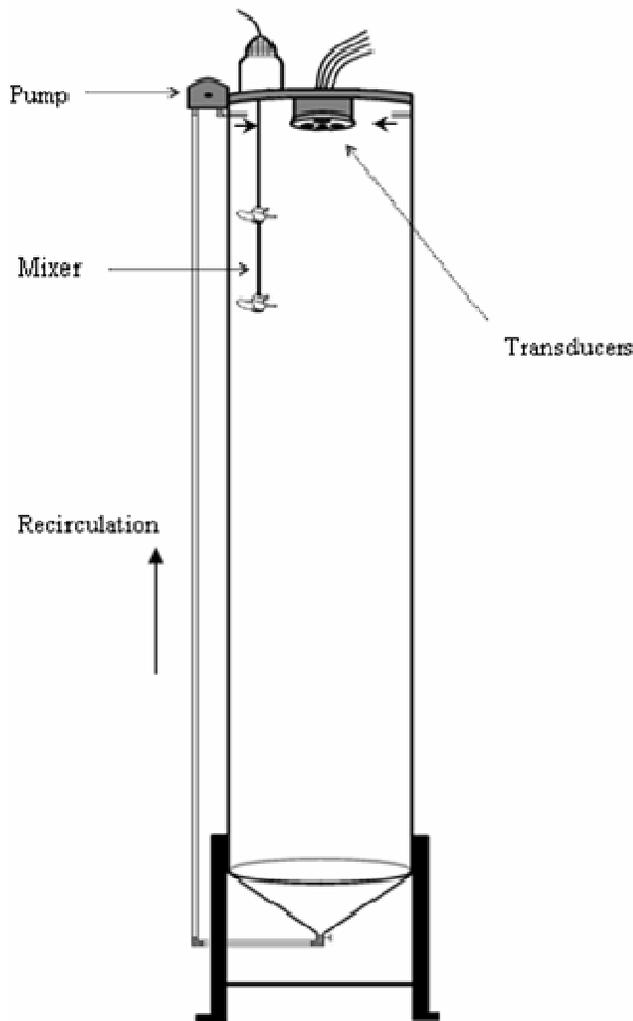


Figure 2. Sediment tower.

sediments. These data were reformulated in terms of the usual acoustic scattering nomenclature that is the form function and the normalized total scattering cross-section, based on a sphere scattering model (Equations 4 and 5).

$$f = \frac{x^2 \left(1 - 0.35e^{-((x-1.5)/0.7)^2} \right) \left(1 + 0.5e^{-((x-1.8)/2.2)^2} \right)}{1 + 0.9x^2} \quad (4)$$

$$\chi = \frac{0.29x^4}{0.95 + 1.28x^2 + 0.25x^4} \quad (5)$$

Measurements

This experiment was carried out at laboratory and field conditions. Laboratory measurements were conducted in a sediment tower, which consisted of a 2.10 m vertical tube with a diameter of 0.40 m and with mixing and re-circulating units (Figure 2). The main objective of the tower's design was to obtain a homogenous suspension of sediments through the depth.

The four frequency acoustic backscatter system (AQUAscat-L) developed by the Aquatec Group, was operated in transceiver mode at 0.5, 1.0, 2.0 and 3.9 MHz (Smerdon, 2005). The transducers were mounted near the top of the tower and their beams were directed vertically downwards. The system measured the backscattered signal at 0.01 m intervals.

The first laboratory measurement was conducted for calibration of AQUAscat devices. The glass spheres, with radiuses of 137 and 163 μm and with a 10% variation in the mean size, were used to prepare suspended sediment and concentration in the tower was kept relatively constant in the range of 0.3-0.4 g/l for each radius. The experimental procedure was as follows; take background readings for 30 min in clear water, add wetted and degassed glass sediment to the tower, allow the mixture to homogenise over a period of about 30 min, record data for 30 min, and take three pumped samples to determine sediment concentration during the recording process. The calibration constant, k_t , was determined from the acoustic backscatter strength of homogenous suspended sediment of known particle size and concentration level for each frequency.

The second laboratory measurements were made with soil sediment (47.7% sand, 14.3% silt, 38.0% clay and sieved with 250 μm) solutions in the sediment tower to evaluate performance of acoustic equations for soil sediment. Sediment concentrations were prepared between 0.0 and 3.0 g/l level, but a homogenous solution was not obtained over 1.0 g/l concentration due to gradual settling of sediment to the bottom of tower during the mixing phase. Therefore, the only concentrations were considered at the range of 0.0 – 1.0 g/L.

Field sediment measurements were made by acoustic and sampling methods during April-September 2008 at Aksu river, in Kahramanaras, Mediterranean region of Turkey at 36° 55' E, 37° 36' N and altitude of 840 m. Aksu river is 115 km long, about 0.20 to 2.00 m deep mid-stream, and about 20-30 m wide. However, the water depth changed between 0.25 and 0.58 m during the experiment. The catchment area is about 646 km^2 and, it represents the heterogenous characteristics of the Mediterranean regions consisting of the wide variety of agricultural systems, forest ecosystems, rangelands, bare rocks and wetland (Yüksel et al., 2008). For sediment concentration measurement river cross section was divided into three subsections. For acoustic measurements transducers were held on water surfaces vertically by means of a metal shaft. Acoustic measurements were made every second for a period of 90 s. Just after acoustic measurements, 500 ml water samples were collected from the 20 and 80% of the total water depth through the profile of acoustic measurements. Sediment concentrations of the collected samples were determined by the filtration method in the laboratory.

RESULTS AND DISCUSSION

Calibration

Acoustic backscatter measurements were collected for 0.5, 1.0, 2.0 and 3.9 MHz. The plots in Figure 3 illustrate the stages in the calibration process. In plot a, measured signals were corrected for the effects of spreading loss and frequency attenuation that are a function of range from the transducer. The apparent increase of signal with range on the 3.9 MHz trace occurs when the recorded signal drops to the system noise floor. In plot b, k_t was calculated assuming the tank has a constant mass concentration based on the pump samples. The 3.9 MHz value steps to zero near 1.6 m range as values beyond

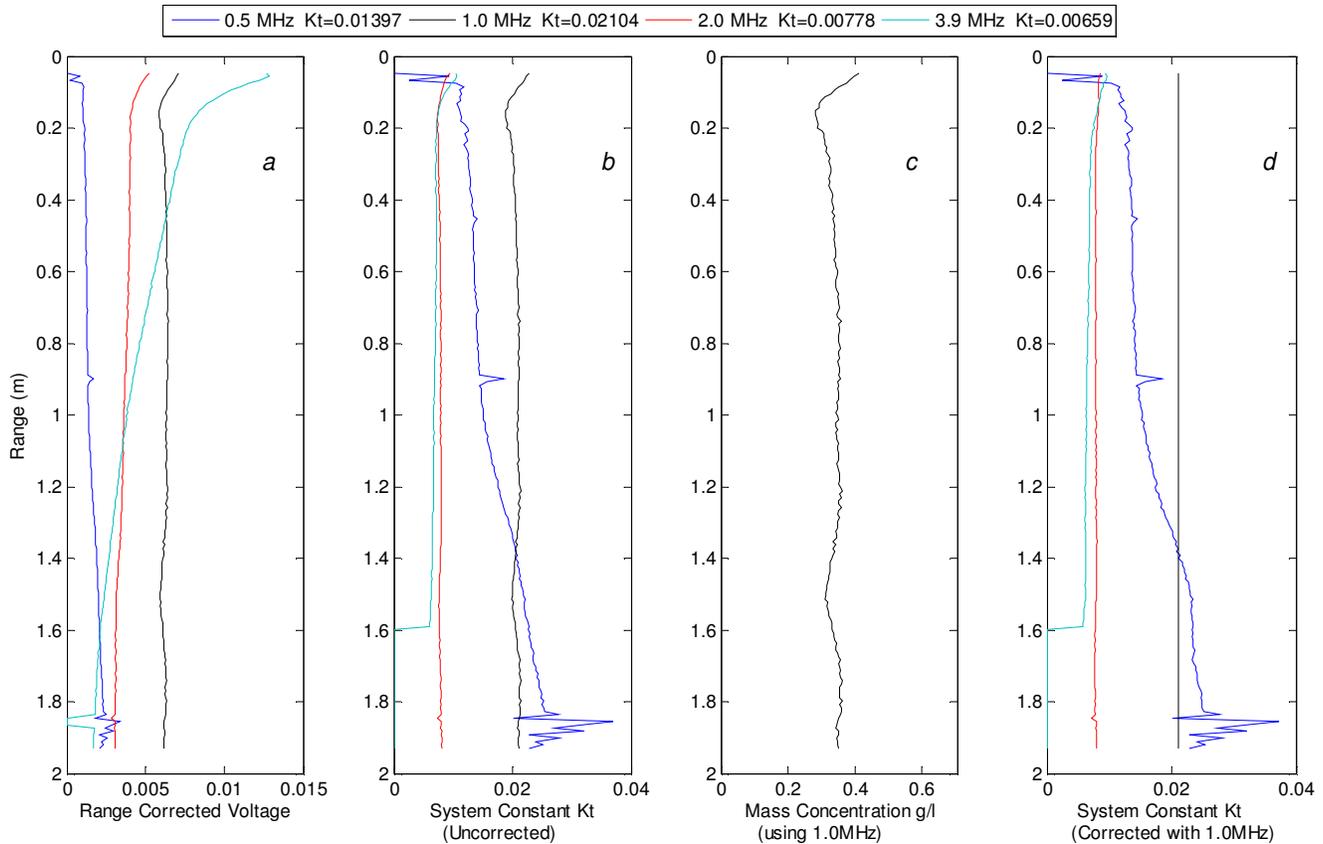


Figure 3. Recorded voltage and system constants.

this range have been discarded because the recorded signal value was too low. In plot c, using the 1 MHz frequency, least affected by sediment-related attenuation, the actual concentration profile was calculated. In plot d, k_t is recalculated for each frequency using the actual concentration profile. The average computed values for k_t were obtained as 0.01397, 0.02104, 0.00778 and 0.00659, respectively, for the four frequencies at the sample depth as presented in Figure 3. Similar results were obtained for two different size glass spheres and represented here for 137 μm .

Laboratory measurement

The sediment concentrations of pumped samples were determined with a gravimetric method and averaged each suspension giving 0.090, 0.294, 0.520, 0.706, and 0.920 g/l. The acoustic sediment concentrations were computed with glass and sand scattering equation (Equations 2, 3, 4 and 5) at the sample depth and presented in Figure 4. The nearfield region of the transducer was apparent in the first 0.1 m range and concentration computing was started from this point. Although the sediment concentration in the tower was nearly uniform due to back-

scattered signal losses with water and particle attenuation (Thorne et al., 1991), sediment concentration dropped with increasing depth. This effect was not seen at the low concentration treatments. Thorne and Hanes (2002) reported that it was difficult to interpret backscattering acoustic waves when sediment was cohesive (clay and mud) and they suggested for further work on the subject.

Figure 4 shows generally good agreement between scattering equations and sediment sample data. In particular, more stable and reasonable values were obtained for low sediment concentration while deviation increased with higher concentration levels. This is due to difficulties experienced in obtaining homogeneity for high concentrations. Here, to compare two scattering equations, the 10-50 cm depth interval was considered and regression analyses with the physical sampling method were given in Figure 5.

The regression equations between scattering equations and sampling method were highly significant for both methods with R^2 of 0.91 and 0.95. Similarly, Wren et al. (2002) found a good relationship between backscatter voltage and sediment concentration with R^2 of 0.8, and Chanson et al. (2008) used backscatter intensity (for 1.2 and 2.4 MHz frequency) and found good agreement with sediment concentration. Here, glass scattering was

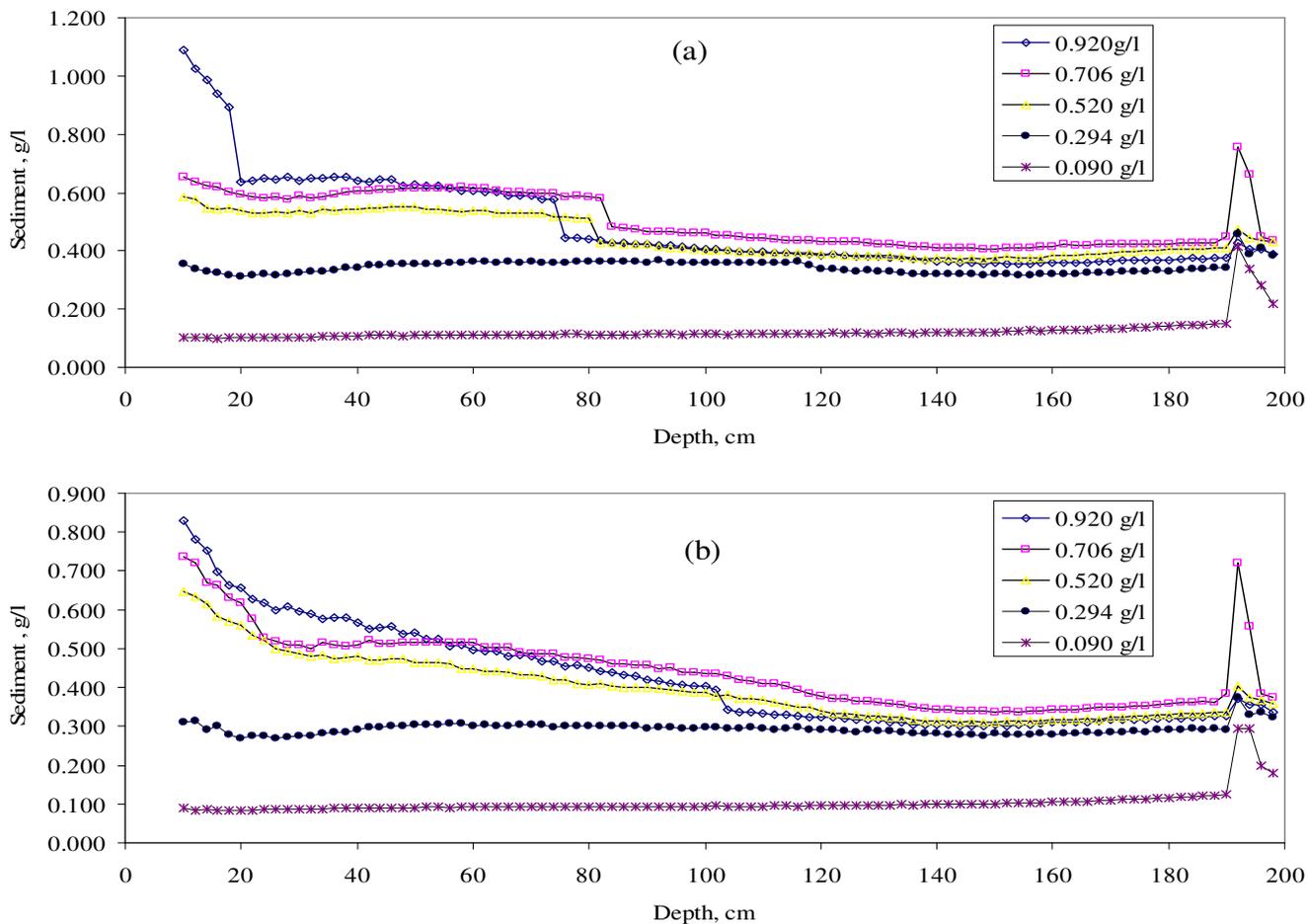


Figure 4. Estimated sediment concentrations by glass (a) and sand (b) scattering equations.

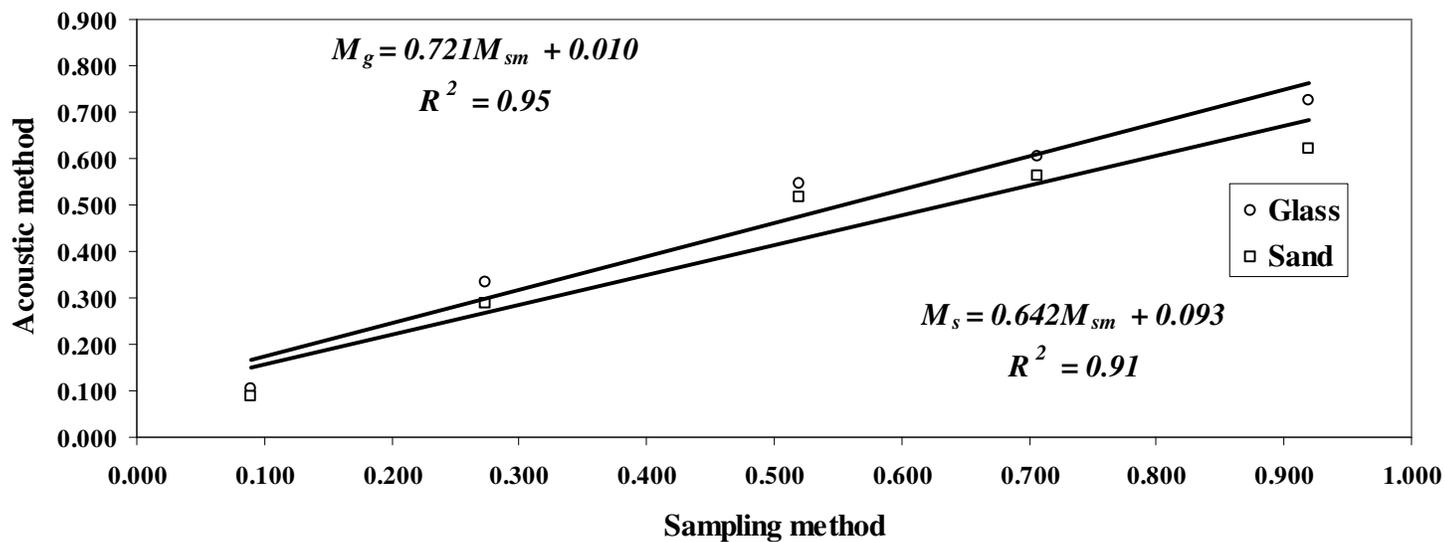


Figure 5. The regression analyses between scattering equations and sampling method. (M is sediment concentration (g/l) and subscripts g , s , and sm are glass, sand scattering equation and sampling method, respectively).

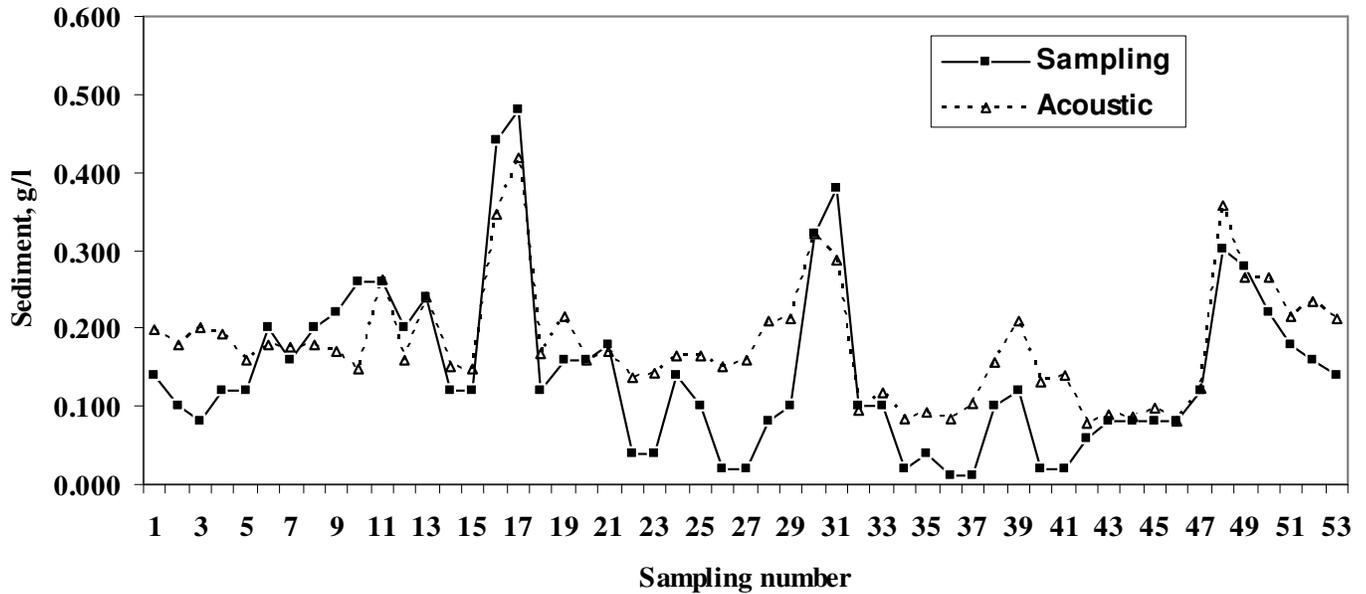


Figure 6. Acoustic and sampling sediment concentrations for river.

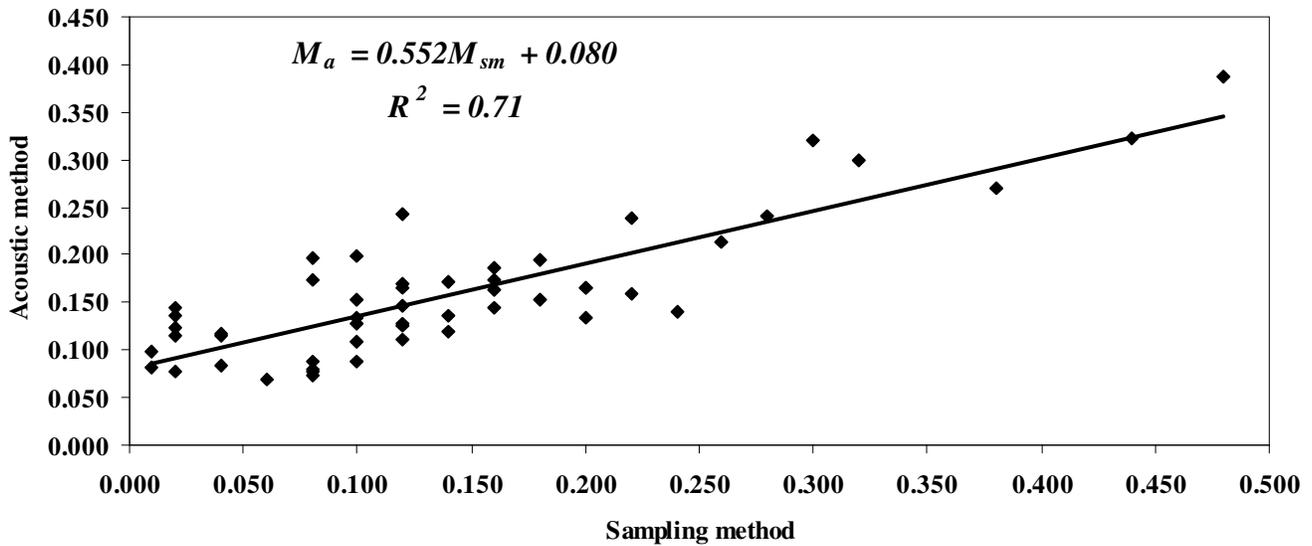


Figure 7. The regression analyses between acoustic and sampling method (M is sediment concentration (g/l) and subscripts a and sm are acoustic and sampling method, respectively).

preferred to be use at field experience due to higher correlation than sandy scattering.

Field measurement

Sediment concentrations at the river were observed between 0.008 and 0.460 g/l. Due to an arid period during the experiment, sediment transport was at a lower level than expected. Sediment size measurements were ignored because sediment consisted of very fine materials

and sediment concentration were in very low level. Measured concentrations of the sampling method were determined at two depths (20 and 80% of the profile) for each profile and presented with acoustic measurements for the same depths in Figure 6. Acoustic inversion with the glass scattering equation was used to compute sediment concentration. The regression analyses (Figure 7) and t-test were performed to compare the performance of the methods and the results are illustrated in Table 1 with the basic statistical parameters.

Generally, reasonable agreement was observed

Table 1. The statistical results of river sediment measurements.

Methods	Mean (g/l)	Min (g/l)	Max (g/l)	Standard deviation	P	RMSE
Acoustic	0.179	0.078	0.418	0.074	0.006**	0.1
Sampling	0.144	0.008	0.480	0.106	-	

**Indicates significance level at 0.01 and RMSE is the root mean square error.

between acoustic and sampling sediment methods. Acoustic method had higher values than sampling method in some applications, especially in low concentrations. This may be because of air bubbles in water observed in natural river flow conditions. In acoustic measurements, bubbles can increase backscattering and it seemingly shows higher sediment concentration (Battisto 2000; Gartner et al. 2001). This situation may especially be more effective in lower concentrations. Medwin and Clay (1998) stated that the acoustic cross-section formed by resonant characteristic of air bubble was larger than the normal physical dimensions. Therefore, in coastal sediment measurements, measurements should be made away from the coast where it is very wavy to reduce the inverse effect of air bubble.

Conclusion

The acoustic method, especially with glass scattering equation, works well for calculating soil sediment in laboratory and river conditions. But this result was obtained for a low concentration range and very fine sediment material. While acoustic backscattering evaluation is simpler in low concentration, the concentration dependent relative effect of biological material or air bubbles on sediment concentration measurements is more significant. In higher sediment concentrations, it is known that scattering properties become more complex especially with different particle sizes (Thorne and Hanes, 2002; Mouraenko, 2004). However, these positive results showed that this method can be applied in shallow river conditions. It has been shown that the method has potential for continuous and reliable sediment measurements in rivers as long as appropriate calibration or regression approaches are used.

ACKNOWLEDGEMENT

Financial support was provided by The Scientific & Technological Research Council of Turkey (TÜBİTAK) for this study. We would like to thank TÜBİTAK for offering this opportunity.

REFERENCES

Battisto GM (2000). Field Measurement of Mixed Grain Size Suspension in the Nearshore under Waves; A Thesis presented to The Faculty of the School of Marine Science, The College of William

- and Mary in Virginia. pp. 16-27.
- Betteridge KFE, Thorne PD, Cooke RD (2008). Calibrating multi-frequency acoustic backscatter systems for studying near-bed suspended sediment transport processes; *Cont. Shelf Res.* 28: 227-235.
- Chanson H, Takeuchi M, Trevethan M (2008). Using turbidity and acoustic backscatter intensity as surrogate measures of suspended sediment concentration in a small subtropical estuary; *J. Environ. Manage.* 88 (4): 1406-1416.
- Crawford AM, Hay AE (1993). Determining suspended sand size and concentration from multifrequency acoustic backscatter; *J. Acoust. Soc. Am.* 94 (6): 3312-3324.
- Flamer GH (1962). Ultrasonic measurements of suspended sediments; Geological Survey Bulletin No 1141-A, United States Government Printing Office, Washington.
- Gartner JW, Cheng RT, Wang P, Richter K (2001). Laboratory and field evaluations for the LISST-100 instrument for suspended particle size determinations; *Mar. Geol.* 175: 199-219.
- Guerrero M, Lamberti A (2008). Field measurements of suspended sediment transport with acoustic multi frequencies technique; *River Flow 2008, Cesme-Izmir Turkey, 3-5 September*, pp. 2335-2341.
- Gaunaurd GC, Uberall H (1983). RST analysis of monostatic and bistatic acoustic echoes from an elastic sphere; *J. Acoust. Soc. Am.* 73: 1-12.
- Hay AE, Sheng J (1992). Vertical profiles of suspended sand concentration and size from multifrequency acoustic backscatter; *J. Geophys. Res.* 97 (10): 15661-15677.
- Medwin H, Clay CS (1998). *Fundamentals of Acoustical Oceanography*; Academic Press, New York, p. 712.
- Mouraenko OA (2004). *Acoustic Measurement Techniques for Suspended Sediments and Bedforms*; Ph. D. dissertation, University of Florida. pp. 7-34.
- Smerdon AM (2005). *AQUAScat; ABS system user manual*. Aquatec Electronics Limited, Hartley Wintney.
- Schaafsma AS, Hay AE (1997). Attenuation in suspensions of irregularly shaped sediment particles: A two-parameter equivalent spherical scatterer model; *J. Acoust. Soc. Am.* 102: 1485-1502.
- Sheng J, Hay AE (1988). An examination of the spherical scatterer approximation in aqueous suspensions of sand; *J. Acoust. Soc. Am.* 83: 598-610.
- Thorne PD, Hardcastle PJ (1997). Acoustic measurements of suspended sediments in turbulent currents and comparison with in-situ samples; *J. Acoust. Soc. Am.* 101 (5): 2603-2614.
- Thorne PD, Hanes DM (2002). A review of acoustic measurement of small-scale sediment processes; *Cont. Shelf Res.* 22: 603-632.
- Thorne PD, Meral R (2008). Formulations for the scattering properties of suspended sandy sediments for use in the application of acoustics to sediment transport; *Cont. Shelf Res.* 28 (2): 309-317.
- Thorne PD, Hardcastle PJ and Soulsby RL (1993). Analysis of acoustic measurements of suspended sediments; *J. Geophys. Res.* 98 (1): 899-910.
- Thorne PD, Buckingham MJ (2004). Measurements of scattering by suspensions of irregularly shaped sand particles and comparison with a single parameter modified sphere model; *J. Acoust. Soc. Am.* 116 (5): 2876-2889.
- Thorne PD, Vincent CE, Hardcastle PJ, Rehman S, Pearson N (1991). Measuring suspended sediment concentrations using acoustic backscatter devices; *Mar. Geol.* 98: 7-16.
- Thosteson ED, Hanes DM (1988). A simplified method for determining sediment size and concentration from multiple frequency acoustic backscatter measurements; *J. Acoust. Soc. Am.* 104-2 (1): 820-830.

Wren D, Vadakapurapu S, Kuhnle R, Chambers J, Barkdoll B (2002). Suspended-Sediment Measurements in Laboratory Flumes Using Acoustic Techniques; Hydraulic Measurements and Experimental Methods Conference, Colorado, USA, July 28-August 1.

Yüksel A, Akay AE, Gundogan R (2008). Using ASTER Imagery in Land Use/cover Classification of Eastern Mediterranean Landscapes According to CORINE Land Cover Project. *Sensors* 8(2):1237-1251