A method for using ADCP echo intensity to track particle movements in Lake Biel

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During the winter of 2009 / 2010, the lake-based water supply plant of the City of Biel (Switzerland) had to interrupt operation, for the first time since the plant became operational in 1975. The reason was an unusually high particle concentrations in the drinking water intake in Lake Biel. The question of the origin of these particles is especially complex as Lake Biel has a short renewal time (~2 months) implying that the circulation patterns are affected by river inflows. Therefore a method with good temporal resolution is required to track particle transport over time. Here we present a method for tracing particle movements and composition in lakes with inhomogeneous particle distribution using Acoustic Doppler Current Profiler echo intensity data. The method includes (i) compensation for signal depletion and (ii) correlation to mass and turbidity observations.

1 Introduction

In recent years Acoustic Doppler Current Profiler (ADCP) echo intensity have been increasingly used to investigate suspended particles transport. Applications include tracing particles resuspended by waves [1, 2], zooplankton migration [3], sediment transport in rivers [4, 5] and particle size estimates [6, 7].

The ADCP echo intensity signal has to be adjusted for power loss due to geometrical spreading, viscous damping, scattering and instrument dependent factors. To overcome this, most authors use the sonar equation in combination with calibration from measurements, e.g. particle size and concentration [8].

In this study we extend the work done by [4, 9, 10] to study particles transport and composition in Lake Biel in western Switzerland. The major difference between the river conditions in [4, 10] and our lake system is that the vertical particle distribution cannot be assumed to be homogenous. Therefore, we investigate a different approach to correct for attenuation caused by suspended particles over the water column.

Here we present a method for combining ADCP echo intensity with turbidity observations, size, volume- and mass- concentration measurements to achieve a corrected backscatter signal in a system with inhomogeneous and changing suspended particle concentration and properties.

2 Method

The method used in this study for converting the ADCP backscattering signal mostly follows the steps described by Moore et al. [4]. However, their study was done with horizontal mounted ADCPs in a river, i.e. a uniform particle composition across the profiling range can be expected. This is not the case in lakes where the particle composition can change considerably in space and over the seasons. Therefore we apply a modified version of their method with mass-, size- and composition measurements of the particles in order to adjust the signal loss due to particle attenuation.

ADCP backscattering signals are delivered to the user in machine units (counts) which have to be converted into a system independent intensity unit, I_{dB} [dB], e.g.[8, 4].

$$I_{dB}=10\log_{10}\left(10^{K\,E/10}-10^{K\,E_{noise}/10}\right) \qquad (1)$$

here E is the ADCP received signal intensity in counts, E_{noise} is the machine noise in counts and k_c is the count to decibel conversion factor. E_{noise} can be estimated if the signal traveling distance is long enough in regions with no expected backscatter or if the attenuation due to particles is significant. K is dependent on electric component temperature, T_e [°C], and the following relationship is used by Moore et al. [4]

$$K=\frac{127.3}{T_e+273} \qquad (2)$$

However, the conversion factor is also hardware dependent [3], and in this study we use:

$$K=\frac{k_i}{T_e} \qquad (3)$$

Where k_i is a scaling factor delivered by Teledyne RD Instruments for each beam, for T_e, the built- in temperature sensor in the ADCP is used.

From the converted signal, Eq. 1, the backscattering strength from particles, also called backscattering level BL [dB], is deduced by adjusting the signal received by the ADCP transducer for power lost due to signal spreading, attenuation and transmission weakening. To compensate for battery power deprivation [11], i.e. signal source depletion, we add a fourth term to the equation given by Moore [9]

$$BL = I_{dB} + 20\log_{10}(r) + 2\alpha r + 20\log_{10}(B/Bfull) \qquad (4)$$

Here B is the decreasing ADCP battery power and Bfull is the battery power at deployment start. The second term compensates for signal power loss due to spherical spreading, r is the distance traveled. The third term handles the total attenuation, α, of the signal caused by the water and particles. Since the signal has to transverse the water column twice the power loss has to be doubled, hence the numbers 20 and 2.

The total attenuation, α [m], can be divided into three parts as described by Moore et al. [4]

$$\alpha = \alpha_w + \alpha_{p.s} + \alpha_{p.v} \qquad (5)$$

α_w represents attenuation caused by heating of the water, loss due to particle scattering is expressed in $\alpha_{p.s}$ and $\alpha_{p.v}$ is loss induced by viscous absorption of the signal in the boundary layer surrounding the particle. The water attenuation term, α_w [m], can be written as proposed by Fisher and Simmons [12]

$$\alpha_w = (55.9 - 2.37T + 4.77 \cdot 10^{-2}\,T^2 - 3.48 \cdot 10^{-4}\,T^3) \cdot 10^{-15}\,f^2 \qquad (6)$$

here T is the water temperature in °C and f is the ADCP signal frequency in Hz. Since the temperature within the signal traversed volume have large seasonal and spatial variations we use vertical moored temperature loggers for T in Eq. 6 as proposed by Lorke et al. [3].

The scattering- and viscous attenuation coefficients can be written as

$$\alpha_{p.s} = M\langle \xi_s(a_s,f) \rangle \qquad (7)$$

$$\alpha_{p.v} = M\langle \xi_v(a_s,f) \rangle \qquad (8)$$

where M is the mass concentration of particles, $\xi_s(a_s,f)$ and $\xi_v(a_s,f)$ is the particle diameter-, a_s, and frequency, f, dependent scattering- and viscous attenuation constants, angular brackets indicates average [9, 14, 15]. According to Moore [9] ξ_v can be expressed as

$$\xi_v = \frac{ks(\sigma-1)^2}{2\rho_s(s^2+(\sigma-\delta)^2)}$$

$$s = \frac{9}{4\beta a_s}(1+1/\beta a_s) \qquad (9)$$

$$\sigma = \frac{\rho_s}{\rho_0}, \quad \delta = \frac{1}{2}(1+9/2\beta a_s), \quad \beta = \sqrt{\frac{\omega}{v}}$$

here k = 2π/λ, λ is the signal wavelength, ρ_s and ρ_o are the particle- and water density, ν is the kinematic viscosity, 1.3 * 10^{-6} m^2 s^{-1}, and ω = 2πf.

ξ_s has its maximum value for particles with a diameter around 1 mm and can be assumed to be zero when the particle diameter drops below 100 µm, the maxima for ξ_v occurs for particle sizes around 1 µm [15].

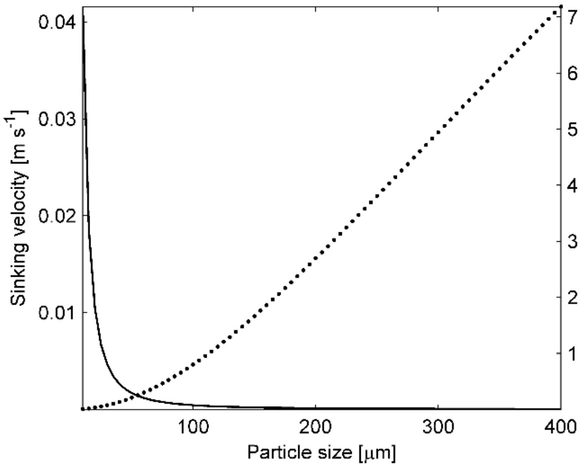

Figure 1. Particle sinking velocity (dots) calculated as in Cheng [16] for 10 °C and particle residence time (line) in Lake Biel calculated with a mean depth of 31 m.

Considering that the particles in a shallow lake have been in suspension for a long time it can be assumed that the majority of the particles with a size exceeding 100 µm have mostly fallen to the lake bottom (Fig. 1). This implies that the majority of the particles interacting with the ADCP signal will have a size smaller than 100 µm. We therefore neglect $\alpha_{p.s}$ in Eq. 5, subsequently Eq. 4 can be written as

$$BL = I_{dB} + 20\log_{10}(r) + 2(\alpha_w + M\langle \xi_v \rangle)r + 20\log_{10}(B/Bfull) \qquad (10)$$

To solve this equation a laser diffraction instrument can be used to measure the particle size and volume concentration. To acquire the particle density the laser diffraction observations is combined with mass measurements from filtration of water samples. These mass samples are furthermore correlated to the corrected backscatter signal in order to obtain the particle concentration. The particle transport can then be attained by combining this backscattering derived concentration with ADCP current measurements.

3 Conclusions

In this study we developed a method for using ADCP echo intensity data to track the compositions and movements of particles in lakes where the vertical particle composition is inhomogeneous. The method offers good temporal resolution of the concentration and movements of the particles and making it a useful tool for model calibration.

A measurement campaign in Lake Biel is currently underway to validate the theory in this study. Three moorings have been deployed in the lake since May 2013. One to two ADCPs with 300, 600, 1200 and 2000 kHz frequency are deployed at each station for tracking particles within different size ranges. In order to observe the vertical temperature structure over time each mooring is equipped with vertically spaced (~5 m) temperature loggers. Particles size, measured with a LISST-100X instrument, and vertical distributed water samples are sporadically being collected to obtain the particles size- and mass distribution. In order to verify the accuracy of this method, stationary turbidity sensors will be deployed and regular CTD profiles of transmission are obtained.

To further develop this method the impact of organic material on the echo intensity can be tested by correlating the backscattering-derived concentration, turbidity and mass observations to measurements of photosynthetically active pigments.

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