



A priori diagnostic for acoustic backscatter inversion to suspended sediment concentration in hyperturbid estuaries

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Abstract. Accurate quantification of sediment transport in fluvial, estuarine and coastal environments depends on reliable estimates of suspended sediment concentrations (SSCs). While Acoustic Doppler Current Profilers (ADCPs) provide depth-resolved backscatter observations that can potentially be converted to SSC, conventional inversion techniques fundamentally depend on the assumption of homogeneous sediment concentration and acoustic scattering/attenuation properties along the acoustic beam. In stratified and hyperturbid conditions, this homogeneity may be compromised, even when the particle size distribution itself remains vertically stable. Strong sediment gradients trigger stratification that either amplifies signal strength at the lutocline or diminishes it by fine-sediment-induced viscous attenuation, possibly invalidating this assumption. To assess whether the assumption of homogeneous medium remains valid under hyperturbid conditions, we propose an *a priori* diagnostic based on the shape of the acoustic backscatter profile. Using changepoint detection, we identify slope breaks in acoustic profiles, which indicate transitions in the effective acoustic regime. These transitions likely indicate a breakdown of the homogeneity assumptions underlying acoustic backscatter inversion techniques. We apply the diagnostic to ADCP measurements (approximately 2 m above the bed) collected in an engineered navigation channel of the Ems Estuary, spanning SSCs of 0.1–100 g L⁻¹, this upper limit corresponding to hyperturbid conditions. Validation against in-situ water samples confirms that profiles without detected changepoints (Type 1) yield reliable SSC estimates, even at concentrations up to 20 g L⁻¹. In contrast, Type 2 profiles exhibit pronounced spikes or slope breaks that may reflect range-dependent acoustic sediment properties. This variation decouples the observed backscatter from a simple, range-invariant relationship with concentration. As a result, the inversion algorithm fails to accurately invert backscatter to concentration, leading to erroneous and unphysical SSC estimates that deviate significantly from in-situ water samples. The proposed diagnostic provides a simple step to flag unreliable profiles and support targeted sampling and interpretation in challenging hyperturbid environments, enabling more reliable estimation of suspended sediment concentrations and associated sediment transport fluxes.



1 Introduction

Accurately measuring suspended sediment concentration (SSC) is crucial for understanding sediment transport, channel siltation, turbidity-driven stratification, and biogeochemical and ecological processes in rivers, estuaries, and coastal waters (Schroetke et al., 2006; Zhou et al., 2021; Hou et al., 2024; Holdaway et al., 1999). Over recent decades, measurement techniques have transitioned from labor-intensive direct in-situ sampling to surrogate methods, notably based on optical sensing and acoustic backscatter. Acoustic backscatter sensors (ABSs) and optical backscatter sensors (OBSs) have been well developed for measuring the profiles of SSC and particle size. However, comprehensively quantifying sediment transport dynamics requires synchronous insights into background flow conditions, typically obtained by deploying a current meter alongside an ABS or OBS. Acoustic Doppler Current Profilers (ADCPs) offer a distinct advantage by providing collocated velocity and backscatter profiles. Although their temporal sampling frequency is inherently coarser than that of laboratory point-measurement sensors, ADCPs enable continuous, high-spatial-resolution profiling over extended periods. Such a continuous monitoring capability allows the capture of intra-tidal and event-scale dynamics (Thorne and Hanes, 2002; Haught et al., 2017). Consequently, the acoustic backscatter recorded by ADCPs has become a widely adopted proxy for SSC in field settings (Wren et al., 2000; Hoitink, 2004; Sassi et al., 2012; Haught et al., 2020; Szupiany et al., 2019; Wood and Gartner, 2010; Holdaway et al., 1999). However, the accuracy of SSC estimates inferred from acoustic backscatter depends critically on the validity of the underlying physical assumptions.

The conversion of backscatter to SSC is inherently site- and time-specific (e.g., Gartner, 2004; Hoitink and Hoekstra, 2005) because the received backscatter depends on the properties of the sediment such as particle size, but also on the number, shape, and composition of scatterers in the ensonified volume (Sassi et al., 2012; Thorne and Hanes, 2002; Schaafsma and Hay, 1997; Moate and Thorne, 2013). In many practical applications, the variation of these properties within the ensonified volume is sufficiently small to be neglected, supporting the assumption of a uniform distribution of acoustic scattering properties (Szupiany et al., 2019; Sassi et al., 2012; Niesten et al., 2024; Haught et al., 2017). Under this premise, range-averaged inversion algorithms treat key acoustic parameters as spatially uniform, representing a homogeneous distribution of sediment acoustic properties.

It is difficult to predict beforehand whether the homogeneity assumption will hold or not. Strong variations in particle size and concentration along the path of the acoustic beam often irregularly degrade the relation between backscatter and SSC (Venditti et al., 2016; Thorne et al., 2021, 1991). Hyperturbid mud environments are particularly challenging because high concentrations of mud attenuate the acoustic signal through viscous absorption, which results from viscous drag between the fluid and the suspended particles. Currently, diagnosing poor inversion performance and identifying violations of the homogeneity assumption require labor-intensive post-processing, such as computing the along-path accumulation of inversion error (Thorne et al., 2011), as well as auxiliary data collection, such as repeated calibrations to determine the inversion coefficients or particle size distribution (PSD) observations (Vergne et al., 2021; Venditti et al., 2016). This motivates the development of an *a priori* assessment method capable of indicating whether the homogeneity assumption is likely to hold and whether acoustic inversion can be applied reliably in hyperturbid field settings.



55 This paper investigates how sediment heterogeneity affects the performance and limitations of the conventional ADCP
backscatter calibration in a mud-dominated environment. An engineered and deepened navigation channel in the Dutch-
German Ems Estuary provides a well-suited field site where strong SSC-induced stratification and abundant fine-particle-
induced sediment attenuation possibly challenge the homogeneity assumption (Becker et al., 2018). The objective of this study
is to develop an *a priori* diagnostic to assess whether ADCP backscatter profiles satisfy the homogeneity requirements on
60 acoustic sediment properties, and whether acoustic inversion can be reliably applied to estimate SSC under hyperturbid condi-
tions. Building on this diagnostic, we evaluate which backscatter profile geometries yield stable and reliable SSC inversions,
particularly under stratified and hyperturbid conditions, and discuss the physical and methodological reasons for inversion
failure.

To address these questions, we employed a frame-based, downward-looking ADCP lowered from a vessel to approximately
65 2 m above the bed where the stratification is most pronounced and concentrations are highest. The acoustic observations were
collected in a hyperturbid estuarine navigation channel where SSC ranges between 0.1 and 100 g L⁻¹, providing profiles with
a range of stratification strengths. Based on the dataset, our methodology proceeds in sequential stages. First, a "slope test"
(changepoint detection) on the acoustic backscatter profiles is proposed, to diagnose if the backscatter profile is consistent with
the assumption of homogeneity. The acoustic backscatter profiles are subsequently classified as Type 1 (consistent with the ho-
70 mogeneity assumption) or Type 2 (inconsistent with the homogeneity assumption). To validate the classification, we implement
an explicit acoustic inversion approach which avoids the mutual dependence of concentration and inversion parameters (Lee
and Hanes, 1995; Thorne and Hanes, 2002; Sassi et al., 2012). The calibration procedure is then extended to depth-varying
calibration coefficients to assess whether the empirical attenuation is depth-dependent. Finally, we use the Richardson number
derived from vertical density gradients and shear to interpret how sediment stratification causes breaks in acoustic profiles,
75 which hamper the inversion of acoustic backscatter to SSC.

2 Material and Methods

2.1 Study site and data collection

On 10 February 2022, 29 September 2024 and 25 January 2025, frame-based ADCP observations were collected in the Emden
Fahrwasser, a hyperturbid navigation channel located in the Ems estuary on the Dutch-German border (Figure 1a, b). The
80 navigation channel is characterized by a pronounced longitudinal SSC gradient, ranging from 0.1 g L⁻¹ on the western (sea)
side to several g L⁻¹ near the eastern (river) side within several kilometers. On the Ems river side, a highly concentrated
benthic suspension (fluid mud) is likely to develop close to the bed (Talke et al., 2009). The sediment deposited in the estuary is
predominantly fine-grained, with mud contents approaching 100% near Emden and an organic fraction of up to 5% (Van Maren
et al., 2016). Particle size distributions (PSDs) measured during our 2024 and 2025 surveys further confirm the predominance
85 of clay-sized material (Figure 3). The hydrodynamic conditions during the three observation periods ranged from well-mixed
to strongly stratified, providing a range of vertical sediment distributions. These pronounced spatial and temporal variations

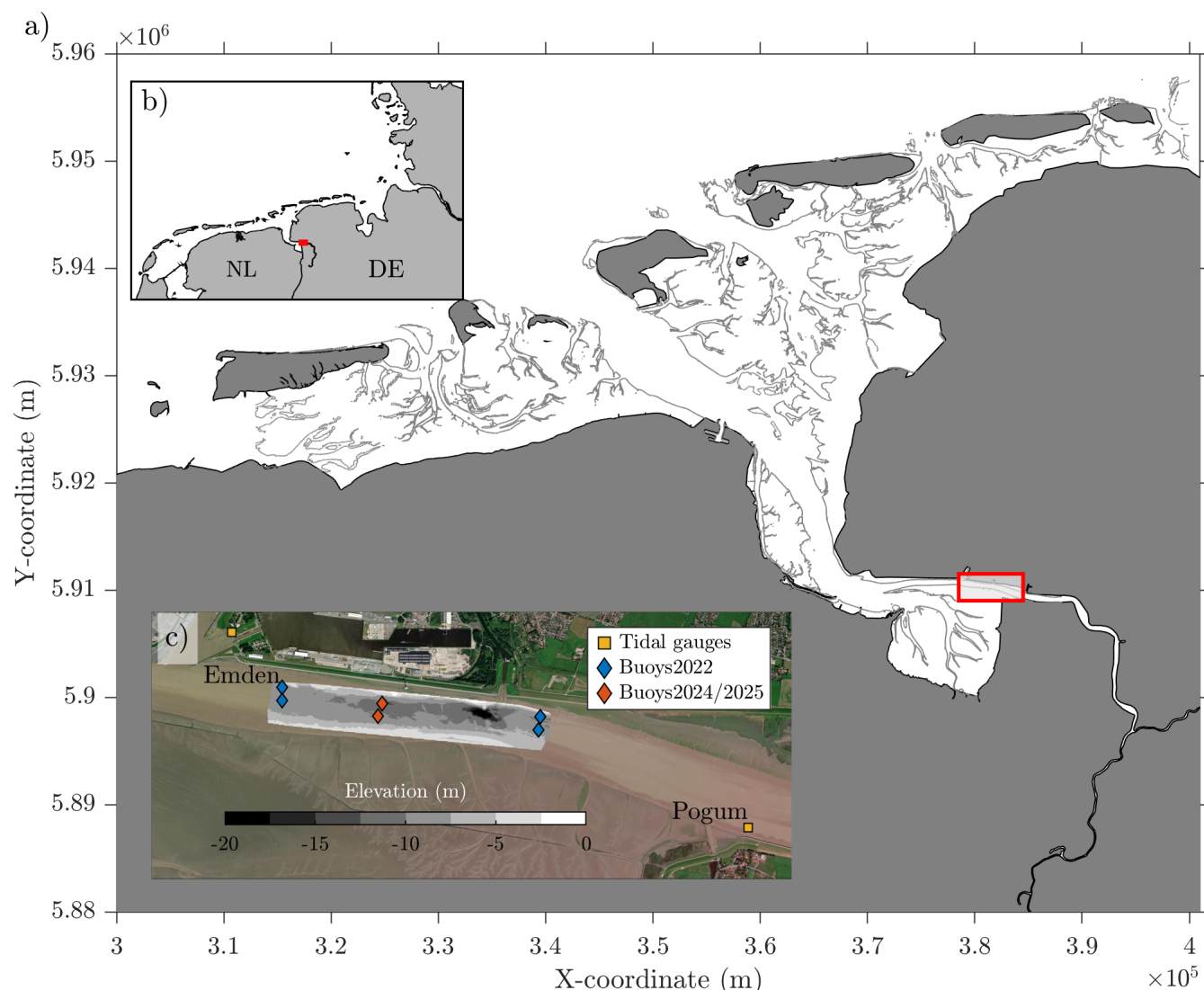


Figure 1. Study area for data collection. (a) The Ems Estuary. (b) Inset showing the location of the Ems Estuary along the Dutch–German border. (c) Zoom-in of the survey region at the Emden Fahrwasser, showing the bathymetry, tidal gauges and buoys for the different campaigns as blue and orange diamonds. Map source of (a) and (b): Rijkswaterstaat servicedesk (<https://www.rijkswaterstaat.nl/formulieren/contactformulier-servicedesk-data>). In (c), the background satellite imagery is from Google Maps (Imagery © 2025 Google), and the bathymetry was measured during our field campaigns in 2022.

in SSC and stratification make the Emden Fahrwasser a suitable natural laboratory for examining the performance of acoustic backscatter inversion under heterogeneous and hyperturbid conditions.

A 1000 kHz downward-looking Nortek Signature ADCP was employed during all three field campaigns (Figure 2). The instrument features four slanted beams (25° from the vertical) for velocity measurements and one dedicated vertical beam for

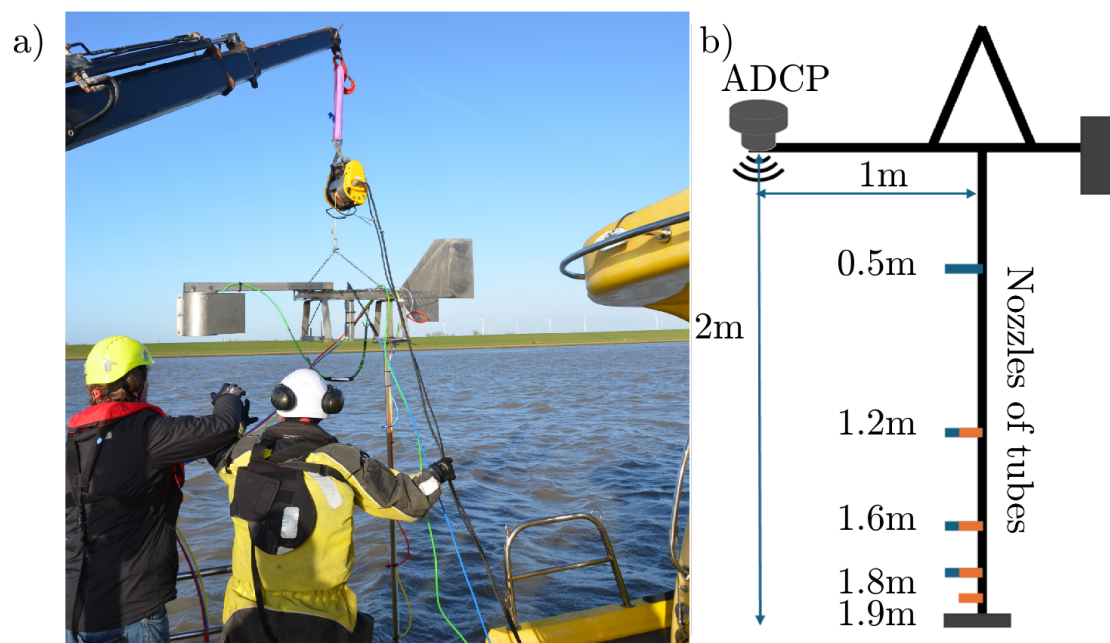


Figure 2. Experimental configuration. Photograph (a) and sketch (b) of the mobile sampling frame, with the downward-looking ADCP as the reference point for the vertical sampling array. Nozzles of tubes for sampling are fixed along the vertical 2-meter-long rod, where orange and blue bars denote the nozzle configurations during the 2022 survey and the 2024/2025 surveys, respectively. The vertical beam of the ADCP is horizontally offset by 1 m from the rod.

echo sounding. The vertical beam provides a high-resolution vertical profile (0.05 m bin size) compared to the slanted beams (0.5 m), allowing small-scale variations in SSC to be resolved. The blanking distance was set to 0.1 m, and the sampling frequency was 1 Hz.

To observe the highly turbid near-bed layer, the ADCP was mounted on a rigid frame (Figure 2). The frame housed four sampling nozzles connected to boat-mounted Verderflex isokinetic pumps. The nozzles (4.5 mm diameter) were positioned at varying vertical distances below the transducer: 1.9, 1.8, 1.6, and 1.2 m in 2022, and 1.8, 1.6, 1.2, and 0.5 m in 2024 and 2025, ensuring that physical water samples were nearly collocated with the ADCP's acoustic sampling volume. Water samples were collected with a pump in 1-liter bottles, with each taking approximately 2 minutes to fill completely after a 3 minute flushing of the tubes. The nozzles were laterally offset from the vertical-beam axis by approximately 1 m, but lateral SSC gradients are expected to be very small compared to the strong vertical stratification characterizing the near-bed layer in this reach. During the survey the vessel was moored to navigation buoys (Figure 1c) to ensure a relatively stable position for sampling. The frame was manually lowered until the ADCP transducer was positioned approximately 2 m above the channel bed. Bed level was determined using the survey vessel's echosounder, while a pressure sensor mounted on the frame at the same position as the



ADCP was used to measure the instrument depth within the water column. During periods of strong flow, some measurements did not extend to the lowermost near-bed layer, likely because the bed elevation at the instrument frame differed from that directly beneath the survey vessel. Once the frame reached the targeted depth, it was kept hovering in a fixed position. Water sampling commenced only after a 2-minute stabilization period, allowing any localized turbulence or sediment resuspension caused by the frame's deployment to be removed by the flow. For calibration and diagnostic analysis, the 2-minute averaged volume backscattering strength from the vertical beam was matched with the corresponding physical water samples, which were collected over an approximately 2-minute bottle-filling period, thereby minimizing non-sediment-related noise.

Table 1. Summary of suspended sediment concentration (SSC) conditions during the 2022, 2024, and 2025 field campaigns.

Campaign	Total samples	Total transects	Min SSC (g L ⁻¹)	Max SSC (g L ⁻¹)	Std(SSC) (g L ⁻¹)
2022	64	16	0.33	100.00	24.74
2024	112	28	0.07	5.13	2.75
2025	101	26	0.10	75.21	11.32

Mass concentrations (Table 1) and PSDs (Figure 3) were determined through laboratory analyses of the water samples collected during the survey campaigns in 2022 (16 profiles; 64 samples), 2024 (28 profiles; 112 samples), and 2025 (26 profiles; 101 samples). The successfully analysed samples were used to invert the acoustic backscatter to sediment concentrations. The samples collected in the 2022 campaign were analysed in the Rijkswaterstaat laboratory. There, PSDs were not analysed. The samples collected in the campaigns of 2024 and 2025 were processed at the Wageningen University laboratory. Here, a MasterSizer-3000 instrument (Malvern Panalytical Ltd., Malvern, UK) was used to obtain the fractional PSD, relying on laser diffraction. The stirrer speed was set to 1400 rotations per minute along with the use of a chemical disperser and ultrasonic vibrations, aiming to retrieve the distributions of primary particles. For all campaigns, the sediment mass concentration was determined using a two-stage filtration procedure to prevent filter clogging and a vacuum was employed to accelerate processing. The water samples were sequentially passed through a coarse pre-filter (pore size $\sim 2.5 \mu\text{m}$) and subsequently through a $0.45 \mu\text{m}$ filter. Both filters were then oven-dried and weighed to calculate the total cumulative sediment mass concentration. Notably, in-situ floc size distributions were not measured from these laboratory water samples, as flocs are highly prone to alteration (such as aggregation or breakage) during sampling, transport, and storage, making laboratory disruption inevitable and unrepresentative of true in-situ conditions (de Lange et al., 2024). The PSD results show that the suspended sediment is clay and silt dominant with the median radius less than $10 \mu\text{m}$. Figure 3b shows the distribution of ka_s , which indicates the scatterers are in the Rayleigh regime. The parameter is used to calculate the acoustic parameters and introduced in Section 2.2.1.

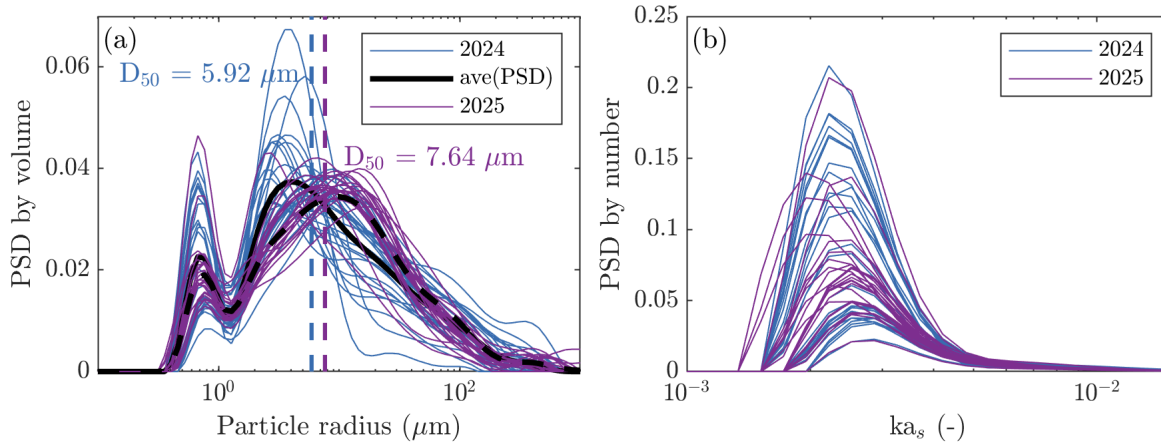


Figure 3. Lab analysed Particle Size Distributions (PSDs) from the 2024 (blue lines) and 2025 (purple lines) surveys. (a) The black solid and dashed lines indicate the average PSD from the water samples of 2024 and 2025 surveys. The blue and purple dashed lines correspond to the median particle radius from 2024 and 2025 surveys. (b) Number distribution of the product ka_s of wave number and particle radius, used to calculate the theoretical acoustic parameters.

2.2 Acoustic backscatter inversion

For acoustic backscatter inversion we follow the theoretical framework of Lee and Hanes (1995) and Thorne and Hanes (2002), as previously applied by Sassi et al. (2012). In this approach, backscatter from the sampled volume is assumed to be dominated by incoherent volume scattering. Under this assumption, the suspended scatterers have phases randomly distributed between 0 and 2π . Furthermore, homogeneous suspension properties are assumed within the ensonified volume. Departing from the conventional implementation of this framework, we relax the depth-invariant calibration assumption to investigate whether empirical acoustic attenuation varies systematically along profiles containing changepoints. Theoretical attenuation is subsequently calculated from measured PSDs to evaluate whether the observed variations in empirical attenuation are consistent with sediment-induced attenuation.

2.2.1 Equation development

The volume scattering strength S_v of sediment suspensions at a range R from an ADCP transducer is equal to the sum of the echo intensity directly measured by the ADCP (EI, dB), attenuation by water and sediment in the two-way path along the range to the sediment suspension, signal loss from spherical spreading and an instrument-specific constant (G):

$$S_v = EI + 2\alpha_w R + 2 \int_0^R \alpha_s(r) dr + 10 \log_{10} \left(\frac{T_T R^2 \psi^2}{L P_T} \right) + G \quad (1)$$



where S_v is in dB, α_w represents sound attenuation due to absorption by water (dB m^{-1}), α_s is attenuation by suspended particles (dB m^{-1}). The fourth term on the right hand side is the signal loss from spherical spreading (dB), where ψ is a function that accounts for the departure from spherical spreading within the near field of the transducer, T_T is the transducer temperature ($^{\circ}$), L is the transmit pulse length (m), P_T is the transmit power (W). The instrument-specific constant is sometimes
145 provided by the manufacturer.

Combining the sum of EI, attenuation by water and spherical spreading in a single term, $S'_{v,\alpha_s=0}$, the sonar equation is rewritten to explicitly relate the volume scattering strength to the local sediment concentration:

$$\begin{aligned} S_v(R) &= S'_{v,\alpha_s=0}(R) + 2 \int_0^R \alpha_s(r) dr + G \\ &= S'_{v,\alpha_s=0}(R) + 2 \int_0^R \xi_{total}(r) M_s(r) dr + G \\ &= 10 \log_{10}(k_s^2(R) M_s(R)). \end{aligned} \quad (2)$$

150 Herein, $S'_{v,\alpha_s=0}$ is readily calculated from raw ADCP data. We capture the combination of scattering and viscous absorption in ξ_{total} ($\text{dB m}^2 \text{ kg}^{-1}$). α_s is written as the product of sediment attenuation ξ_{total} and mass concentration M_s , and k_s^2 describes the scattering properties of the suspended sediment ($\text{dB m}^{-1} \text{ kg}^{-1}$). Equation (2) shows which factors impact the inversion relationship. The mutual dependence of M_s , S_v and distance-integrated acoustic attenuation complicates ADCP backscatter calibrations. To estimate M_s , profiles of S_v have to be corrected for sound attenuation, which in turn depends on M_s (Thorne
155 and Hanes, 2002).

In the Rayleigh scatter regime ($ka_s \ll 1$, where k is the wave number for the given acoustic frequency and a_s is particle radius), the acoustical scattering cross-section is much smaller than the geometrical cross-section because the sound waves bend around, and are hardly affected by, acoustically small non-resonant bodies (Medwin and Clay, 1997). For a spherical particle acting as a Rayleigh scatterer, the acoustical scattering property can be expressed as:

$$160 \quad k_s^2 = \frac{3\vartheta k^4}{\rho_s} \langle a_s^3 \rangle \quad (3)$$

where ρ_s is the density of the sphere (2650 kg m^{-3}), ϑ is a material parameter which reads (Anderson, 1950):

$$\vartheta = \left(\frac{e-1}{3e} \right)^2 + \frac{1}{3} \left(\frac{g-1}{2g+1} \right)^2 \quad (4)$$

where e is the ratio of the elasticity of the sphere to that of the medium and g is the ratio of the density of the sphere to that of the medium. The angle brackets denote the operation

$$165 \quad \langle a_s \rangle = \int_0^{\infty} a_s n(a_s) da$$

where $n(a_s)$ represents the particle size distribution by number. Attenuation of sound by sediment can be attributed mainly to the scattering of sound by particles ($\alpha_{s,scat}$) and viscous absorption resulting from fluid-particle interactions ($\alpha_{s,visc}$). The



local sediment attenuation α_s is given by:

$$\begin{aligned}\alpha_s &= \xi_{theo} M_s \\ &= (\xi_{scat} + \xi_{visc}) M_s \\ &= \alpha_{s,scat} + \alpha_{s,visc}\end{aligned}\tag{5}$$

170 where ξ_{scat} and ξ_{visc} are scattering and viscous attenuation coefficients, with units of $\text{dB m}^2 \text{ kg}^{-1}$.

Sound attenuation due to suspended sediment within the Rayleigh scattering regime has been extensively analysed by Urlick (1948) and utilized by Hoitink and Hoekstra (2005); Moore et al. (2012); Gartner (2004), who demonstrated that acoustic absorption is a function of particle radius, expressed as:

$$\alpha_{s,scat} = \frac{k^4 a_s^3}{96 \rho_s} \frac{20}{\ln 10} M_s\tag{6}$$

175

$$\begin{aligned}\alpha_{s,visc} &= \frac{k(\sigma - 1)^2 s}{2 \rho_s (s^2 + (\sigma + \delta)^2)} \frac{20}{\ln 10} M_s \\ s &= \frac{9}{4b \langle a_s \rangle} \left(1 + \frac{1}{b \langle a_s \rangle} \right) \\ \sigma &= \frac{\rho_s}{\rho_w} \\ \delta &= \frac{1}{2} \left(1 + \frac{9}{2b \langle a_s \rangle} \right) \\ b &= \sqrt{\left(\frac{\pi f}{\nu} \right)}\end{aligned}\tag{7}$$

Herein, ρ_w is the water density assumed as $1 \times 10^3 \text{ kg m}^{-3}$, ν is kinematic viscosity of water, which is taken as $1 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$; here $f = 1 \times 10^3 \text{ kHz}$.

The sediment attenuation α_s is a function of acoustic frequency and particle size, and it increases linearly with sediment concentration. Figure 4 shows the variation of α_s across varying particle sizes at the constant operating frequency of the ADCP. Across all evaluated mass concentrations, viscous absorption ($\alpha_{s,visc}$) dominates for fine-grained particles with radius smaller than $140 \mu\text{m}$, whereas scattering loss ($\alpha_{s,scat}$) becomes the primary mechanism for larger particles. The total sediment attenuation α_s exhibits peaks at around $1\text{-}2 \mu\text{m}$ and larger than $1000 \mu\text{m}$. The latter is outside the size range of interest.

The dominant viscous attenuation results from viscous drag between the fluid and the particle, which is difficult to characterize purely from the particle size distribution under hyperturbid conditions. Therefore, we adopt an empirical inversion method, replacing the parameter k_s^2 , which originates from idealized acoustic theory, by an effective empirical parameter K_s . Following the method from Thorne and Hanes (2002), Eq. (2) can be rewritten explicitly as:

$$\frac{\beta(R)}{M_s(R)} = K_s(R) \left(1 - \frac{\ln 10}{5} \int_0^R \frac{\xi_{total}(r)}{K_s(r)} \beta(r) dr \right),\tag{8}$$

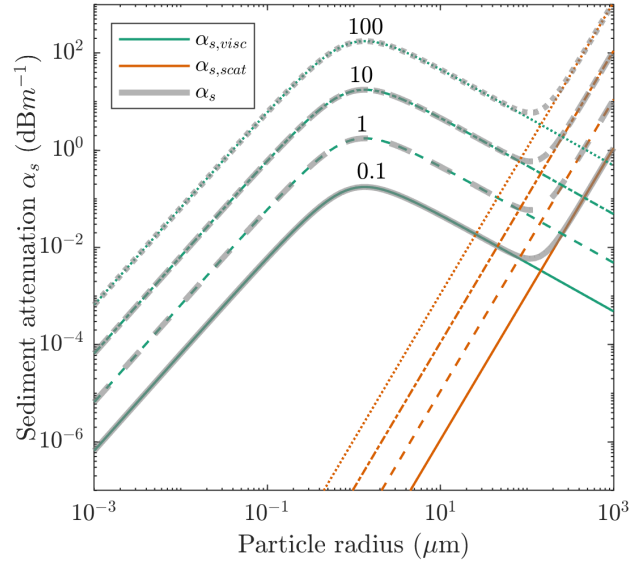


Figure 4. Contributions of viscous absorption ($\alpha_{s,visc}$) and scattering loss ($\alpha_{s,scat}$) to total sediment attenuation α_s at 1000 kHz. Line styles correspond to mass concentrations of 0.1 g L^{-1} (solid), 1 g L^{-1} (dashed), 10 g L^{-1} (dash-dotted), and 100 g L^{-1} (dotted).

where

$$\beta(R) = 10^{\frac{S'_{v,\alpha_s=0}(R)}{10}} \quad (9)$$

$$K_s(R) = \frac{k_s^2(R)}{10^{\frac{G}{10}}} \quad (10)$$

Herein, the acoustical scattering property (k_s^2) is replaced by the relative scattering area per unit sediment concentration (K_s), parametrizing the effect of the acoustical scattering and other unresolved effects. Equation (8) indicates that the sediment attenuation estimation is not affected by the unknown instrument-dependent constant G , since G enters only as a scaling factor in the equation.

Rather than deriving k_s^2 from the sediment particle properties, the empirical approach necessitates estimating or calibrating K_s . While being explicit, Eq. (8) is hard to use for calibration due to the presence of the product of the unknown coefficient K_s and an integral. The goal is now to estimate the empirical model parameters K_s and ξ_{total} from sediment sample data (M_s) and backscatter profile data (β).

2.2.2 Simplified parameter estimation problem and empirical parameters

To simplify the estimation problem explained above, sediment properties within the ensonified ADCP volume, including sediment scattering and attenuation characteristics, are often assumed to be homogeneous. Then, K_s and $\bar{\xi}_{total}$ are assumed



independent of the vertical position R and as a result, Eq. (8) reduces to

$$\frac{\beta(R)}{M_s(R)} = K_s - \frac{\ln 10}{5} \bar{\xi}_{total} \int_0^R \beta(r) dr. \quad (11)$$

205 which is a rearrangement of Eq. (13) of Sassi et al. (2012), with their R_{ref} chosen to equal 0 herein. The equation is rewritten to emphasize our interest in the parameters K_s and $\bar{\xi}_{total}$ appearing linearly in Eq. (11). In this rewritten equation, K_s is determined by β and cannot be related to the real PSD. Based on Eq. (11), the unknown scalar parameters K_s and $\bar{\xi}_{total}$, representing acoustic scattering and attenuation, can be estimated using at least two water samples collected within each profile to avoid the impact of temporal variation of K_s on $\bar{\xi}_{total}$. The water samples closest to the ADCP and closest to the
210 bed are used for calibration in our study. To evaluate the performance of the inversion, the middle two are used for validation. The details are described in Appendix A. The calibrated parameter $\bar{\xi}_{total}$ is further compared with the theoretical value ξ_{theo} to evaluate whether the empirically inferred attenuation is physically consistent with the sediment properties observed in the field.

2.2.3 Vertically varying calibration

215 When the backscatter profile is nonlinear with range, adopting a depth-averaged estimate of in-situ attenuation introduces inaccuracy (Haught et al., 2017), and the two calibration parameters ξ_{total} and K_s may need to vary over depth for the empirical model to be adequate. In our study area, the particle size distribution does not exhibit significant vertical variation based on our observations, which is consistent with the results from Merckelbach (2006). We expect K_s to be less range dependent than ξ_{total} , because K_s is often assumed to be a function of the PSD. However, the viscous-attenuation-dominated ξ_{total} is related
220 to the particle-fluid interaction (Guerrero et al., 2016; Hanes, 2012). We estimate K_s profile-by-profile using only the two water samples closest to the ADCP, where cumulative sediment attenuation remains relatively small due to the short acoustic path. Once the value of K_s specific for the profile is determined, we calculate the corresponding depth-dependent ξ_{total} based on SSC of the water samples. The method for obtaining depth-varying calibrated acoustic parameters is further described in Appendix B.

2.3 Changepoint detection

225 A linear dependence of $S'_{v,\alpha_s=0}$ on range is consistent with locally constant values of K_s and ξ_{total} . Conversely, changepoints in $S'_{v,\alpha_s=0}$ indicate spatial heterogeneity of the ensonified medium, which may arise from range-varying SSC, K_s and ξ_{total} , and their interactions. While heterogeneity in SSC alone does not violate the assumptions of Eq. (11), under hyperturbid conditions, sharp concentration gradients are often accompanied by changes in particle properties. We therefore hypothesize
230 that, under hyperturbid conditions, a significant break in the slope of $S'_{v,\alpha_s=0}$ indicates that the commonly applied assumption of range-invariant K_s and ξ_{total} is invalid, whereas the absence of changepoints indicates that these calibration parameters can be considered approximately constant over the range of interest. This hypothesis is tested against water samples in Figure 7 and 9.



Here, we introduce a systematic, shape-based changepoint detection procedure applied to the $S'_{v,\alpha_s=0}$ profiles, independent
235 of the concentration validation described below, which we then use to classify profiles *a priori*. First, we apply a linearity-
based changepoint detection to the $S'_{v,\alpha_s=0}$ profiles to separate profiles with changepoints from those without, resulting in two
profile types: Type 1 (no changepoint detected) and Type 2 (one or more changepoints detected) (Figure 5). In Section 3.1,
we will show that Type 1 profiles show high consistency between the inverted and measured mid-depth values of SSC, while
Type 2 profiles exhibit large discrepancies between the inverted SSCs and the SSCs from the two mid-depth water samples.
240 The analysis range begins 0.5 m from the ADCP transducer to avoid near-field effects and terminates at the depth of the water
sample closest to the bed. Backscatter data outside this window were omitted, as no localized sediment concentration data were
available to validate the inversion results.

Changepoints were detected using piecewise linear models of the form $y(i) = ax(i) + b + \epsilon(i)$, where a and b are the slope and
intercept, respectively. Model parameters were estimated based on least squares and the corresponding sum of squared errors
245 (SSE) was computed. The optimal set of changepoints was identified using MATLAB's "findchangepoints" function, which mini-
mizes the total SSE subject to a standard, objective penalty against overfitting. This procedure follows the optimal partitioning
framework of Killick et al. (2012), providing an efficient and statistically principled approach for changepoint detection.

To assess the robustness of the classification, changepoint detection was repeated using penalty values ranging from 10 to
30. The resulting Type 1 / Type 2 classification was unaffected by this range of penalty values. Within the set of Type 2 profiles,
250 however, the number of detected changepoints varied for a small subset of profiles exhibiting a mid-depth peak, likely because
these peaks are typically confined to only 2–3 data points and are therefore more sensitive to the choice of penalty parameter.
These results indicate that the overall diagnostic is robust to the choice of penalty parameter, although the precise number of
changepoints detected within sharply peaked Type 2 profiles should be interpreted with some caution.

2.4 Richardson number

255 To assess the impact of stratification on acoustic homogeneity, we calculate the gradient Richardson number incorporating the
SSC effect on density (Richardson, 1920):

$$Ri_{SSC} = \frac{-g}{\rho} \frac{\partial \rho / \partial z}{(\partial u / \partial z)^2 + (\partial v / \partial z)^2} \quad (12)$$

where u and v are the two horizontal velocity components measured by ADCP, ρ is the density as a linear function of mass
concentration M_s ,

$$260 \quad \rho = \rho_w + nM_s \quad (13)$$

Herein, n is the relative density of suspended sediment to water, assumed to be 0.62. Salinity is neglected because the observed
SSC range in this study (up to 100 g L^{-1}), which is expected to dominate the density structure in the highly turbid near-bed
layer relative to salinity variations.

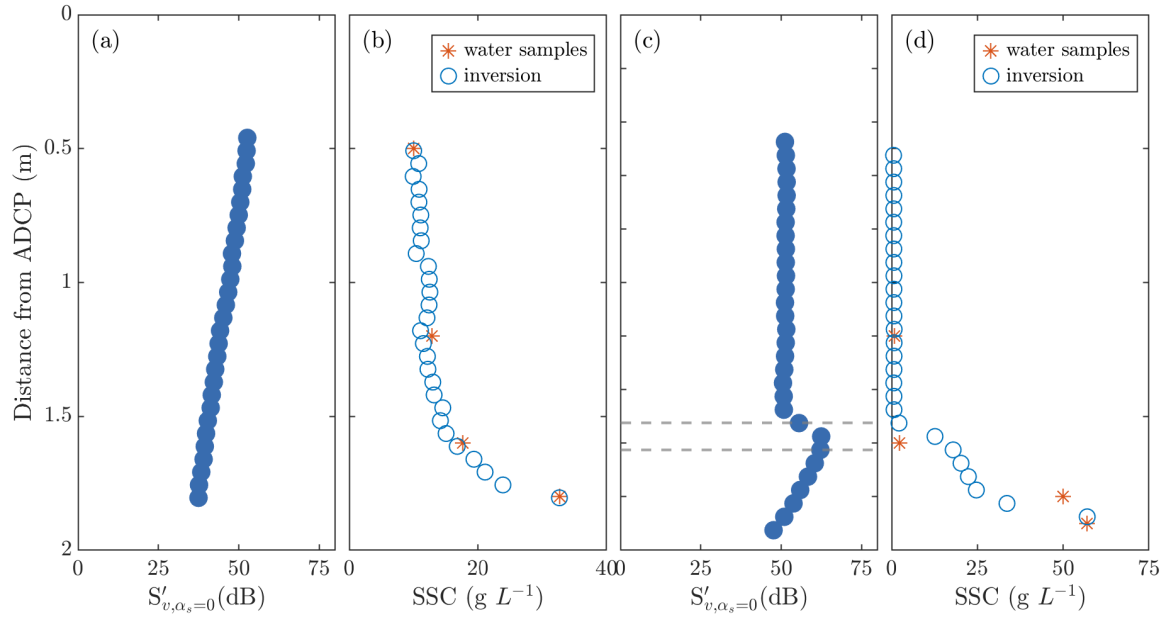


Figure 5. Profiles of $S'_{v, \alpha_s=0}$ computed from 2-min averaged values, with the corresponding concentration profiles. (a, b) Example for Type 1 (Survey 2025), with no change points detected in the backscatter data. (c, d) Example for Type 2 (Survey 2022), with two change points identified in the backscatter profile. Grey dashed lines indicate the locations of change points.

3 Results

265 3.1 Backscatter profile classification and calibration

To investigate the impact of change points on the performance of the acoustic backscatter inversion, echo intensity (EI) and backscatter profiles ($S'_{v, \alpha_s=0}$) collected during the three field campaigns are grouped into Type 1 and Type 2 as illustrated in Figure 6. Profiles associated with non-monotonically increasing concentration trends with depth are identified as outliers. Across all measurements, the profiles do not decay to the noise floor (NF) within the range of interest. In Type 1 cases, the
270 $S'_{v, \alpha_s=0}$ profiles increase or decrease gradually and roughly show a linear relationship with normalized distance from the sensor. The corresponding SSC profiles typically show mild density gradients, with slight fluctuations occurring in regions where SSC values were below 1 g L^{-1} .

In contrast, the Type 2 profiles exhibit substantial variability within individual verticals, indicating less consistency in the backscatter strength distribution over depth. Unlike the Type 1 profiles, some $S'_{v, \alpha_s=0}$ profiles in Type 2 feature a clear mid-
275 depth peak, while others show progressive tendency shifts. The Type 2 SSC profiles show significantly higher sediment concentrations in general, with most cases exceeding 10 g L^{-1} . The Type 2 SSC profiles increase steeply with distance, suggesting strong vertical stratification or elevated near-bed sediment loads.

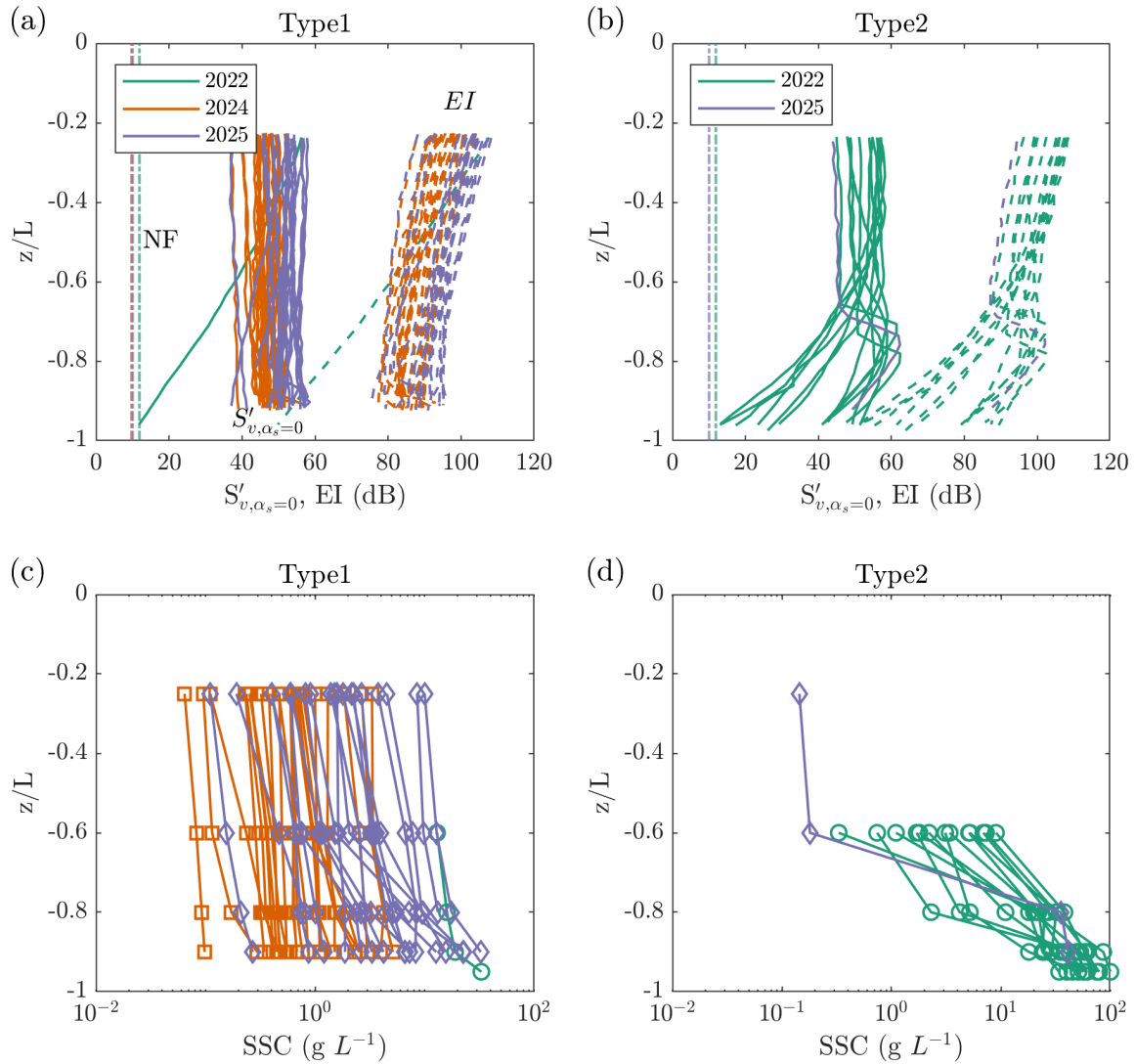


Figure 6. Acoustic profiles of backscatter strength ($S'_{v, \alpha_s=0}$, solid lines) and echo intensity (EI, dashed lines) (a, b), and SSC profiles (c, d) from the three surveys, classified as Type 1 (a, c) and Type 2 (b, d). The Y-axis is the distance from the frame-mounted ADCP along the rod, normalized by the rod length $L = 2$ m (Figure 2). The SSC sample positions in (c) and (d) correspond to the nozzle positions in Figure 2. Dash-dotted lines denote the noise floor (NF) of each survey.

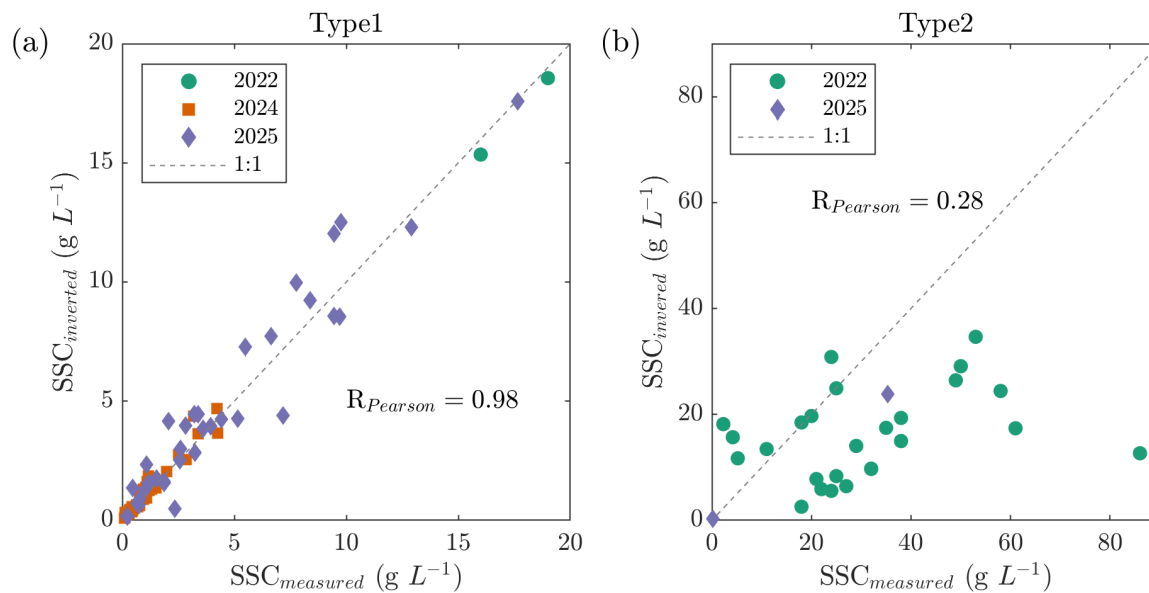


Figure 7. Comparison of acoustically derived concentration ($SSC_{inverted}$) and measured concentration ($SSC_{measured}$) at the two mid-depth validation samples for the 2022, 2024 and 2025 surveys. The classification is the same as in Figure 6. $R_{Pearson}$ is the Pearson correlation coefficient.

Figure 7 illustrates the influence of changepoints in the backscatter profiles on the performance of acoustic backscatter inversion. Type 1 profiles (no changepoints identified, Figure 7a) show a strong linear relationship between the SSC derived from physical water samples and ADCP-derived SSC ($R_{Pearson} = 0.98$). The agreement remains close to the 1:1 line across the full validation range, including concentrations up to approximately $20 g L^{-1}$. In contrast, agreement between ADCP-derived SSC and SSC measured from physical water samples is poor for Type 2 profiles, with a Pearson correlation coefficient of only 0.28. The divergence between ADCP-derived estimates and water sample-derived SSC values becomes more pronounced for higher concentrations. Most of the estimates are low compared to the corresponding values from water samples. Notably, several Type 1 profiles reached elevated concentrations, while maintaining good agreement with the validation measurements up to the highest observed concentration among the Type 1 validation samples ($\sim 20 g L^{-1}$; Figure 7a). Type 2 profiles, however, show substantial deviations from the 1:1 line over the same concentration range (Figure 7b). These results suggest that the reduced inversion performance of Type 2 profiles cannot be attributed to elevated SSC alone, but is instead associated with the presence of changepoints in the backscatter profiles.

3.2 Comparison of theoretical and empirical sediment attenuation

To assess whether the theoretical attenuation model (Eqs. 5–7) adequately represents the field observations in the fine-grained environment, we calculated theoretical attenuation using primary particle size distributions and subsequently compared it with empirical attenuation derived from acoustic backscatter profiles. For each measurement profile, the particle size distribution



is assumed uniform in the vertical. Because particle size distribution was not recorded during the 2022 survey, a temporally
 295 constant distribution based on the average particle size distribution from 2025 was assumed for that year, in order to estimate the
 relative importance of viscous ($\alpha_{s,visc}$) versus scattering ($\alpha_{s,scat}$) attenuation across all surveys. This assumption is supported
 by Figure 3b, which shows that the particle size distributions by number remained similar in shape across seasons, with minimal
 variation between September 2024 and January 2025.

Assuming a temporally constant PSD, the magnitude of theoretical scattering attenuation ($\alpha_{s,scat}$) and viscous attenuation
 300 ($\alpha_{s,visc}$) can be estimated, since both parameters depend primarily on the general shape of the PSD. However, because the
 assumption renders the theoretical attenuation ξ_{theo} time-invariant for the 2022 survey, it precludes evaluating whether the
 agreement between ξ_{theo} and the empirical $\bar{\xi}_{total}$ varies over time for this survey. The comparison, presented later in this
 section, is therefore restricted to the 2024 and 2025 surveys, for which PSDs were directly measured.

In Table 2 the ranges and mean values of theoretical scattering attenuation ($\alpha_{s,scat}$) and viscous attenuation ($\alpha_{s,visc}$) are
 305 shown. Overall, attenuation was highest during the 2022 survey and lowest during the 2024 survey. These patterns closely
 align with the sediment concentrations, which peaked in 2022 and reached the lowest levels in 2024 (Table 1). Across all three
 surveys, theoretical attenuation is overwhelmingly dominated by viscous attenuation rather than by scattering loss, with the two
 mechanisms differing by several orders of magnitude. This dominance is consistent with the fine-grained (clay- and silt-sized)
 sediment characterizing the study area (Figure 3).

Table 2. Range and mean values of theoretical scattering and viscous attenuation for the survey campaigns of 2022, 2024, and 2025.

Year	Scattering Attenuation $\alpha_{s,scat}$ (dB m ⁻¹)		Viscous Attenuation $\alpha_{s,visc}$ (dB m ⁻¹)	
	Range	Mean value	Range	Mean value
2022	3.66×10^{-9} – 1.11×10^{-6}	3.41×10^{-7}	0.138–41.950	12.90
2024	8.24×10^{-10} – 3.12×10^{-7}	1.36×10^{-8}	0.055–1.150	0.33
2025	1.15×10^{-9} – 8.34×10^{-7}	7.63×10^{-8}	0.034–39.051	3.69

Note: Theoretical values for 2022 are estimated using the average PSD from the 2025 survey, as PSD was not measured in 2022.

310 Figure 8 compares the theoretical attenuation ξ_{theo} with the empirical depth-averaged attenuation $\bar{\xi}_{total}$. Theoretical attenu-
 ation was computed from Eqs. (6)–(7) using the measured particle size distributions from the 2024 and 2025 surveys, whereas
 $\bar{\xi}_{total}$ was calculated from Eq. (11) using backscatter profiles collected concurrently with the water samples. Because the PSD
 was not measured during the 2022 survey, that year is excluded from this comparison. Each point represents the depth-averaged
 $\bar{\xi}_{total}$ and ξ_{theo} for one profile shown in Figure 6, with color indicating the corresponding depth-averaged SSC. $\bar{\xi}_{total}$ was esti-
 315 mated from the two calibration water samples (closest to the ADCP and closest to the bed; see Section 2.2.2), while ξ_{theo} was
 computed from the measured PSD, independent of the water sample calibration. Type 1 profiles (no changepoints) are shown
 as unfilled markers with colored outlines, and Type 2 profiles (with changepoints) as filled markers.

The two attenuation estimates show a marked discrepancy across the full concentration range, with the majority of data
 points plotted below the 1:1 line, indicating that ξ_{theo} systematically underestimates $\bar{\xi}_{total}$. At low SSC (below 1 g L⁻¹), this

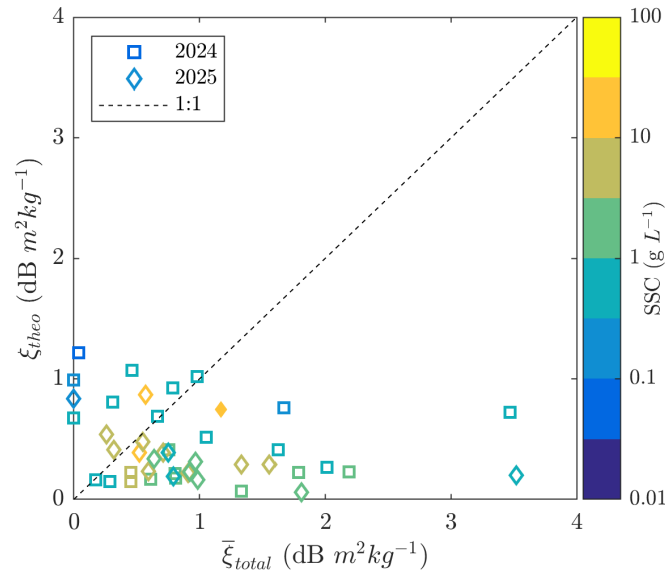


Figure 8. Comparison between the empirical depth-averaged sediment attenuation $\bar{\xi}_{total}$ derived from ADCP observations and theoretical attenuation ξ_{theo} calculated from PSDs. Colors indicate the depth-averaged SSC of the water samples. Open and filled markers denote Type 1 and Type 2 profiles, respectively. Only the 2024 and 2025 surveys, for which PSDs were measured, are included.

discrepancy is most pronounced, where $\bar{\xi}_{total}$ ranges widely, up to several $\text{dB m}^2 \text{kg}^{-1}$, likely because the cumulative sediment attenuation along the profile is small and the empirical estimate becomes more sensitive to environmental noise. At higher SSC, both estimates become more tightly clustered and the discrepancy between ξ_{theo} and $\bar{\xi}_{total}$ decreases.

Overall, these results indicate that theoretical attenuation derived from measured PSD does not reliably reproduce empirical attenuation, particularly at low SSC where the empirical estimate itself is poorly constrained. Although the depth-averaged estimates agree more closely at higher SSC, this agreement does not necessarily reflect a valid homogeneity assumption, as the following section shows that pronounced vertical variation in ξ_{total} can persist beneath a seemingly consistent depth-averaged value. Theoretical attenuation therefore cannot be used as a substitute for empirical calibration in acoustic inversion in this clay/silt-dominated, hyperturbid environment.

3.3 Vertical variation of empirical sediment attenuation

To directly validate whether the homogeneity assumption is satisfied in Type 1 and Type 2 profiles, the vertical sediment attenuation corresponding to the acoustic profiles is evaluated (Figure 9). We compute the ratio of depth-varying ξ_{total} to depth-averaged $\bar{\xi}_{total}$, where ξ_{total} is obtained with the method described in Appendix B.

For Type 1 profiles, the ratio $\xi_{total}/\bar{\xi}_{total}$ remains nearly uniform and clusters around unity across the ensonified range, indicating a relatively stable vertical sedimentary regime and yielding a constant slope in $S'_{v,\alpha_s=0}$. This is consistent with

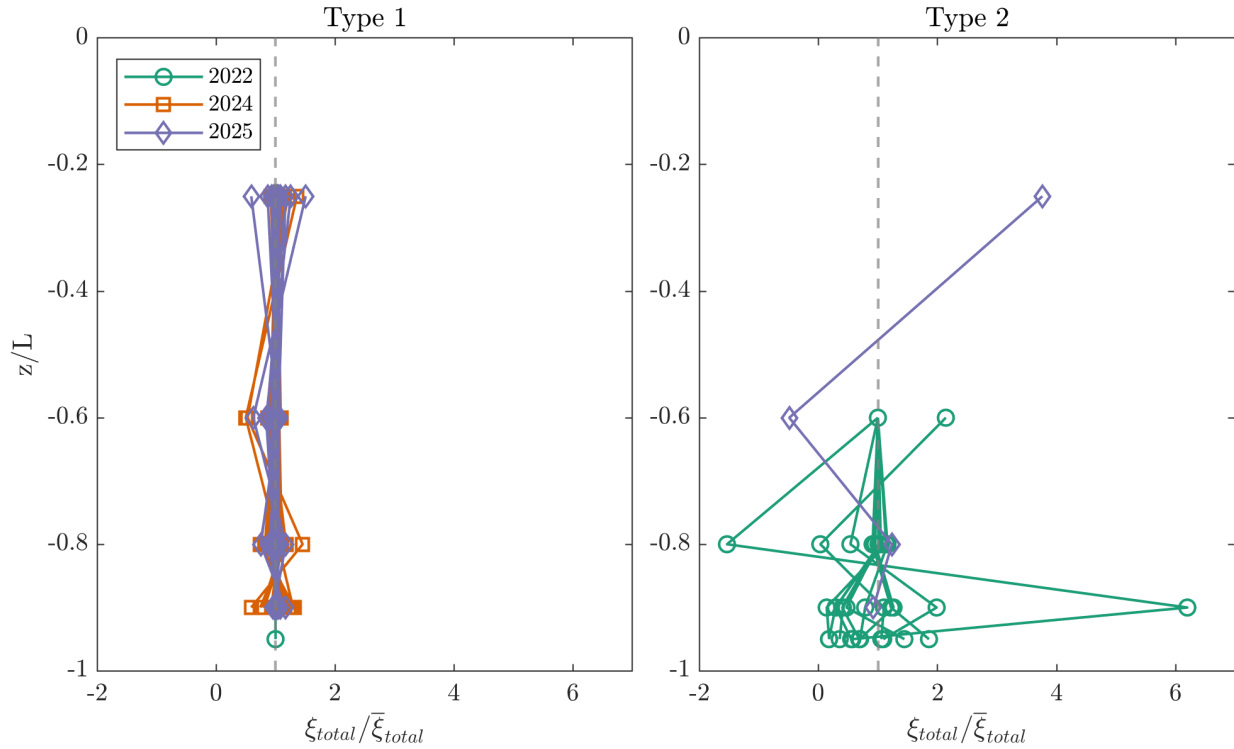


Figure 9. Profiles of ξ_{total} normalized by the depth-averaged values $\bar{\xi}_{total}$, as a function of normalized distance from the frame-mounted ADCP along the rod ($L = 2$ m, Figure 2b). Three profiles with $\bar{\xi}_{total} \approx 0$ (two from the 2024 survey and one from the 2025 survey, see Figure 8) are excluded, because the ratio becomes numerically unstable.

335 approximately linear profiles of $S'_{v,\alpha_s=0}$ in Figure 6a. There are more fluctuations in the vertical distribution of $\xi_{total}/\bar{\xi}_{total}$ in the profiles when sediment concentration is low. This is because the backscatter signal is sensitive to environmental noise at low concentrations, as demonstrated in Haught et al. (2017). In addition, the depth-averaged $\bar{\xi}_{total}$ approaches zero, which amplifies the fluctuations in the vertical. Despite slight variations of ξ_{total} over the verticals, the profiles allow the sediment properties to be considered homogeneous.

340 For Type 2 profiles, in contrast, $\xi_{total}/\bar{\xi}_{total}$ shows pronounced variations over the vertical. Several negative values of empirical ξ_{total} are observed in profiles featuring a sharp peak. A negative value of ξ_{total} is non-physical. It may indicate an underestimation of K_s by the depth-constant calculation at the specific location, for which ξ_{total} numerically compensates. This vertical divergence indicates that the vertical profiles of acoustic sediment properties undergo severe variations along the range, which violates the homogeneity assumption.

345 Figure 10 shows that the standard deviation of the normalized $\xi_{total}/\bar{\xi}_{total}$ profiles increases with the gradient Richardson number. The gradient Richardson number spans a wide range, from below 10^{-2} to over 10^3 , indicating that the three field campaigns capture profiles with markedly different stratification strengths.

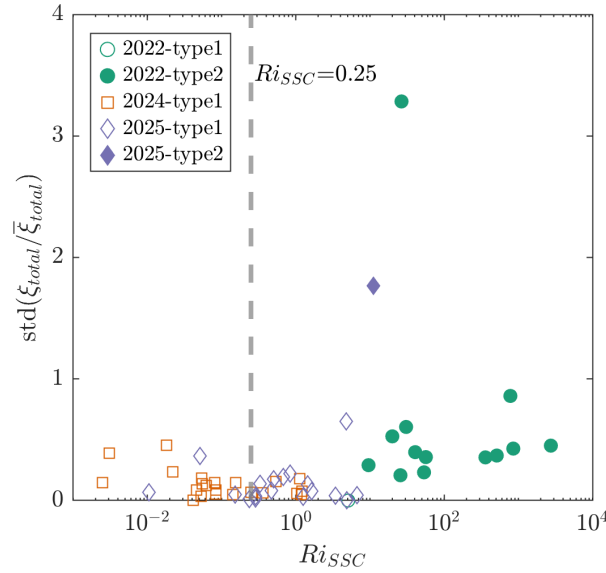


Figure 10. Standard deviation of the normalized $\xi_{total}/\bar{\xi}_{total}$ profiles is correlated with the gradient Richardson number, which includes the SSC-induced density gradient within the ensonified volume. The grey dashed line marks the critical value of 0.25, above which shear-driven turbulent mixing is theoretically suppressed by density stratification (e.g., Miles, 1961). Colors indicate the field campaigns. Open and filled markers denote Type 1 and Type 2 profiles, respectively. As in Figure 9, three profiles with $\bar{\xi}_{total} \approx 0$ (two for 2024 survey and one for 2025 survey) are excluded, because near-zero $\bar{\xi}_{total}$ disproportionately amplifies the normalized $\xi_{total}/\bar{\xi}_{total}$ ratio and makes its standard deviation unreliable.

Above the critical value of $Ri_{SSC} = 0.25$, shear-driven turbulent mixing is theoretically suppressed by density stratification, a regime referred to as inactive mixing. A substantial portion of the profiles are characterized by inactive mixing in the near-bed region ($Ri_{SSC} > 0.25$), consistent with the strong stratification characterizing this hyperturbid system. Figure 10 shows that the classification of Type 1 / Type 2 correlates with the gradient Richardson number: nearly all Type 2 profiles are characterized by $Ri_{SSC} > 10$, indicating strong stratification, whereas most Type 1 profiles fall below or near the critical value of 0.25, consistent with active, shear-dominated mixing. This pattern suggests that the occurrence of changepoints is associated with reduced turbulent mixing under strong density stratification.

The standard deviation of $\xi_{total}/\bar{\xi}_{total}$ shown here is only roughly estimated due to the coarse sampling resolution. Nonetheless, its increase with Ri_{SSC} supports the interpretation that the occurrence of changepoints is linked to stratification, which invalidates the homogeneity assumption required for conventional acoustic inversion to SSC. The few elevated standard deviations among Type 1 profiles at low gradient Richardson numbers likely reflect the sensitivity of the backscatter signal to environmental noise under low SSC, which amplifies the standard deviation without necessarily reflecting stronger vertical heterogeneity. Profiles for which $\bar{\xi}_{total}$ was very close to zero were treated as outliers and excluded from Figures 9 and 10 altogether, as the resulting ratio becomes inaccurate and no longer meaningful.



4 Discussion

In this study, we find that strong stratification, reflected by the gradient Richardson number accounting for the sediment effect on density (Ri_{SSC}), is associated with vertical variation in acoustic sediment properties. These variations appear to produce structural breaks in acoustic backscatter profiles, indicating a breakdown of the homogeneity assumption underlying conventional acoustic backscatter inversion and degrading inversion performance. Our results show that when no changepoints are detected in the backscatter profiles directly retrieved from the ADCP ($S'_{v,\alpha_s=0}$), a clear linear trend is observed in the backscatter-range relation. We refer to those as Type 1 profiles. This linear behavior is typically manifest when the sediment regime is mixed, i.e. when both sediment scattering and attenuation remain relatively uniform along the acoustic beam. Many existing range-resolved acoustic inversion examples in field and laboratory conditions show that backscatter strength and distance from the ADCP have a linear relation (e.g., Haught et al., 2017; Guerrero and Di Federico, 2018; Venditti et al., 2016). By assuming homogeneous concentrations and particle size distributions, the slope of backscatter profiles represents the sediment attenuation coefficient α_s , while the intercept represents backscatter strength at a given sediment concentration.

The results show that in high turbidity environments, many profiles may deviate significantly from a linear fit, exhibiting distinct slope breaks identified as changepoints. We label those as Type 2 profiles. Based on the vertical variation of empirical ξ_{total} (Figure 9), the slope of the backscatter profile ($S'_{v,\alpha_s=0}$) with distance from the transducer is inherently governed by spatial fluctuations in sediment characteristics (k_s^2 , ξ_{scat} , and ξ_{visc}) within the ensonified volume, which is attributable to the strength of stratification. When these properties vary along the acoustic beam rather than remaining constant, the common assumption of a homogeneous medium through which sound propagates is invalid. This observed sensitivity aligns with findings by Vergne et al. (2021), who reported that the relationship between SSC and backscatter is susceptible to changes in particle characteristics, which dynamically alter the ratio of attenuation to backscatter, and compromises inversion efficiency. Although direct range-resolved observations of backscatter profiles under a heterogeneous distribution of sediment concentrations remain scarce in the literature, substantial empirical evidence from point-measurements supports this physical behavior. Numerous studies utilizing Acoustic Doppler Velocimeters (ADVs) have demonstrated that the relationship between sediment concentration and acoustic amplitude follows a distinct two-phase trend (Reungoat et al., 2019; Brown and Chanson, 2012; Keevil et al., 2015). A monotonic increase in backscatter with increasing SSC occurs at low concentrations ($< 5\text{--}8 \text{ g L}^{-1}$), which subsequently reverses into a decreasing trend at higher SSCs due to strong signal attenuation. When a sharp SSC gradient is encountered, sediment properties can be expected to vary along the corresponding range-resolved profile. Inhomogeneity not only hampers acoustic inversion, but also complicates the inversion in optical applications. Even in laser-based sensing, the variations in aerosol particle composition or spectral shape change the backscatter to extinction ratio, presenting a challenge for the optical inversion (Klett, 1985).

The Type 2 profiles in this study correspond to conditions with large density gradient and strong stratification (Figure 6b,d and Figure 10). This stratification often leads to variation in acoustic sediment properties along the profile, violating the homogeneity assumption required by conventional inversion methods. Under these conditions, inversions fail when using our single-frequency explicit method. The range-inversion problem is also not resolved by existing multi-frequency acoustic



devices, since the commonly used multi-frequency explicit inversion likewise relies on the homogeneity assumption (Moore et al., 2013; Haught et al., 2020). While such explicit methods can optimize performance under idealized, well-controlled settings, they cannot overcome the spatially varying concentration gradients. Alternative approaches, such as the iterative implicit formulations proposed by Hurther et al. (2011) and Thorne et al. (2011), utilize dual frequencies by assuming a known, range-invariant particle size distribution to solve the concentrations bin by bin. These approaches introduce substantial errors when the sediment attenuation has a significant impact on the backscattering signal.

Visual inspection of Type 2 profiles suggests two recurring patterns among the structural breaks, broadly corresponding to the mid-depth peak and progressive tendency shifts noted in Section 3.1. These patterns, described qualitatively below, appear to be associated with distinct physical mechanisms; a more rigorous, quantitative distinction—for example based on peak sharpness—is left for future work. The first pattern is characterized by a more gradual backscatter development along the acoustic path, where cumulative attenuation increasingly dominates acoustic propagation. The second pattern features a more pronounced, sharp acoustic jump (or spike) that typically manifests around high water slack. This pattern is induced by stratification when turbulence is suppressed (Becker et al., 2018; Schrottke et al., 2006). In those profiles, the detected changepoint with the strongest discontinuity is likely located at the lutocline. Unlike the first pattern, where the concentration increases gradually, the water column is separated into dilute fluid and fluid mud. The reflected signal from the interface between dilute fluid and fluid mud, corresponding to the lutocline, is much stronger than the backscattered signal from suspended particles (Ha et al., 2011), which significantly hampers the acoustic inversion.

The changepoint detection presented above was applied and validated specifically in a hyperturbid setting. However, the phenomenon it detects is not exclusive to such conditions. Vertical heterogeneity in sediment properties can also arise under lower overall SSC, as long as a sufficiently sharp vertical gradient is present. Such sharp distributions commonly occur during sediment entrainment following slack water in tidal estuaries, or where salinity and sediment stratification interact (e.g., in salt-wedge estuaries). In those scenarios, the detected changepoint indicates the heterogeneity in sediment concentration but no longer serves as an indicator of inversion failure, because sediment attenuation α_s remains negligible at low concentrations, and a backscatter-dominant regime persists along the entire acoustic beam. This heterogeneity does not lead to range-varying sediment scattering and attenuation. Then, a stable and predictable power-law relationship can be expected between backscatter strength and concentration across the profile.

The changepoint is used diagnostically, but it arises physically from vertical heterogeneity. In this study, we assume a depth-constant backscattering coefficient, thereby attributing vertical variations in the effective acoustic sediment properties entirely to ξ_{total} . An estimate obtained solely from the particle size distribution may not adequately represent the in-situ ξ_{total} , particularly in fine-grained, highly stratified environments such as the Ems Estuary. Not only may stratification affect the interaction between the fluid and particles (Hanes, 2012; Guerrero et al., 2016), but irregular particle shapes, varying incident angles, and multiple scattering effects under high-concentration conditions may also cause in-situ parameters to deviate from their theoretical values (Santos et al., 2020; Huang et al., 2018; Tonge et al., 2021). Flocculation is an additional factor that can alter both K_s and ξ_{total} in muddy environments. Specifically, it can affect the effective scattering cross-section and the viscous attenuation, respectively (Pedocchi and Mosquera, 2022; Vincent and MacDonald, 2015; Fugate and Friedrichs, 2003). Therefore,



in-situ sediment properties are no longer solely a function of the particle size distribution (MacDonald et al., 2013). A detailed treatment of flocculation dynamics is beyond the scope of this study, but its potential influence further underscores the difficulty of predicting in-situ acoustic parameters from a PSD alone. These mechanisms collectively highlight the challenges in predicting in-situ acoustic parameters, and underscore the need for structural evaluation of backscatter profiles. In the absence of changepoints, ADCP backscatter profiles can indeed yield trustworthy SSC estimates, even under high turbidity.

5 Conclusions

We developed an *a priori* diagnostic for assessing the applicability of acoustic backscatter inversion in hyperturbid environments. The diagnostic identifies changepoints in backscatter profiles ($S'_{v,\alpha_s=0}$), which indicate violations of the homogeneity assumption underlying conventional inversion approaches. Profiles without changepoints (Type 1) yielded accurate SSC estimates when validated against SSC derived from water samples, including concentrations up to 20 g L^{-1} , whereas profiles containing changepoints (Type 2) generally showed poor inversion performance across a comparable or wider concentration range. This contrast indicates that inversion failure in hyperturbid conditions is associated primarily with structural heterogeneity along the acoustic beam rather than with elevated concentration itself.

Type 2 profiles were associated with strong vertical variability in empirically derived acoustic attenuation and elevated density stratification, suggesting that sediment-induced density stratification alters the effective acoustic properties along the propagation path. A comparison between theoretical attenuation, computed from measured particle size distributions, and empirical attenuation further showed that theoretical predictions do not reliably reproduce in-situ attenuation in this clay/silt-dominated environment, underscoring the challenge of predicting acoustic sediment properties from PSDs alone, and the corresponding need for structural evaluation of backscatter profiles. The proposed changepoint diagnostic therefore provides a simple and practical tool for identifying profiles for which conventional acoustic inversion is likely to be reliable and for flagging conditions associated with fluid mud and strong stratification, supporting more targeted sampling strategies in challenging hyperturbid environments.

This study is based on observations from a single navigation channel and a limited number of survey campaigns; the generalization of the specific concentration threshold identified here (i.e., reliable inversion up to $\sim 20 \text{ g L}^{-1}$ in Type 1 profiles) to other hyperturbid estuaries with different sediment compositions or hydrodynamic regimes remains to be tested. Furthermore, the two structural-break patterns identified among Type 2 profiles (gradual decay versus sharp lutocline-related spikes) were distinguished qualitatively. A more quantitative classification, for instance based on peak sharpness, would strengthen the physical interpretation of these patterns and is recommended for future work. Despite these limitations, the diagnostic approach itself—based solely on the shape of the backscatter profile—requires no additional instrumentation and can be readily applied to existing and future ADCP datasets collected in other stratified, sediment-laden environments.



Code and data availability. A MATLAB toolbox was used to read and pre-process raw ADCP data, which is publicly available at: <https://github.com/bartverm/adcpools.git>. There are no restrictions on the data used in this study. The bathymetry data used for large scale map was requested through the servicedesk data of Rijkswaterstaat (<https://www.rijkswaterstaat.nl/formulieren/contactformulier-servicedesk-data>). Water level data from the German monitoring stations included in this study can be accessed through the Federal Maritime and Hydrographic Agency (BSH) at <https://wasserstand-nordsee.bsh.de>. All measurement data and analysis scripts supporting this study are archived and available at 4TU.ResearchData: <https://doi.org/10.4121/60df7c4f-ca47-4ad0-8a7d-1962077ed09d.v1>.

Appendix A: Simple Linear regression for the full profile

The water samples closest to the ADCP and closest to the bed are used for calibration in our study. To evaluate the performance of the inversion, the middle two are used for validation. We denote the number of water samples by N_s and distances to the transducer by $R_j, 1 \leq j \leq N_s$, and write $\beta_j = \beta(R_j)$ and $M_{sj} = M_s(R_j)$. Further, to evaluate the integral appearing in the right hand side of Eq. (11), a trapezoidal integration rule was employed, whose numerical value with upper limit R_j is denoted by I_j . Accordingly, a system of 2 equations with 2 unknowns is obtained, reflecting the assumption of uniform sediment scattering and attenuation characteristics:

$$\begin{pmatrix} \beta_1/M_{s1} \\ \beta_{N_s}/M_{sN_s} \end{pmatrix} = \begin{pmatrix} 1 & -\frac{\ln 10}{5} I_1 \\ 1 & -\frac{\ln 10}{5} I_{N_s} \end{pmatrix} \begin{pmatrix} K_s \\ \bar{\xi}_{total} \end{pmatrix}. \quad (\text{A1})$$

The ordinary least squares solution to the above system yields estimates of the parameters K_s and $\bar{\xi}_{total}$ in the present empirical model.

Appendix B: Depth-varied calibrated acoustic parameter

The depth-varying $\xi_{total}(r)$ profile is progressively resolved by discretizing the water column into i discrete layers. Assuming a piecewise constant attenuation within each layer, the continuous profile $\xi_{total}(r)$ can be approximated using an indicator function:

$$\xi_{total}(r) \simeq \sum_{j=1}^i \xi_{total,j} \cdot \mathbf{1}_j(r) \quad (\text{B1})$$

where the indicator function $\mathbf{1}_j(r)$ defines the vertical boundaries of the j -th layer at r_j :

$$\mathbf{1}_j(r) = \begin{cases} 1, & r \in (r_{j-1}, r_j] \\ 0, & r \notin (r_{j-1}, r_j] \end{cases} \quad (\text{B2})$$



Consequently, the integral governing the sound attenuation in Eq. (11) can be transformed into a discrete summation over successive layers, yields:

$$\begin{aligned} \frac{\beta(R_i)}{M_s(R_i)} &\simeq K_s - \frac{\ln 10}{5} \int_0^{R_i} \left[\sum_{j=1}^i \xi_{total,j} \cdot \mathbf{1}_j(r) \right] \beta(r) dr \\ &= K_s - \frac{\ln 10}{5} \sum_{j=1}^i \xi_{total,j} \int_{r_{j-1}}^{r_j} \beta(r) dr \end{aligned} \quad (B3)$$

where $\xi_{total,j}$ represents the localized total attenuation coefficient within the j -th layer. This algebraic formulation allows the attenuation profile to be solved recursively from the transducer downward to the bed.

Author contributions. SB conducted the data analysis and prepared the original draft. SB and HJ contributed to the development of the methodology. SB, HJ, LX, and AJFH contributed to the fieldwork. AJFH contributed to the conceptualization of the study, supervision, and funding acquisition. All authors contributed to the interpretation of the results and the review and revision of the manuscript.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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