



# Using turbidity and acoustic backscatter intensity as surrogate measures of suspended sediment concentration in a small subtropical estuary

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## Abstract

The suspended sediment concentration is a key element in stream monitoring, although the turbidity and acoustic Doppler backscattering may be suitable surrogate measures. Herein a series of new experiments were conducted in laboratory under controlled conditions using water and mud samples collected in a small subtropical estuary of Eastern Australia. The relationship between suspended sediment concentration and turbidity exhibited a linear relationship, while the relationships between suspended sediment concentration and acoustic backscatter intensity showed a monotonic increase. The calibration curves were affected by both sediment material characteristics and water quality properties, implying that the calibration of an acoustic Doppler system must be performed with the waters and soil materials of the natural system. The results were applied to some field studies in the estuary during which the acoustic Doppler velocimeter was sampled continuously at high frequency. The data yielded the instantaneous suspended sediment flux per unit area in the estuarine zone. They showed some significant fluctuations in instantaneous suspended mass flux, with a net upstream-suspended mass flux during flood tide and net downstream sediment flux during ebb tide. For each tidal cycle, the integration of the suspended sediment flux per unit area data with respect of time yielded some net upstream sediment flux in average.

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**Keywords:** Turbidity; Acoustic backscatter intensity; Suspended sediment concentration SSC; Subtropical estuary; High-frequency suspended sediment flux

## 1. Introduction

A key element in stream monitoring is the choice of a measuring technique of suspended sediment concentration (SSC). Several studies suggested that acoustic backscattering and turbidity may be suitable surrogate measures for SSC (e.g. Thorne et al., 1991; Thevenot and Kraus, 1993). While earlier studies recorded backscatter strength only, the development of acoustic Doppler velocimetry (ADV) allows the simultaneous measurements of instantaneous velocities and acoustic backscatter strength at a single point with relatively high frequency. The ADV instrument's acoustic backscatter amplitude may be related to the instantaneous SSC with proper calibration (e.g. Fugate and Friedrichs, 2002) (Table 1). This approach was

extended to ADCP systems (e.g. Holdaway et al., 1999; Hill et al., 2003). Tables 1 and 2 summarise some relatively recent studies with acoustic Doppler systems and optical turbidity metres. Most studies were conducted in rivers and coastal zones with non-cohesive sediments.

In the present study, the writers investigated the relationships between turbidity, ADV backscatter intensity and SSC in a small subtropical estuary with cohesive bed materials. New experiments were conducted under controlled conditions using commercially available instruments. The aim of the paper is to assess the ability of an ADV to measure accurately instantaneous suspended sediment flux in a small subtropical system with fine cohesive sediment materials (mud and silt). The results are applied to some field data sets conducted with the same instruments in a small estuarine zone in Eastern Australia. The results include the simultaneous measurements of turbulent velocities and SSC at high frequency for long durations.

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Table 1  
Correlations between acoustic backscatter intensity and suspended sediment concentration

Reference	Correlation	Conditions
Kawanisi and Yokosi (1997)	SSC = 3 × BSI 0 ≤ SSC ≤ 80 mg/l SSC in mg/l BSI ∝ 10 <sup>0.043 × Ampl</sup>	Ota diversion channel, Hiroshima Bay (Japan) ADV (10 MHz) Bottom sediment ≤ 88 μm
Sontek (1997)	10 × log <sub>10</sub> (SSC) ∝ BSI; SSC in mg/l	Sontek ADV
Nortek (2001)	SSC ∝ BSI	Nortek ADVs
Nikora and Goring (2002)	SSC = 0.56 × BSI 2 ≤ SSC ≤ 400 mg/l SSC in mg/l BSI ≈ 0.00003 × (10 <sup>0.0434 × Ampl<sub>1</sub></sup> + 10 <sup>0.0434 × Ampl<sub>2</sub></sup> + 10 <sup>0.0434 × Ampl<sub>3</sub></sup> )	Balmoral Irrigation Canal (New Zealand)
Voulgaris and Meyers (2004)	log <sub>10</sub> (SSC) = 10.8 × log <sub>10</sub> (BSI) − 17.8 2 ≤ SSC ≤ 100 mg/l SSC in mg/l	Bly Creek, North Inlet NC (USA) Sontek ADV (10 MHz)
Merkelbach (2006)	BSI = 10 × log <sub>10</sub> (SSC) + K <sub>o</sub>	Random phase model
Present study	SSC = 0.9426 × [1 − exp(−0.1109 × BSI)] 0 ≤ SSC ≤ 0.71 g/l, 0.06 ≤ BSI ≤ 12.21 SSC in g/l SSC = 3.7582 × [1 − exp(−0.02157 × BSI)] 0 ≤ SSC ≤ 0.78 g/l, 0.009 ≤ BSI ≤ 10.6 SSC in g/l	Eprapah Creek water and bed material sample 1 (R = 0.996)  Brisbane tap water and Eprapah Creek bed material sample 1 (R = 0.998)

Note: There are basic differences in the definition of backscatter intensity BSI.

## 2. Experimental setup and instrumentation

### 2.1. Presentation

Eprapah Creek is a subtropical stream located in the Eastern part of Australia, close to Brisbane City. The creek flows directly into the Moreton Bay at Victoria Point off the Pacific Ocean. The estuarine zone is a relatively small estuary with a narrow, elongated and meandering channel (Fig. 1). The water depth is typically about 1–2 m mid-stream, the width is about 20–30 m with a muddy river bed, and the tidal range is between about 1.3 m (neap tides) and 2.5 m (spring tides).

Some water and soil samples were collected about mid-estuary in July 2006 (Site 2B, Fig. 1). The soil sample 1 consisted of fine silt and mud material collected on the stream bed, while the soil sample 2 was collected on the bank just below the high water mark. The sample 2 was slightly coarser than the bed material sample 1, but the granulometry was not tested. For each laboratory test, a known mass of sediment was introduced in a water tank which was continuously stirred with a submerged pump (Fig. 2). The mass of wet sediment was measured with a Sartorius™ Type 1518 (serial 3506057) balance. The mass concentration was deduced from the measured mass of sediment and water tank volume. All the experiments were conducted within 28 h from the sample collection. In addition, some tests were conducted with Brisbane tap

water to assess the effects of water quality. Table 3 summarises the laboratory experiment conditions.

The laboratory experiments were conducted with a Sontek™ 2D microADV (16 MHz, serial number A641F) system and a YSI6600™ probe (Fig. 2). The acoustic backscatter amplitude measurements were conducted with the microADV (16 MHz) system using the same configuration employed in the field (pulse length, scan rate) but a lower velocity range (10 cm/s) to minimise the Doppler noise effects. The ADV signal outputs were scanned at 50 Hz for 3 min for each test. The average amplitude measurements represented the average signal strength of the ADV receivers. The backscatter intensity (BSI) was related to the signal amplitude as:

$$BSI = 10^{-5} \times 10^{0.043 \times Ampl}, \quad (1)$$

where BSI is the acoustic backscatter amplitude and Ampl is the average signal amplitude data measured in counts by the ADV system. The coefficient 10<sup>−5</sup> was a value introduced to avoid large values of BSI (Nikora and Goring, 2002).

The turbidity and other physio-chemistry properties including temperature, conductivity, pH and dissolved oxygen were measured with the YSI™ 6600 probe. During the laboratory tests, the probe sensors were placed beside the microADV sampling volume. Further details on the laboratory tests were reported in Chanson et al. (2006).

Table 2  
Correlations between turbidity and suspended sediment concentration

Reference	Correlation	Conditions
Gippel (1995)	$\text{Turb} = 0.84 \times \text{SSC} + 4.62$	Eden catchment, Victoria (Australia)
	$2 \leq \text{SSC} \leq 153 \text{ mg/l}$ SSC in mg/l and Turb in NTU $\text{Turb} = 0.85 \times \text{SSC} + 1.97$ $2 \leq \text{SSC} \leq 868 \text{ mg/l}$ SSC in mg/l and Turb in NTU	Latrobe River, Victoria (Australia)
	$\text{Turb} = 2.43 \times \frac{\text{SSC}}{d_{50}^{0.42}}$	Multiple regression ( $R^2 = 0.33$ )
Lewis (1996)	$3.6 \leq d_{50} \leq 52 \mu\text{m}$ , $d_{50}$ in $\mu\text{m}$ $\sqrt[3]{\text{SSC}} = a \times \sqrt[3]{\text{Turb}} + b$	Caspar Creek, CA (USA) for 1991–1993
	$5 \leq \text{SSC} \leq 2,000 \text{ mg/l}$ , $5 \leq \text{Turb} \leq 600$ SSC in mg/l and Turb in NTU $\log_{10}(\text{SSC}) = a \times \log_{10}(\text{Turb}) + b$	Caspar Creek, CA (USA) for 1994–1995
Grayson et al. (1996)	$10 \leq \text{SSC} \leq 1000 \text{ mg/l}$ , $20 \leq \text{Turb} \leq 250$ SSC in mg/l and Turb in NTU $\text{SSC} = 0.92 \times \text{Turb} - 0.76$	Latrobe River, Vic. (Australia) for April 1992
Smith and Davies-Colley (2002)	$0 \leq \text{SSC} \leq 140 \text{ mg/l}$ , $0 \leq \text{Turb} \leq 125$ SSC in mg/l and Turb in NTU $\text{Turb} = 160 \times \text{SSC}^{0.92}$	Esopus Creek, NY (USA) Storm events
	$0 \leq \text{SSC} \leq 30 \text{ g/m}^3$ (?), $10 \leq \text{Turb} \leq 1,000$ SSC in $\text{g/m}^3$ (?) and Turb in NTU $\text{Secchi} = -4.09 \times \text{Turb}^{-0.76}$	Esopus and Schoharie catchments, NY (USA)
Mitchell et al. (2004)	$0.2 \leq \text{Secchi} \leq 4.7 \text{ m}$ , $\leq \text{Turb} \leq 40 \text{ NTU}$ Secchi in m and Turb in NT $\text{SSC} = 0.8088 \times \text{Turb} - 12.571$	Pagham estuary (UK)
Pavanelli and Bigi (2005)	$10 \leq \text{SSC} \leq 105 \text{ g/l}$ , $50 \leq \text{Turb} \leq 150$ SSC in g/l and Turb in NTU $\text{SSC} = 0.00065 \times \text{Turb} + 2.78$	Sillaro torrent (Italy) Sediment (clay and silt < 0.2 mm)
Present study	$1.5 \leq \text{SSC} \leq 30 \text{ g/l}$ , $0 \leq \text{Turb} \leq 35,000$ SSC in g/l and Turb in NTU $\text{SSC} = 0.00485 \times \text{Turb} - 0.0350$	Eprapah Creek water and bed material sample 1 ( $R = 0.995$ )
	$0 \leq \text{SSC} \leq 0.71 \text{ g/l}$ , $7 \leq \text{Turb} \leq 151 \text{ NTU}$ SSC in g/l and Turb in NTU $\text{SSC} = 0.00419 \times \text{Turb} + 0.00359$ $0 \leq \text{SSC} \leq 0.78 \text{ g/l}$ , $0 \leq \text{Turb} \leq 187 \text{ NTU}$ SSC in g/l and Turb in NTU	Brisbane tap water and Eprapah Creek bed material sample 1 ( $R = 0.9997$ )

Notes:  $a$  and  $b$  are linear regression constants.

## 2.2. Data accuracy

The accuracy on the ADV velocity measurements was 1% (Sontek, 1997). With the physio-chemistry probe YSI6600, the data accuracy was  $\pm 5\%$  for turbidity. Further the data accuracy was  $\pm 0.5\%$  for conductivity,  $\pm 0.15^\circ\text{C}$  for temperature,  $\pm 0.2$  unit for pH and  $\pm 2\%$  of saturation concentration for dissolved oxygen.

The mass of wet sediment was measured with an accuracy of less than 0.01 g, and the SSC was estimated with an accuracy of less than 0.00025 g/l.

The suspended sediment fluxes were estimated with an error of less than 2%.

## 3. Measurements of suspended sediment concentration

### 3.1. Laboratory experiments

During the laboratory tests, the relationships between turbidity, acoustic backscatter amplitude, acoustic BSI and SSC were tested systematically for turbidities between 0 and 200 nephelometer turbidity units (NTU). Some experimental data are shown in Figs. 3 and 4. The results indicated the good correlation between all the data showing consistently a monotonic increase in SSC with increasing turbidity and increasing BSI. The relationship between SSC and turbidity was linear (Fig. 4) while the

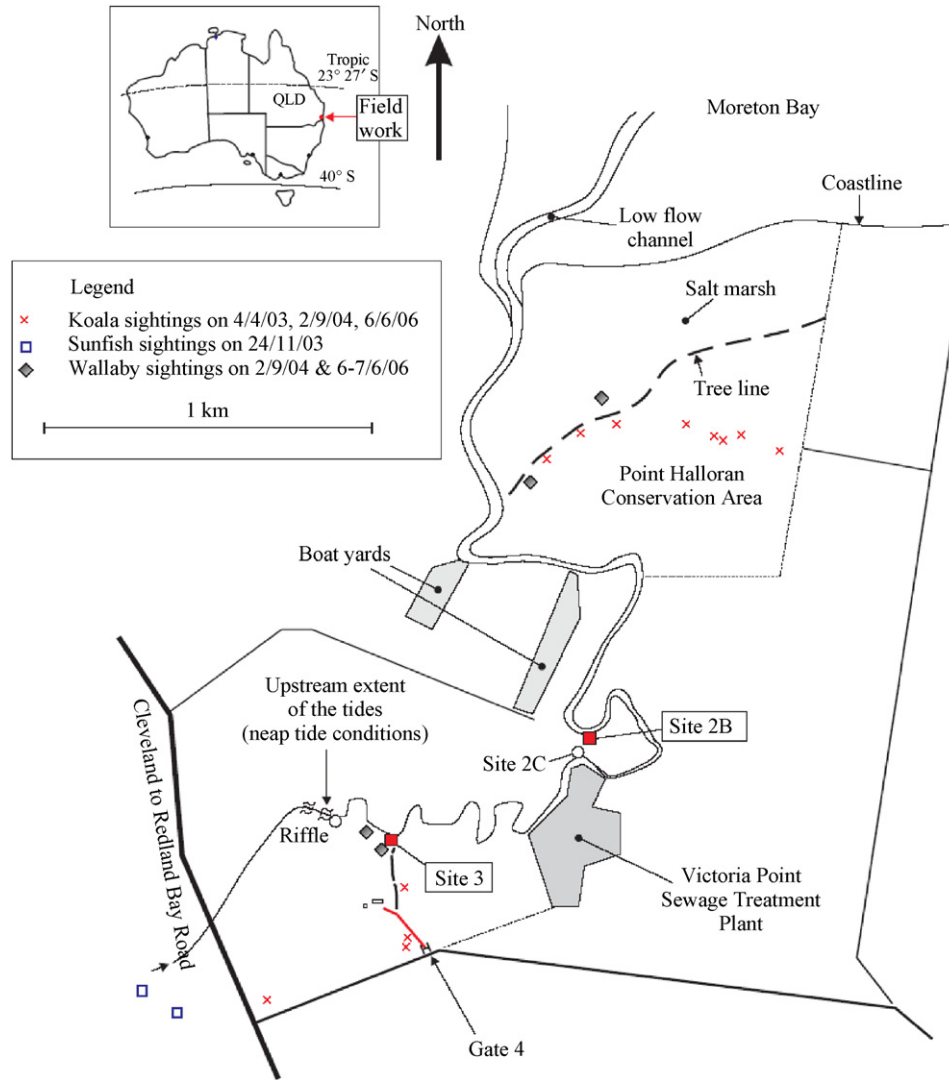


Fig. 1. Eprapah Creek estuarine zone (longitude: 153.30°E; latitude: -27.56°S)—red square: instantaneous velocity and water quality measurement site in 2005 and 2006.

relationships between SSC and BSI, and turbidity and BSI were non-linear (Fig. 3). For the laboratory tests with Eprapah Creek waters and the bed material sample 1, the best fit relationships were

$$SSC = 0.9426 \times [1 - \exp(-0.1109 \times BSI)]$$

with  $R^2 = 0.9924$  (19 points), (2)

$$SSC = 0.00485 \times Turb - 0.0350$$

with  $R^2 = 0.9922$  (19 points), (3)

$$Turb = 171.06 \times [1 - \exp(-0.1593 \times BSI)]$$

with  $R^2 = 0.9884$  (19 points), (4)

where SSC is in g/l, the turbidity Turb is in NTU and the BSI is defined using Eq. (1).  $R^2$  is the square of the normalised coefficient of correlation. Eqs. (2) and (3) are compared with the data in Figs. 3 and 4.

The sediment material had a substantial effect on the results (Figs. 3 and 4). The sample 2 was coarser than the bed sample 1, and it consisted of a mix of mud and fine sand. The tests with that soil sample yielded different turbidity and acoustic amplitude readings for a given SSC, although the overall trends were similar with both soil samples.

The effect of water quality was seen by comparing the tests with Eprapah waters and Brisbane tap waters with the same sediment sample (bed material sample 1). Parts of the soil sample 1 were used with Eprapah Creek waters and the experiments were repeated with other parts of the same soil sample using Brisbane tap waters. The best fit correlations for Brisbane tap water data are shown in Figs. 3 and 4 with a thick solid line. The relationship between SSC and BSI was nearly linear with Brisbane tap waters, but it was non-linear, close to a power law with Eprapah Creek waters (Fig. 3). The differences in water quality included some different water conductivities but also some difference in bio-chemical and biological contents.

Practically, it is recommended to use simple, robust calibration curves that increase monotonically with an increasing BSI as shown above. More “advanced” correlation functions are not recommended for field work



Fig. 2. Photographs of the laboratory experiment 060712b (Eprapah Creek water, sediment sample: 2 (bank material), SSC = 0 g/l (no added sediment)). The YSI 6600 probe is on the left and the microADV system is on the right.

applications because they might lead to meaningless results for large ADV backscatter intensity readings. For example, some quadratic relationships between SSC and BSI were tested. The results yielded meaningless negative extrapolated estimates of SSC and turbidity when the average backscatter amplitude exceeded 145–150 counts as observed during some field studies (studies E4 and E6, Table 4).

### 3.2. Field experiment

During a field study (E4), an older ADV Sontek™ 3D ADV (10 MHz, serial 0510) and a YSI6600 probe were deployed side by side next to the river bed about mid-estuary. The ADV and turbidity sampling volumes were placed at 5 cm above the bed, and the data were logged continuously at 25 and 0.33 Hz, respectively, for 10 h (Table 4). Both the signal amplitude and turbidity data showed a turbid event for about 2 h during the early flood tide (Fig. 5A). For that turbid event, there was a good correlation between the turbidity and acoustic BSI. Fig. 5B presents a comparison between the field data and Eq. (4) which was obtained with the 2D microADV (16 MHz) system. The results highlighted the same trend for both ADV systems. The quantitative results were however different: e.g. for a turbidity of 80 NTU, the older ADV (10 MHz) system gave only about half of the BSI measured by the newer micro-ADV (16 MHz) system. The differences were caused by a combination of differences in water quality between 2 September 2004 (field study E4) and 11 July 2006 (present study), and the lesser performances of the ADV (10 MHz) system. Thorne et al. (1991) suggested that the sensitivity of ADV to fine sediments increased with the system frequency i.e., 10 MHz vs. 16 MHz herein.

Table 3  
Summary of laboratory experiments and physio-chemical properties

Reference	Waters		Sediment samples			SSC range (g/l)
060711E	Water collection at Eprapah Creek, Site 2C					–
060711	Eprapah Creek		Sample 1 Eprapah Creek (Site 2B), bed material			0–0.71
060712a	Eprapah Creek		Sample 1 Eprapah Creek (Site 2B), bed material			0–0.54
060712b	Eprapah Creek		Sample 2 Eprapah Creek (d/s Site 2B), bank material			0–0.47
060712c	Brisbane tap water		Sample 1 Eprapah Creek (Site 2B), bed material			0–0.78
Reference	Turbidity (NTU)	Conduction (mS/cm)	Temperature (°C)	DO (% saturation)	pH	Remarks
060711E	7.43	33.29	18.61	90.2	7.42	Date: 11 July 2006, early ebb tide (10:15 a.m.)
060711	7.25 <sup>a</sup>	33.32 <sup>a</sup>	19.26 <sup>a</sup>	96.1 <sup>a</sup>	7.52 <sup>a</sup>	Date: 11 July 2006 (14:12 h)
060712a	8.07 <sup>a</sup>	33.2 <sup>a</sup>	17.16 <sup>a</sup>	95.13 <sup>a</sup>	7.62 <sup>a</sup>	Date: 12 July 2006 (08:56 h)
060712b	7.87 <sup>a</sup>	33.4 <sup>a</sup>	17.23 <sup>a</sup>	94.3 <sup>a</sup>	7.63 <sup>a</sup>	Date: 12 July 2006 (10:26 h)
060712c	0 <sup>a</sup>	0.45 <sup>a</sup>	17.57 <sup>a</sup>	89.4 <sup>a</sup>	7.66 <sup>a</sup>	Date: 12 July 2006 (13:00 h)

<sup>a</sup>At the start of each experiment (prior to sediment supply, SSC = 0).

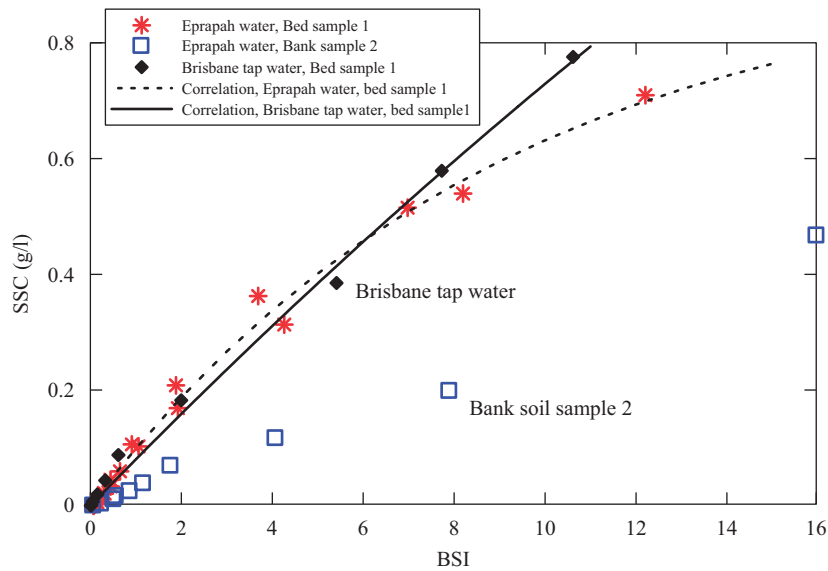


Fig. 3. Relationship between suspended sediment concentration (SSC; in g/l) and backscatter intensity (BSI; Eq. (1)). Eq. (2) is shown in thin dotted line.

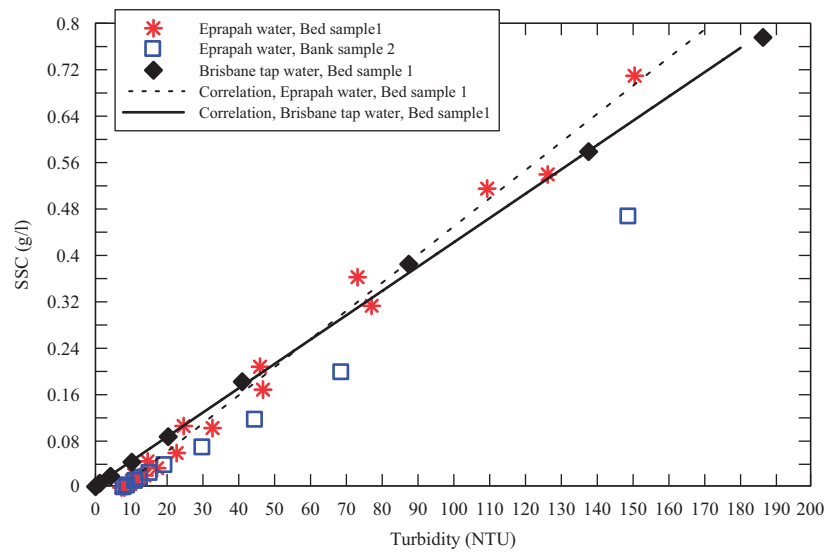


Fig. 4. Relationship between suspended sediment concentration (SSC; in g/l) and turbidity (Turb in NTU). Eq. (3) is shown in thin dotted line.

Table 4  
Turbulence field measurements at Eprapah Creek, Qld, Australia

Reference	Dates	Tidal range (m)	ADV system(s)	ADV sampling rate (Hz)	YSI 6600 sampling rate (Hz)	Sampling elevation (m above bed)	Sampling duration (h)	Sampling location
E4	2/09/04	1.81	10	25	0.33	0.052	6 and 3	Site 2B, AMTD 2.1 km, 10.4 m from left bank, 0.052 m above bed
E6	16–18/05/05	1.36	10 and 16	25 and 25	0.0833	0.2 and 0.4	49	Site 2B, AMTD 2.1 km, 10.4 m from left bank, 0.2 and 0.4 m above bed
E7	5–7/06/06	1.38	16	50	0.0833	0.2	50	Site 3, AMTD 3.1 km, 4.2 m from right bank, 0.2 and 0.4 m above bed

Notes: AMTD: adopted middle thread distance measured upstream from river mouth. References: Chanson et al. (2005b) and Chanson and Trevethan (2006).

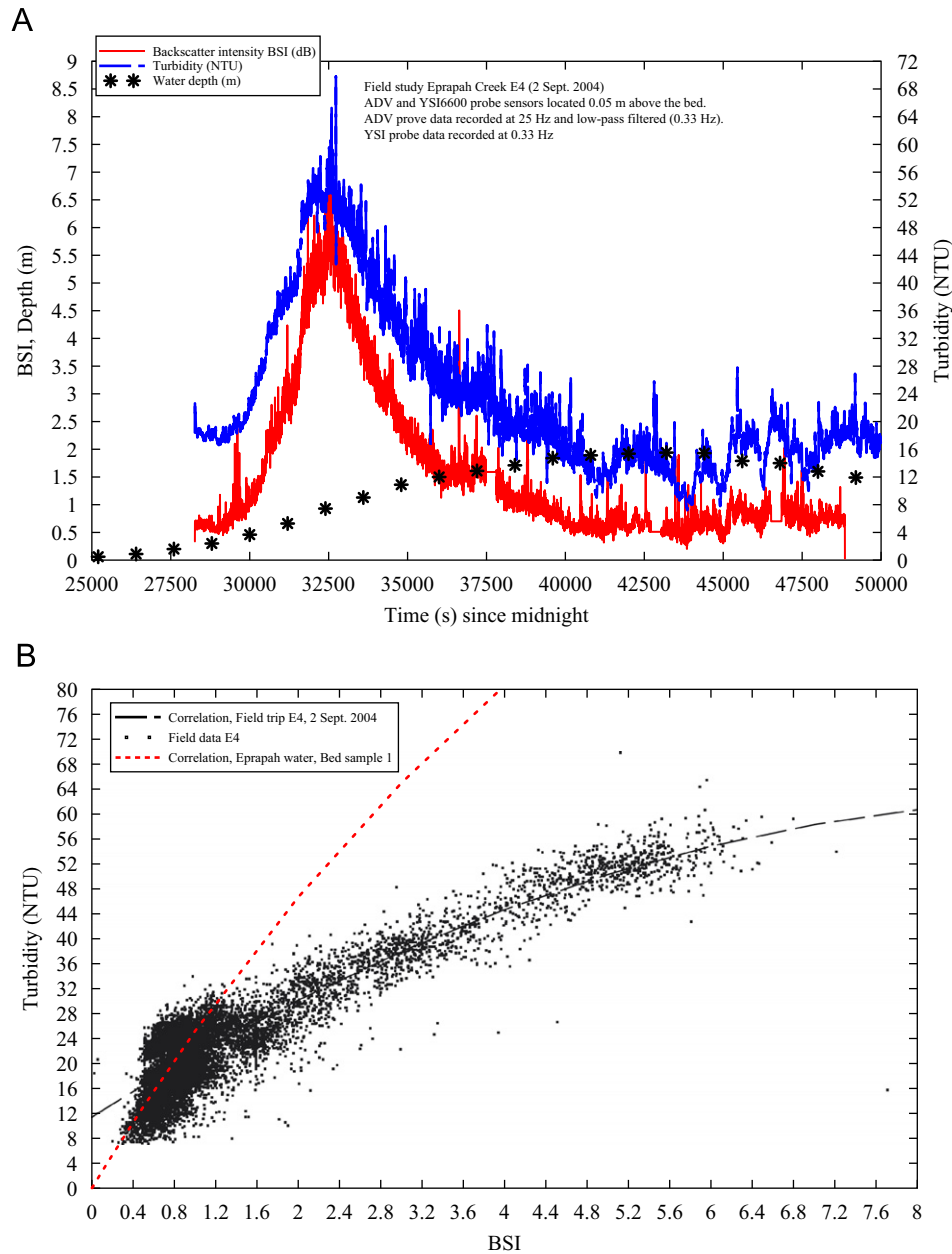


Fig. 5. Turbidity and backscatter intensity (BSI; Eq. (1)) measurements during the field study E4 on 2 September 2004 in Eprapah Creek estuary between 8:00 and 14:00 h. (A) Time-variations of turbidity and backscatter intensity. (B) Relationship between turbidity and backscatter intensity for the Sontek<sup>TM</sup> 3D ADV (10 MHz, serial 0510). Comparison with Eq. (4) obtained with the Sontek<sup>TM</sup> 2D microADV (16 MHz, serial A641F).

#### 4. Field measurements of instantaneous suspended sediment flux

##### 4.1. Instantaneous suspended sediment flux per unit area

The results were applied to two field studies (E6 and E7) in the estuarine zone of Eprapah Creek (Table 4). During these studies, the same microADV (16 MHz, serial A641F) system was deployed with its sampling volume located at 0.20 m above the bed. The microADV system was scanned continuously at 25 or 50 Hz for 50 h. The field study E6 was conducted mid-estuary (Site 2B), while the study E7 was conducted 1 km upstream in the upper-estuary zone where

the channel is narrower (Site 3). Both sites are highlighted in Fig. 1. Fig. 6 shows the surveyed cross-sections, and the high and low water levels during the study E6. Both studies were performed during neap tide conditions. Fig. 7 presents the time variations of instantaneous streamwise velocity data for each 50 h period. The velocity data were post-processed using the technique developed by Chanson et al. (2005a). The measured water depths are also shown in Fig. 7, and the data indicated some tidal diurnal inequality, with a major tide and a minor tide for each 24 h 50 min tidal cycle. The velocity data illustrated the tidal forcing with the flood tides ( $V_x < 0$ ) and ebb tides ( $V_x > 0$ ) especially mid-estuary (Fig. 7A). The magnitude of the

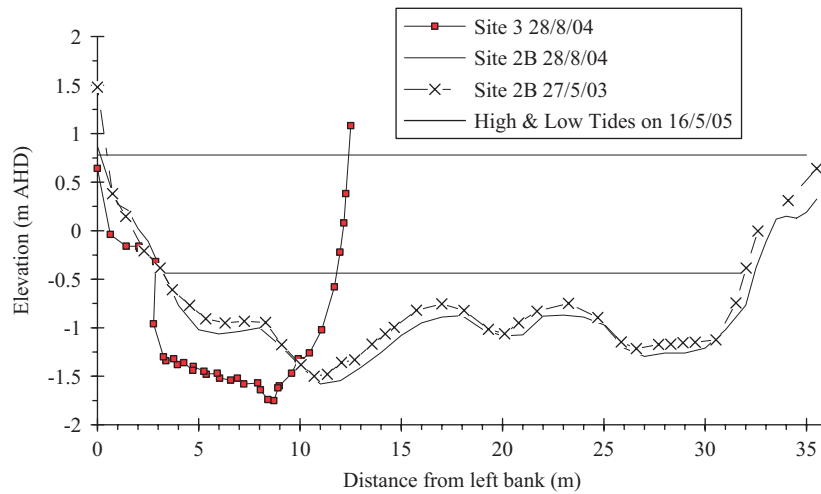


Fig. 6. Surveyed cross-sections of the estuarine zone looking downstream. The vertical elevation is measured from the Australian height datum (AHD).

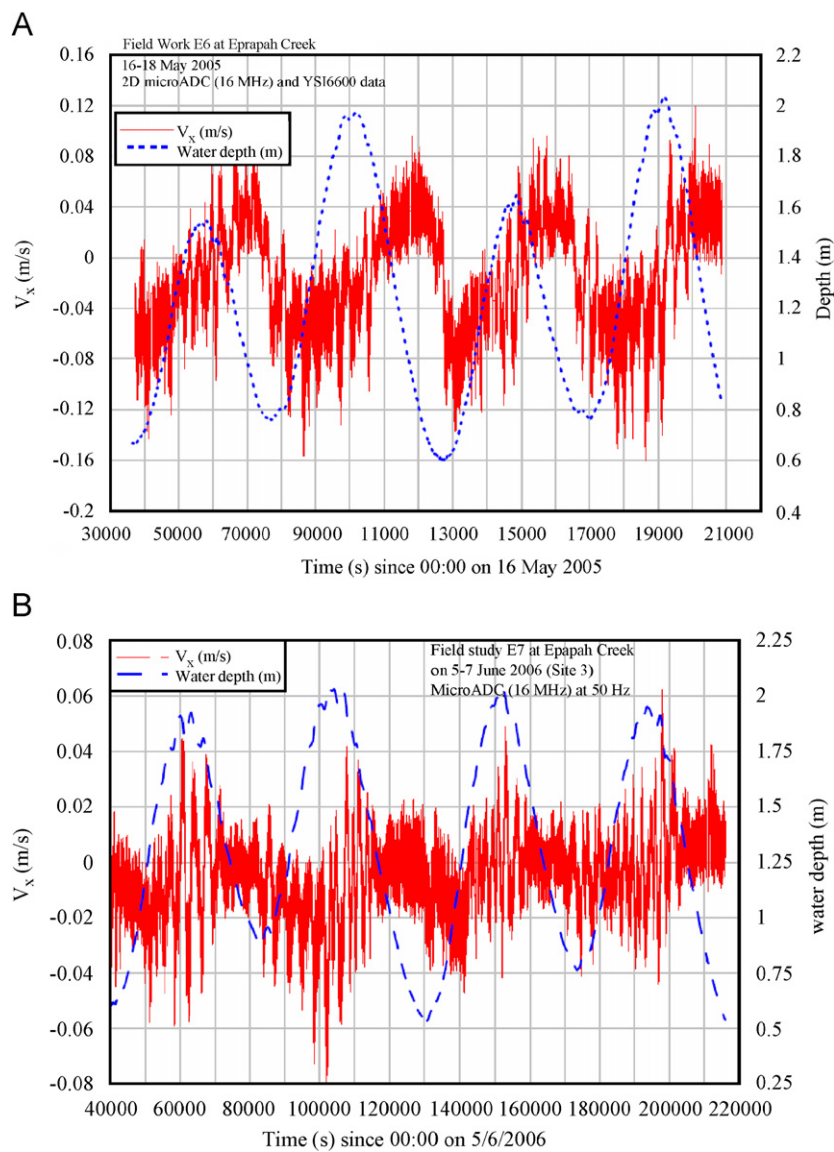


Fig. 7. Time variations of water depth ( $m$ ) and streamwise velocity ( $V_x$ , positive downstream) during two field studies in Eprapah Creek estuary. (A) Field study E6 (16–18 May 2005) at Site 2B mid-estuary (AMTD 2.1 km). (B) Field study E7 (5–7 June 2006) at Site 3 in the upper estuary (AMTD 3.1 km).



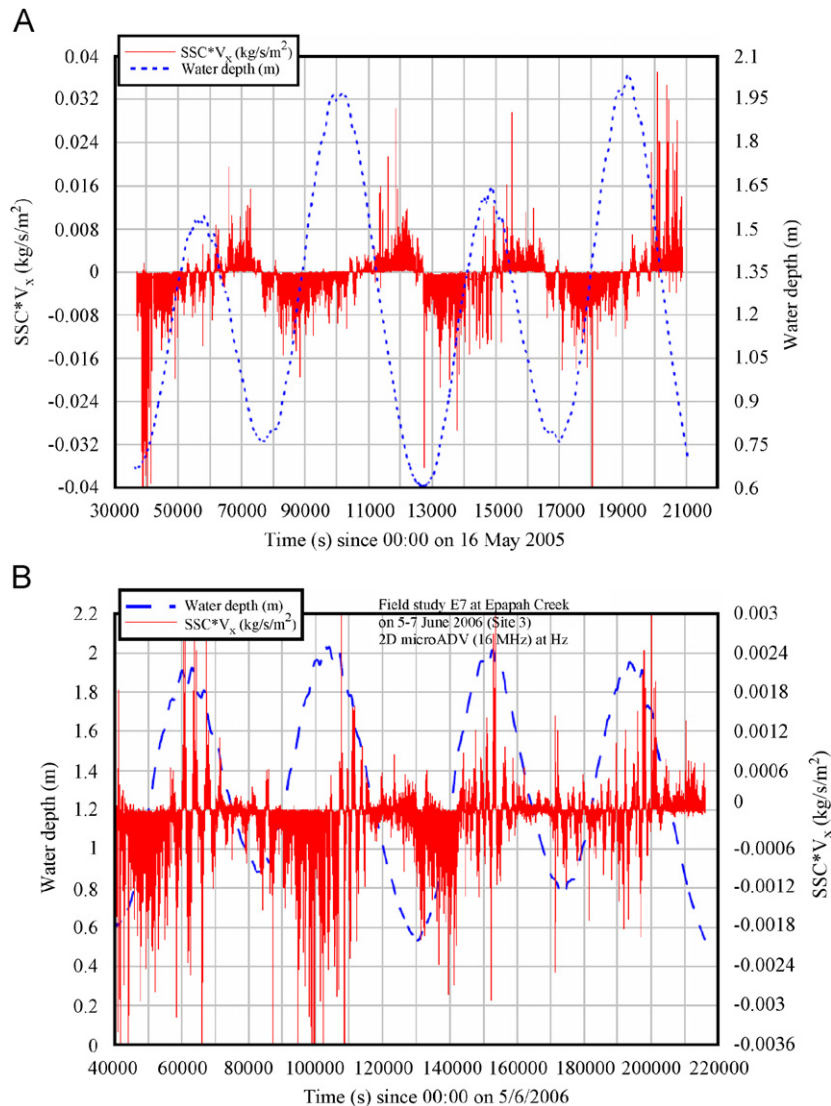


Fig. 8. Time variations of suspended sediment flux per unit surface area ( $SSC \times V_x$ , positive downstream) and measured water depth during two field studies. (A) Field study E6 (16–18 May 2005) at Site 2B mid-estuary (AMTD 2.1 km). (B) Field study E7 (5–7 June 2006) at Site 3 in the upper estuary (AMTD 3.1 km).

flood tide velocity was typically larger than that of the ebb tide flow. Note the different vertical scales of Figs. 7A and B. The velocity magnitudes were about two times smaller in the upper estuary during the study E7. The data showed also some low-frequency fluctuations of streamwise velocity with periods between 20 min and 2 h. These low-frequency oscillations were believed to be linked with some internal and external resonance.

The instantaneous advective suspended sediment flux per unit area  $q_s$  was calculated as

$$q_s = SSC \times V_x, \quad (5)$$

where  $q_s$  and  $V_x$  are positive in the downstream direction. SSC was calculated using Eq. (2) applied to the post-processed backscatter amplitude signal. The results are presented in Fig. 8 in terms of the instantaneous sediment flux  $q_s$  per unit area and they are compared with the

measured water depth at the sampling site. The results characterise the fluctuations of suspended sediment flux per unit area for each 50 h study. The suspended sediment flux per unit area data showed an upstream, negative suspended sediment flux during the flood tide and a downstream sediment flux during the ebb tide (Fig. 8). For each field study, the instantaneous sediment flux data  $q_s$  showed considerable time-fluctuations that derived from a combination of velocity and SSC fluctuations. The suspended sediment flux per unit area data presented some high-frequency fluctuations with some form of sediment flux bursts that were likely linked to and caused by some turbulent bursting phenomena next to the bed. Some low-frequency fluctuations in sediment flux were also observed, including some multiple direction reversals around slack tides, always at high tides and sometimes at low tides (Fig. 8).

#### 4.2. Net sediment flux per unit area

For each study and for each tidal cycle (24 h 50 min.), the sediment flux data were integrated with respect of time. The result gives a net sediment mass transfer per unit area through the sampling volume during a tidal cycle:

$$\int_{24 \text{ h } 50 \text{ min}} \text{SSC} \times V_x \, dt. \quad (6)$$

For each field study, the net sediment mass transfer per unit area was negative, and Eq. (6) yielded  $-22.3$  and  $-20.8 \text{ kg/m}^2$  for each tidal cycle during the study E6, and  $-6.66$  and  $-1.81 \text{ kg/m}^2$  for each tidal cycle during the study E7. That is, the net sediment flux over a full tidal cycle corresponded in average to an upstream net suspended sediment transfer. Several researchers investigated the net suspended sediment flux in estuaries of subtropical and tropical river estuaries during similar dry conditions and tidal ranges. Previous results showed a similar net upstream sediment transfer in dry weather: e.g. Larcombe and Ridd (1992), Hossain et al. (2001), Kawanisi et al. (2006). However, during rain storms and wet weather the net sediment mass flux is positive in the downstream direction.

A striking feature of the analysed data sets is the large fluctuations in the suspended sediment fluxes during the tidal cycles. This feature was rarely documented, but an important difference between the ADV data sets used in this study from earlier reported measurements is that the present data were collected continuously at high frequency (25 and 50 Hz) during relatively long periods. It is however acknowledged that the present study was a point measurement. Any extrapolation would imply that the sampling volume was representative of the entire creek cross-section.

#### 5. Summary and conclusion

A series of experiments were performed to test the usage of turbidity and acoustic BSI as surrogate estimates of the SSC. The experiments were conducted in laboratory under controlled conditions using water and mud samples collected in a small subtropical estuary of Eastern Australia. They were performed with a microADV (16 MHz) system and a YSI<sup>TM</sup> 6600 probe using two types of muddy material. All the relationships showed a monotonic increase with a linear relationship between SSC and turbidity while the others were non-linear.

The present results confirmed earlier findings that the calibration curves (e.g. turbidity vs. SSC, BSI vs. SSC) are affected by the sediment material characteristics and by the water quality. The results demonstrated that the calibration of an acoustic Doppler system must be performed with the waters and soil materials of the natural system. Importantly, the calibration of the acoustic Doppler system is specific to the instrument itself. A limited comparison between an older ADV (10 MHz) system and a microADV (16 MHz) showed some marked differences.

The results were applied to two field studies that were conducted with continuous high-frequency sampling in the small estuary of Eprapah Creek with the same microADV system. The application yielded the instantaneous suspended sediment flux per unit area. The sediment flux data showed an upstream mass flux during the flood tide and a downstream sediment flux during the ebb tide. Some high-frequency fluctuations in mass flux were believed to be some form of sediment flux bursts linked to and caused by some turbulent bursting phenomena next to the bed. Some low-frequency fluctuations in suspended sediment flux were noted, including some multiple direction reversals around tide slacks. For each tidal cycle of 24 h 50 min, the suspended sediment flux data were integrated with respect to time to yield a net sediment mass transfer per unit area. For both field studies, the net sediment flux over a tidal cycle was on average upstream.

It must be stressed that the present work highlighted a number of limitations. The calibration relationships were based upon a 2-day-period study, and the results might not be suitable for field studies at Eprapah Creek with different water quality conditions. The calibration curves were also specific to the microADV unit at the time of the tests. Furthermore, the present work was conducted for a subtropical estuary with relatively low turbidity levels. The maximum turbidity recorded during several field studies was about 80 NTU. The present results are not applicable to turbid flows with high SSCs.

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