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USING TURBIDITY AND ACOUSTIC BACKSCATTER INTENSITY AS SURROGATE MEASURES OF SUSPENDED SEDIMENT CONCENTRATION. APPLICATION TO A SUB-TROPICAL ESTUARY (EPRAPAH CREEK)

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USING TURBIDITY AND ACOUSTIC BACKSCATTER INTENSITY AS SURROGATE MEASURES OF SUSPENDED SEDIMENT CONCENTRATION. APPLICATION TO A SUB-TROPICAL ESTUARY (EPRAPAH CREEK)

by

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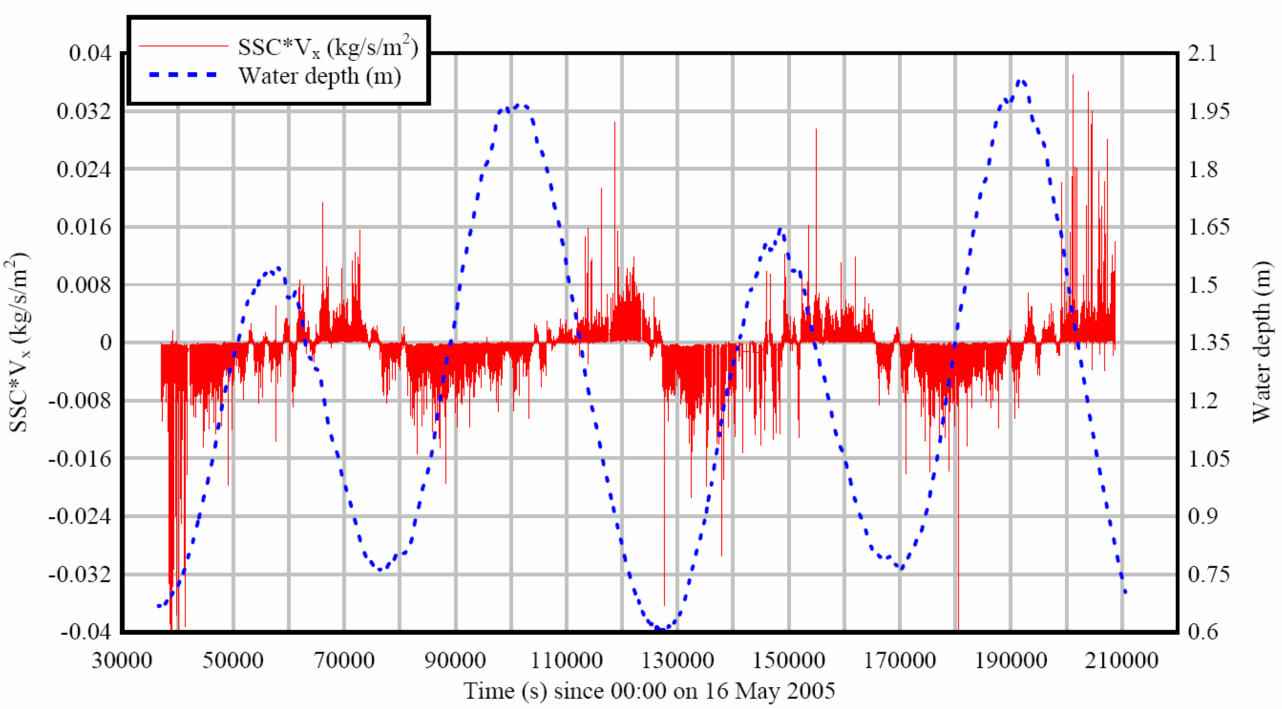

Suspended sediment flux per unit surface area (SSC*V_X) and measured water depth during the field study E6 (16-18 May 2005) in Eprapah Creek estuary for a 50 hours period

ABSTRACT

A key element in stream monitoring is the choice of a measuring technique of suspended sediment concentration (SSC). Several studies suggested that turbidity and acoustic Doppler backscattering may be suitable surrogate measures for SSC. A series of new experiments were conducted in laboratory under controlled conditions using water and soil samples collected in a small sub-tropical estuary of Eastern Australia. The tests were conducted with a microADV (16 MHz) system and a YSI™ 6600 probe using two types of sediment material : some fine mud collected on the bed and some slightly coarser material collected on the bank slope. In addition, some experiments were repeated with the creek estuarine waters and with Brisbane tap waters. The best fit relationships were established in terms of the suspended sediment concentration (SSC) as a function of the acoustic backscatter intensity (BSI), the SSC as a function of the turbidity, and the turbidity as a function of the acoustic backscatter intensity.

The present results confirmed earlier findings that the relationships presented some monotonic increase. The calibration curves were however affected by the sediment material characteristics and by the water quality. The results indicated that the calibration of an acoustic Doppler system must be performed with the waters of the natural system (creek waters) and with some bed material. Importantly the calibration of an ADV system is specific to the unit itself. Its calibration relationships are functions of the water quality and sediment properties, but also of the intrinsic characteristics of the emitter and receivers. A limited comparison between an ADV (10 MHz) and a microADV (16 MHz) indicated that the newer microADV system could detect significantly more counts per unit volume than the older unit. The results were applied to some earlier field measurements conducted continuously at high frequency for 50 hours each in Eprapah Creek with the same microADV system. For each field study, the instantaneous suspended sediment flux per unit area data showed some high-frequency bursts that were believed to be linked to some turbulent bursting phenomena next to the bed. For each tidal cycle, the suspended sediment flux data were integrated with respect of time. The results yielded a net sediment mass transfer per unit area of about -20 kg/m^2 per tidal cycle during the first study conducted mid-estuary and of about -4 kg/m^2 per tidal cycle for the second study performed in the upper estuary. That is, the net sediment flux over a full tidal cycle was upstream in average, and the finding was consistent with earlier studies in sub-tropical rivers during dry conditions for a similar tidal range.

It must be stressed that the present work highlighted a number of limitations. The present calibration relationships might not be suitable for earlier 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, and they were developed for a subtropical estuary with relatively low turbidity levels.

Keywords : Turbidity, Acoustic backscatter intensity, Suspended sediment concentration, SSC, Subtropical estuary (sub-tropical estuarine system), Acoustic Doppler velocimeter, Suspended sediment transport, High-frequency suspended sediment flux.

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NOTATION

The following symbols are used in this report :

Ampl	acoustic Doppler signal amplitude (counts); in the present study, Ampl is the average ADV amplitude (counts);
$Ampl_i$	acoustic Doppler signal amplitude (counts) measured by the receiver i;
a	constant;
BSI	backscatter intensity;
b	constant;
i	integer;
q_s	advective suspended sediment flux per unit area ($kg.m^{-2}.s^{-1}$)
R	normalised coefficient of correlation;
Secchi	Secchi disk reading (m);
SSC	suspended sediment concentration (kg/m^3, or mg/l);
V_x	instantaneous streamwise velocity component (m/s) positive downstream;
Turb	turbidity (NTU);

Subscript

i	ADV receiver i;

Abbreviations

ADV	acoustic Doppler velocimeter;
NTU	nephelometer turbidity units;

1. INTRODUCTION

A key element in stream monitoring is the choice of a measuring technique of suspended sediment concentration (SSC). Several studies suggested that turbidity and acoustic Doppler backscattering may be suitable surrogate measures for SSC.

The acoustic Doppler velocimetry (ADV) is designed to record instantaneous velocity components at a single-point with relatively high frequency. Measurements are performed by measuring the velocity of particles in a remote sampling volume based upon the Doppler shift effect (e.g. VOULGARIS and TROWBRIDGE 1998, McLELLAND and NICHOLAS 2000). The probe head includes usually one transmitter and three receivers ([1]). An ADV system records simultaneously 12 values with each sample: three velocity components, three signal strength values, three correlation values and three signal-to-noise ratios ([2]). Signal strengths and correlations are used primarily to determine the quality and accuracy of the velocity data (e.g. McLELLAND and NICHOLAS 2000, CHANSON et al. 2005). But the signal strength (i.e. acoustic backscatter strength) may be related to the instantaneous suspended sediment concentration with proper calibration (e.g. Sontek 1997, FUGATE and FRIEDRICHS 2002, NIKORA and GORING 2002, VOULGARIS and MEYERS 2004) (Table 1). This approach was extended to ADCP systems (e.g. HOLDAWAY et al. 1999, HILL et al. 2003). MERCKELBACH (2006) discussed the SSC surrogate measure deduced from acoustic backscatter data. He argued that the particle spatial distributions may induce some incoherent backscatter which may affect the relationship between backscatter intensity and SSC. While most turbulence studies are focused on the velocity signals, the present study is focused on the acoustic backscatter intensity/amplitude ([3]).

An optical turbidity meter (e.g. probes YSI™ 6600 and Hatch™ 2100AN) provides an estimate for the SSC by measuring the attenuation of a light beam thorough the water sample. It may be equipped with a self-cleaning optical sensor in some cases. The turbidity units are NTU where one nephelometric turbidity unit (NTU) is the turbidity resulting from a suspension of one part per million (ppm) of silica, usually formazine. With fine materials, PAVANELLI and BIGI (2005) noted that the suspended sediment concentrations (SSC) can be derived with a high reliability from the turbidity and that the SSC-NTU regression showed a very high correlation ($R^2 = 0.99$). The regression are however a function of the sediment properties and granulometry, the water colour and sometimes the instrumentation (Table 2). Turbidity readings are very sensitive to the variations in the size distributions and composition of suspended solids (LEWIS 1996). SMITH and DAVIES-COLLEY (2002) stressed that the presence of coarse materials may affect adversely any correlation. Generally the best correlations are obtained in creeks where the sediment properties are relatively constant (GIPPEL 1995).

In the present study, the researchers investigated the relationships between turbidity, acoustic Doppler backscatter intensity/amplitude and suspended sediment concentration (SSC) in the small subtropical estuary of Eprapah Creek (Australia). New experiments were conducted under

[1]In the present study, the Sontek™ microADV (16 MHz) system had two receivers, while the Sontek™ UW ADV (10 MHz) unit had 3 receivers.

[2]In addition, the Sontek™ ADV and microADV systems provided a communication error flag for each sample.

[3]Note that there are several definitions of the "backscatter intensity" (BSI). Some researchers defined the "backscatter intensity" as being proportional to the signal strength or amplitude (e.g. THEVENOT and KRAUS 1993, FUGATE and FRIEDRICHS 2002). In that case, the "backscatter intensity" (BSI) is expressed in dB. Some studies approximated the "backscatter intensity" with the signal-to-noise ratio (SNR) but this is incorrect. Other studies defined the "backscatter intensity" as $BSI \propto 10^{\text{Signal strength}}$ (e.g. KAWANISI and YOKOSI 1997, NIKORA and GORING 2002). In the present series of experiments, we defined the backscatter intensity BSI as : $BSI = 1\,E\text{-}5 * 10^{0.043*Ampl}$ where Ampl is the average signal amplitude data measured in counts by the ADV system.

controlled conditions and some data sets previously collected in Eprapah Creek estuary were re-analysed.

Table 1 - Correlations between acoustic backscatter intensity and suspended sediment concentration

Reference (1)	Correlation (2)	Conditions (3)
KAWANISI and YOKOSI (1997)	SSC = 3*BSI $0 \le SSC \le 80$ mg/l SSC in mg/l $BSI \propto 10^{0.043*Ampl}$	Ota diversion channel, Hiroshima Bay(Japan). ADV (10 MHz). Bottom sediment ≤ 88 µm.
Sontek (1997)	$10*\log_{10}(SSC) \propto BSI$ SSC in mg/l	Sontek ADV.
Nortek (2001)	$SSC \propto BSI$	Nortek ADVs.
NIKORA and GORING (2002)	SSC = 0.56*BSI $2 \le SSC \le 400$ mg/l SSC in mg/l $BSI \approx 0.00003 * (10^{0.0434*Ampl_1} + 10^{0.0434*Ampl_2} + 10^{0.0434*Ampl_3})$	Balmoral Irrigation Canal (New Zealand).
FUGATE and FRIEDRICHS (2002)		Cherrystone, Chesapake Bay VA (USA). Sontek ADV.
VOULGARIS and MEYERS (2004)	$\log_{10}(SSC) = 10.8*\log_{10}(BSI) -17.8$ $2 \le SSC \le 100$ mg/l SSC in mg/l	Bly Creek, North Inlet NC (USA). Sontek ADV (10 MHz).
MERCKELBACH (2006)	$BSI = 10 * \log_{10}(SSC) + K_o$	Random phase model.
Present study	SSC = 0.9426 * (1 - exp(-0.1109 * BSI)) $0 \le SSC \le 0.71$ g/l, $0.06 \le BSI \le 12.21$ SSC in g/l	Eprapah Creek water & bed material sample 1 (R = 0.996).
	SSC = 3.7582 * (1 - exp(-0.02157* BSI)) $0 \le SSC \le 0.78$ g/l, $0.009 \le BSI \le 10.6$ SSC in g/l	Brisbane tap water & Eprapah Creek bed material sample 1 (R = 0.998).

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

Table 2 - Correlations between turbidity and suspended sediment concentration

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

Notes : a, b : linear regression constants

2. EXPERIMENTAL METHOD

2.1 FIELD STUDY SITE

Eprapah Creek (Longitude 153.30º East, Latitude -27.567º South) is a subtropical stream located in the Eastern part of Australia, in the Redlands Shire close to Brisbane City (Fig. 1). The creek flows directly into Moreton Bay at Victoria Point off the Pacific Ocean. The stream is 12.6 km long with about 3.8 km of estuarine zone. The catchment area is about 39 km^2. In the estuary, the water depth is typically about 1 to 2 m mid-stream, the width is about 20-30 m, and the river bed is muddy. This is a relatively small estuary with a narrow, elongated and meandering channel (Fig. 1).

Several field experiments were conducted in the estuarine zone of Eprapah Creek (Australia) between April 2003 and June 2006 (e.g. CHANSON et al. 2005b) (Table 3). During each field study, both a turbidity meter and some ADV system(s) were deployed and sampled at high frequency (Table 3).

Table 3 - Turbulence field measurements at Eprapah Creek QLD, Australia

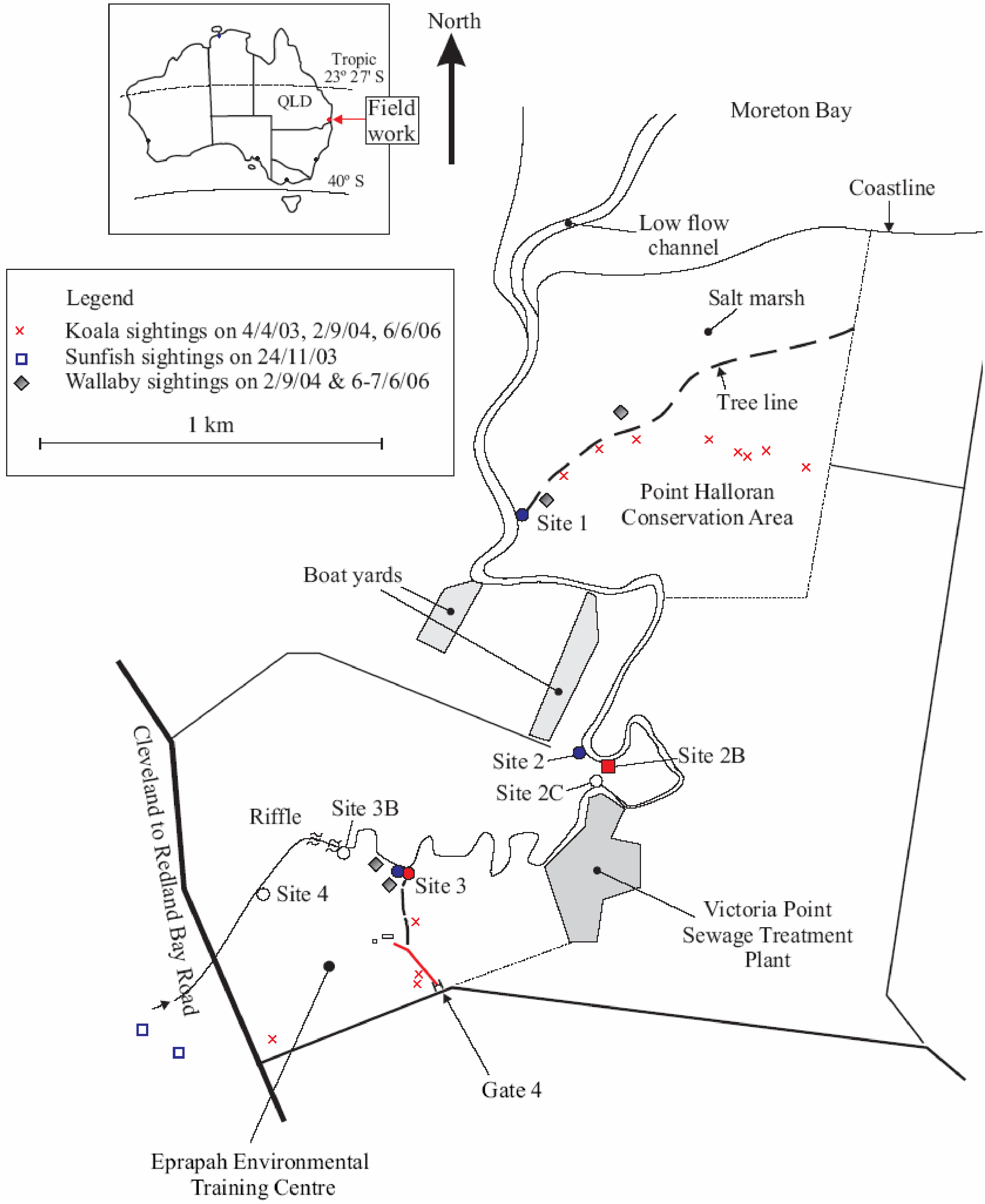
Ref. (1)	Dates (2)	Tidal range (m) (3)	ADV system(s) (4)	ADV Sampling rate (Hz) (5)	YSI 6600 Sampling rate (Hz) (6)	Sampling elevation (7)	Sampling duration (8)	Sampling location (9)
E1	4/04/03	1.84	10 MHz	25	0.2	0.5 m below surface	9 × 25 min	AMTD 2.1 km, 14.2 m from left bank, 0.5 m below surface.
E2	17/07/03	2.03	10 MHz	25	0.2	0.5 m below surface	8 hours	AMTD 2.0 km, 7.7 m from left bank, 0.5 m below surface.
E3	24/11/03	2.53	10 MHz	25	0.5	0.5 m below surface	7 hours	AMTD 2.1 km, 10.4 m from left bank, 0.5 m below surface.
E4	2/09/04	1.81	10 MHz	25	0.33	0.052 m above bed	6 & 3 hours	AMTD 2.1 km, 10.4 m from left bank, 0.052 m above bed.
E5	8-9/03/05	2.37	10 MHz	25	0.167	0.095 m above bed	25 hours	AMTD 2.1 km, 10.4 m from left bank, 0.095 m above bed.
E6	16-18/05/05	1.36	10 MHz & 16 MHz	25 & 25	0.0833	0.2 & 0.4 m above bed	49 hours	AMTD 2.1 km, 10.4 m from left bank, 0.2 & 0.4 m above bed.
E7	5-7/06/06	1.38	10 MHz & 16 MHz	25 & 50	0.0833	0.2 & 0.4 m above bed	50 hours	AMTD 3.1 km, 4.2 m from right bank, 0.2 & 0.4 m above bed.

Note: AMTD: Adopted Middle Thread Distance measured upstream from river mouth.

References: CHANSON (2003), CHANSON et al. (2005b), TREVETHAN et al. (2006), CHANSON and TREVETHAN (2006).

Fig. 1 - Eprapah Creek estuarine zone : map and definition sketch

Blue circle : water quality and fish sampling station in 2003 and 2004. Red circle : instantaneous velocity and water quality measurement site in 2003, 2004 and 2006. Red square : instantaneous velocity and water quality sampling site in 2003, 2004, and 2005.



2.2 LABORATORY CALIBRATION TESTS

Eprapah Creek waters and bed material were collected about mid-estuary on 11 July 2006. Figure 2 illustrates the locations of the water and soil samples. The soil sample 1 consisted of fine mud and silt materials collected on the stream bed, while the soil sample 2 was collected on the bank just

below the high water mark (Fig. 3). The sample 2 was slightly coarser than the bed material sample 1, but the granulometry was not tested. Table 4 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. 4). The calibration of the microADV and turbidity meter was accomplished by measuring the signal amplitude and turbidity of known, artificially produced concentrations of material obtained from some bed material sample. All the calibration experiments were conducted within 28 hours from the sample collection (Tables 4 and 5). In addition one series of tests was conducted with Brisbane tap water to assess the effects of the water quality.
For each test, a known mass of sediment was introduced in the water tank which was continuously stirred with a submerged pump (Fig. 4). (In addition the tank was stirred manually during the most turbid water tests to prevent any sediment deposition on the tank bottom.) 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 wet sediment and the measured water tank volume.

Fig. 2 - Water and soil sampling sites on 11 July 2006
(A) Aerial view of the sampling sites (Photograph Source Google Earth™)

(B) View from the river of the soil sampling locations (Photograph Courtesy of Dr M. TAKAHASHI)

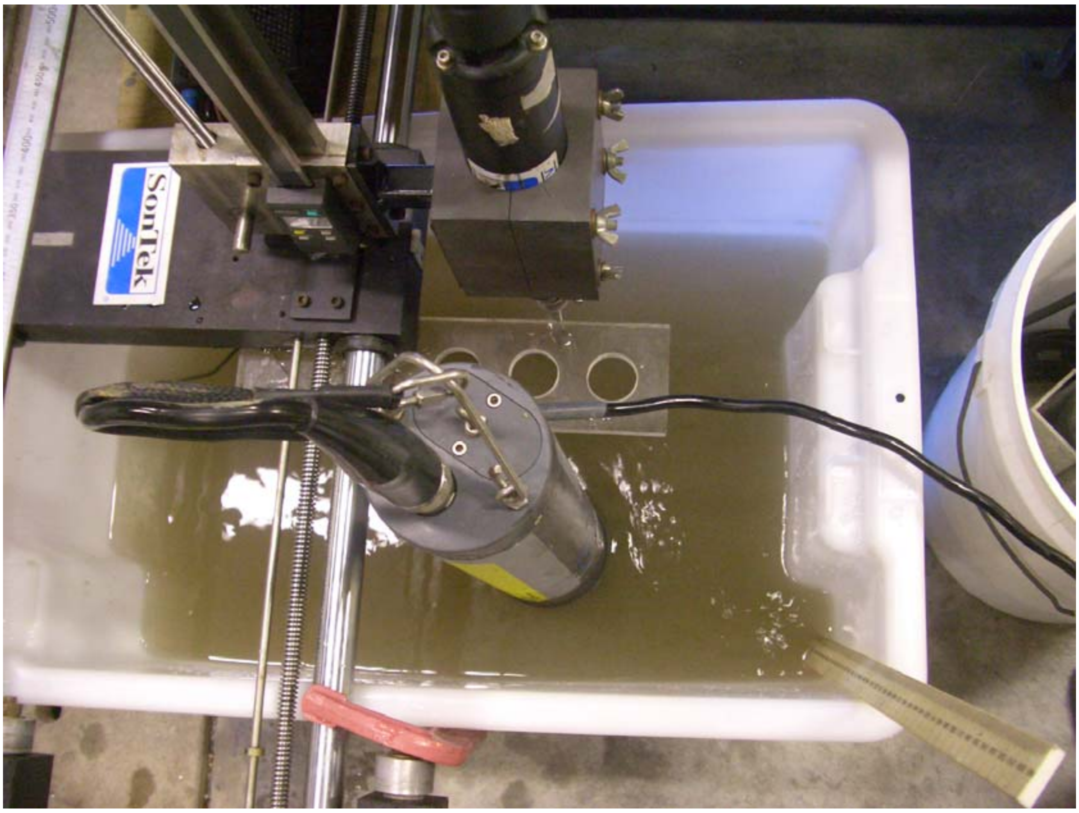
Fig. 3 - Photograph of soil samples

(A) River bed material (sample 1) at mid ebb tide - Note the toad fish swimming next to the bank

(B) Wet sediment sample 2 in the laboratory

Fig. 4 - Photographs of the laboratory experiments (Photographs M. TAKEUCHI)
(A) Water : Eprapah Creek, 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

(B) Water : Eprapah Creek, Sediment sample: 1 (Bed material), SSC = 0.710 g/l - The YSI 6600 probe is on the bottom, the microADV system is on the top, and the pump is located on the top left corner of the water tank - The suspended sediment was hand-mixed during that test



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 minutes for each test. The average amplitude measurements represented the average signal strength of the two ADV receivers. They were measured in counts ([4]). The backscatter intensity was deduced from the average amplitude as :

$$BSI = 1 E\text{-}5 * 10^{0.043 * Ampl} \tag{1}$$

where the backscatter intensity BSI is dimensionless and the average amplitude Ampl is in counts. The coefficient 1 E-5 is a value introduced to avoid large values of backscatter intensity (e.g. NIKORA and GORING 2002). Note that the microADV signal was post-processed with the software WinADV™ to remove the communication errors. (No further processing was performed.)
The turbidity and other physio-chemistry properties were measured with the YSI™ 6600 probe. During the laboratory tests, the probe sensors were placed beside the microADV sampling volume. For each test, the YSI6600 probe data were the averages of 3 readings.

2.3 DATA ACCURACY

The accuracy on the ADV velocity measurements was 1%.
With the physio-chemistry probe YSI6600, the data accuracy was ±5% for turbidity. (Note that the turbidity spike filter was on.) Further the data accuracy was : ±0.5% for conductivity, ±0.15ºC for temperature, ±0.2 unit for pH, ±2% of saturation concentration for dissolved oxygen. The data accuracy was ±5% for turbidity. Note that the turbidity spike filter was on.

[4]One count equals 0.43 dB.

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.

Table 4 - Summary of laboratory calibration experiments

Reference (1)	Waters (2)	Sediment samples (3)	SSC range g/l (4)	Turbidity range NTU (5)	Remarks (6)
060711E	Water collection at Eprapah Creek, Site 2C		--	6.6-8.0	Date: 11 July 2006, early ebb tide (10:15am)
060711	Eprapah Creek	Sample 1 Eprapah Creek (Site 2B), bed material	0-0.71	7.2-150.4	Date: 11 July 2006 (Start: 14:12).
060712a	Eprapah Creek	Sample 1 Eprapah Creek (Site 2B), bed material	0-0.54	8.1-126.2	Date: 12 July 2006 (Start: 08:56).
060712b	Eprapah Creek	Sample 2 Eprapah Creek (downstream of Site 2B), bank material	0-0.47	7.9-148.8	Date: 12 July 2006 (Start: 10:26).
060712c	Brisbane tap water	Sample 1 Eprapah Creek (Site 2B), bed material	0-0.78	0-186.3	Date: 12 July 2006 (Start: 13:00).

Table 5 - Summary of physio-chemical properties of the water samples at the start of each experiment (prior to sediment supply, SSC = 0)

Ref. (1)	Waters (2)	Turbidity range NTU (3)	Conduct. mS/cm (4)	Temperature Celsius (5)	DO % Sat. (6)	pH (7)	Remarks (6)
060711E	Water collection at Eprapah Creek, Site 3B	7.43 [6.6-8.0]	33.29 [33.09-33.44]	18.61 [18.41-18.74]	90.2 [88-93.9]	7.42 [7.41-7.44]	Date: 11 July 2006, early ebb tide (10:15am)
060711	Eprapah Creek	7.25	33.32	19.26	96.1	7.52	Date: 11 July 2006 (14:12).
060712a	Eprapah Creek	8.07	33.2	17.16	95.13	7.62	Date: 12 July 2006 (08:56).
060712b	Eprapah Creek	7.87	33.4	17.23	94.3	7.63	Date: 12 July 2006 (10:26).
060712c	Brisbane tap water	-0.53	0.45	17.57	89.4	7.66	Date: 12 July 2006 (13:00).

Note : [..-..] : range.

3. EXPERIMENTAL RESULTS

3.1 LABORATORY TESTS

For the experimental data, we tested systematically the relationships between turbidity, acoustic backscatter amplitude, acoustic backscatter intensity and suspended sediment concentrations (SSC) for turbidities between 0 and 200 NTU. The experimental results are summarised in Figures 4 to 7. The full data sets are reported in Appendix A. The best fit relationships are detailed in Appendix B. Overall, the best, most meaningful correlations were established in terms of the suspended sediment concentration (SSC) as a function of the acoustic backscatter intensity (BSI), the SSC as a function of the turbidity, and the turbidity as a function of the acoustic backscatter intensity (Fig. 5 to 7).

First let us note the good correlation between all the data showing consistently a monotonic increase in suspended sediment concentration with increasing turbidity and increasing backscatter intensity. The relationship between SSC and turbidity was linear while the relationships between SSC and backscatter intensity, and turbidity and backscatter intensity, were non-linear (App. B).

Second the sediment material had a substantial effect on the results (Fig. 5 to 7). 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 suspended sediment concentration, compared to the results obtained with the bed sample 1. Although the overall trends were similar between both soil samples, the quantitative coefficients were different between different (App. B).

Third the effect of water quality was clearly seen by comparing the tests with Eprapah waters and Brisbane tap waters with the same sediment sample (bed material sample 1). For example, the relationship between SSC and backscatter intensity (BSI) was nearly linear with Brisbane tap waters, but it was non-linear, closer to a power law with Eprapah Creek waters (Fig. 5). The differences in water quality included some different water conductivities, but also some difference in bio-chemical and biological contents. For example, the Brisbane tap waters were treated and drinkable, while the Eprapah Creek waters were taken downstream of a sewage treatment plant outfall (Fig. 1).

For the laboratory tests with Eprapah Creek waters and the bed material (sample 1), the best fit relationships were :

$$SSC = 0.9426 * (1 - \exp(-0.1109 * BSI)) \qquad (2)$$

$$SSC = 0.00485 * Turb - 0.0350 \qquad (3)$$

$$Turb = 171.06 * (1 - \exp(-0.1593 * BSI)) \qquad (4)$$

where the suspended sediment concentration SSC is in g/l, and the turbidity Turb is in NTU and the backscatter intensity BSI is defined using Equation (1). Equations (2) to (4) are compared with the data in Figures 5 to 7.

Fig. 5 - Relationship between suspended sediment concentration (SSC in g/l) and backscatter intensity (BSI, Eq. (1)) - Comparison between the data and Equation (2)

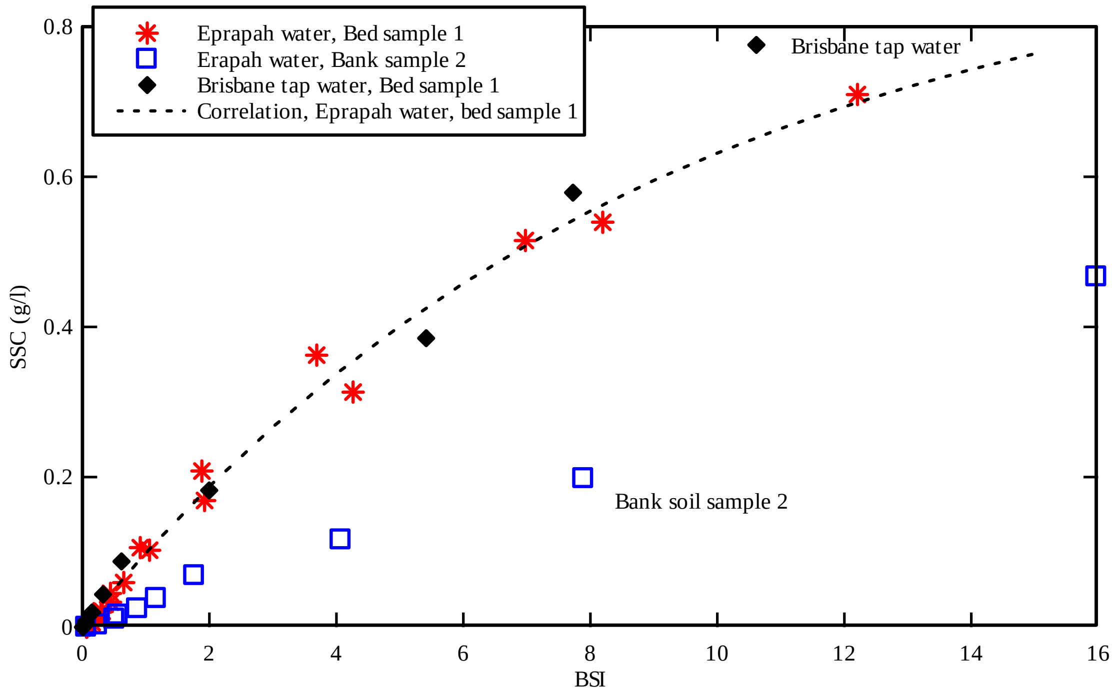


Fig. 6 - Relationship between suspended sediment concentration (SSC in g/l) and turbidity (Turb in NTU) - Comparison between the data and Equation (3)

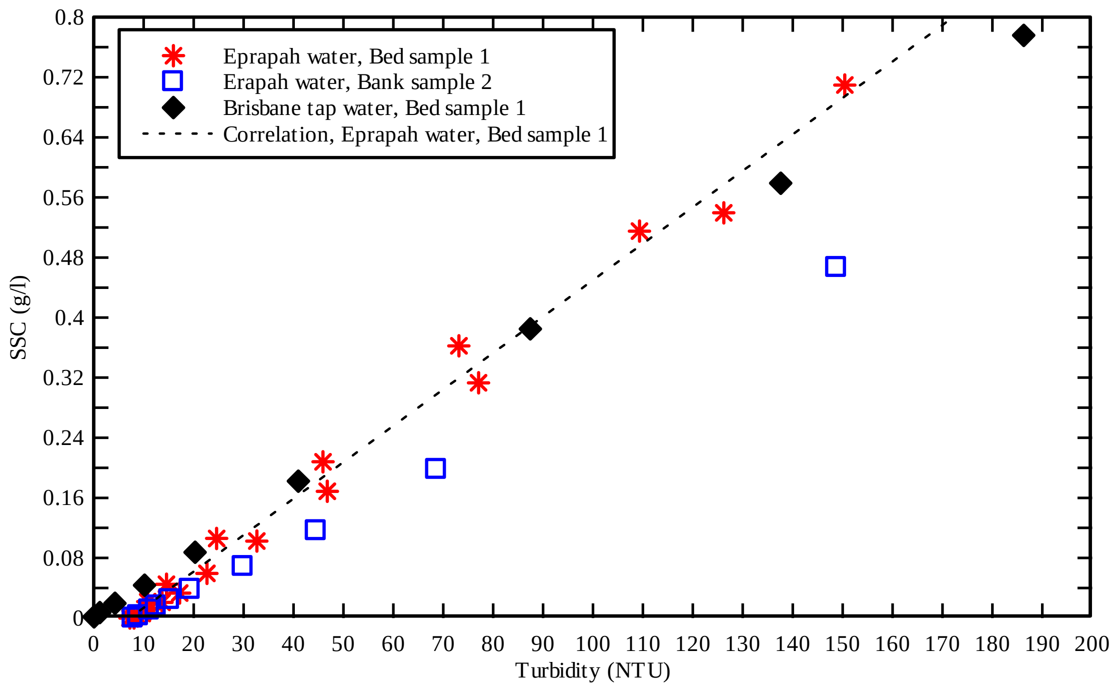
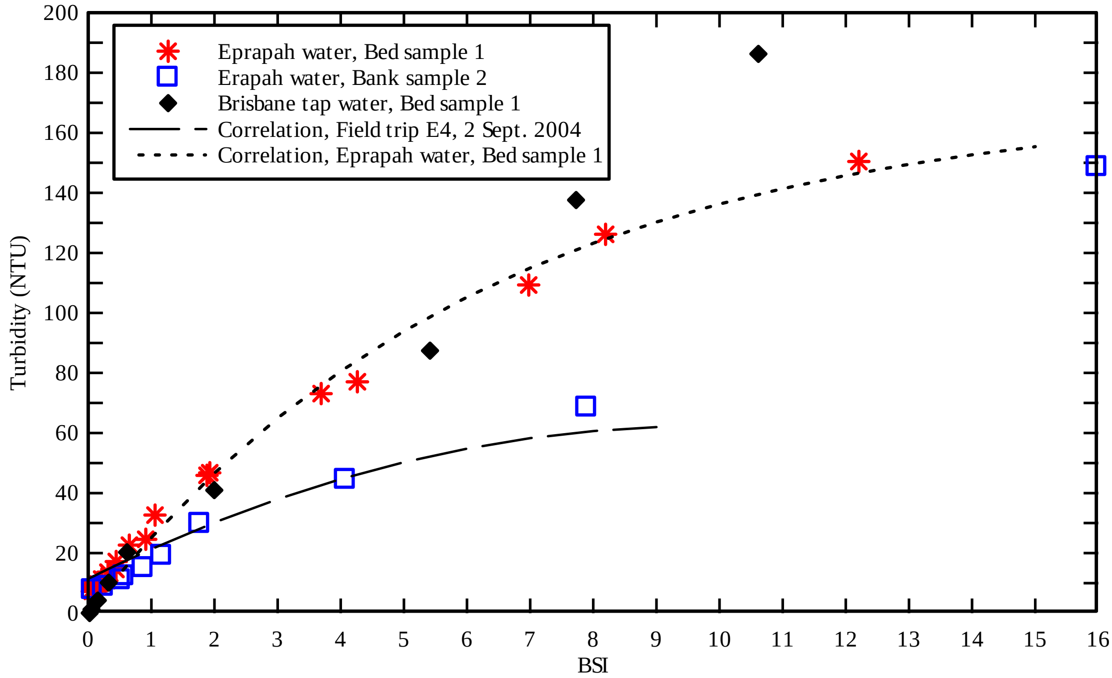


Fig. 7 - Relationship between turbidity (Turb in NTU) and backscatter intensity (BSI, Eq. (1)) - Comparison between the data and Equations (4) and (5)



Discussion

In practice, some advanced best fit relationships are not always recommended for field work applications because they might lead to meaningless results for large backscatter intensity readings. For example, some quadratic relationships between SSC and backscatter intensity were tested for the field work E6 data set (Table 3) (App. B). The results yielded meaningless negative suspended sediment concentration and turbidity estimates when the average backscatter amplitude exceeded 145 to 150 counts.

Practically it is recommended to use simple, robust calibration curves that increase monotonically with an increasing backscatter intensity.

3.2 FIELD STUDY

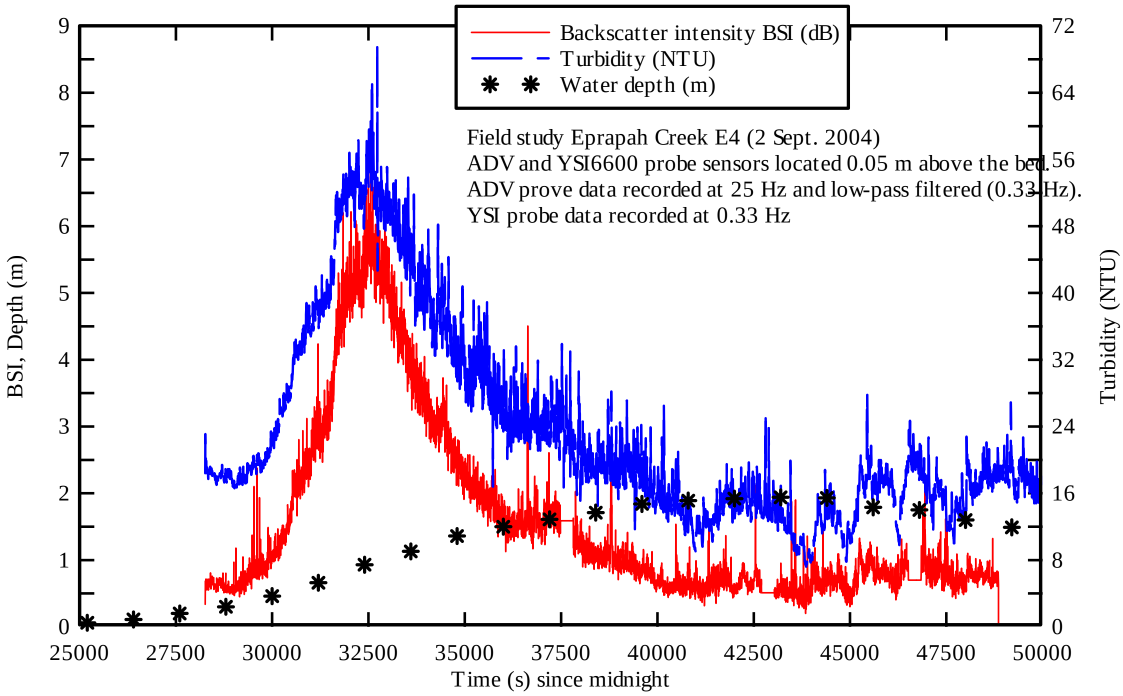
For one field study (E4), a Sontek™ 3D ADV (10 MHz, serial 0510) system and a YSI6600 probe were deployed side by side next to the river bed (Tables 3 & 6). The ADV and turbidity sampling volumes were placed at 5 cm above the bed, and the data were logged at 25 Hz and 0.33 Hz respectively between 7:55 and 18:00. Both the signal amplitude and turbidity data showed a turbid event for about 2 hours during the early flood tide (Fig. 8A).

For that turbid event, there was a good correlation between the turbidity and acoustic backscatter intensity that is illustrated in Figure 8. The best data fit for the ADV system was :

$$\text{Turb} = 11.433 + 10.462 * \text{BSI} - 0.5385 * \text{BSI}^2 \qquad (5)$$

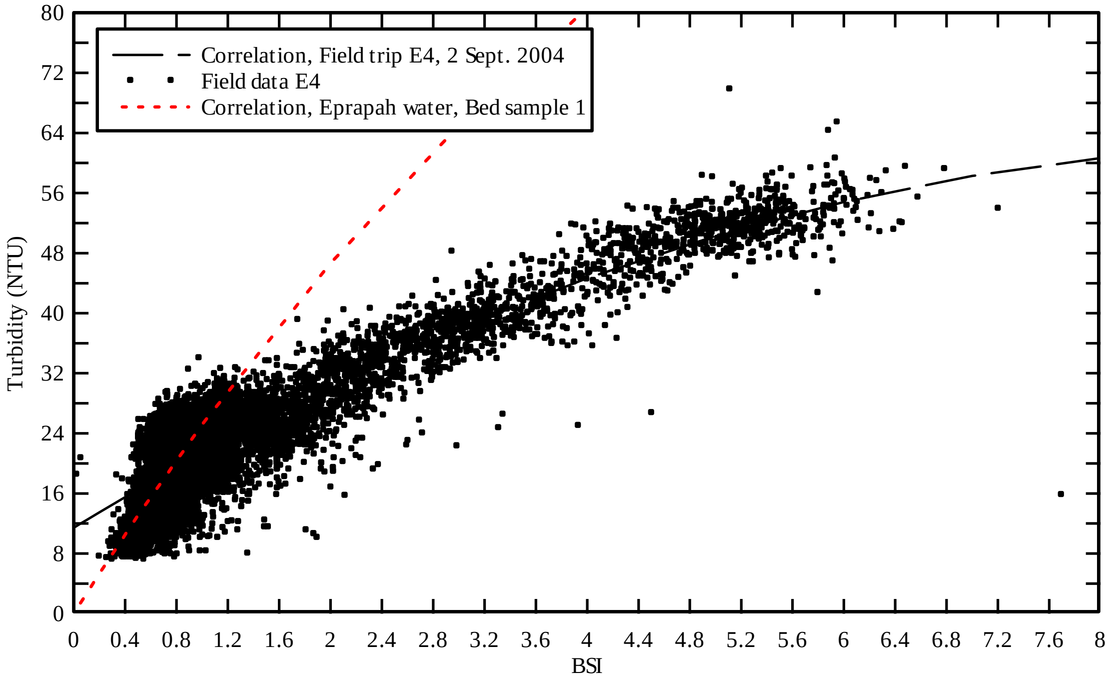
where the turbidity Turb is in NTU and the backscatter intensity BSI is defined using Equation (1). Equation (5) is compared with the data in Figure 8B. Equation (4), obtained with the microADV (16 MHz) system, is also shown in Figure 8B. The results highlighted the same trend in terms of turbidity versus backscatter intensity for both ADV systems. The quantitative results were however different : e.g., for a turbidity of 80 NTU, Equation (5) corresponds only to about half of the backscatter intensity measured by the newer microADV (16 MHz) system. It is possible that the differences may be caused by some differences in water quality between the 2 September 2004 (Field study E4) and 11 July 2006 (Water sampling, present study). It is believed however that the contrast reflected the lesser performances of the older ADV (10 MHz) system. Since the control volume of the microADV system was two to three times smaller than the control volume of the ADV system, the present results suggested that the older ADV (10 MHz) system detected 30% less total counts, and 60% less counts per unit sampling volume for a turbidity of 80 NTU.

Fig. 8 - Turbidity (Turb in NTU) and backscatter intensity (BSI, Eq. (1)) measurements during the field study E4 (2 Sept. 2004) in Eprapah Creek estuary between 8:00 and 14:00
(A) Time-variations of turbidity (Turb in NTU) and backscatter intensity (BSI, Eq. (1))



(B) Relationship between turbidity (Turb in NTU) and backscatter intensity (BSI, Eq. (1)) - Comparison with Equations (4) and (5)

Study	Date	Waters	ADV system	Velocity range (m/s)	Scan rate (Hz)	Turbidity meter
Field study Eprapah E4	2 Sept. 2004	Eprapah Creek	Sontek™ 3D ADV (10 MHz, serial 0510)	0.30	25	YSI™ 6600
Laboratory tests	11-12 July 2006	Eprapah Creek	Sontek™ 2D microADV (16 MHz, serial number A641F)	0.10	50	YSI™ 6600



4. APPLICATION

4.1 SUSPENDED SEDIMENT FLUX

The present results were applied to the earlier field studies E6 and E7 in Eprapah Creek estuarine zone (Tables 3 & 6). During these field studies, the same microADV (16 MHz) system was deployed about mid-estuary (Site 2B, E6) and in the upper estuary (Site 3, E7) (Fig. 1). For each study, its sampling volume was located at 0.20 m above the bed, and the microADV system was scanned continuously at 25 or 50 Hz for 50 hours (Table 6). The field study E6 was conducted mid-estuary (Site 2B, Fig. 1), while the field study E7 was conducted 1 km upstream in the upper estuary zone where the channel is narrower (Site 3, Fig. 1). Both studies were performed during neap tide conditions. The details of the tidal range, instrumentation location and water physio-chemical properties are summarised in Table 6.

Figure 9 presents the time variations of instantaneous streamwise velocity data for the 50 hours period ([1]). The measured water depths are also shown. These were recorded with a pressure sensor located at 0.4 m above the bed. Figure 9 indicates some tidal diurnal inequality with a major tide and a minor tide for each 24 h 50 min. full 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. 9A). The magnitude of the flood tide velocity was typically larger than that of the ebb tide flow. Note the different vertical scales of Figures 9A and 9B. 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 minutes to 2 hours that were discussed by CHANSON (2003) and TREVETHAN et al. (2006). These low-frequency oscillations were believed to be linked with some internal and external resonance.

Figure 10 presents the time variations of instantaneous acoustic backscatter intensity data (Eq. (1)) for 50 hours. The signal amplitude and backscatter intensity data showed some fluctuations throughout the entire field studies, including during the tidal slacks (high and low tides) ([2]). We note however some low-frequency oscillation patterns that may be linked with the low-frequency fluctuations of streamwise velocity.

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

$$q_s = SSC * V_x \qquad (6)$$

where q_s and V_x are positive in the downstream direction. In Equation (6), the suspended sediment concentration SSC is in kg/m^3, the streamwise velocity component V_x is in m/s and the sediment flux per unit area is in kg/s/m^2. The suspended sediment concentration (SSC) was calculated using Equation (2) applied to the post-processed backscatter amplitude signal ([3]), and the streamwise velocity V_x signal was post-processed using the method of CHANSON et al. (2005a). The results are presented in Figure 11 in terms of the instantaneous sediment flux q_s.

The sediment flux data showed typically an upstream, negative suspended sediment flux during the flood tide and a downstream, positive sediment flux during the ebb tide (Fig. 11). For each field study, the instantaneous sediment flux data q_s showed considerable time-fluctuations that derived from a combination of velocity and suspended sediment concentration fluctuations. The suspended sediment flux data demonstrated some high-frequency fluctuations with some form of sediment flux

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[1]The data were post-processed ADV data. The post-processing technique was that developed by CHANSON et al. (2005a).

[2]Note that the Eprapah Creek waters were relatively clear. The water turbidity rarely exceeded 30 NTU (see also Section 3.2).

[3]A preliminary data check showed a large number of amplitude "spikes/peaks" when the velocity data points that were deemed erroneous using the method of CHANSON et al. (2005a). It is believed that these signal amplitude "spikes/peaks" might be caused by some electronic noises and inherent errors of the ADV system, rather than by some genuine suspended sediment clouds. These amplitude "spikes/peaks" were therefore removed and replaced.

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. 11). At the start of each field study, some large suspended sediment fluxes were observed. It is believed that these high suspended sediment flux readings were caused by sediment material agitation when the instrumentation was installed. In addition, during the study E6, it is possible that some high sediment flux data were the result of the passage of a front observed at 12:22 on the 16 May 2005 (i.e. t = 44,520 s) (TREVETHAN et al. 2006). Lastly note the smaller sediment flux measurements during the field study E7. These resulted from a combination of lower advective velocities (Fig. 9) and smaller backscatter intensity data (Fig. 10).

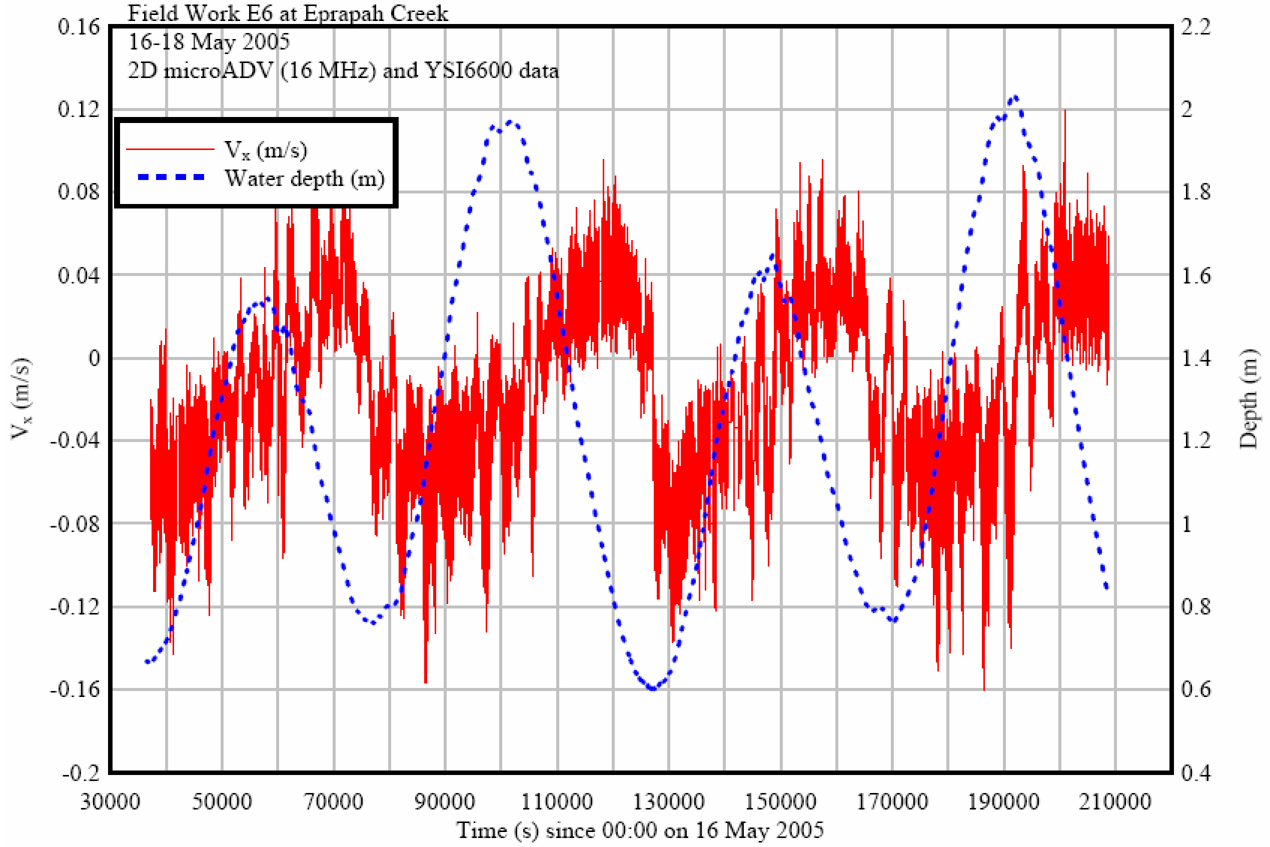
For each study and for each tidal cycle (24 h 50 min.), the sediment flux data were integrated with respect of time. The result gives the net sediment mass transfer per unit area during a full tidal cycle:

$$\int_{24\text{ h }50\text{ min.}} SSC * V_x \, dt \qquad (7)$$

For the field study E6, the net sediment mass transfer per area was negative and Equation (7) yielded -22.3 and -20.8 kg/m^2 for each tidal cycle. That is, the net sediment flux over a full tidal cycle corresponded in average to an upstream net suspended sediment transfer. For the field study E7, the net sediment mass transfer per area was also negative. Equation (7) yielded -6.66 and -1.81 kg/m^2 for each tidal cycle. In average the net sediment flux was upstream.

Fig. 9 - Instantaneous microADV measurements during the field studies E6 (16-18 May 2005) and E7 (5-7 June 2006) in Eprapah Creek estuary for a 50 hours period - Time-variations of water depth (m) and streamwise velocity (V_x, positive downstream)

(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)

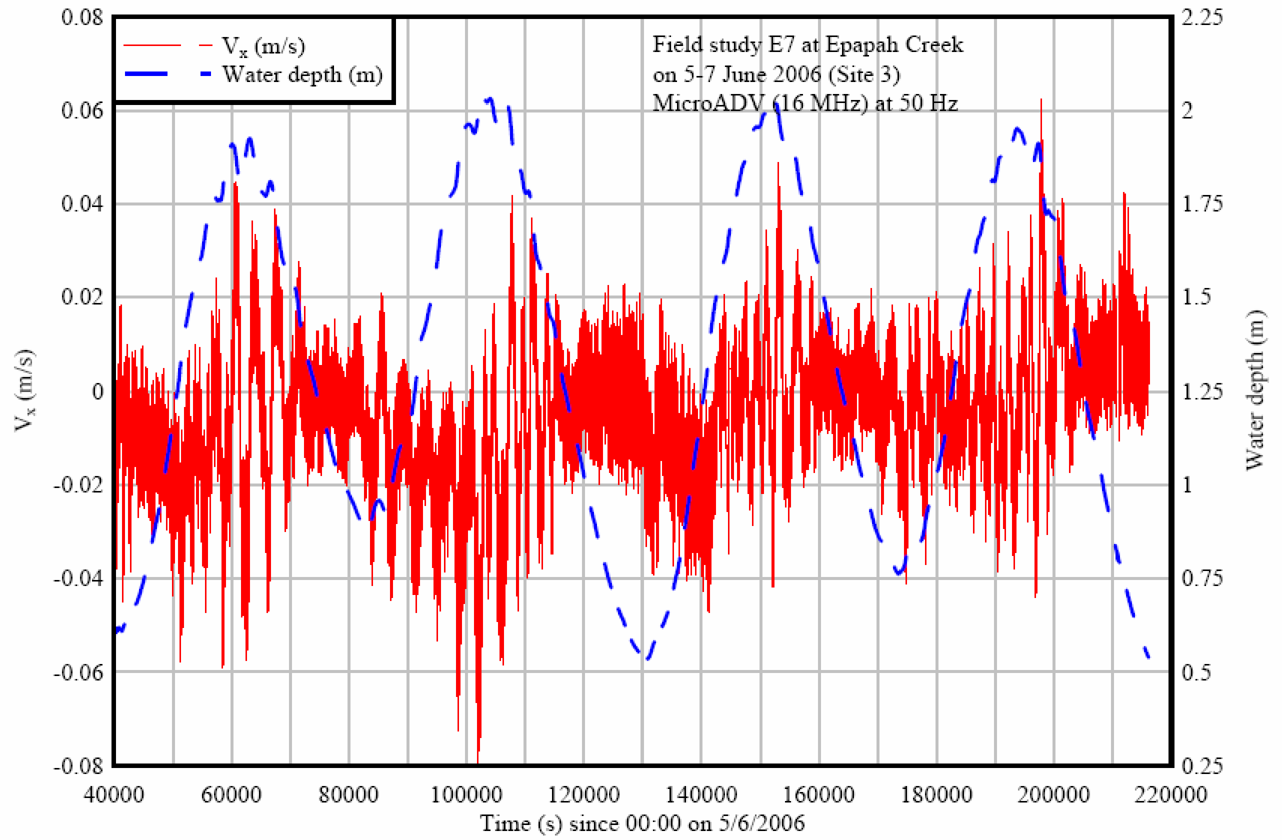
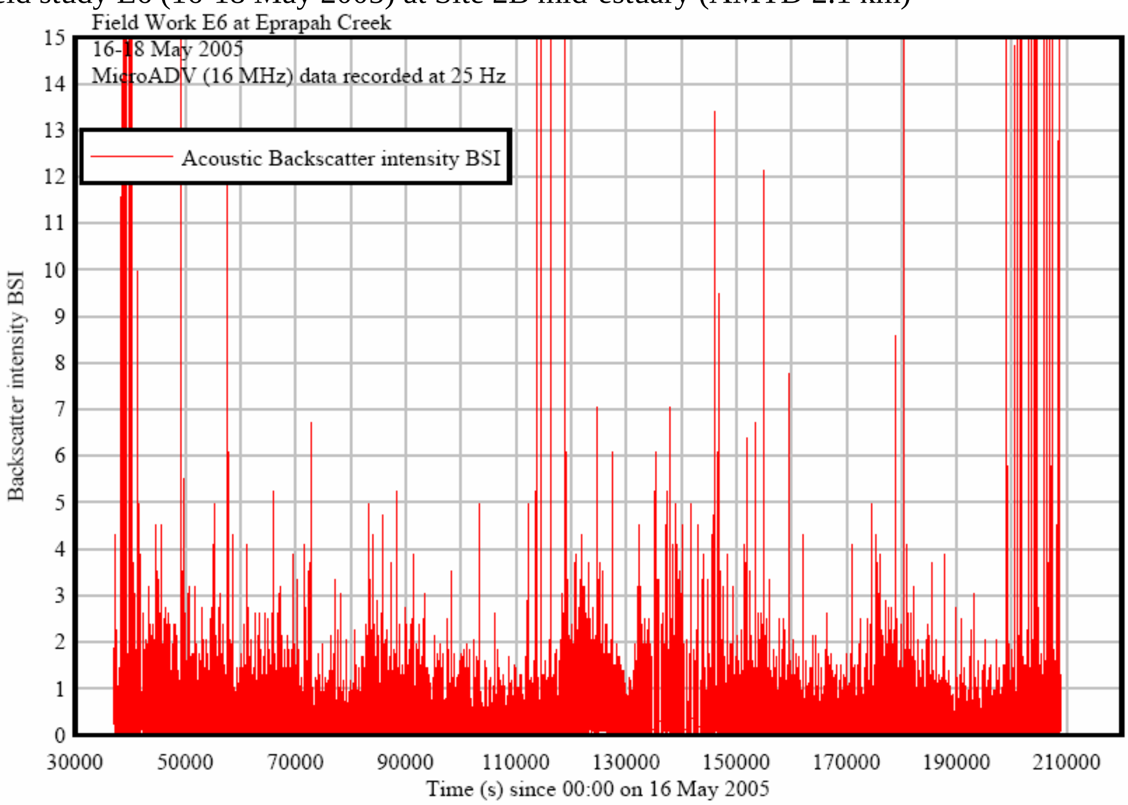


Fig. 10 - Instantaneous microADV measurements during the field studies E6 (16-18 May 2005) and E7 (5-7 June 2006) in Eprapah Creek estuary for a 50 hours period - Time-variations of backscatter intensity (BSI, Eq. (1))

(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)

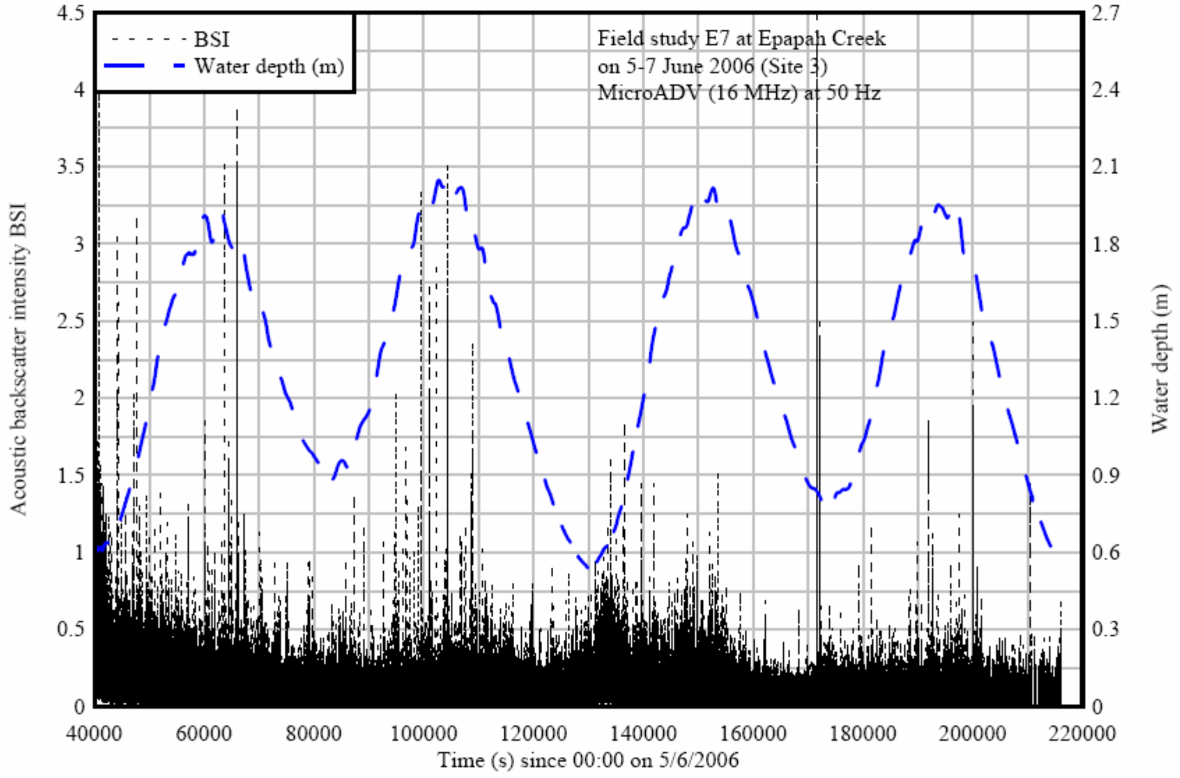
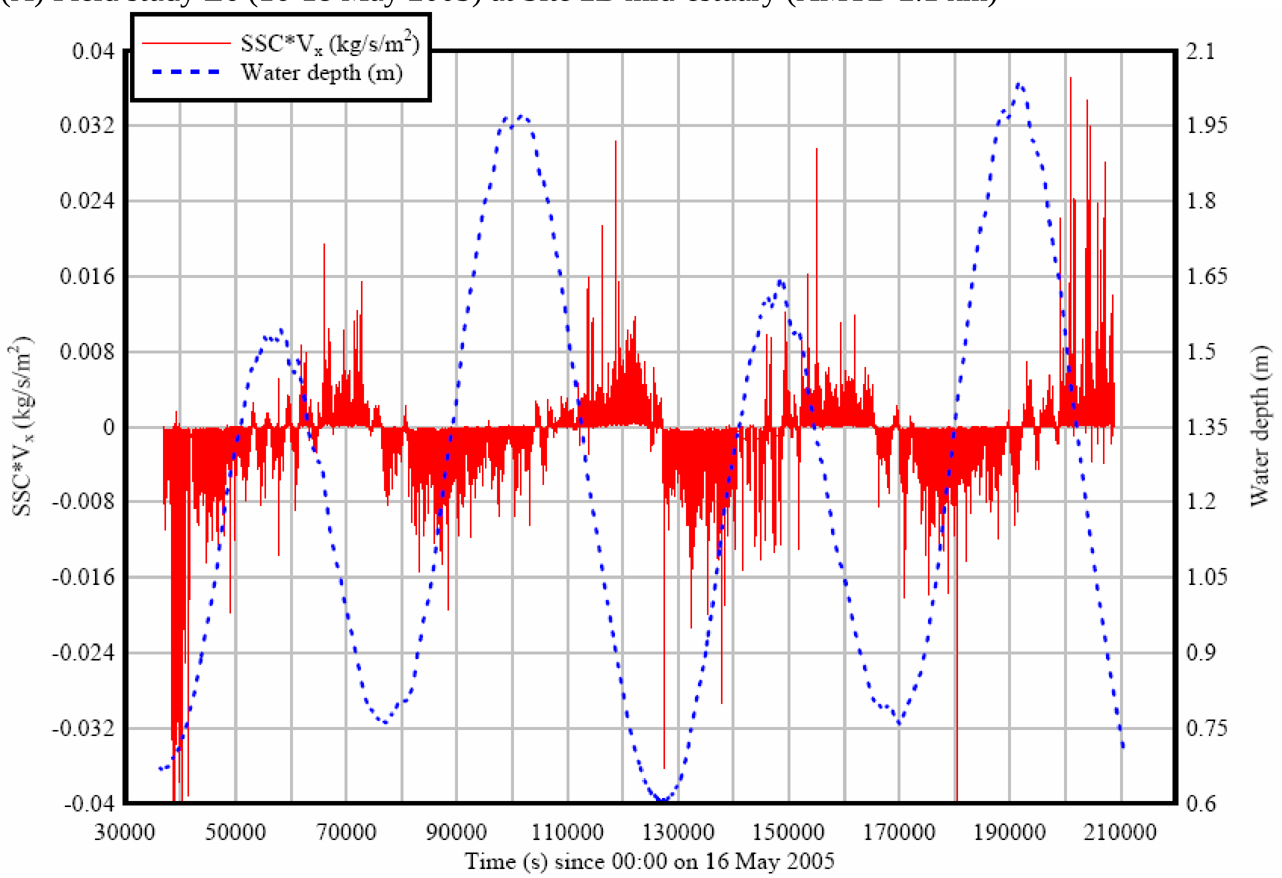
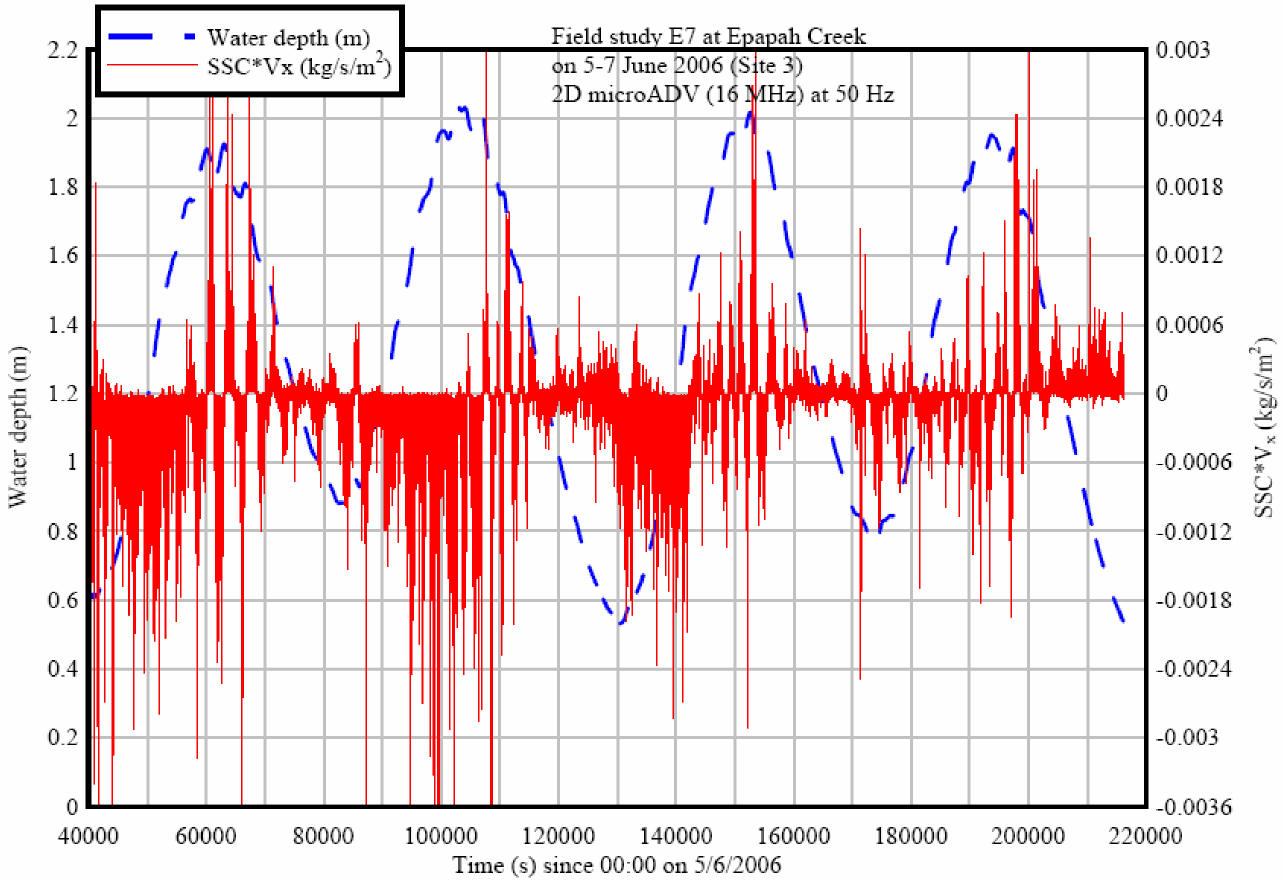


Fig. 11 - Advective suspended sediment motion during the field studies E6 (16-18 May 2005) and E7 (5-7 June 2006) in Eprapah Creek estuary for a 50 hours period - Time variations of suspended sediment flux per unit surface area ($SSC*V_X$, positive downstream) (Eq. (6)) and measured water depth

(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)



The net sediment mass transfer per area appeared to be relatively little affected by some activities in the creek. In the field study E6 (16-18 May 2005), the first full tidal cycle was almost uneventful, but for a front observed at the start and some residual effects of the instrumentation installation. In contrast, the second tidal cycle was affected by significant powered boat activities in front the ADV system between 13:30 and 17:00 on 17 May 2005 (i.e. t = 135,000 to 147,600). During the field study, the first tidal cycle was uneventful. There were however some boat activities besides the microADV system during the second tidal cycle (Table 6).

<u>Discussion</u>

Some researchers studied the net suspended sediment flux in estuaries. Some studies showed also an upstream net sediment transfer in sub-tropical rivers during dry conditions and for a similar tidal range. For example, LARCOMBE and RIDD (1992), HOSSAIN et al. (2001), KAWANISI et al. (2006).

An interesting study was conducted by KAWANISI et al. (2006) using an ADCP system. In the middle of a 3 months continuous study, an accidental upstream gate failure generated a small flood event lasting for 2 days. The net suspended sediment flux was downstream during the artificial flood event, but it was in average upstream during the rest of study.

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.

Table 6 - Field investigations at Eprapah Creek in 2004 and 2005 - Comparison with present experiments

Field study reference	E4	E6	E7	Present study
Date	2 Sept. 2004	16-18 May 2005	5-7 June 2006	11 July 2006
Maximum tidal range (Victoria Point)	1.81m	1.36	1.38	2.41
Remarks	Long drought period	Heavy Navigation passages on 17 May 2005 between 13:29 and 17:00	Navigation passages on 6 June 2006 between 15:40 and 16:30 & on 7 June 2006 between 10:30 & 10:55	Water and sediment sampling
Acoustic Doppler velocimetry				
ADV system	Sontek™ 3D ADV (10 MHz, serial 0510)	Sontek™ 3D ADV (10 MHz, serial 0510) & Sontek™ 2D microADV (16 MHz, serial number A641F)	Sontek™ 2D microADV (16 MHz, serial number A641F)	Sontek™ 2D microADV (16 MHz, serial number A641F)
ADV sampling period(s)	7:55-13:40 14:26-17:57	09:50 on 16 May 2005 to 10:36 on 18 May 2005	11:07 on 5 June 2006 to 12:07 on 7 June 2006	N/A
ADV velocity range (m/s)	0.30	1.0	0.30	0.10
Continuous sampling frequency (Hz)	25	25	50	50
Sampling volume location	Site 2B, 0.0525 m above bed, 10.7 m from left bank	Site 2B, 10.7 m from left bank microADV : 0.2 m above bed ADV : 0.4 m above bed	Site 3, 4.2 m from right bank microADV : 0.2 m above bed	Laboratory tests
Physio-chemistry sampling	YSI 6600 probe	YSI 6600 probe	YSI 6600 probe	YSI 6600 probe
Continuous sampling site	Site 2B, 0.0525 m above bed, 10.4 m from left bank	Site 2B, 0.4 m above bed, 10.4 m from left bank	Site 3, 0.4 m above bed, 4.2 m from right bank	
Continuous sampling frequency (Hz)	0.33	0.0833 (every 12 s)	0.0833 (every 12 s)	N/A
Water temperature (ºC)	17.14 ([1]) [15.9-18.1]	21.1 ([1]) [20.2-21.8]	18.87 ([1]) [18.37-19.28]	18.6
Conductivity (mS/cm)	48.6 ([1]) [41.0-53.6]	47.2 ([1]) [43.9-50.2]	47.3 ([1]) [46.05-47.94]	33.3
Turbidity (NTU)	22.9 ([1]) [7.2-80]	12.6 ([1]) [3.4-*70*]	9.29 ([1]) [3.4-24.1]	7.43
DO (% Sat)	69.9 ([1]) [43-95]	--	39.1 ([1]) [20.4-54.8]	90.2
pH	7.37 ([1]) [6.68-7.79]	7.80 ([1]) [7.45-8.05]	7.3 ([1]) [7.01-7.55]	7.42

Notes: ([1]) : mean values [extreme values in square brackets] for the study period; *Italic data* : possibly incorrect data.

4.2 NOTE ON THE RELATIONSHIP BETWEEN TURBIDITY AND BACKSCATTER INTENSITY

During the field study E6, the YSI6600 turbidity probe sensor and the Sontek™ 3D ADV (10 MHz, serial 0510) system were located at 0.4 m above the bed at the same location as the microADV system (Table 6). The ADV (10 MHz) sampling volume was 0.2 m above the microADV sampling volume and the YSI6600 probe was 0.3 m beside the ADV system.

For that study, Equation (4) was tested and compared with the turbidity measurements. The estimated turbidity data were deduced from the low-pass filtered acoustic backscatter intensity measurements. The comparative results are presented in Figure 12. The results showed that the turbidity predictions were lower than and up to half of the measured values (Fig. 12). The finding was consistent throughout the field study and it was not expected. The microADV sensor was closer to the bed and it should be expected that the turbidity estimates at 0.2 m above the bed would be larger than the measured turbidity at 0.4 m above the bed.

For the same study, Figure 13 shows the measurements of acoustic backscatter intensity and turbidity at 0.4 m above the bed. The former was conducted with the ADV (10 MHz) system while the latter was measured with the YSI6600 probe. Figure 13A shows the time-variations for the 50 hours study. Figure 13B compare the experimental data with Equation (4) and (5). The latter was derived for the same ADV (10 MHz) unit, based upon a turbid event in the field study E4 (Section 3.2).

Fig. 12 - Comparison between calculated turbidity (Eq. (4)) and measured turbidity during the field study E6 (16-18 May 2005) in Eprapah Creek estuary for a 50 hours period

Parameter	Equation	Probe	Scan rate (Hz)	Sensor elevation (m)
Predicted turbidity	Eq. (4)	Sontek™ 2D microADV (16 MHz, serial number A641F)	25	0.2 m above bed
Measured turbidity	--	YSI™ 6600	0.0833	0.4 m above bed

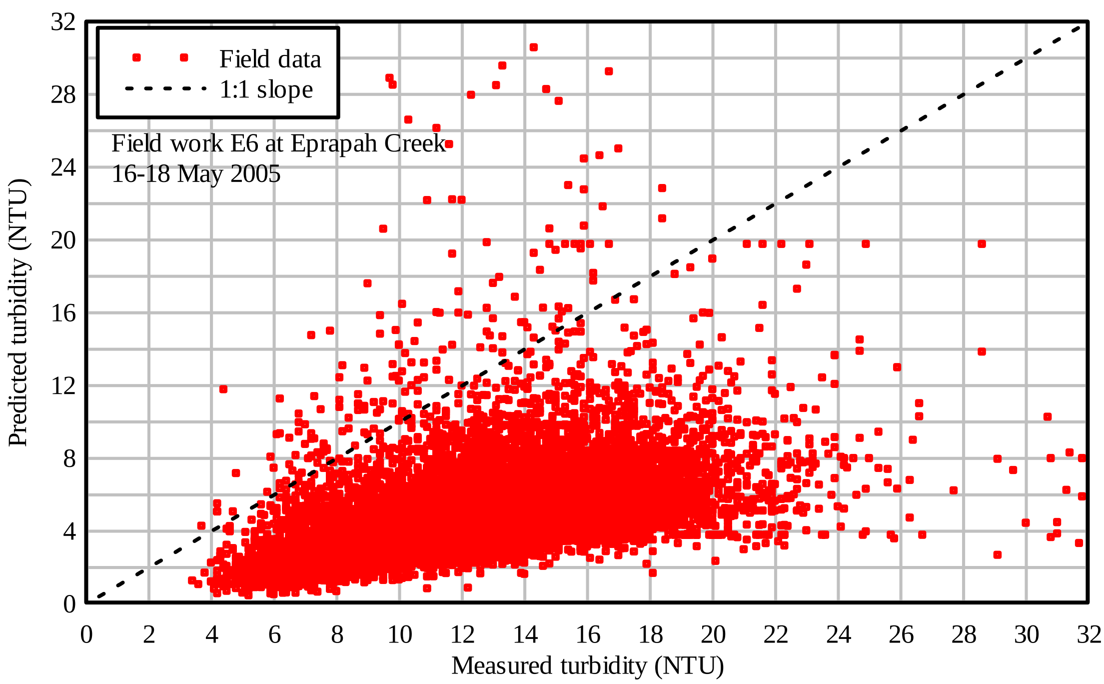
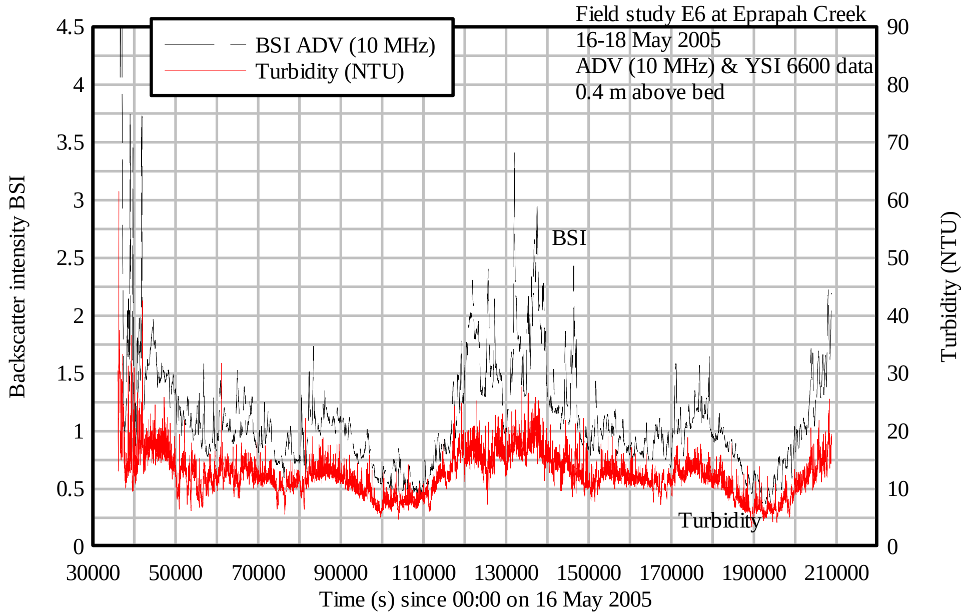


Fig. 13 - Measurements of acoustic backscatter intensity (Eq. (1)) with the ADV (10 MHz) and turbidity during the field study E6 (16-18 May 2005) in Eprapah Creek estuary for 50 hours

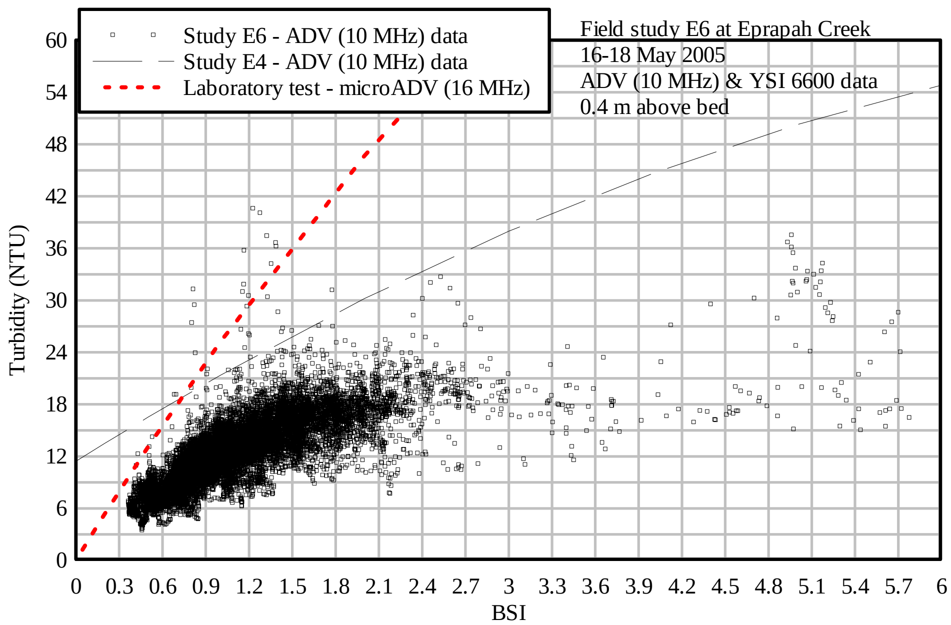
(A) Time variations of acoustic backscatter intensity and turbidity at 0.4 m above the bed

Parameter	Equation	Probe	Scan rate (Hz)	Sensor elevation (m)
Backscatter intensity BSI	Eq. (1)	Sontek™ ADV (10 MHz, serial number 0510)	25	0.4 m above bed
Measured turbidity	--	YSI™ 6600	0.0833	0.4 m above bed



(B) Relationship between turbidity (Turb in NTU) and backscatter intensity (BSI, Eq. (1)) - Comparison with Equations (4) and (5)

Parameter	Equation	Probe	Scan rate (Hz)	Sensor elevation (m)
Backscatter intensity BSI	Eq. (1)	Sontek™ ADV (10 MHz, serial number 0510)	25	0.4 m above bed
Measured turbidity	--	YSI™ 6600	0.0833	0.4 m above bed



Both Figures 12 and 13 highlight that the relationship between turbidity and backscatter intensity might be affected by some changes in Eprapah water properties over time. Equation (4) was developed for and based upon Eprapah waters collected in July 2006. Equation (5) was developed for a turbid event on 2 September 2004. These water quality conditions were possibly not reproduced on 16-18 May 2005 (study E6) (Fig. 13).

5. SUMMARY AND CONCLUDING REMARKS

A series of new laboratory experiments were performed to test the usage of turbidity and acoustic backscatter intensity as surrogate estimates of the suspended sediment concentration (SSC). The experiments were conducted in laboratory under controlled conditions using water and soil samples collected in a small sub-tropical estuary of Eastern Australia. Indeed THEVENOT and KRAUS (1993) stressed that "field calibration is undesirable not only because of the difficult requirement of taking concurrent water samples, but also because of the time lag for the sample analysis". The new laboratory experiments were conducted with a microADV (16 MHz) system and a YSI™ 6600 probe using two types of sediment material. These were some fine mud collected on the creek bed and some slightly coarser material collected on the bank slope just below the high water mark. For the fine bed material, the experiments were repeated with the creek estuarine waters and with Brisbane tap waters.

The best fit relationships were established in terms of the suspended sediment concentration (SSC) as a function of the acoustic backscatter intensity (BSI), the SSC as a function of the turbidity, and the turbidity as a function of the acoustic backscatter intensity (Fig. 4 to 6). All relationships showed a monotonic increase. While the relationship between SSC and turbidity was linear, 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 quantitative calibration data showed a significant effect of the sediment material and of the water sample. The results demonstrated that the calibration of an acoustic Doppler system must be performed with the waters of the natural system (creek waters) and with some bed materials. Note also that the tests must be conducted within 72 hours after water collection to prevent some degradation of the water quality including biological and bio-chemical properties.

Importantly the calibration of the acoustic Doppler system is specific to the unit itself. Each ADV unit must be calibrated independently. Its calibration curve is a function of the water quality and sediment properties, but also of the intrinsic characteristics of the emitter and receivers. A limited comparison between an ADV (10 MHz) system and a newer microADV (16 MHz) showed some marked differences. The results suggested that the newer microADV (16 MHz) could detect significantly more counts per unit volume than the older unit.

The results were applied to two earlier field studies conducted for 50 hours each in Eprapah Creek with the same microADV system. The application yielded the instantaneous suspended sediment flux per unit area data at high frequency (25 and 50 Hz). The sediment flux data showed typically an upstream mass flux during the flood tide and a downstream sediment flux during the ebb tide. Some high-frequency fluctuations in masss 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 two tidal cycle of 24 h 50 min., the suspended sediment flux data were integrated with respect of time. The results yielded a net sediment mass transfer per unit area of -22 and -21 kg/m^2 during the first study conducted mid-estuary and or -6 and -2 kg/m^2 during the second study performed in the upper estuary. That is, the net sediment flux over a full tidal cycle was in average upstream, and it seemed little affected by some human activities in the creek.

It must be stressed that the present work highlighted a number of limitations. The present calibration might not be suitable for earlier 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. They would become invalid if the ADV unit is mishandled or becomes damaged. Lastly the present work was conducted for a subtropical estuary with relatively low turbidity levels. The maximum turbidity recorded during seven field studies was about 80 NTU and the present tests were conducted with turbidities up to 200 NTU. The results are not applicable to turbid flows with high suspended sediment concentrations.

6. ACKNOWLEDGMENTS

The writers thank Professor Shin-ichi AOKI (Toyohashi University of Technology) for his detailed review of the report and his valuable comments.
The writers acknowledge the strong support and assistance of John FERRIS (Qld E.P.A.).

APPENDIX A - EXPERIMENTAL DATA

A.1 PRESENTATION

The relationships between turbidity, acoustic backscatter amplitude/intensity and suspended sediment concentration were tested in laboratory under controlled conditions. The experiments were performed using waters collected in a small sub-tropical estuary (Eprapah Creek) and sediment samples collected on the creek bed and bank. Artificially-produced concentrations of suspended sediment were made and all the calibration experiments were conducted within 28 hours from sample collection. Table A-1 summarises the laboratory test conditions.

For each test, the mass of wet sediment was measured with a Sartorius™ Type 1518 (Serial 3506057) balance with an accuracy of less than 0.01 g. The mass concentration was calculated from the measured mass of wet sediment and the measured water volume.

During the laboratory tests, an optical turbidity meter and an acoustic Doppler velocimeter were scanned for 3 minutes per test. The velocimeter was a Sontek™ micro-ADV (16 MHz, serial number A641F) with a two-dimensional side-looking head with a distance to sampling volume of 5 cm. The ADV system was logged continuously at 50 Hz for 3 minutes for each test. Next to the ADV system, a physio-chemical probe YSI™ 6600 was installed and three readings were taken during the 3 minutes.

The basic probe outputs included the turbidity in NTU (YSI6600) and the average signal amplitude (in counts) for the ADV. The average amplitude represents the average signal strength of the two ADV receivers. It is measured in counts. The acoustic backscatter amplitude measurements were conducted using the same configuration employed in the field (pulse length, scan rate), but a lower velocity range (10 cm/s) was selected to minimise Doppler noise effects. The backscatter intensity was deduced from the average amplitude as :

$$\text{BSI} = 1\text{ E-5} * 10^{0.043 * \text{Ampl}} \qquad \text{(A-1)}$$

where the backscatter intensity BSI is dimensionless and the average amplitude Ampl is in counts. The coefficient 1 E-5 is a value introduced to avoid large values of backscatter intensity (e.g. NIKORA and GORING 2002).

Table A-1 - Summary of laboratory tests

Ref. (1)	Waters (2)	Sediment samples (3)	Water volume l	SSC range g/l (5)	Turbidity range NTU (6)	Remarks (7)
060711E	Water collection at Eprapah Creek, Site 2C		120	--	6.6-8.0	Date: 11 July 2006, early ebb tide (10:15am)
060711	Eprapah Creek	Sample 1 Eprapah Creek (Site 2B), bed material	40	0-0.71	7.2-150.4	Date: 11 July 2006 (Start: 14:12).
060712a	Eprapah Creek	Sample 1 Eprapah Creek (Site 2B), bed material	40	0-0.54	8.1-126.2	Date: 12 July 2006 (Start: 08:56).
060712b	Eprapah Creek	Sample 2 Eprapah Creek (d/s Site 2B), bank material	38	0-0.47	7.9-148.8	Date: 12 July 2006 (Start: 10:26).
060712c	Brisbane tap water	Sample 1 Eprapah Creek (Site 2B), bed material	40	0-0.78	0-186.3	Date: 12 July 2006 (Start: 13:00).

A.2 EXPERIMENTAL DATA

Location :	The University of Queensland (Australia)
Dates :	11-12 July 2006
Experiments by :	M. TAKEUCHI, M. TREVETHAN and H. CHANSON
Data processing by:	M. TAKEUCHI and H. CHANSON
Soil and water samples :	Water samples collected in the estuarine zone of Eprapah Creek at Site 2C on 11 July 2006 around 10:00-10:30 during the early ebb tide. Soil samples collected in the estuarine zone of Eprapah Creek at and next to Site 2B on 11 July 2006 around 11:00-11:30 during the early ebb tide.
Instrumentation :	Sontek™ micro-ADV (16 MHz, serial number A641F) with a two-dimensional side-looking head scanned at 50 Hz for 3 minutes for each test. YSI™ 6600 probe No. 4 provided by the Qld E.P.A.. A minimum of 3 readings were taken for each test and averaged.
Comments :	Water and soil sample collection on a sunny day. All the samples were kept in sealed, water tight containers until testing.

Physio-chemistry of the collected waters

Eprapah Creek waters were collected next to the free-surface using six 20 L containers. The physio-chemistry of each water container was measured on-site with the YSI 6600 probe.

Water bucket No.	Time (YSI)	Turbidity	Conductivity	Temperature	DO	pH
	hh:mm:ss	NTU	mS/cm	Celsius	% Sat	
1	10:16:16	7.6	33.09	18.74	93.9	7.44
2	10:17:58	6.6	33.25	18.66	89.4	7.42
3	10:18:58	7.3	33.32	18.55	88.6	7.42
4	10:19:42	7.7	33.23	18.62	90.5	7.41
5	10:20:55	7.4	33.44	18.41	88	7.41
6	10:24:24	8	33.39	18.65	90.6	7.42
Average:	--	7.43	33.29	18.61	90.17	7.42

Laboratory tests

YSI6600 probe measurements

Ref.	Test	Water sample	Water volume	Water bucket No.	Sediment sample	Sediment mass	SSC	Turbidity	Conductivity	Temperature	DO	pH
			L			g	g/L	NTU	mS/cm	Celsius	% Sat	
060711a	01	Eprapah Creek	40	1, 2, 3	Sample 1 bed material	0	0	7.25	33.32	19.26	96.10	7.52
060711a	02					0.875	0.0219	10.80	33.26	19.30	96.40	7.55
060711a	03					1.799	0.0450	14.57	33.25	19.30	96.43	7.56
060711a	04					4.238	0.1059	24.60	33.24	19.31	96.50	7.57
060711a	07					8.322	0.2081	45.92	33.24	19.31	96.58	7.59
060711a	05					14.497	0.3624	73.13	33.24	19.33	96.60	7.60
060711a	06					20.606	0.5152	109.30	33.24	19.34	96.70	7.61
060711a	08					28.385	0.7096	150.43	33.24	19.35	96.70	7.62
060712a	01	Eprapah Creek	40	3, 4, 5	Sample 1 bed material	0	0	8.07	33.20	17.16	95.13	7.62
060712a	02					0.105	0.00263	8.80	33.20	17.19	95.50	7.63

060712a	03					0.24	0.0060	9.70	33.21	17.20	96.00	7.64
060712a	04					0.492	0.0123	11.33	33.21	17.21	96.23	7.65
060712a	05					0.833	0.0208	13.67	33.22	17.22	96.60	7.67
060712a	06					1.331	0.0333	17.20	33.23	17.24	97.30	7.69
060712a	07					2.376	0.0594	22.67	33.24	17.26	97.47	7.70
060712a	08					4.098	0.10245	32.67	33.25	17.28	97.77	7.72
060712a	09					6.747	0.1687	46.77	33.26	17.31	98.00	7.73
060712a	10					12.527	0.3132	77.07	33.27	17.34	98.17	7.74
060712a	11					21.583	0.5396	126.20	33.28	17.37	99.33	7.74
060712b	02	Eprapah Creek	38	5,6	Sample 2 bank material	0	0	7.87	33.38	17.23	94.30	7.63
060712b	03		38	5,6		0.123	0.00324	8.93	33.40	17.26	94.63	7.64
060712b	04		38	5,6		0.413	0.01087	11.13	33.40	17.29	94.93	7.65
060712b	05		38	5,6		0.619	0.01630	12.50	33.41	17.31	95.30	7.66
060712b	06		38	5,6		0.934	0.0246	15.17	33.42	17.34	95.57	7.67
060712b	07		38	5,6		1.454	0.0383	19.30	33.42	17.37	95.95	7.68
060712b	08		38	5,6		2.61	0.0687	29.90	33.43	17.40	96.25	7.69
060712b	09		38	5,6		4.423	0.1164	44.58	33.44	17.44	96.78	7.70
060712b	10		38	5,6		7.527	0.1981	68.63	33.45	17.48	97.03	7.71
060712b	11		38	5,6		17.737	0.4668	148.78	33.46	17.53	97.40	7.71
060712c	01	Tap Water	40	--	Sample 1 Bed material	0	0	-0.53	0.45	17.57	89.40	7.66
060712c	02					0.063	0.00157	0.03	0.45	17.60	89.90	7.71
060712c	03					0.288	0.0072	1.20	0.45	17.63	90.43	7.74
060712c	04					0.782	0.01955	4.23	0.46	17.66	90.80	7.76
060712c	05					1.747	0.0437	10.17	0.46	17.70	91.33	7.78
060712c	06					3.505	0.0876	20.30	0.46	17.74	91.97	7.80
060712c	07					7.288	0.1822	40.97	0.46	17.81	92.83	7.84
060712c	08					15.4	0.385	87.43	0.47	17.86	93.53	7.86
060712c	09					23.156	0.5789	137.60	0.48	17.95	94.40	7.89
060712c	10					31.028	0.7757	186.27	0.48	17.99	94.90	7.91

2D microADV system measurements

Ref.	Test	Avg Ampl counts	Avg BSI Eq. (A-1)	Avg Correl %	Avg SNR dB	Std Ampl counts	Std BSI Eq. (A-1)	Std Correl %	Std SNR dB
060711a	01	86.53	0.065	85.66	23.88	6.02	0.068	8.65	2.59
060711a	02	100.67	0.294	84.05	30.18	7.07	0.423	11.90	3.04
060711a	03	105.73	0.441	81.73	32.35	6.05	0.454	13.89	2.60
060711a	04	113.55	0.911	83.57	35.71	5.51	0.744	12.13	2.37
060711a	07	121.07	1.882	84.22	38.95	5.17	1.475	11.81	2.22
060711a	05	128.22	3.690	81.47	42.02	4.77	2.200	12.48	2.05
060711a	06	134.62	6.977	81.46	44.77	4.89	4.113	12.83	2.10
060711a	08	140.48	12.207	69.77	47.29	4.52	6.429	17.84	1.94
060712a	01	88.10	0.072	80.71	24.34	5.36	0.056	13.05	2.31
060712a	02	91.81	0.112	77.12	25.94	6.25	0.116	15.11	2.69
060712a	03	94.87	0.153	72.97	27.25	6.35	0.179	16.54	2.73
060712a	04	98.02	0.215	71.32	28.61	6.42	0.298	16.84	2.76
060712a	05	101.98	0.313	71.14	30.31	6.33	0.390	17.24	2.72
060712a	06	105.78	0.443	70.26	31.94	6.02	0.485	16.97	2.59
060712a	07	110.07	0.651	71.63	33.79	5.51	0.608	17.08	2.37
060712a	08	115.26	1.058	68.92	36.01	5.16	0.814	17.45	2.22
060712a	09	121.20	1.925	66.47	38.57	5.32	1.660	17.75	2.29
060712a	10	129.32	4.263	70.18	42.06	5.38	2.979	17.82	2.32
060712a	11	136.22	8.195	72.20	45.03	4.91	4.938	16.86	2.11
060712b	02	86.40	0.064	81.33	23.82	6.08	0.061	10.12	2.61
060712b	03	100.48	0.239	82.83	29.88	4.87	0.162	9.43	2.09
060712b	04	108.59	0.509	82.01	33.37	3.92	0.259	10.33	1.68
060712b	05	109.60	0.563	81.93	33.80	3.83	0.361	10.28	1.65
060712b	06	114.03	0.867	83.44	35.70	3.70	0.484	9.87	1.59

060712b	07	116.82	1.163	83.53	36.90	4.05	0.741	9.95	1.74
060712b	08	121.19	1.765	85.08	38.78	3.87	0.855	8.74	1.66
060712b	09	129.49	4.073	83.05	42.35	4.14	2.294	9.97	1.78
060712b	10	136.18	7.896	84.94	45.23	4.23	4.016	9.61	1.82
060712b	11	143.81	15.975	82.17	48.51	3.01	5.099	9.99	1.29
060712c	01	57.25	0.009	75.60	11.50	13.21	0.031	13.60	5.68
060712c	02	68.99	0.024	84.49	16.55	12.87	0.063	9.32	5.53
060712c	03	80.09	0.052	80.87	21.32	10.64	0.124	11.82	4.58
060712c	04	93.73	0.152	69.99	27.19	7.99	0.192	16.96	3.43
060712c	05	102.90	0.325	71.71	31.13	5.96	0.274	16.44	2.56
060712c	06	109.61	0.616	74.40	34.02	5.44	0.561	15.03	2.34
060712c	07	121.17	1.997	78.89	38.98	5.98	1.858	12.28	2.57
060712c	08	131.86	5.414	77.97	43.59	5.21	3.561	12.40	2.24
060712c	09	135.50	7.727	74.26	45.15	5.16	4.850	13.53	2.22
060712c	10	138.29	10.615	75.20	46.35	8.16	5.891	13.86	3.51

Notes: 2D microADV data scanned at 50 Hz for 3 minutes; Ampl: acoustic backscatter amplitude (counts); Avg: time-averaged; Correl: correlation; SNR: signal to noise ratio; Std: standard deviation.

APPENDIX B - CORRELATIONS BETWEEN TURBIDITY, ACOUSTIC BACKSCATTER INTENSITY AND SUSPENDED SEDIMENT CONCENTRATION

B.1 LABORATORY TESTS

For the data sets reported in Appendix A, we tested systematically the relationships between turbidity, acoustic backscatter amplitude, acoustic backscatter intensity and suspended sediment concentrations (SSC) for turbidities ranging from 0 to 200 NTU. The best (most meaningful) correlations were established in terms of the turbidity versus SSC, acoustic backscatter intensity versus SSC, and acoustic backscatter intensity versus turbidity.

B.1.1 Best fit relationships

For the relationships between the turbidity and SSC, acoustic backscatter intensity and SSC, and acoustic backscatter intensity and turbidity, the best fit relationships are given below.

Relationship between suspended sediment concentration (SSC) and turbidity (Turb)

Water and sediment samples	Relationship	R
Eprapah Creek & Bed material sample 1	SSC = 0.00485 * Turb - 0.0350 $0 \le$ SSC ≤ 0.71 g/l, $7 \le$ Turb ≤ 151 NTU SSC in g/l and Turb in NTU	0.9951
Brisbane tap water & Bed material sample 1	SSC = 0.00419 * Turb + 0.00359 $0 \le$ SSC ≤ 0.78 g/l, $0 \le$ Turb ≤ 187 NTU SSC in g/l and Turb in NTU	0.9997

Water and sediment samples	Relationship	R
Eprapah Creek & Bed material sample 1	Turb = 204.315 * SSC + 7.548	0.9951
Brisbane tap water & Bed material sample 1	Turb = 238.70 * SSC -0.833	0.9997

Relationship between suspended sediment concentration (SSC) and acoustic backscatter intensity (BSI)

Water and sediment samples	Relationship	R
Eprapah Creek & Bed material sample 1	SSC = - 0.000714 + 0.0965 * BSI - 0.00323 * BSI^2 $0 \le$ SSC ≤ 0.71 g/l, $0.06 \le$ BSI ≤ 12.21 SSC in g/l	0.9955
Brisbane tap water & Bed material sample 1	SSC = 0.0108 + 0.0756 * BSI - 0.000360 * BSI^2 $0 \le$ SSC ≤ 0.78 g/l, $0.009 \le$ BSI ≤ 10.6 SSC in g/l	0.9983

Water and sediment samples	Relationship	R
Eprapah Creek & Bed material sample 1	BSI = 0.135 + 6.34 * SSC + 14.894 * SSC^2	0.9967
Brisbane tap water & Bed material sample 1	BSI = - 0.120 + 12.788 * SSC + 1.446 * SSC^2	0.9984

Notes : Relationships developed for the Sontek™ micro-ADV (16 MHz, serial number A641F) with two-dimensional side-looking head; BSI = 1E-5*$10^{0.043 \text{ * Ampl}}$; Ampl: average backscatter amplitude in counts.

Relationship between turbidity (Turb) and acoustic backscatter intensity (BSI)

Water and sediment samples	Relationship	R
Eprapah Creek & Bed material sample 1	$Turb = 6.952 + 20.189 * BSI - 0.699 * BSI^2$ $7 \le Turb \le 151$ NTU, $0.06 \le BSI \le 12.21$ Turbidity in NTU	0.9979
Brisbane tap water & Bed material sample 1	$Turb = 2.363 + 16.716 * BSI + 0.0558 * BSI^2$ $0 \le Turb \le 187$ NTU, $0.009 \le BSI \le 10.6$ Turbidity in NTU	0.9979

Water and sediment samples	Relationship	R
Eprapah Creek & Bed material sample 1	$BSI = -0.0695 + 0.0248 * Turb + 0.000362 * Turb^2$	0.9984
Brisbane tap water & Bed material sample 1	$BSI = -0.115 + 0.0580 * Turb + 0.00000138 * Turb^2$	0.9979

Notes : Relationships developed for the Sontek™ micro-ADV (16 MHz, serial number A641F) with two-dimensional side-looking head; $BSI = 1E\text{-}5*10^{0.043 * Ampl}$; Ampl: average backscatter amplitude in counts.

B.1.2 Practical relationships

The correlations presented in section B.1.1 are valid only within the range of the laboratory tests. In practice, the backscatter intensity may exceed these limits in the field. This could yield to meaningless estimates of the suspended sediment concentration SSC. For example, the above quadratic relationships for SSC and turbidity as functions of backscatter intensity were tested for the microADV data set obtained during the field work E6 at Eprapah Creek (Table 3). The results yielded "negative" suspended sediment concentration and turbidity estimates when the average backscatter amplitude exceeded 145 to 150 counts. Clearly these quadratic relationships should not be used outside of their range of validity, including for field work applications.

The writers developed some simpler relationships which increased monotonically with increasing backscatter intensity. Although these yielded slightly lower correlation coefficients, they were deemed more robust and they may be better suited to field study applications. For the relationships between the turbidity, SSC and acoustic backscatter intensity, the recommended relationships are listed below.

Relationship between suspended sediment concentration (SSC) and turbidity (Turb)

Water and sediment samples	Relationship	R
Eprapah Creek & Bed material sample 1	$SSC = 0.00485 * Turb - 0.0350$ $0 \le SSC \le 0.71$ g/l, $7 \le Turb \le 151$ NTU SSC in g/l and Turb in NTU	0.9951
Brisbane tap water & Bed material sample 1	$SSC = 0.00419 * Turb + 0.00359$ $0 \le SSC \le 0.78$ g/l, $0 \le Turb \le 187$ NTU SSC in g/l and Turb in NTU	0.9997

Relationship between suspended sediment concentration (SSC) and acoustic backscatter intensity (BSI)

Water and sediment samples	Relationship	R
Eprapah Creek & Bed material sample 1	SSC = 0.9426 * (1 - exp(-0.1109 * BSI)) $0 \le SSC \le 0.71$ g/l, $0.06 \le BSI \le 12.21$ SSC in g/l	0.9962
Brisbane tap water & Bed material sample 1	SSC = 3.7582 * (1 - exp(-0.02157* BSI)) $0 \le SSC \le 0.78$ g/l, $0.009 \le BSI \le 10.6$ SSC in g/l	0.9976

Notes : Relationships developed for the Sontek™ micro-ADV (16 MHz, serial number A641F) with two-dimensional side-looking head; BSI = 1E-5*$10^{0.043 * Ampl}$; Ampl: average backscatter amplitude in counts.

Relationship between turbidity (Turb) and acoustic backscatter intensity (BSI)

Water and sediment samples	Relationship	R
Eprapah Creek & Bed material sample 1	Turb = 171.06 * (1 - exp(-0.1593 * BSI)) $7 \le Turb \le 151$ NTU, $0.06 \le BSI \le 12.21$ Turbidity in NTU	0.9942
Brisbane tap water & Bed material sample 1	Turb = 1407.37 * (1 - exp(-0.013181 * BSI)) $0 \le Turb \le 187$ NTU, $0.009 \le BSI \le 10.6$ Turbidity in NTU	0.9973

Notes : Relationships developed for the Sontek™ micro-ADV (16 MHz, serial number A641F) with two-dimensional side-looking head; BSI = 1E-5*$10^{0.043 * Ampl}$; Ampl: average backscatter amplitude in counts.

B.2 FIELD STUDY E4

For one field study (E4), the Sontek™ 3D ADV (10 MHz, serial 0510) system and a YSI6600 probe were deployed side-by-side next to the river bed. The ADV and turbidity sampling volumes were 5 cm above the bed, and the data were logged at 25 and 0.33 Hz. Both the signal amplitude and turbidity data showed a turbid event for about 2 hours during the early flood tide. For that event, the signals were correlated.
Note that the ADV data set was post-processed using the technique of CHANSON et al. (2005) and the data were low-pass filtered at 0.33 Hz before the correlation calculations.

Relationship between turbidity (Turb) and acoustic backscatter intensity (BSI)

Water and sediment samples	Relationship	R
Eprapah Creek Field Study No. 4, early ebb tide	Turb = 11.433 + 10.462 * BSI - 0.5385 * BSI^2 $7.2 \le Turb \le 70$ NTU, $0.26 \le BSI \le 7.7$ Turbidity in NTU	0.9047
	BSI = 0.826 - 0.05046 * Turb + 0.00259 * $Turb^2$	0.951

Notes : Relationships developed for the Sontek™ ADV (10 MHz, serial 0510) with three-dimensional down-looking head; BSI = 1E-5*$10^{0.043 * Ampl}$; Ampl: average backscatter amplitude in counts.

B.3 FIELD STUDY E6

For the field study E6 (16-18 May 2005), the Sontek™ 3D ADV (10 MHz, serial 0510) system and a YSI6600 probe were deployed side-by-side at 0.4 m above the bed. The ADV and turbidity sampling volumes were 0.3 m apart horizontally, and the data were logged at 25 and 0.083 Hz respectively. For the entire field study, the signals were correlated. Note that the ADV and YSI6600 probe data sets were averaged at 0.1 Hz before the correlation calculations.

The results showed relatively lower correlations than during the field study E4 (paragraph B.2).

Relationship between turbidity (Turb) and acoustic backscatter intensity (BSI)

Water and sediment samples	Relationship	R
Eprapah Creek Field Study No. 6, 16-18 May 2005	Turb = 22.273 * (1 - exp(-0.788 * BSI)) $11 \le$ Turb ≤ 62 NTU, $0.4 \le$ BSI ≤ 5.8 Turbidity in NTU	0.801

Notes : Relationships developed for the Sontek™ ADV (10 MHz, serial 0510) with three-dimensional down-looking head; BSI = $1E\text{-}5 \cdot 10^{0.043 \cdot \text{Ampl}}$; Ampl: average backscatter amplitude in counts.

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