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Published

2006

Journal Title

Journal of Coastal Research

Journal of Coastal Research	SI 39	520 - 525	ICS 2004 (Proceedings)	Brazil	ISSN 0749-0208

Location of Turbidity Maxima Within a Microtidal Estuary and Some Limitations of Laser *In Situ* Particle Sizing

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ABSTRACT

HUNT, S.; LEMCKERT, C. J. and SCHACHT, C., 2006. Location of Turbidity Maximum Within a Microtidal Estuary and Some Limitations of Laser In Situ Particle Sizing. Journal of Coastal Research, SI 39 (Proceedings of the 8th International Coastal Symposium),520 - 525. Itajaí, SC, Brazil, ISSN 0749-0208.

A study of suspended sediment concentration properties has been undertaken in a predominately microtidal estuary using an *in situ* profiling instrument package comprising a LISST-100 particle sizer and SeaBird CTD. This novel instrumentation arrangement permitted the simultaneous sampling of temperature, conductivity, pressure, transmissiometry and particle volume concentration (as a function of particle size) during profiling operations. The estuary was found to have two types of turbidity maxima. The first was associated with bottom resuspension, its vertical extend being inhibited by water column stratification. The second was associated with inflow, which was found to have high concentrations of fine particles whose concentration increased with inflow rate. The particles were observed to flocculate rapidly when the salinity of the inflow water reached about 5 $^0/_{00}$. The location of the 5 $^0/_{00}$ isohaline was found to be a power law function of the inflow rate, indicating that microtidal estuaries can be readily dominated by inflow water properties. The results from the study also showed that stratification could significantly influence the LASER derived results, and therefore care must be taken when using devices like the LISST-100 in stratified environments.

ADDITIONAL INDEX WORDS: *Flocculation, LISST-100.*

INTRODUCTION

Turbidity maxima (TM) are regions of elevated suspended sediment concentration within estuarine systems. TMs are significant as they can strongly influence chemical, physical and biological processes, including reduction of primary production by lowering sub-surface light levels (CLOERN, 1987), enhancement of navigation channel sedimentation (JOHANNESSON *et al.*, 2000), and movement of sediment attached pollutants resulting from adsorption (LEVASSEUR, *et al.* 2000) and flocculation (CALIANI *et al.*, 1997).

Within microtidal estuaries TM suspended sediment concentrations during non-flood events are significantly less than levels found in macrotidal and mesotidal estuaries (eg MONBET, 1982 and HUGHES *et al.*, 1998). In microtidal estuaries fluvial input properties, flocculation and wind induced resuspension play a significant role in determining the suspended concentration levels, and the location and behaviour of any TM (eg ALTHAUSEN and KJERFVE, 1992, SONDI, *et al.*, 1995, BOOTH *et al.*, 2000 and HUNT and LEMCKERT, 2000). HUGHES *et al.* (1998) found that gravitational circulation and tidal asymmetry (which are significant controlling mechanisms in larger tidal range estuaries) did not satisfactorily explain the position of the TM within the microtidal Hawksbery River estuary, Australia. Instead, the relatively fixed location of the TM during low flow events appeared to be the result of an erosion-lag process (favouring up-estuary suspended sediment transport), combined with a local divergence in tidal velocity residuals (favouring down-estuary suspended sediment transport). However, the suggested TM fixing mechanism required further investigation and validation.

While there have been numerous studies on suspended sediment behaviour within coastal waters and TM, a lack of suitable sampling equipment has meant that a relatively limited number of studies have investigated the distribution patterns of particle sizes and volume concentrations. This information is important as it can reveal critical details on processes such as flocculation/deflocculation and bed deposition/resuspension. Work reported to date in this area using rapid-sampling LASER based devices and labour-intensive slow-sampling video devices reveals a complex interaction between particle size, particle concentration, turbidity and estuarine dynamics (eg VAN DER LEE, 2000). LAW *et al.*, (1997) used a Par-tec 100 (Lasentec Inc.) *in situ* focused laser reflectance particle-sizing instrument to measure the chord length of particles (range 2-1000 mm) in 38 logarithmically distributed size intervals. The instrument was deployed in the macrotidal Humber Estuary, UK, by suspending it at depths (1 m intervals) for periods of 2-5 min. It was found that particle size varied as a function of time and space. The largest median particle diameters were observed during the highest flow periods, while the smallest median diameters were found during slack water times; thus indicating that resuspension was a dominant particle suspending mechanism. Significantly, they also found that when *in situ* measurements were compared with laboratory derived measurements of the same water samples, the former recorded significantly higher mean particle size values. It is likely this is due to the collection process having generated shear flows capable of inducing aggregate dissociation; implying the necessity of conducting *in situ* measurements if particle size distributions are to be correctly analysed and interpreted.

This paper presents the results of a field program that investigated both the particle size distribution and volume concentration of suspended sediment within a predominately partially mixed subtropical estuary that was subjected to a range of fresh water inflow conditions.

METHODOLOGY

The study area chosen for this investigation was the microtidal Coomera River estuary, Queensland, Australia (see Figure 1). This estuary has previously been subjected to very little scientific study, despite its location within a region of rapid

Figure 1. Location map of Coomera River, Queensland, Australia, with the surveying sites marked by the solid squares. The location of the tidal limit (square box) shows corresponds to the position of a rock weir.

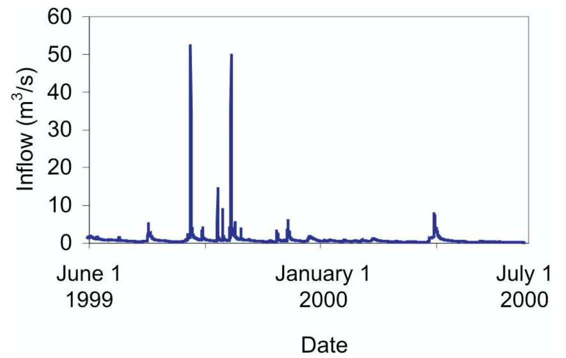

Figure 2. Average monthly inflow rates from June 1999 to July 2000.

urbanisation and light commercial growth. The estuarine component of the river is 18.95km with an average depth of 4 m and a 1.7 m spring tidal range. The estuary forms the lower reaches of the Coomera River, which has a catchment area of 430 km^2. The downstream end of the estuary opens into a large bay that has free exchange with the open ocean, while a low rock weir sets the upstream limit.

From June 1999 to July 2000 (the study period), the mean monthly freshwater flow rates into the river via the low rock weir ranged between 0.99 and 2.2 m3/s, while daily peak values reached 50 m^3/s (see Figure 2). Stratification within the estuary was dominated by salinity variations with temperature effects playing a minor role. Suspended sediment concentrations are usually < 72 mg/l, with an estuary average value O(10) mg/l. As a consequence of the microtidal range some degree of vertical stratification persists throughout the upper reaches of the estuary, even under very low inflow rate conditions (HUNT and LEMCKERT, 2000).

In an effort to develop an understanding of particle distribution patterns within the estuary, sampling was carried out *in situ* as withdrawing samples (for analysis in a laboratory) could result in aggregate destruction and additional flocculation/deflocculation. While a number of devices exist for *in situ* measurements (eg THOMSEN *et al.,* 1996 and LAW *et al.*, 1997 and VAN DER LEE, 2000), this study used a Sequoia Scientific Laser *In Situ* Scattering and Transmissiometry device (LISST-100) to measure profiles of suspended sediment concentrations as a function of particle size. Briefly, the LISST-100 directly measures the angular distribution of forward scattered light energy resulting from the projection of a laser over a 5 cm path length. The light energy is detected by a 32 ring detector, with the results converted to volume concentration as a function of particle size (32 logarithmically distributed bin sizes in the range 1.25-250 mm), using an inverse transformation program supplied by the manufacturer. The total amount of non-scattered transmitted light is detected by a photodiode set directly in line with the transmitted laser (ie a measure of light transmission). Further details of the LISST-100 and its performance are detailed in TRAYKOVSKI *et al.*, (1999), who used an earlier model with a smaller particle size class range, and in AGRAWAL and POTTSMITH (2000).

The LISST-100 was cradled in a support frame to enable it to be readily profiled through the water column. Attached to the LISST-100 was a Seabird SBE-37SI conductivity, temperature and depth (CTD) serial interface sensor. The CTD sensor records conductivity in the range 0-7 S/m with an initial accuracy of 0.0003 S/m and resolution of 0.00001 S/m, temperature in the range -5 to 35 °C with an initial accuracy of 0.002 °C and resolution of 0.0001 °C, and depth in the range 0-100 m with an initial accuracy of 0.1 m and resolution of 2 mm. Signals from the CTD were logged internally by the LISST-100, thus ensuring synchronisation of the particle size distribution and CTD data. Salinity and subsequently density were determined from the equations of state for standard seawater.

During each survey the LISST-100/CTD package was lowered at a typical speed of 0.1 m/s with data recorded at 0.5 Hz, with profiling operations performed at 16 sites along the estuary (see Figure 1), with a complete river transect taking less

Table 1. *Summary of the experimental conditions. Dashed line indicates the* $5\,^0/_{00}$ *was located upstream of sampling locations.*

Experiment Date	Tidal Range (m)	$5\,^0/_{00}$ Distance from Mouth (km)	Q (m^3/s) 4 day average
10/08/1999	1.15	18.7	0.61
24/08/1999	0.85	-	0.36
31/08/1999	1.15	17.6	2.09
7/09/1999	1	17.5	0.84
14/09/1999	0.98	18.9	0.58
21/09/1999	0.67	-	0.37
28/09/1999	1.45	-	0.38
5/10/1999	1.24	13.8	3.6
12/10/1999	1.21	17.2	1.2
19/10/1999	0.83	16.8	1.4
10/11/1999	1.31	15	5.9
16/11/1999	0.81	17.3	1.6
23/11/1999	1.71	17.8	0.80
2/02/2000	0.7	-	0.60
14/03/2000	0.57	17.8	0.96
5/04/2000	1.51	-	0.30
2/06/2000	1.33	-	0.31

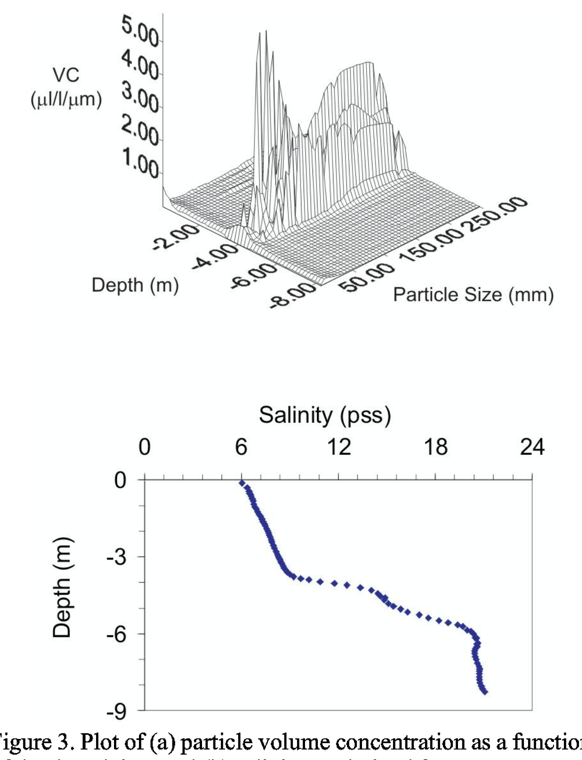

Figure 3. Plot of (a) particle volume concentration as a function of depth and time and (b) salinity, as derived from a LISST-100 cast performed at 1346 on 31/8/1999.

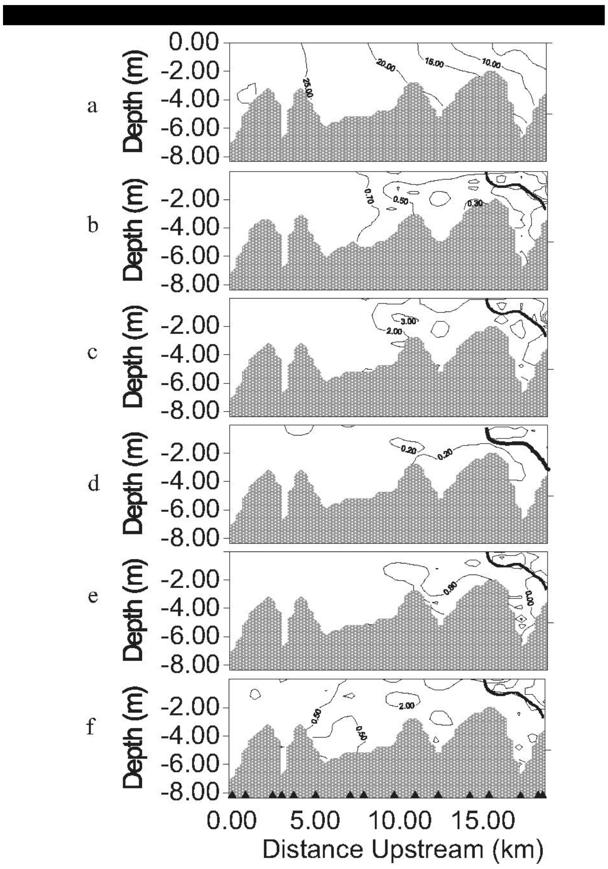

Figure 4. Contour plots of (a) salinity in $^0/_{00}$, (b) transmission in arbitrary units, (c) log [total [VC] ?l/l], (d) log [5 ?m [VC] ?l/l], (e) log [50 ?m [VC] ?l/l] and (f) log [230 ?m [VC] ?l/l] for data collected by the LISST-100 on 19/10/1999 during the ebb tide. Black triangles indicate study site locations. Bold contour indicates $5^0/_{00}$ position.(c).

than 2 hours and biased towards the tidal cycle so that during a flood tide sampling commenced at the mouth, while for an ebbing tide sampling commenced at the upper reach. Due to shallow water, the uppermost sampling site was restricted to 100 m downstream from the rock weir.

An example of the data derived from the LISST-100/CTD package is presented in Figure 3. The data were collected at 17 km upstream on 31/8/1999 at 1346 hrs. Figure 3.a. is a wire frame 3d plot of particle size Volume Concentration [VC] presented as a function of particle size and depth. It is important to note that in order to obtain total volume concentration for a particular depth one merely integrates the [VC] spectrum. Figure 3.a. shows how the [VC] changes significantly with both depth and particle size, with the largest particles associated with the strong salinity gradient observed at 4 m (Figure 3.b). It is evident that by using the lisst-100 in this innovative profiling manner (since all reported sampling with these devices has been conducted on fixed frames) one can gain a wealth of information pertaining to the structure of an estuarine water column.

RESULTS

Figures 4, 5 and 6 present some of the results derived from inflow rates of respectively increasing magnitude into the microtidal Coomera River estuary. The salinity contours (Figures 4.a, 5.a. and 6.a) reveal that the estuary was partially stratified with a gradual increase in salinity with depth and distance upstream. A deep hole within the estuary at 17 km upstream remained vertically stratified under all conditions studied. Data presented in Figure 6.a show the result of collecting data near the bottom of the tide. Here the isohalines have been stretched out along the surface. When data were collected near the top of the tide (as presented in Figure 5.a), the isohalines were compressed upstream as ocean water moved into the system.

Uncalibrated transmission measurements derived from the LISST-100 are presented in Figure 4.b., 5.b. and 6.b. While it is

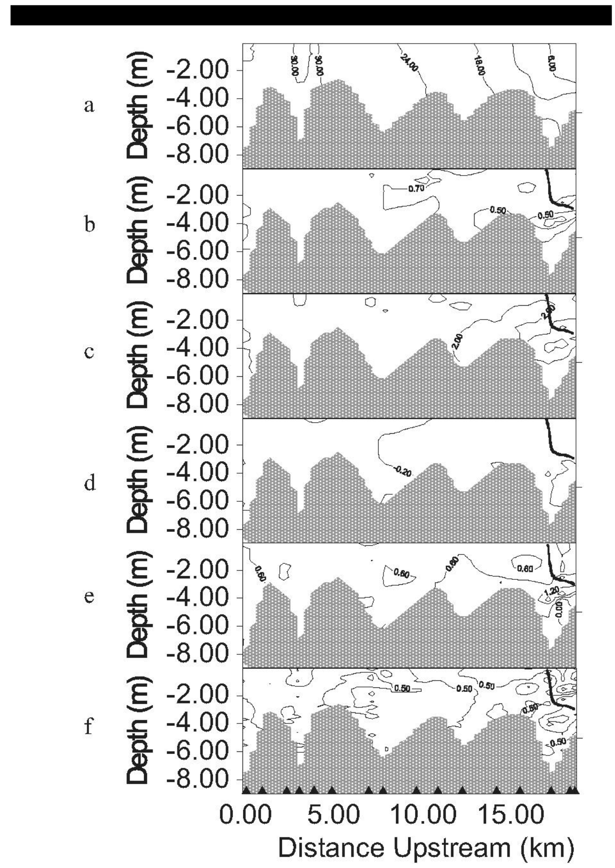

Figure 5. Same as Figure 4 but data collected on 31/8/1999 during the ebb tide.

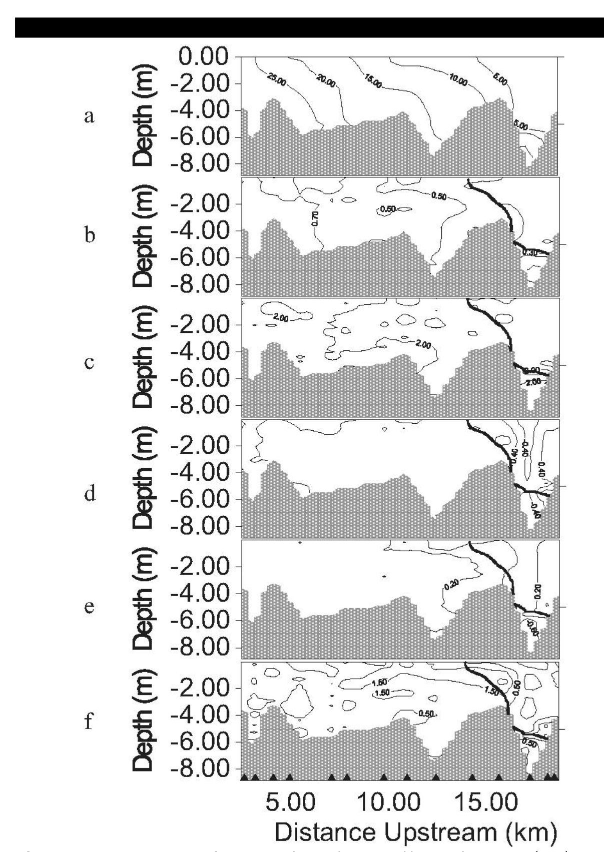

Figure 6. Same as Figure 4 but data collected on 10/11/1999 during the ebb tide.

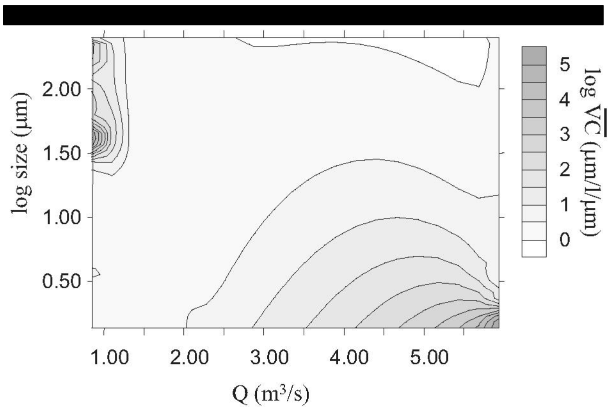

Figure 7. Contour plot of [[VC]] (with each particle size averaged over the entire depth) as a function of inflow rate and log (particle size) as derived from data collected 100 m from the tidal limiting weir when the salinity < $1\,^0/_{00}$.

recognised that transmission signals do not necessarily relate to suspended sediment concentrations (eg Jago and Bull, 2000) they are a measure of relative turbidity, and therefore important in characterising estuarine properties. In Figure 4.b the transmission patterns encountered during a low inflow period are presented. On this day, the inflow water had high transmission levels, which rapidly dropped around the $5\,^0/_{00}$ region. The low transmission levels observed at mid depth around 10 km appears to be an isolated patch whose source and properties are unknown. When the 5 mm [VC] contours (Figure 4.d) are compared to the transmission levels there is a strong relationship, while this is significantly reduced when the larger 230 mm are examined (Figure 4.e). The total [VC] levels were generally opposite to the transmission levels (Figure 4.c); these results indicate that while larger particles may add more readily to the measured [VC], smaller particles have a greater influence in decreasing light transmission. This is particularly evident near the bed at approximately 15 km where there were low [VC] levels for the larger particles. Note that the 5 mm and 230 mm particle size ranges were chosen for presentation as they are representative size classes for the primary particles and expected floc sizes, respectively.

As the inflow rate into the estuary increased inflow transmission levels decreased (see Figure 5.b) with the total [VC] remaining relatively constant along the estuary (Figure 5.c). As was the case for the low inflow rate event there was a zone of decreased transmission levels near the bed at 15 km. Once again this was associated with high levels of small particles, but in this instance increased levels of larger particles were also observed.

The properties of a relatively high flow rate event are presented in Figure 6. The inflow water now had very low transmission levels (Figure 6.b) and high 5 mm [VC]'s (Figure 6.d), with a distinct change in properties near the $5\,^0/_{00}$ isohaline. Here the [VC] of 5 mm particles decreases dramatically even though the overall volume concentration changes little (Figure 6.c). For this particular inflow rate the LISST-100 was unable to determine [VC]'s at the deep hole (located 17 km upstream) between 5.3 and 5.6 m. To compensate for this in the development of the contour plots the values in this region were set to that of adjacent recorded values before contouring was performed.

DISCUSSION

An important zone within many estuarine systems is the region corresponding closely to the $5\,^0/_{00}$ isohaline, as this marks the zone of most likely and significant flocculation (DYER, 1986). As observed in Figures 4, 5 and 6 the location of the $5\,^0/_{00}$ isohaline was influenced by the inflow rate. Past studies of estuarine systems have found that position of the $5\,^0/_{00}$ isohaline may be predicted using a variety of relationships between inflow and ambient estuarine properties. (see the discussions of KURUP *et al.*, 1998 and UNCLES *et al.*, 1998). For a microtidal estuary KURUP *et al.* (1998) found that the location of the $5\,^0/_{00}$ isohaline could be predicted using the simple relation:

$$X = aQ^b \qquad (01)$$

where X is the surface position of the $5\,^0/_{00}$ isohaline along the estuary, Q is the inflow rate and a and b are estuary specific constants. For a 30 km section of the microtidal Swan River Estuary, Australia, KURUP *et al.* (1998) found a correlation coefficient of 0.86 when the flow rate was averaged over 7 preceding days. The high correlation coefficient shows that the freshwater inflow rate was the dominant mechanism controlling the position of the $5\,^0/_{00}$ isohaline, with tidal motions having a significantly reduced influence. For the 140 km macrotidal Humber Estuary, UK, UNCLES *et al.* (1998) found Eq.1 also applied when the flow rate was averaged over the preceding 31 days, but there was increased variance due to the increased and certainly expected importance of tidal flows.

For the 18.95 km long microtidal Coomera River estuary the values of a and b in Eq. 1 (using simple regression analysis) were found to be 1.38 and 0.86 respectively, with a correlation coefficient of 0.72 (n=11), when the flow rate was averaged over the 4 days preceding the survey event. This averaging period was found to give the best correlation. The $5\,^0/_{00}$ isohaline was observed up to 5 km from the tidal limit, which is a significant distance in terms of the total estuarine length. Combining this outcome with those mentioned above indicates that the shorter the estuary and the smaller the tidal range the greater the impact the freshwater inflow rate has on the $5\,^0/_{00}$ location within microtidal estuaries. It is also interesting to note that since the yearly averaged inflow rate into the estuary is 1.8 m3/s the dominant location of he $5\,^0/_{00}$ line will be approximately 16.7 km, which corresponds closely to the deep hole.

A persistent bottom TM, whose vertical extent reached up to 2 m from the bed, was found to exist 15 km upstream. The suspended matter within this TM (as depicted in Figures 4, 5 and 6) was generally dominated by smaller particles, with larger ones being significantly less prevalent. Since the TM is located in a region of high salinity (> $15\,^0/_{00}$) the aggregation of primary particles into flocs would not have been favoured (DYER, 1986). The persistence of this TM indicates that the zone had sufficiently high velocity shears to resuspend settled sediment, with the high levels of salinity, and hence density, stratification limiting the vertical extent over which the sediment could be transported.

The second region of persistent high turbidity levels was found to extend over the length of the freshwater inflow. Figures 4, 5 and 6 show how the levels of turbidity dramatically decrease when, due to the freshwater inflow being diluted with the estuarine salt water, the salinity reaches levels of approximately $5\,^0/_{00}$. The river water was observed to carry high levels of small particles, with the [VC] of smaller particles dramatically rising as the inflow rate increased (see Figure 7). The rapid loss of these small particles and the significant rise of

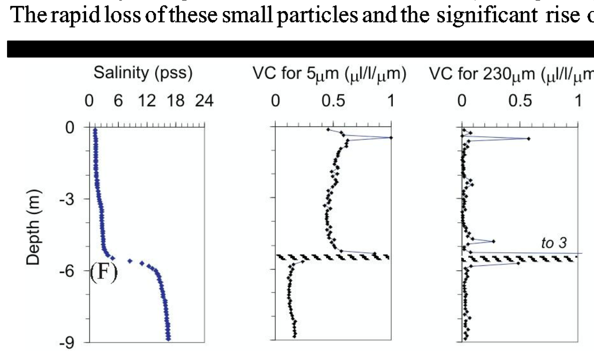

Figure 8. Plot of (a) salinity, (b) [[VC]] for 5µm, and (c) [[VC]] for 230µm for data collected on 10/11/1999 at 1118 hrs at 17 km (deep hole). NB the shaded region indicates unresolved signal.

larger particles in the vicinity of the 5 $^0/_{00}$ isohaline indicates that significant flocculation occurred quickly. This observation agrees with the findings of EISMA (1986), ALTHAUSEN and KJERFVE (1992) and SONDI *et al.* (1995), who all found that small primary particles could rapidly undergo salt induced flocculation under favourable conditions. Typically, such conditions prevail when salinity levels are around 5-8 $^0/_{00}$ and where turbulent intensities are low to avoid significant shear-induced aggregate destruction. The gradual loss of suspended material matter with downstream distance indicates that material was settling on the bed throughout the estuary as the freshwater inflow progressed downstream.

As a direct consequence of the rapid removal of small particles by flocculation was that the levels of transmission (and hence turbidity) also decreased rapidly downstream from the 5$^0/_{00}$ isohaline. The second TM was therefore found to extend over the length of the inflows; indicating that it is more appropriate to refer to this salinity-limited turbid inflow as a Turbidity Maxima Front (hereinafter referred to as a TMF). Eq.1 also predicts the position of the TMF, since the TMF corresponds to the location of the 5 $^0/_{00}$ isohaline. That is, the typical place of the TMF will be approximately 16.7 km upstream, which corresponds to the deep hole. Since flocculated particles settle faster than their primary components, the bed of the deep hole should be covered in high levels of fine sediment. This indeed was found to be the case.

During the high inflow rate event recorded on 11/10/1999, the deep hole at 17 km upstream was found to experience large changes in water properties (see Figures 6 and 7). When the LISST/CTD package was lowered through the water column analysis of the recorded data revealed that between 5.3 and 5.6 m the Laser system gave no data, indicating that either the water was either exceedingly turbid resulting in light blocking, or the observed high water density gradients induced significantly high diffraction resulting in the laser missing it target sensor. While no independent data were available to clarify the issue of high concentration levels, some qualitative laboratory tests were conducted to see if high-density gradients could strongly influence the LISST laser beam. The tests involved lowering the LISST through a laboratory tank set up with a stably stratified two-layer system (salt water layer on the bottom and a fresh water layer on top) and recording the transmission data. The tests revealed that under extreme stratification conditions transmission levels readily reduced, but that under non-extreme conditions levels were unaffected. From the laboratory data this limit appeared to correspond to a buoyancy frequency (=g/?(d?/dz), where g is the acceleration due to gravity, ? is the water density and z is depth) = 0.6 sec^{-1}, while the field data suggests a level = 0.3 sec^{-1}, thus indicating (as would be expected) the level depends upon the orientation of the LASER beam relative to the stratification surface. This aspect requires further quantitative study in order to ensure the LISST particle size data is correctly interpreted. It is important to note that the buoyancy frequencies observed in the field data (except that near the strong level of stratification observed in Figure 8) were less than the critical level = 0.3 sec^{-1}.

To explain the lack of particles in the deep hole under strong stratification conditions it is necessary to consider the hydrodynamics occurring at the salinity (and hence density) interface. Under low flow rate conditions the salinity of the estuary gradually increases and more saline water moves up estuary. When the river flow rate increases, fresh water will flow into the estuary and over the more dense salty water. If the inflow rate has relatively low energy it will be unable to purge saltier water from deep holes (DEBBLER and ARMFIELD, 1997). Subsequently, a zone of high stratification will develop that separates relatively stationary dense bottom water from a less dense surface overflow; this was the case for the hole at 17 km. For this hole on the high inflow rate day, salinity conditions were such that flocculation was favoured at the interface (see Figure 6 and 7). The lack of small particles below the interface can be attributed to the process known as interface sharpening (see DEBBLER and ARMFIELD, 1997). That is, even though flocs were formed at the interface the rapid entrainment of hole-fluid into the turbulent surface overflow stripped away the newly formed flocs and advected them downstream before they had time to fall down through the interface and into the deeper water. The effect of stratification at the 17 km hole had the additional property of protecting the bottom sediments from high shear flows, as it effectively isolated the denser water within the hole from the overflow. However, when flow is sustained for long enough, or flow rate is sufficiently high, all the dense water will be flushed out and the bottom sediments exposed to high shear, which in turn will flush them out as well.

CONCLUSIONS

The microtidal Coomera River estuary, which was dominated by partially stratified conditions, was studied over a one-year period, with a variety of inflow conditions examined. The estuary was found to have two distinct zones of enhanced turbidity. One TM was located adjacent to the bed at 15 km, and was found to extend up to 2 m in the vertical and 1 km in the horizontal. The vertical extent appeared to be limited by water column stratification with the resuspended/unsettled matter dominated by finer material when compared to the adjacent waters. The second TM, here referred to as a TMF, is associated with the turbid freshwater inflow, and extends from the tidal limiting weir to the 5$^0/_{00}$ isohaline region. At this point, rapid flocculation of fine suspended material was observed to occur, which in turn increased turbidity levels.

The location of the 5 $^0/_{00}$ isohaline, and hence the position of the TMF, were found to be a simple power law function of the averaged freshwater inflow rate. In keeping with KURUP *et al.* (1998), this result indicates that the position of the 5 $^0/_{00}$ isohaline, the location of the TMF and the highest levels of expected flocculation activity within microtidal estuaries could be readily dominated by the inflow rate. This information can now be used in the development of management plans for the Coomera River estuary and similar microtidal regions as we now have a tool for predicting the extent the turbid inflow material moves into the estuary before if flocs and settles.

An additional and highly significant outcome of the study was the observed limitations of *in situ* measurements of particle size distribution using LASER type systems. It was found that strong stratification could significantly influence the results, and therefore care must be taken when using devices like the LISST-100 in stratified environments. A simple measure that could be used to determine if transmission derived data were corrupted by stratification may be to simultaneously record an independent measure of particle concentration (eg. nephelometry) and if the transmission signals varied greatly from the independent measure than the particle size data may be considered suspect. Alternatively, but significantly more difficult, would be to record actual diffraction and eliminate data that does not satisfy yet to be determined conditions.

ACKNOWLEDGEMENTS

The authors would like to thank the school of engineering for their continued support for this project. The third author is presently supported by a phd scholarship from the cooperative research centre for coastal zone, estuary and waterway management.

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