A novel method for sampling the suspended sediment load in the tidal environment using bi-directional time-integrated mass-flux sediment (TIMS) samplers

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ARTICLE INFO

Article history:
Received 2 January 2017
Received in revised form
13 June 2017
Accepted 18 August 2017
Available online 6 September 2017

Keywords:
Sediment samplers
Sediment traps
Sediment analysis
Estuarine dynamics
Suspended sediment load
Core sound
North Carolina

ABSTRACT

Identifying the source and abundance of sediment transported within tidal creeks is essential for studying the connectivity between coastal watersheds and estuaries. The fine-grained suspended sediment load (SSL) makes up a substantial portion of the total sediment load carried within an estuarine system and efficient sampling of the SSL is critical to our understanding of nutrient and contaminant transport, anthropogenic influence, and the effects of climate. Unfortunately, traditional methods of sampling the SSL, including instantaneous measurements and automatic samplers, can be labor intensive, expensive and often yield insufficient mass for comprehensive geochemical analysis. In estuaries this issue is even more pronounced due to bi-directional tidal flow. This study tests the efficacy of a time-integrated mass sediment sampler (TIMS) design, originally developed for uni-directional flow within the fluvial environment, modified in this work for implementation the tidal environment under bi-directional flow conditions. Our new TIMS design utilizes an 'L' shaped outflow tube to prevent backflow, and when deployed in mirrored pairs, each sampler collects sediment uniquely in one direction of tidal flow. Laboratory flume experiments using dye and particle image velocimetry (PIV) were used to characterize the flow within the sampler, specifically, to quantify the settling velocities and identify stagnation points. Further laboratory tests of sediment indicate that bidirectional TIMS capture up to 96% of incoming SSL across a range of flow velocities (0.3–0.6 m s^{-1}). The modified TIMS design was tested in the field at two distinct sampling locations within the tidal zone. Single-time point suspended sediment samples were collected at high and low tide and compared to time-integrated suspended sediment samples collected by the bi-directional TIMS over the same four-day period. Particle-size composition from the bi-directional TIMS were representative of the array of single time point samples, but yielded greater mass, representative of flow and sediment-concentration conditions at the site throughout the deployment period. This work proves the efficacy of the modified bi-directional TIMS design, offering a novel tool for collection of suspended sediment in the tidally-dominated portion of the watershed.

1. Introduction

Coastal watersheds and estuaries directly connect terrestrial and oceanic environments with fine-grained (<62.5 μm) sediment dominating the material transported within these systems (Frank, 1981; Meybeck, 1984; Allan, 1986; Walling, 1989; Ludwig and Probst, 1998; Bianchi and Mead, 2009). The fine-grained

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Abbreviations: TIMS, Time Integrated Mass Sediment sampler; SSL, Suspended Sediment Load; OD, Outer Diameter; ID, Internal Diameter; PIV, Particle Image Velocimetry; PVC, polyvinylchloride (PVC); PS, Point Sample; SS, Sediment Sampler.

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https://doi.org/10.1016/j.ecss.2017.08.029

suspended sediment load (SSL) directly influences coastline evolution (Syvitski et al., 2005), habitat maintenance and development (Fagherazzi et al., 2012), and ecological health within the estuary and coastal habitats (Syvitski et al., 2005). Nutrient and contaminant transport have been shown to be intimately tied to the sediment flux (Smith et al., 2001; Syvitski et al., 2005), as trace elements bind to the SSL while in transport within the aquatic environment (Correll et al., 1992; Turner and Millward, 2002; Kronvang et al., 2003; Jha et al., 2007; Horowitz et al., 2008). Anthropogenic influence through land-use modification, urbanization and industrialization have significantly modified sediment, nutrient and contaminant load to rivers and coastal environments (Syvitski et al., 2005). Sediment-associated heavy metals within river and estuarine environments, often from anthropogenic sources, account for a significant portion (at times >90%) of the overall metal load (Martin and Meybeck, 1979; Cheung et al., 2003; Audrey et al., 2004). Additionally, global climate change and sea-level rise are thought to further impact the overall SSL within the watershed and estuary (Walling and Webb, 1996; Walling and Fang, 2003; Kirwan et al., 2010). These findings highlight the importance of quantifying the source and abundance of the SSL within the coastal watershed. Representative samples of SSL are critical in the quantification of geochemical fluxes and water quality within the watershed, specifically with sufficient mass of sediment for analysis of particle size composition, organic matter and carbon content, isotopic and geochemical concentrations, and nutrient and contaminant abundance (Smith and Owens, 2014). Manual sampling techniques of the SSL, while the traditional standard for accuracy relative to automated and indirect approaches (Wren et al., 2000), can be time and labor intensive, especially when attempting to capture SSL during an event. Given the episodic nature of SSL transport, it is difficult to obtain high temporal resolution sampling and capture infrequent high-magnitude events when using manual sampling alone (Grieve, 1984; Cuffney and Wallace, 1988; Ongley, 1992; Keesstra et al., 2009; Perks et al., 2014). Automated samplers, including rising and falling limb bottle samplers (Frank, 1981) and pump/vacuum operated equipment (e.g., Russell et al., 2000), while less time and labor intensive, are expensive and cannot be deployed in areas where inundation is likely, which prevents large-scale deployment within the watershed and system-wide characterization of SSL. With both sampling techniques, mass of sediment is generally insufficient to conduct geochemical analyses except from integrated samples or samples of high-magnitude runoff events.

An innovative solution for the collection of suspended sediment transported in small, lowland river catchments was first proposed by Phillips et al. (2000). The Phillips et al. (2000) time integrated mass sediment (TIMS) sampler was designed to trap sediment through the principles of sedimentation, with the ability to collect representative suspended sediment samples over the sampling period with enough sample mass for assessment of the physical, geochemical and magnetic properties of the sediment (Phillips et al., 2000; Russell et al., 2000; Smith and Owens, 2014; Perks et al., 2014). Given the sampler's ability to constantly sample suspended sediment over a range of flow conditions, a continuous multi-event record of the suspended sediment flux can be obtained from a single deployment (Phillips et al., 2000; Russell et al., 2000; Walling, 2005; Perks et al., 2014). Due to its cost-effective simple design and construction, with relatively little maintenance and no power requirement upon deployment, the TIMS sampler has been implemented around the world in a variety of fluvial environments (e.g. Ankers et al., 2003; Laubel et al., 2003; Evans et al., 2006; Fox and Papanicolaou, 2007, 2008; McDowell and Wilcock, 2007; Walling et al., 2008; Poulenard et al., 2009; Fukuyama et al., 2010; Collins et al., 2010; Wilson et al., 2012; Owens et al., 2012; Voli et al., 2013; Smith and Owens, 2014), with modifications for optimal operation within higher energy systems (e.g., enlargement of the collector and/or inflow tube; McDonald et al., 2010; Perks et al., 2014).

In this paper, we describe modifications to the original Phillips et al. (2000) design which allows for the collection of SSL in a bi-directional flow regime, typical of a tidal environment. Where possible, laboratory and field assessment were replicated from the work of Phillips et al. (2000) for comparison to the original sampler function and efficiency. The objective of this work was to 1) characterize the flow and quantify theoretical particle settle velocities within the TIMS sampler, 2) test the efficiency of the modified design to collect and trap suspended sediment, and 3) test the efficiency of the modified design within the intertidal environment relative to traditional sampling techniques. To address our first objective, laboratory analysis utilizing dye-flume and particle image velocimetry (PIV) allowed for the characterization of flow and quantification of particle settling potential within the sampler. Further laboratory analysis after Phillips et al. (2000), utilizing chemically dispersed sediments pumped through the sampler, tested the trapping efficiency of the modified design. Finally, field testing was conducted under natural conditions within tidal creeks in two distinct locations, utilizing both the modified TIMS design and traditional manual single time point sampling. Particle-size composition and overall mass of sediment samples from the modified TIMS design and the single time point samples were compared to assess the benefits and deficits of the TIMS sampling technique for implementation within the tidal environment relative to traditional sampling methods.

2. Methods

2.1. Sampler design and modifications

The Phillips sampler was designed to continuously trap suspended sediment load in environments with uni-directional flow (e.g., fluvial channels). Phillips et al. (2000) presents a full description of flow characteristics within the sediment sampler and relationships between ambient, inlet and sampler velocities. Flow enters the sampler at ambient velocity through a narrow (4-mm diameter) inflow tube. As flow moves into the sampler's main body (98-mm diameter x 1-meter length), velocity decreases in proportion to the increase in cross sectional area, promoting sedimentation of particles in the sampler, with water exiting the sampler through a similar 4-mm outflow tube to allow for unimpeded flow (Fig. 1).

The bi-directional TIMS sampler design proposed in this study was built following the original dimensions and design description from Phillips et al. (2000), with modifications (i.e., modified outflow tube, addition of vents) for use in systems with bi-directional flow (i.e. tidally influenced environments). Like the original design, the body of the sampler is made of commercially-available polyvinylchloride (PVC) pipe, 98-mm internal diameter by 1-meter length, sealed using end caps with internal 'O-ring' seals (Phillips et al., 2000). In addition to the residence time of the sampler (which precludes the ability for most autotrophs to survive), the opaque PVC prevents fouling from photosynthetic processes within the main body of the sampler when deployed within the estuarine environment.

The inflow and outflow tubes and connectors were modified from the original design, which were made of semi-rigid nylon pneumatic tubing (6 mm (OD) x 4 mm (ID) x 150 mm) with an internal cross-sectional area of 12.6 mm^2 with a polyethylene funnel placed over the inlet tube to streamline the sampler body and minimize turbulence or disruption of ambient flow (Phillips

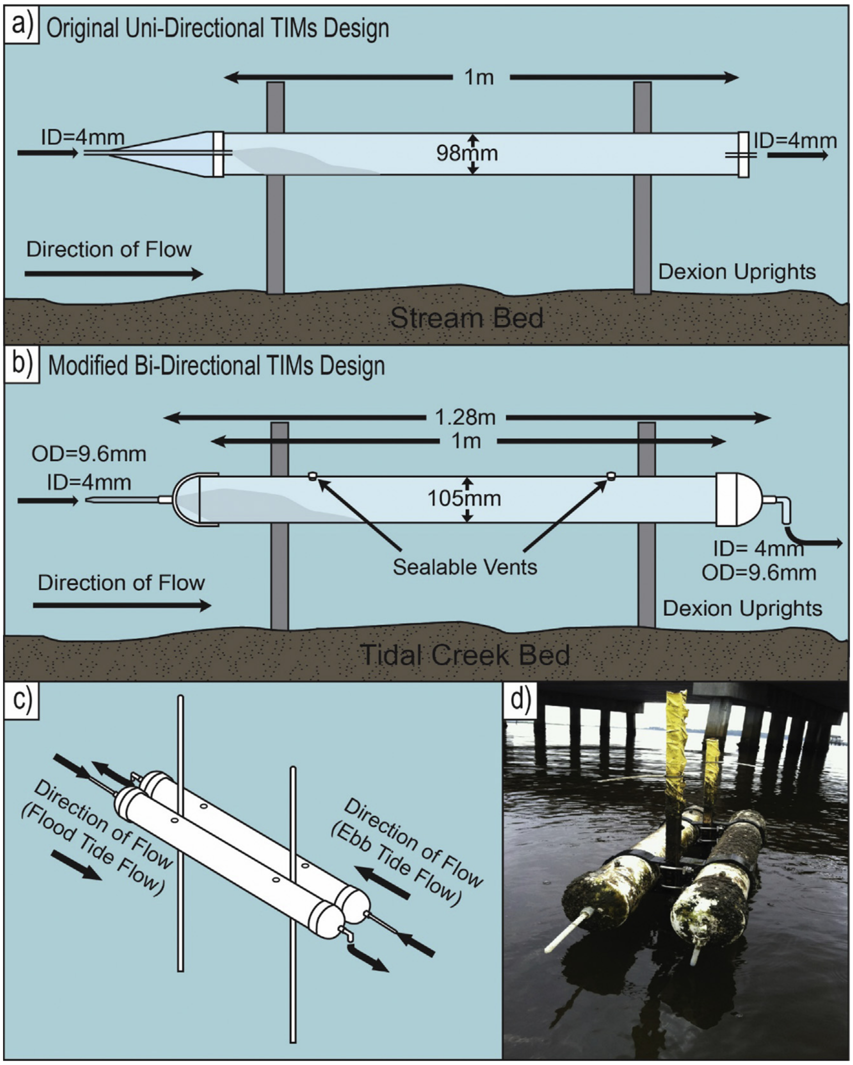


Fig. 1. (a) Cross-sectional view of the original Phillips et al. (2000) TIMS design; (b) Cross-sectional view of modified bi-directional TIMS design for collection of suspended sediment tidal flow; (c) Three-dimensional view of modified bi-directional design, showing how sediment is collected uniquely in each direction of tidal flow; (d) Picture of the mounted modified design in implementation in a tidal creek.

et al., 2000). In the bi-directional sampler design the inflow and outflow tubes are made of rigid 9.5 mm (OD) x 4 mm (ID) x 150 mm long nylon tubing to keep inflow tube aligned with ambient flow within the tidal environment (further equipment description in Appendix A.3). Exposed ends were chamfered at 45° at the entry and exit points to reduce turbulence in a similar fashion to the funnel proposed in Phillips et al. (2000) (Fig. 1; Appendix A.3). Inflow tubes were attached to sampler end-caps using a ¼ National Pipe Thread (NPT) pipe to Swagelok tube fitting screwed flush to the internal surface of the endcap (Fig. 1; equipment description in Appendix A.3). To prevent air bubbles within the sampler, which could impede normal flow conditions, two sealable vents were added along the top of the sampler main body. Given the changes in water-level that occur in the tidal environment, these vents allow for any air that may have entered the sampler during low water-level conditions to escape prior to peak flow (further description provided in Appendix A.3).

The most important modification made to the original Phillips TIMS design is the 'L' shaped outflow tube which prevents sediment entry into the sampler during flow reversal (Fig. 1). Outflow tubes are identical to inflow tubes in tapering and internal diameter, cut to a length of 150 mm. Outflow tubes are attached to sampler end caps using a ¼ NPT pipe to Swagelok elbow fitting screwed flush to the internal surface of the end cap. The perpendicular orientation of the outflow tube relative to ambient flow prevents sediment laden water from re-entering the sampler when flow reverses. Epoxy-coated dexion uprights were used to hold the samplers in place to prevent corrosion within the marine environment, as corrosion could impact the geochemical signature of the collected sample. Two samplers were mounted parallel to each other and flow vectors, with inflow tubes oriented in opposing directions, held onto uprights using 'C' PVC-pipe clamps attached with fabricated stainless steel holders (Fig. 1 c, d). Mounting the samplers parallel to each other in opposing sampling directions allows for collection of material uniquely in each direction of flow.

2.2. Fluid dynamics — particle image velocimetry (PIV)

Particle Image Velocimetry (PIV) is an optical method for tracking flow and obtaining instantaneous velocity measurements (Westerweel, 1997). In laboratory testing of the bi-directional TIMS design, PIV allowed for qualitative and quantitative assessment of fluid motion within the main body of the sampler. Assessment using 2D Planar PIV was conducted in a 27-m long wave tank, with a 130-mJ, Dual Cavity Nd:YAG laser pulsed at approximately 14 Hz and a LaVision Imager Pro camera with 1800 × 1200 resolution (14-bit digital output, 14 frames sec^{-1}, with a pixel size of 7.4 × 7.4 μm; Fig. 2 a,b). To visualize the particles, the laser was mounted to a cart above the collector and a laser sheet, which was generated by adding a 10-mm focal length cylindrical lens to the laser optics, illuminated an x-z section (x is along the length of the collector and the wave tank and z is along gravity) of the collector while the camera took images of the region of interest from the side (Fig. 2 a, b). 10-μm diameter hollow glass spheres were seeded into the sampler prior to the assessment. A bi-directional TIMS design with an acrylic transparent body was used, so assessment of particle movement could be made. Using a water depth of 30 cm and centrifugal pump, a quasi-uniform channel flow of 0.06–0.1 m s^{-1} was established and sustained throughout testing, consistent with typical flow velocities within tidal marshes and adjacent tidal creeks (Bayliss-Smith et al., 1979; Leonard and Luther, 1995). The camera mounted to the side of the tank obtained images of the entire internal diameter of the sampler throughout the analysis. Initial images were acquired at 2 Hz, but required subsampling to 0.2 Hz for the analysis due to the reduction of speed within the sampler. The images of the particles are then analyzed using a software program that scans an image pair to see where the particles have moved via cross-correlation, determining particle velocity. To further inspect the velocity field within the sampler, 3 vertical profiles of the 2D vectors were obtained at 3 different distances (48 cm, 53 cm, 60 cm) along the length of the sampler.

2.3. *Sampler efficiency - laboratory assessment*

Following the laboratory investigation from Phillips et al. (2000), sediment-sampler efficiency was assessed prior to field deployment through a series of experiments that compared the total mass and particle composition of sediment retained in the sampler and outflow material to the known input sample at different ambient flow velocities. It is important to note that this study (both in the laboratory and field experiments) was concerned with the retention of the sediment fraction rather than inclusion of biogenic material for assessment of trapping efficiency, and therefore reports sediment distributions based on particle size, and does not report density measurements in either experiment. A sample representative of sediment from Core Sound, North Carolina, was obtained by combining and homogenizing 8 grab samples taken from bed sediment throughout the estuary. The homogenized sample was placed in a muffle oven at 550 °C for four hours to remove organic material, 5-g sub-samples were disaggregated ultrasonically in a solution of 5% sodium metaphosphate. Utilizing a the same pump design described in the sediment efficiency experiments from Phillips et al. (2000) and used for the dye-fluid dynamics study (presented in the Appendix A.1.2), the 5-g sample was dispersed in 5 L of water (concentration of 1000 mg L^{-1}), kept in dispersion throughout the experiment on a stir plate with a magnetic stirrer, and pumped through a ¼ inch polyethylene tube into the inlet and the main body of the sampler. The outlet pipe was connected through similar tubing to a peristaltic pump which allowed for pump speed, and therefore flow speed, of the dispersed sediment to be drawn through the sampler at a constant rate. For consistency, the same flow velocities used in Phillips et al. (2000) of 0.3 m s^{-1} and 0.6 m s^{-1} were applied by maintaining discharges from the peristaltic pump of 24.9 and 242.1 mL min^{-1}, respectively. After the entire sediment sample had passed through the sampler, 5 L of deionized water (DI) water was passed through to flush the system. Discharged material from the outflow tube was collected throughout the experiment in a 25-L container. At the end of the experiment material in the outflow container and the sample retained in the sediment sampler were individually centrifuged, freeze dried and weighed to obtain retained sediment mass. The grainsize distributions were subsequently determined for input, retained and discharged samples using a Cilas 1180 Particle Size Analyzer, which allows for particle size measurement between 0.04 and 2500 μm in 100 size fractions by laser diffraction. The Kolmogorov-Smirnov two-sample statistical test was applied, after Phillips et al. (2000), to statistically test comparability of the particle size distributions of the inflowing material relative to retained sediment in the sampler and outflow material.

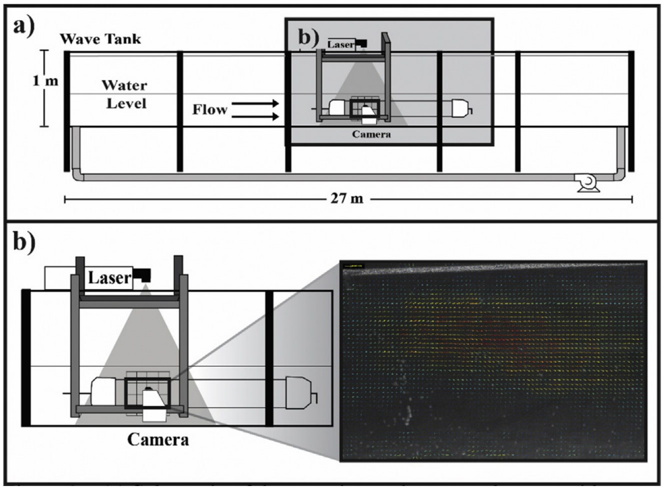


Fig. 2. (a) Schematic of the experimental wave tank setup with water depth of 30 cm to generate uniform channel flow via centrifugal pump; (b) Closer view of camera and laser mounts relative to sediment collector throughout experiment, imagining glass particles inside collector by laser generated sheet perpendicular to the camera; an example of the raw camera image with flow vectors superimposed.

2.3.1. *Field assessment*

To understand the sediment sampler efficiency during field deployment, samplers were deployed in two tidal creeks that flow into Core Sound, North Carolina. The first sampler was placed in a tidal creek directly adjacent to a fringing marsh (Fig. 3) and the second sampler was deployed in a tidal creek that drains overland flow from a large (160 km^2) agricultural site (Fig. 3). Both sampling locations are within the semi-diurnal tidal environment, allowing for the unique collection of suspended sediment in reversing flow and variable velocities multiple times per day. The bi-directional TIMS samplers were deployed so that water-level was above the collector during low-low tide, approximately 0.5 m above the sediment bed in both locations. HOBO U20 water-level loggers (0–4 m range) were mounted to the center of the sampler at each site to determine water level relative to the sediment sampler during the sampling period. Samplers were deployed at both sites over a 3 ½ day period from May 25th, 2014 through May 28th, 2014, with no precipitation occurring at either site over the sampling period. Manual single time point samples of suspended sediment were collected daily around high and low tide throughout the semi-diurnal tidal cycle, allowing for a total of 16 manual point samples throughout the 3 ½ -day sampling period. Manual point samples of near surface water were collected through bucket retrieval at the height of inflowing water into the TIMS sampler at each location, filling a 20-L carboy at each sampling. At the end of the sampling period, sediment from the bi-directional TIMS sampler was extracted by manual swirling and draining of the

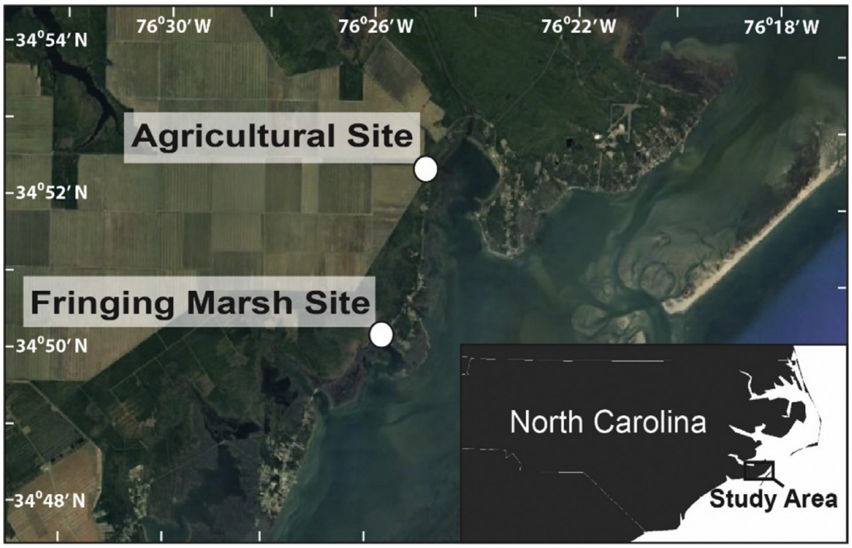


Fig. 3. Field map showing sediment collector sampling locations at agricultural and fringing marsh locations along the shoreline of Core Sound, North Carolina.

main body into a 20-L carboy through the inlet spout, followed by flushing of the sampler with site water into the carboy until all sediment was retrieved. Sediment from both the manual point samples and the samplers was recovered through centrifugation (3500 RPM for 10 min). All samples were freeze dried, weighed and underwent particle-size analysis using the Cilas 1180 Particle Size Analyzer. Samples were disaggregated by sonication during particle-size analysis. Distributions of particle size are presented as weight percent distributions, d_{50} range and mean d_{50} values for both the single time point samples and retained sediment from the samplers.

3. Results

3.1. Fluid dynamics – particle image velocimetry

PIV gives both a qualitative and quantitative analysis of the velocity field within the sediment sampler. The velocity is assumed to reach steady-state through the length of the sampler, after which it is likely that there is little change in the characteristic velocity field over time. Clear flow dynamics emerged within the upstream 1/3 of the sampler, and assuming steady-state dynamics, allowed for general qualitative and quantitative analysis of flow within the sampler.

Theoretically, for efficient collection of the suspended-sediment load, the velocity field within the sampler should be slow enough to allow particulates to fall out of suspension. Additionally, as eddies are mainly what keeps particles in suspension (Oroskar and Turian, 1980), it is important to measure fluctuations in vertical velocity, *w*'. Along the upstream 1/3 of the sampler, there was free-stream flow in the upper part of the sampler, with some weaker return flow at the bottom. Neutrally buoyant particle paths projected by the PIV data show a downward trend for most starting heights. These particle paths of water showed overall downward trend in flow, indicating that aliquots of water (and sediment) will be directed downward toward the bottom of the sampler. Much of the time, flow in the upstream 1/3 of the sampler was exceedingly slow relative to ambient flow, with an average flow in the sampler of 10^{-4} m s^{-1} relative to ambient flow between 0.06 and 0.1 m s^{-1}. Using Reynold's number, a dimensionless quantity that determines the ratio of inertial to viscous forces, it is possible to characterize expected flow regimes in ambient flow versus expected flow within the sampler design itself. The corresponding Reynold's number within the sediment sampler is ~0.5, consistent with what would be expected for laminar flow, with an external flow Re that exceeds 20,000, consistent with turbulent flow, indicating the high potential for sediment fallout within the main body of the sampler during through flow conditions.

To further inspect the velocity field, 3 vertical profiles of the 2D vectors at 3 different down collector distances (from nozzle inlet tip into collector, 48 cm, 53 cm and 60 cm) were obtained along the length of the first 1/3 of the sampler, showing the velocity vectors along the depth of the sediment sampler at each location (Fig. 4). In the vertical, starting at $y = 0$ cm, velocity increases from the top of the sampler down. Maximum velocity is from 2 cm to about 6 cm from the top ($y = 0$). Flow velocity decreases from 6 to 10 cm at the bottom, where there is a slight return of flow, expected due to boundary layer dynamics.

The Durand method for critical velocity is one of the more well-known and established methods for characterization of critical flow (Wasp et al., 1977; Oroskar and Turian, 1980; Onishi et al., 2002). Using this method, critical velocity (m s^{-1}) is determined by the equation (1)

$$v_t = F^*\sqrt{2g(1-s)D}^*(d_p/D)^{1/6} \tag{1}$$

where F is an empirical factor, s is the ratio of the particle density to the water density, d_p is the particle diameter (mm), D is the pipe diameter (m), and g is acceleration due to gravity (9.81 m s^{-2}) (Oroskar and Turian, 1980). This equation (1) predicts that for a 0.1-mm particle, the critical velocity needed to keep the particles from forming bedforms is 0.9 m s^{-1} to 1.4 m s^{-1}. With this in mind, even for clay particles, the critical velocity based on the Wasp-modified Durand equation (1) above is 0.5 m s^{-1}, with a range from 0.12 to 0.48 m s^{-1} (dependent on the eddy fraction within the sampler), which are two to three orders of magnitude higher than the velocities measured in the sediment sampler.

3.2. Sampler trapping efficiency – laboratory assessment

For the sediment trapping efficiency experiments, this study only reports results for particle size rather than density. Like results from Phillips et al. (2000), the sampler was effective in retaining the silt and clay fraction through a range of flow velocities. However, some of the coarse fraction started to settle in the tubing prior to

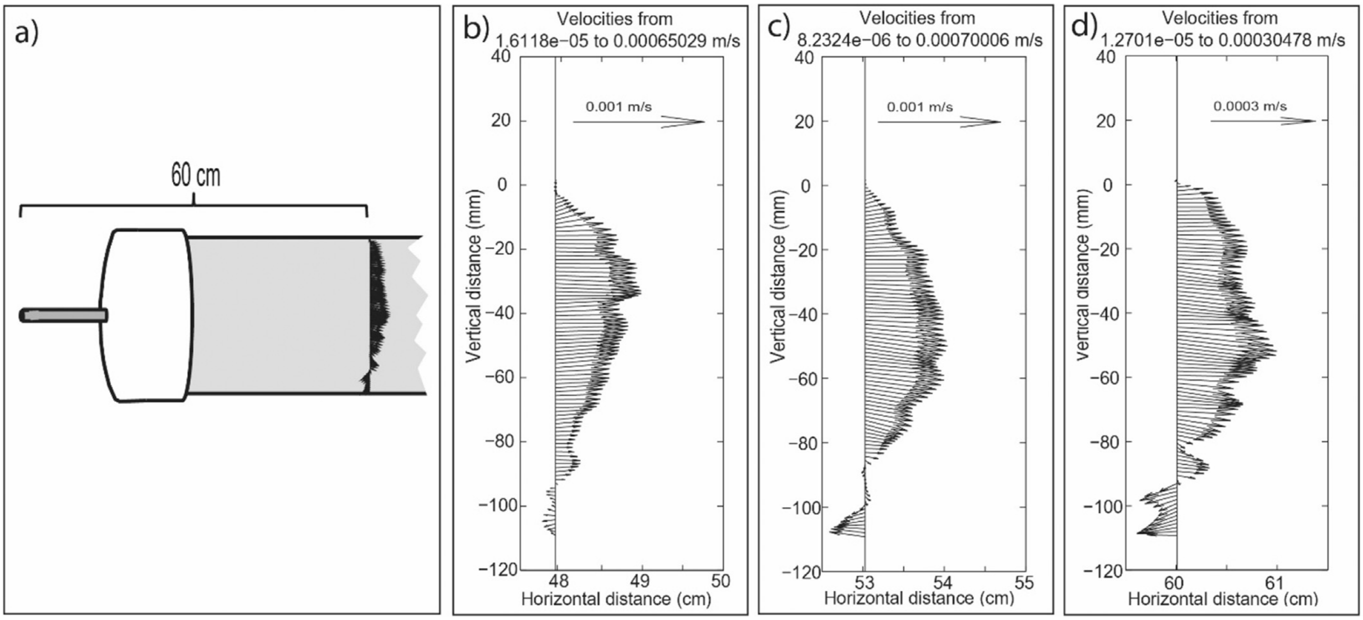


Fig. 4. (a) Simple cartoon of velocity profile within the sediment collector and 60 cm from the nozzle inlet tip. Velocity vectors along collector noted from the tip into the collector at horizontal distances of (b) 48 cm, (c) 53 cm and (d) 60 cm. Note that the laser sheet bisected the 10.5 cm diameter sediment sampler along its long axis, so these vectors are in the center of the cylinder.

entry into the sampler, particularly at the lower 0.3 m s^{-1} velocity. This complication is not noted in the Phillips work, and is likely due to 1) the presence of a coarser fraction in the sample used during our experiment or 2) the tubing that was used to draw the sample into the sampler from the glass beaker, rather than directly inserting the inflow tube into the bottom of the beaker as was done in the Phillips experiment. Despite this complication, sediment retention within the sampler, which was calculated based on the overall dry weight of retained and outflow material, accounted for 93–96 (±1.5) percent of the overall retained and outflowing material during laboratory experiments (Table 1). Like Phillips et al. (2000), the sampler retained sediment across the range of particle sizes present within the inflowing sample, but did show an over sampling of coarser sediment relative to the inflowing suspended sediment (Fig. 5). Likewise, the outflowing sediment not retained within the sampler is substantially finer than the inflowing sediment (Fig. 5). As expected and reported in Phillips et al. (2000), sediment retention efficiency (based on mass) decreases with increasing velocity, although the difference in efficiency between the velocities is much less (~3%) in the modified sampler design relative to the original sampler (~15–21%) presented in Phillips et al. (2000). It is also worth noting that the outflowing material is significantly finer than that of the inflowing sample, with a d_{50} value for outflowing material under 7 μm at the highest tested velocity (Table 1). Statistical analysis using the Kolmogorov-Smirnov two-sample statistical test were applied to compare particle size distributions between inflowing, retained and outflowing material, and are presented in Table 2. The p-values from this test indicate that the outflow material was significantly different than the inflowing sample at both velocities, but there was no significant difference in the distribution of the inflowing material relative to the retained sample at either velocity.

3.3. *Sampler trapping efficiency - field assessment*

Grain-size distributions are comparable between the sediment collector and the single-time point samples for each site and tidal current flow direction (Figs. 6 and 7, Table 3). An average of the single time point distributions at each site are presented for each tidal current flow direction (Figs. 6 and 7) relative to the sediment sampler distribution. There are differences in the distributions of sediment grainsize between locations. The grainsize distributions in both the single time point and TIMS sampler showed slightly bimodal distributions during both ebb and flood tide conditions, with d_{50} values between ~12 and 14 μm, whereas the agricultural site showed a coarser, unimodal distribution, with larger d_{50} values (~14–15 μm) representing coarser sediment in the agricultural site.

Within site variations in distributions between ebb and flood tide flow directions showed minimal differences in the averaged single time point samples. However, although minimal differences in tidal flow occurred, the single time point and TIMS sediment samples corresponded well between ebb and flood current samples in both the marsh and agricultural sites (Figs. 6 and 7, respectively). Statistical analysis through the Kolmogrov-Smirnov test verified that there is no significant difference in the averaged distribution of single-time point samples and sediment sampler samples for each site and current direction (Table 3). Similar to the correspondence in distribution, d_{50} values for single-time and sediment sampler samples were comparable within the two environments (Table 3).

Table 1
Sediment percent (%) mass retention and d_{50} values for laboratory studies of full-scale sampler.

Ambient Flow Velocity (m/s)	Sediment Retained by Sampler (%)	Inflowing Sediment d_{50} (μm)	Retained Sediment d_{50} (μm)	Outflow Sediment d_{50} (μm)
0.3	95.6 (±1.5)%	26.8	22.7	2.6
0.6	93.3 (±1.5)%	29.1	30.1	6.7

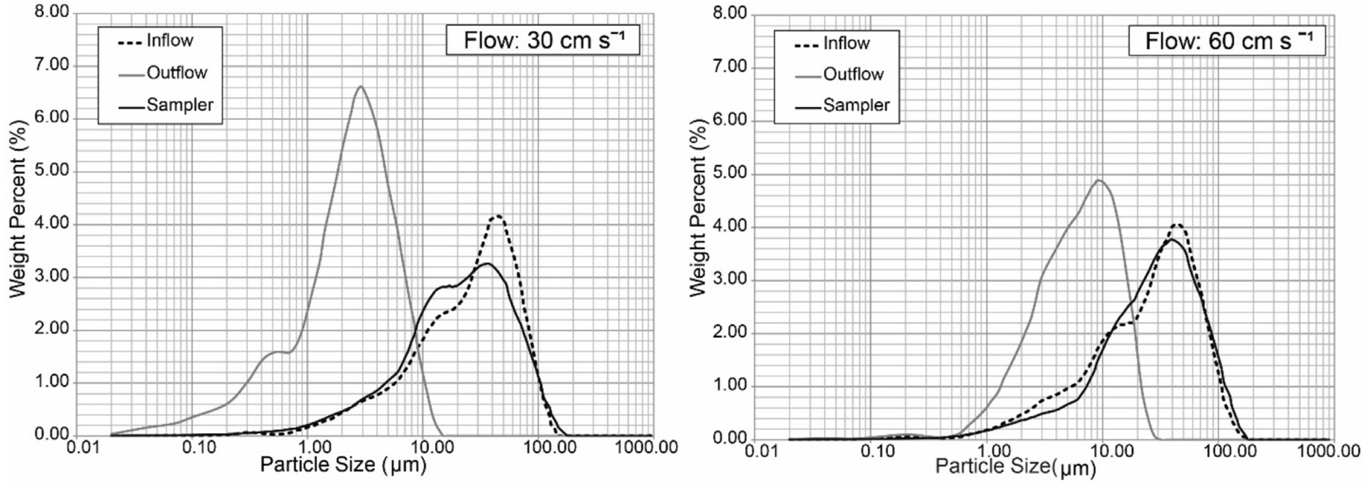
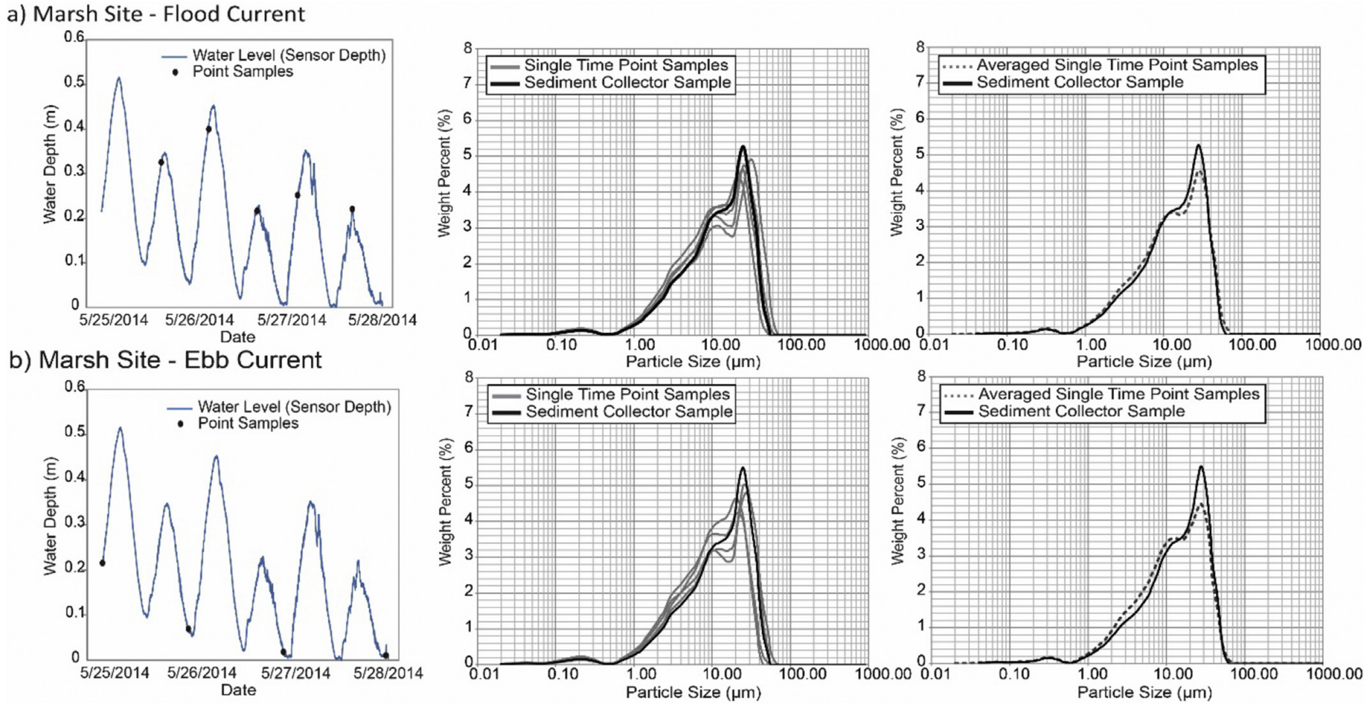


Fig. 5. (Left to right) Comparison of particle size distribution by weight percent for inflow, outflow and retained sediment within the collector for velocities of 0.3 m s^{-1} and 0.6 m s^{-1} (respectively).

Table 2
Kolmogorov Smirnov (K-S) test results for similarity of particle size distributions in laboratory experiments with full-scale sampler.

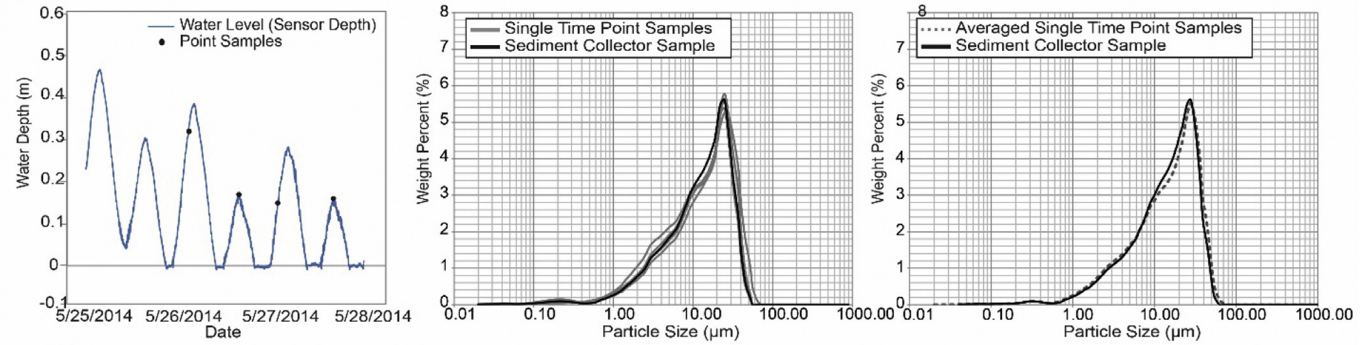
Ambient Flow Velocity (m/s)	Inflowing vs. Retained Sediment p-value	Inflowing vs. Outflowing Sediment p-value
0.3	0.794	0.0004
0.6	0.961	0.003


a) Marsh Site - Flood Current

b) Marsh Site - Ebb Current

Fig. 6. Marsh site water level in tidal creek based on sensor depth (mounted in center of collector), with sample collection date and comparison of particle size distribution by weight percent at each point sample and average point sample with sediment retained in collector over sampling period relative to collector samples for (a) Flood and (b) Ebb current conditions.

a) Agricultural Site - Flood Current



b) Agricultural Site - Ebb Current

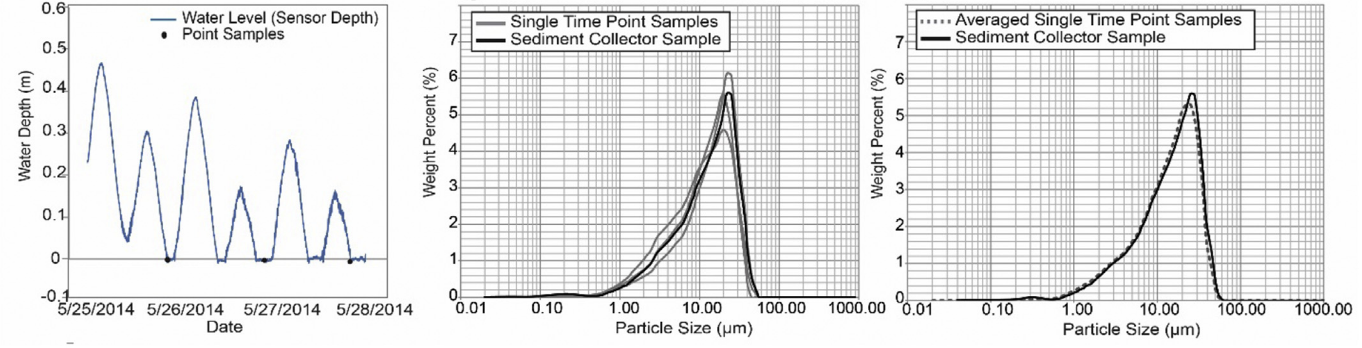


Fig. 7. Agricultural site water level in tidal creek based on sensor depth (mounted in center of collector), with sample collection date and comparison of particle size distribution by weight percent at each point sample and averaged point sample with sediment retained in collector over sampling period relative to collector samples for (a) Flood and (b) Ebb current conditions.

Table 3
Characteristics of sediment (i.e. d_{50}, Kolmogorov Smirnov (K-S) test for similarity between samples) collected from single point samples (P.S.) and full-scale sediment samplers (S.S.) in both ebb and flood directions of tidal flow in field placements at two locations.

Site Location and Tidal Current	No. of Point Samples (P.S.)	d_{50} P.S. Range (μm)	Average d_{50} P.S. (μm)	d_{50} Sediment Sampler (S.S.) (μm)	K-S Test p-value
Marsh - Ebb	4	10.5–14.1	12.2	14.3	1
Marsh - Flood	5	10.9–15.0	13.0	14.0	0.961
Agricultural - Ebb	3	12.0–16.9	14.2	15.0	1
Agricultural - Flood	4	13.1–17.2	15.2	14.9	1

4. Discussion

4.1. Modified TIMS design

4.1.1. Outflow tube and pressure gradient

During flume studies the modified ‘L’ shaped design of the outflow tube was tested to assess its ability to collect an unbiased sample during reversal of flow (Appendix A.1.1, A.1.2). As observed, the modified design did not allow for entry of dye through the outflow tube when flow was reversed, with stagnation of dye primarily occurring within the sampler upon initial reversal of flow. Although no back flow into the sampler occurred when flow within the flume was reversed, a small negative pressure gradient was created within the sampler when flow was reversed to the peak tested speed of 0.6 m s^{-1}, as water was displaced from within the outlet tube due to flow along the outlet surface. This effect could cause a small amount of sediment laden water to be pulled into the inflow tube when flow is reversed. However, any sediment reuptake would be very small relative to the overall retained sample even in the most extreme of conditions. To fully characterize whether uptake and retention of fine grained material is possible during normal, much lower estuarine flow conditions, which are more on the order of ~0.03–0.10 m s^{-1} (Leonard and Luther, 1995), further testing with PIV analysis may be useful.

Some proposed further modifications to the sampler design to address the potential of a negative pressure gradient developing in reverse flow include asymmetrical tapering around the outlet or a check-valve along the entry point of the outflow tube. However, these modifications pose a risk of increased turbulence around the mouth of the outflow tube, or, in the case of the check-valve, increased probability of failure under field conditions. Therefore, the potential disadvantages of these further modifications are likely to outweigh their advantages in the field and the simple modified ‘L’ shape outflow tube design tested in this study is likely a better fit for field deployment.

4.1.2. Inlet tube and dead zones

In the original Phillips design, the inflow tubes extended 20 mm into the main body of the sampler, resulting in ‘dead-zones’, which were noted as important features for further reduced flow and increased ability for sediment fallout to occur (Phillips et al., 2000). Within the proposed modifications to the bi-directional TIMS design, the inflow tube is installed directly into the ¼ NPT pipe to Swagelok fitting, allowing for a flush entry point into the main body of the sampler. This begs the question of whether it would be possible to further reduce flow speeds within the sampler by extending the inflow tube into the main-body of the sampler, creating dead-zones within the bi-directional TIMS design.

Although useful to consider, quantification of the fluid dynamics within the collector via PIV analysis indicates that the modified design should be capable of velocities that would be conducive to fine-grained sediment fallout equal to or even better than what is reported in Phillips et al. (2000). This is further verified in the results from the laboratory sediment efficiency experiments, which indicate the modified design is able to capture the fine-grained sediment fraction, with no significant difference in distribution between the inflowing and captured sediment, with greater retention rates overall reported in the modified design relative to what was reported in the original TIMS design.

Furthermore, from a practical standpoint, the modified design, which does not have the inflow tube inserted into the main body of the sampler, allows for easier and more complete sample collection in the field. In the modified design, sediment is drained directly through the sampler inflow tube into a 20-L carboy and flushed with clean water prior to removing the end cap. Having an inflow tube that is flush with the surface of the interior of the sampler prevents build-up or even loss of material, especially the fine sediment fraction, which would be more likely to adhere to the inserted inflow tube. With the lack of quantitative evidence for increased efficiency with the inclusion of dead zones, and the practical advantages of the modified bi-directional TIMS design for sample collection while in the field, it is difficult at this point to justify the inclusion of dead-zones in the modified design. Other modifications to the bi-directional TIMS design, including the potential inclusion of baffles and/or spiral baffles for further impedance of flow and prevention of fine-grained resuspension, should be quantitatively explored for improved performance of the bi-directional TIMS design.

4.2. *Laboratory efficiency*

Both dye (Appendix A.1.1, A.1.2) and PIV experiments indicated the downward trend in particle movement, with substantial reduction of velocity within the sampler relative to ambient flow velocities. Critical velocity, as calculated by the Durand method, further indicates that clays should fall out of suspension within the sampler.

Sampler efficiency experiments of overall mass of sediment retained within the sampler relative to outflow material indicated up to 96% retention, with only a small reduction of retention to 93% with a doubling in velocity. Likewise, the grain-size distributions and d_{50} values of the inflowing and retained sampler samples correlated well. Of the fraction of material that made it through the sampler, the grain-size was fine silt to clay (Table 1). It is important to note that laboratory and field experiments considered only the dense sediment fraction, and did not consider low density organic/biogenic material in this analysis. Further characterization of the trapping efficiency should incorporate the organic fraction, including differential particle densities, to verify the high retention rates observed during these experiments.

As discussed, laboratory experiments utilized chemically dispersed or disaggregated sediments for grain-size analysis. This allowed for a high-resolution grain-size distribution to be analyzed for both retained and outflow material from the sampler. However, as discussed in Phillips et al. (2000), in the natural riverine environment fine sediment is often transported in aggregate form. Due to the larger particle size and density of aggregates, a higher velocity is required to keep particles in motion, allowing for greater fallout and therefore higher trapping efficiency within the sampler when sediment is transported as an aggregate rather than individual particles. The transport of particles as aggregates within the estuarine environment is well documented and potentially more prominent than in rivers due to conditions within the estuarine environment like ionic strength, bi-directional collision potential, higher biogenic content, that facilitate particle aggregation during transport (Avnimelech et al., 1982; Van Leussen, 1988; Winterwerp, 1998; Milligan and Hill, 1998). Therefore, relative to laboratory testing, this would indicate that aggregation of fine-grained material within the estuarine environment would further facilitate increased trapping efficiency of the modified bi-directional TIMS design.

4.3. *Sediment trapping efficiency in the estuarine environment*

Field experiments indicate good retention of sediment in the modified sampler design relative to single time point samples extracted at the marsh and agricultural sites. Sediment distributions between sites did appear different, with material collected from the agricultural site being overall coarser than the marsh sampling location. Sediment sampler grain-size distributions fit the range of grain-size distributions measured for the corresponding single time point samples. Distributions from the averaged single time point samples and the sediment samplers were nearly identical at each site. This indicates the potential of the modified design to collect an unbiased integrated sediment sample through time in diverse estuarine sub-environments.

Ebb and flood current grain-size distributions were similar at each site for both the sediment sampler and single time point samples. Since the samplers are mounted in the same location, oriented in opposing directions of flow, it is unlikely that the material would be significantly different between the ebb and flood current directions, as the samplers are likely sampling the same material in each direction of flow. Within the constraints of the sampling done for this work, it is apparent that the grain-size distributions and d_{50} values for the single time point samples for each site and current direction matched the equivalent retained sediment sampler sample well. Although distributions between the sampling methods were comparable, the bi-directional sediment collector design required significantly less work to obtain the sample, and greater relative sample mass than single time point samples. Additionally, this time integrated sediment sample incorporates sediment transported during peak flow conditions, allowing for the capture of event scale, daily and monthly variation in sediment flux within the estuarine environment, a resolution that is difficult and expensive to achieve using traditional sampling methods. Although this work clarifies the fluid dynamics of the modified design within the laboratory setting, performance and retention is likely to vary based on the environment in which the sampler is deployed. When implementing this modified design within a new environment, it is recommended that a field assessment of sediment distribution through grain-size analysis of single time-point samples relative to sediment sampled in the sampler be implemented to verify trapping efficiency prior to large scale deployment. Additionally, although out of the scope of this work, it is important to note that biogeochemical properties of the sediment may alter while the sampler is in field deployment, especially for extended periods of time, and it is recommended that this be taken into consideration if investigating the biogeochemical signature of sediment sampled using this method.

5. Conclusions

The modified bi-directional TIMS design represents a novel approach to the collection of suspended sediment in environments where flow direction reverses, making it ideal for use within the estuarine environment. Through extensive assessment of the fluid dynamics within the sampler, including flume, dye and PIV analysis, this work validates that flow within the sampler is substantially reduced relative to ambient flow velocity. Additionally, influent dye aliquots tended to flow downward in the sampler, indicating that influent sediment-laden aliquots will also flow downward upon entry into the sampler, resulting in particle capture within the sampler. Quantitative analysis through PIV experiments allowed for a more robust understanding of the fluid dynamics within the collector to be developed. PIV results indicate that flow rate reduction within the sampler is conducive to the fallout of fine silts to clays from suspension. Although the modified design lacks the dead-zones noted in the original TIMS design due to the lack of insertion of the inflow tube into the main body, quantitative analysis of the fluid dynamics indicate that the modified design should collect fine grained silt and clay regardless of the presence of dead-zones within the sampler. Given similar trapping efficiency, the modified TIMS design is favorable for prevention of sample loss when emptying the unit in the field.

Sampler collection efficiency was assessed in both laboratory and field experiments, and in both assessments indicated the modified TIMS design collected representative sediment samples. In laboratory experiments, the sampler had up to a 96% retention rate relative to total retained and outflow material, with 93% retention when ambient velocity was doubled. The fine-grained material exiting the sampler at the highest velocity during the experiment had a d_{50} of 7 μm or less and although that material was significantly different than the inflow material, there was no significant difference between inflowing sediment and the retained sample at either of the velocities tested. This warrants further investigation of flow regimes within the sampler to determine if the modifications to the bi-directional TIMS sampler design increase sampling efficiencies overall relative to the original TIMS sampler design, making this modified design more efficient than the original design for deployment in both uni-directional and bi-directional flow regimes.

Field experiments utilized single-time point samples and the modified TIMS design over a three-day period in a marsh and agricultural environment within the estuary. Although differences in sediment distributions were noted between sampling locations, the retained sediment within the modified TIMS design compares well with equivalent single-time point samples collected over the same period. Unlike the small mass collected in the single-time point samples, the bi-directional TIMS sampler has the capacity to obtain an integrated sediment sample over the collection period, allowing for collection over multiple time-scales. This study verifies the usefulness of the modified bi-directional TIMS design for collection of suspended sediment in the tidal environment, allowing for an inexpensive time-integrated suspended sediment sampler for use within the estuarine environment.

Acknowledgements

Funding for research and support were provided through the NC Sea Grant (NCSG 2010-1707-01 E/GS-4F) and UNC University Research Council (URC) small grant program. Personal support was also provided through the NSF Graduate Research Fellowship (NSF GRFP) and UNC Graduate School Dissertation Completion Fellowship awarded to Emily Elliott. Thanks also to the University of North Carolina Department and Institute of Marine Sciences, Joint Applied Math and Marine Sciences Fluids Lab and Environmental Sciences and Engineering Design Center for facilities and equipment. Special thanks for laboratory and field assistance to William Flowers, Maggie Esch, Anna Jalowska, Ethan Theuerkauf, Justin Ridge, Lisa Nigro, Beth Vandusen, Theresa O'Meara, and John Gunnell for field and laboratory processing and support.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.ecss.2017.08.029.

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