Estuarine, Coastal and Shelf Science 199 (2017) 14–24

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

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

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
0272-7714/

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