Seasonal influences on the ecomorphodynamics of a hypertidal salt marsh and tidal creek system

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Abstract

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Seasonal variability in the ecomorphodynamics of a Bay of Fundy tidal creek and salt marsh was analyzed to better understand how these systems might respond to potential tidal energy extraction. Data were collected for 62 tides for deposition, sediment concentration, velocity, grain size, and vegetation at four stations from the creek thalweg to the marsh surface. Deposition rates varied spatially from 56.4 $g \cdot m^{-2}$ at the creek thalweg to 15.3 $g \cdot m^{-2}$ at the marsh surface. Deposition and erosion were both most active in late fall and winter. This seasonal change, led by higher sediment concentrations, was strongest at the creek and marsh bank. Sediments were predominantly deposited in floc form (76-83%), and grain size of both suspended and deposited material was more influenced by a large rainfall event than seasonality. Understanding the mechanism of sediment transport is crucial to anticipate changing sedimentation patterns due to anthropogenic and climatic influences.

July 31, 2014

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Chapter 1:

Introduction

The study of ecomorphodynamics encompasses the coupling of biological and physical processes; it is the interaction and adjustment of topography, hydrodynamics, vegetation, morphologies and the change in sediment dynamics that follows (Townend et al., 2010; Coco et al., 2013). Salt marshes and tidal creeks are essential components of intertidal ecomorphodynamics (D'Alpaos, 2011). Because these intertidal zones have intrinsic value, it is important to understand how they behave. Possible threats to intertidal areas include, among others, climate change and tidal energy extraction. To be able to determine the magnitude of the change imposed by anthropogenic factors, the natural variability of the system must first be known. Intertidal systems in the hypertidal category, such as the ones in the Upper Bay of Fundy, still require more research to completely understand the sediment dynamics (O'Laughlin and van Proosdij, 2012). Salt marshes in the Upper Bay of Fundy experience seasonal variations in temperature, precipitation, and presence of ice (van Proosdij et al., 2006b; Townend et al., 2010; Tao, 2013; Mulligan et al., *submitted*). This thesis aims to quantify the seasonal component of sediment dynamics in a tidal creek and salt marsh system while investigating potential factors that drive sediment behaviour. Both spatial and temporal variations are considered in this study, as both are essential for understanding of sediment dynamics in salt marshes and tidal creeks (Temmerman et al., 2003b).

1.1 Salt Marshes

Salt marsh and tidal creek systems are natural ecosystems found in many coastal areas. The geographical range of these habitats extends from temperate to high latitudes and they exist where energy levels are low enough that vegetation can grow and thrive even where they will be frequently inundated (Allen, 2000; Friechrichs and Perry, 2001). Salt marshes are critical habitats for many species. They also protect the coast from incoming wave and storm surge activity through dissipation of energy by their gentle slope gradient and their robust and salt-tolerant vegetation (Mitsch and Gosselink, 2000; Townend et al., 2010; Vandenbruwaene et al., 2011). The ability of these systems to grow in the presence of sea level rise makes them an important ecosystem for coastal defence (Graham and Manning, 2007). However, with more rapid sea level rise and increased storms becoming more of a concern, the importance of functioning salt marshes is heightened (Wang et al., 2010). Despite their ecological and coastal resilience significance, salt marshes around the world are likely to change due to anthropogenic activities, such as harbor dredging or building causeways (Friedrichs and Perry, 2001; van Proosdij et al., 2006; Wang et al., 2010; Smith and Friedrichs, 2011; Vandenbruwaene et al., 2011).

Salt marshes are predominantly accretional as sediments deposit in the marsh vegetation when the marsh is inundated at high tide (Davis, 1983). Salt marshes respond to sea level rise, and are thought to be able to accommodate sea level rise (Graham and

Manning, 2007). A drop in sea level, however, would likely lead to the loss of marsh because of the lack of water getting to the high marsh (Allen, 2000). More recent research proposes that some salt marshes will not be able to withstand rapid sea level rise (Kirwan and Temmerman, 2009; Mudd et al., 2010). This is true particularly for marshes which are lower in the tidal frame. With higher water levels, the vegetation in the low marsh could be inundated for longer periods than they can survive. With the loss of vegetation, there will be less opportunity for sediment to be trapped and deposited, therefore leading to lowering of the surface.

Macrotidal marshes are ones which have a tidal range greater than 4 m (Friedrichs and Perry, 2001). Hypertidal marshes are a subcategory of macrotidal marshes and are classified as the ones that have a tidal range of 6 m or higher (van Proosdij et al., 2010; O'Laughlin, 2012). Salt marshes in the Upper Bay of Fundy, including the one used as a study site for this research, are classified as hypertidal marshes with tides reaching up to 16 metres in some regions (Greenberg et al., 1997; Desplanque and Mossman, 2004; Shaw et al., 2010; van Proosdij et al., 2010; O'Laughlin, 2012). Macrotidal marshes, compared to microtidal marshes have a greater potential to sustain themselves and remain in equilibrium because of their large supply of sediment (Friedrichs and Perry, 2001). In addition, these marshes frequently develop extensive marsh networks with tidal creeks and mudflats which supports the development of an accreting marsh with abundant sediment supply (Friedrichs and Perry, 2001). A characteristic of macrotidal marshes which differentiates them from microtidal marshes is that they depend on frequently repeated tidal action (French and Spencer, 1993) while microtidal marshes are more likely to respond more drastically to single events such as a large storm surge (Townend et al., 2010). This hypothesis will be further investigated in Chapter 2.

1.2 Sediment Dynamics

Sediment deposition will occur when there is both availability and opportunity for sediment to settle. Availability factors, which increase the presence of sediment, include water depth (Christie et al., 1999; Détriché et al., 2011), flow velocity (van Maren and Winterwerp, 2013), turbulence (Leonard and Luther, 1995; Neumeier and Amos, 2006b), hydroperiod (Allen, 2000) and the behaviour of vegetation (Boorman, 1999; Leonard and Reed, 2002; Mudd et al., 2010). Opportunistic factors leading to deposition include high suspended sediment concentration (Leonard, 1997; Temmerman et al., 2003b), grain size (Law et al., 2008; O'Laughlin et al., 2014), flocculation (Eisma, 1986; van Leussen, 1999), bathymetry (Coco et al., 2013), and meteorological conditions, namely wind and rain (Christie et al., 1999; Bartholdy et al., 2004; Murphy and Voulgaris, 2006). The links between all these different factors determine the sedimentation rates and the balance between sediment deposition and erosion (Leonard, 1997). For example, high suspended sediment concentrations coupled with low turbulence will facilitate deposition (Friedrichs and Perry, 2001), whereas low suspended sediment concentration and high turbulence will lead to less deposition.

In the Bay of Fundy marsh system being studied, the sediment is mostly mud, which is classified to have a diameter less than 63 μm (Krumbein and Pettijohn, 1938). Mud is affected by cohesion. The grain size threshold for cohesively behaving sediment has been reported to be from 10 μm (McCave et al., 1995), 16 μm when more than 7.5%

of material is 4 μm or smaller (Law et al., 2008), to 50 μm (Partheniades, 2009). Because of the fine-grained nature of the sediments in the Bay of Fundy, flocculation plays an important role in sediment transport and deposition. When grains are in flocculated form, their settling rate is increased (Kranck, 1975; Sternberg et al., 1999; Milligan et al., 2007). Flocculation is enhanced by suspended sediment concentration because larger concentrations lead to a greater chance that grains will collide to form flocs (Milligan et al., 2007).

Salt marsh sediment dynamics change over the yearly seasonal cycle because of variations in water properties, vegetation growth, and meteorological patterns, as well as organisms present, such as has been shown in Murphy and Voulgaris (2006) in South Carolina, Coulombier et al. (2012) in the St. Lawrence Estuary, and Tao (2013) in the Bay of Fundy. Winter brings colder temperatures, increased storm activity with more waves leading to resuspension of material and presence of ice (van Proosdij et al., 2006b; Argow et al., 2007; Mulligan et al., *submitted*). In the summer and late fall, vegetation growth is at its peak, interrupts the flow and causes wave dissipation (Möller, 2006). The abundance of microphytobenthos also allows the accumulation of fine sediment in the summer as they increase critical erosion shear stress of the sediment (de Jonge and van Beusekom, 1995; D'Alpaos, 2011).

1.3 Motivation

This research is motivated by the development of tidal power in the Bay of Fundy which has the potential to alter the sediment dynamics in the intertidal zone. These impacts in the intertidal zone including, among others, changing depositional patterns and change in vegetation communities, are known as the far field impacts. The development and implementation of tidal power is important to Nova Scotia because it is a dependable source of renewable energy and would help the province reach its renewable energy goals (Whitford, 2008). The province's *Environmental Goals and Sustainable Prosperity Act* outlines a goal of having greenhouse gas emissions 10% below 1990 levels by the year 2020. Nova Scotia has a *Renewable Electricity Plan* which requires that by 2015, the province will be powered by 25% renewable electricity, with a second goal of having that percentage increase to 40% by 2020. The Bay of Fundy has a tremendous potential for energy conversion because of the immense volume of water moving in and out of the area twice per day with the tides. Because the regime of tidal cycles is predictable, in-stream tidal power energy generation can be provided on a routine schedule. This is an advantage of tidal power when compared to other green energy generation options which vary with supply or with meteorological conditions that cannot be predicted over long periods. Tidal turbine developments have made great progress in the United Kingdom (Neill et al., 2009). The Minas Passage, has potentially the greatest amount of available tidal energy but because of strong currents there are design challenges to overcome. The average current in the Minas Passage is 3.28 $m \cdot s^{-1}$, with maximum speeds up to 5 $m \cdot s^{-1}$ (Karsten et al., 2008). The near field effects from tidal energy extraction are currently better understood than the far field effects (Garrett and Cummins, 2005; Sun et al., 2008; O'Laughlin, 2012). In the far field, the consequences are expected to be nonlinear and to differ from site to site (Polagye and Malte, 2011). Larger scale models (coarse resolution) have been developed to look at the impacts of tidal energy on sediment transport and hydrodynamics (Wu et al., 2011; Tao, 2013) but finer resolution models are required to represent the intertidal zone because they are able to characterize the tidal creeks within this zone.

This thesis forms part of a larger research project funded by the Offshore Energy Research Association of Nova Scotia being conducted in collaboration with the Bedford Institute of Oceanography (Fisheries and Oceans Canada), Queen's University and Dalhousie University. This larger project seeks to model the potential far-field effects of tidal in-stream energy conversion devices in the Minas Passage. Tidal in-stream energy conversion devices are superficially similar to wind turbines in that they convert the kinetic energy of the water flowing through the turbine. Because these turbines are in a water medium and are extracting energy from this water medium, they will change water currents in proximity to the turbines. Consequently, far-field impacts on the environment are anticipated including potential changes in sedimentation rates and change in water level (Neill et al., 2009; Polagye and Malte, 2011). Recent models suggest that installing a commercial turbine field will result in a decrease in energy to the intertidal zones of the Bay of Fundy (Karsten et al., 2008). A change in water level will make a difference in the tidal prism of the intertidal creeks, and in the marsh surface area inundated at high tide (O'Laughlin and van Proosdij, 2012). Further understanding of what a decrease in tidal energy could do to intertidal ecosystems is necessary. In a numerical modelling study, Polagye and Malte (2011) emphasize the need for site specific modelling to estimate far-field results of energy extraction from tidal turbines. Data and knowledge gained within this thesis will serve as critical inputs for validation of hydrodynamic and sediment transport models currently being developed (van Proosdij et al., 2014).

1.4 Thesis Organization

This thesis is constructed in manuscript format. Chapter 2 and Chapter 3 will be submitted for publication as separate articles to *Geomorphology* and *Estuarine, Coastal and Shelf Science* respectively and are formatted as such. All references however, are provided at the end of the thesis to prevent duplication. The thesis will examine sediment transport patterns and the factors influencing sediment deposition. Chapter 2 focuses on the ecomorphodynamics over different temporal scales, ranging from individual tides to yearly cycles, and different spatial scales, ranging from individual sampling points to a creek system. Examining sediment processes at different temporal and spatial scales helps extrapolation to the longer time scales of predictive models. Chapter 3 focuses on the sediment characteristics of both deposited and suspended material and explores the influence of episodic events such as rainfall on grain size distributions. The influence of flocculation on sediment deposition will also be examined in this chapter. Chapter 4 is a synthesis of the work completed and explores the applications to modelling being carried out in collaboration with Queen's University.

Chapter 2:

Seasonal controls on the ecomorphodynamics of a macrotidal creek and salt marsh

To be submitted to: Geomorphology

2.1 Introduction

Understanding the underlying principles controlling how salt marshes and tidal creeks behave is important. Salt marshes serve vital roles for our ecosystems, acting as niche habitats for certain organisms as well as providing coastal protection from storms through wave attenuation (Daborn et al., 1993; Goodwin et al., 2001; Granek et al., 2009; Townend et al., 2010; Shi et al., 2012). Semidiurnal tidal salt marshes are inundated with sediment laden waters and through various feedbacks of sediment transfer, these intertidal systems may gain or lose sediment leading to adjustments of morphology. In turn, these morphology adjustments will impact hydrodynamics and sediment transport patterns.

The purpose of this chapter is to examine the seasonal controls on the ecomorphodynamics of a hypertidal, temperate tidal creek and salt marsh system. Ecomorphodynamics encompasses the interaction and modification in several geomorphic components including topography, hydrodynamics, and the vegetative community and how these interact with sediment dynamics.

Salt marshes, like other wetlands, are in the process of attaining an equilibrium state. The period of time for which a marsh is considered close to equilibrium is typically between decades and centuries. Salt marshes tend to accumulate more sediment when they are younger and when they have high sediment supply (Allen, 2000). Once a marsh reaches a mature stage, it will accumulate new sediment at a much slower rate even when it is in an accretion stage (Temmerman et al., 2004). In salt marshes, surface elevation change results from both inorganic sediment deposition as well as below-ground organic production. In the Bay of Fundy, inorganic sediment deposition is a much greater contributor to surface elevation change than below-ground organic production, which makes it a minerogenic system (Shaw and Ceman, 1999; van Proosdij et al., 2006b).
When a change is imposed that alters the accretion processes, the system can respond quickly and alter its route to equilibrium which in turn may increase the time to reach equilibrium (French, 2006; Townend et al., 2010).

Vegetation plays an important role in sediment accumulation rates and location. Because *Spartina alterniflora*, which is present in the low marsh at the site in this study, traps sediment, growth of *Spartina alterniflora* leads to more sediment deposition, therefore causing more accretion and the salt marsh adjusts upward. In contrast, sea level rise leads to increased flooding of the low marsh, which may lead to vegetation die off, therefore reduced opportunity of sediment trapping and the salt marsh will respond by adjusting downward (Morris et al., 2002).

Anthropogenic stressors imposed on the natural system, such as dyking, the building or removal of causeways or dams, dredging (Friedrichs and Perry, 2001; van Proosdij et al., 2009) and potentially the energy extraction from tidal turbines, can lead to changes in sedimentation patterns (Karsten et al., 2008; Polagye and Malte, 2011; O'Laughlin and van Proosdij, 2012). Hydrodynamic models of a commercial field of tidal in-stream energy conversion devices (TISEC) in the Minas Passage have projected a decrease in currents within far-field intertidal areas (Karsten et al., 2008). This has the potential to alter the mobility and deposition of intertidal sediments (Law et al., 2008). In addition, a change in the tidal range is expected. Karsten et al. (2008) predict a 5% decrease in tidal range with 2.5 GW of energy extraction, which would mean less flooding of the high marsh and, therefore, less sediment being delivered to sustain a salt marsh's elevation within the tidal frame (O'Laughlin and van Proosdij, 2012). While contemporary salt marshes function and develop within coastal landscapes which have been altered through anthropogenic processes, the key question is whether the ecomorphodynamic responses to commercial scale TISEC devices occur within the range of natural variability. To answer this question, further empirical data are needed to understand natural variability of sediment dynamics in intertidal systems. In addition, few field studies exist that span the full seasonal spectrum of a microthermal climate. Examining spatial and temporal patterns and processes which control sediment transport and deposition will help predict potential changes in sediment dynamics imposed on these systems (Leonard, 1997; Morris et al., 2002; Mudd et al., 2004). Identifying relationships between hydrodynamics and sediment behaviour as well as characterization of spatial hydrodynamic patterns in mudflat and salt marsh ecosystems also aids the understanding of species habitats (Bouma et al., 2005).

Murray et al. (2008) argue that vegetated tidal marsh platforms may be the environment where the coupling of biophysical processes stands out the most. Three components are working together. These are the biology, the flow, and the sediments. The response of the sediment to the biology and the hydrodynamics control sediment transport on a marsh (D'Alpaos, 2011). There are various factors that have been found to influence sediment dynamics on a salt marsh and these may fall in two categories: opportunity and availability (van Proosdij et al., 2006a). Sediment has to be available and have the opportunity to deposit. When both of these occur simultaneously, deposition of sediment on the bed occurs. Factors falling into the availability category include suspended sediment concentration (Temmerman et al., 2004), flocculation (Christiansen et al., 2000), and meteorological conditions such as rain and wind (Mwamba and Torres, 2002; Murphy and Voulgaris, 2006; French et al., 2008). Opportunity factors include current velocities, turbulence (Christiansen et al., 2000), grain size, water depth, hydroperiod, and the behaviour of vegetation (Yang et al., 2008). Sediment erosion is controlled by the shear stresses applied to the bed from both currents and waves (Woodroffe, 2003; Shi et al., 2012), as well as sediment characteristics such as bulk density (Mehta, 1984; D'Alpaos, 2011). Sediment erosion itself is also controlled by coupled physical and biological processes such as sediment adhesion caused by extracellular polymeric substances secretion which then limits erosion (Garwood et al., 2013).

Suspended sediment concentration is a very important factor because it essentially represents how much sediment in the water column is available for deposition (Ganju et al., 2005; van Proosdij et al., 2006a; O'Laughlin and van Proosdij, 2012). The balance between having higher suspended sediment concentration either during the flood phase or the ebb phase of the tidal cycle is also important. If the incoming suspended sediment supply is higher than the outgoing supply, there is material available to cause the marsh to undergo accretion, while if the suspended sediment concentration is higher during the ebb phase then there is a net loss of sediment and the marsh is likely to be in a deficit of sediment (Fettweis et al., 1998; Dyer et al., 2000b; Davidson-Arnott et al., 2002). The timing of the peaks in concentration can be caused by different processes as well. Fagherazzi et al. (2010) found that incoming suspended sediment concentration was controlled by the presence of wind-derived waves while suspended sediment concentration on the ebb portion of the tide is controlled by local velocities rather than wind-wave conditions (Ralston and Stacey, 2007). Callaghan et al. (2010) found wind-waves to apply a large bed shear stress on the bottom sediment when compared to either tidally driven or wind driven currents.

Rainfall has been found to influence how much sediment is in suspension by resuspending material from the bed (Mwamba and Torres, 2002; Murphy and Voulgaris, 2006) and has also been known to influence creek morphology (Allen, 2000; Davidson-Arnott et al., 2002). The proximity to tidal creeks has also been recognized as an advantage for deposition because the creeks are a source of sediment for the rest of the marsh and receive more sediment supply (Christiansen et al., 2000).

Longer inundation times provide more opportunity for grains to settle (Temmerman et al., 2003b; Voulgaris and Meyers, 2004).

In terms of biology, it is generally accepted that vegetation slows down the velocity of the water in its canopy which in turn can facilitate sediment deposition (Leonard and Reed, 2002; Leonard and Croft, 2006; Neumeier and Amos, 2006a). The attenuation of current velocity within the canopy increases exponentially with increasing stem density (Graham and Manning, 2007). Above the vegetation canopy, the state of the water often becomes more turbulent because of turbulent eddies being emitted from the moving vegetation (Neumeier and Amos, 2006a). The presence of vegetation has two roles: the first is to promote sediment settling within the vegetation, and the second is to protect the substrate, preventing erosion (Townend, 2010).

Even without the presence of vegetation, hydrodynamics control how sediment is being deposited. Flow asymmetry is important for sediment transport (Boon, 1975) as high asymmetry may lead to sediment being transported further inland (van Maren and Winterwerp, 2013).

Some of these factors (e.g. vegetation, concentration) have been shown to vary seasonally. Seasonal variations in salt marsh sediment dynamics are, in part, due to changes in biological activity that occur in summer more than in winter (Hutchinson et al., 1995; Temmerman et al., 2003b). In temperate marshes such as the ones found in the East Coast of Canada, vegetation is a seasonal factor because of its yearly cycle. Another thing that introduces seasonal differences is the present of ice, which can occur between December to April and is able to carry sediments which otherwise may not have been able to make the same trajectory (van Proosdij et al., 2006b). Suspended sediment concentration is another of these factors that have been found to vary seasonally (French et al., 2008; Tao, 2013). This occurs because of increased storms in the winter leading to more waves which are able to cause sediment resuspension. Wiberg et al. (2013) found that in a mesotidal Willapa Bay channel, the difference in mobility of sediment in winter from summer can lead to an order of magnitude difference in concentration values. Coulombier et al. (2012), in a St. Lawrence Estuary study, found the suspended sediment concentration to be higher in winter because of increased wave activity resuspending sediment as well as vegetation being shorter. Suspended sediment concentration in summer was lower because the waves were weaker and the vegetation was at its peak biomass and attenuating the currents close to the bed.

Seasonal patterns are not consistent between salt marshes in different regions. For example in South Carolina, Murphy and Voulgaris (2006) found suspended sediment concentrations to be higher in the summer because of increased input by heavy rainfall. For the Bay of Fundy, where this study was conducted, suspended sediment concentrations are higher in the winter than in the summer months (Tao, 2013). This is hypothesized to be because of more waves in the winter (Mulligan et al., *submitted*), and less biofilms in the winter (Tao, 2013).

The factors which influence sediment transport will be examined and linked to the change in creek morphology. A rough mass balance approach of the sediment budget will be conducted to determine during which time period deposition and erosional events occur. Larger scale changes within the creek as well as tidal cycle scale changes are considered. Objectives are (1) to examine suspended sediment concentration, velocities and sediment flux patterns over single tidal cycles, (2) to determine which factors most influence deposition between marsh zones, (3) to determine which factors vary seasonally and how that impacts seasonal deposition, and (4) to explore the sediment budget of the creek using both a suspended sediment flux method and an elevation change method to assess a sediment budget and explain its seasonal pattern.

2.2 Study Site

The study took place in a tidal creek marsh complex located on Kingsport marsh in the Minas Basin of the Upper Bay of Fundy (Figure 2.1). The Minas Basin is characterized by tidal ranges as high as 16 m (Scott and Greenberg, 1983; Eisma, 1998), and high suspended sediment concentrations (van Proosdij et al., 2009). Intertidal salt marsh suspended sediment concentrations here can range from 30 – 3000 $mg \cdot l^{-1}$ (Amos and Mosher, 1985; O'Laughlin and van Proosdij, 2012). Based on satellite observations, concentrations in the Minas Basin are at their maximum at the end of the winter season and minimum during the end of the summer (Tao, 2013). Because of the large tidal amplitude in the Bay of Fundy, the intertidal zone is extensive.

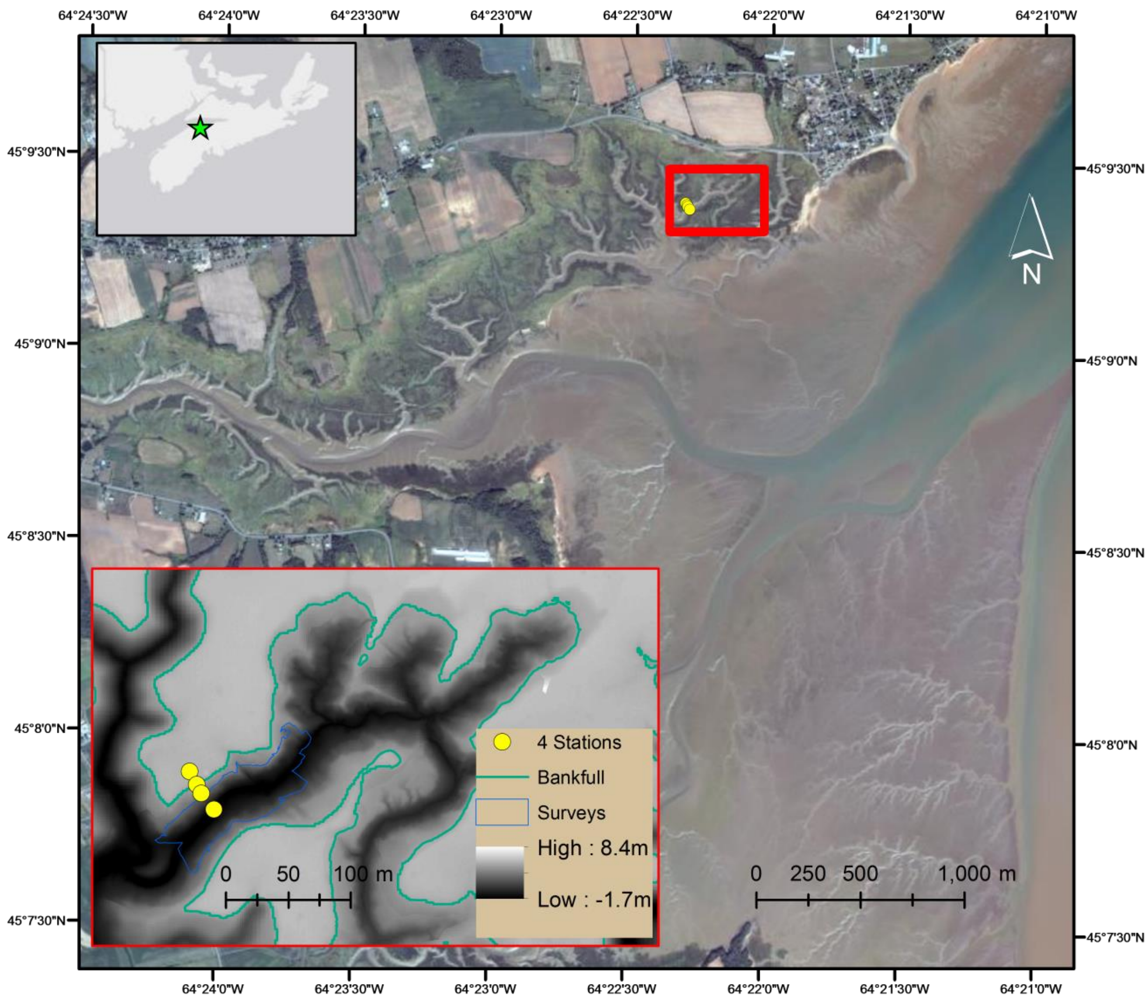

Figure 2.1: Study creek and four sampling stations. Digital elevation model in the red inset box is a mosaic of the LiDAR data and automated total station survey data. The blue outline represents the area that is common between all surveys and was used for the volume calculations.

Kingsport marsh is a temperate marsh which has semidiurnal tides and receives very different meteorological conditions from the summer to the winter. The winter is characterized by an ephemeral ice crust and ice blocks on the marsh which presents a mechanism for sediment transport (van Proosdij et al., 2006b; Argow et al., 2007; Coulombier et al., 2012). Tidal height varied from 6.3 m to a maximum of 8.4 m of water within the creek. The study creek drains an area of 76 000 m^2 and holds a volume of water of 131 000 m^3 at a bankfull level of 5.75 m above mean water level relative to the Canadian Geodetic Vertical Datum of 1928 (CGVD28), which is measured by the mean water level at five tide gauges throughout Canada.

The extensive high marsh is dominated by *Spartina patens* and the low marsh is dominated by *Spartina alterniflora*, which is a common vegetation species found in marshes through the coast of Nova Scotia as well as the eastern coast of the United States (Morris et al., 2002; Mudd et al., 2004; Bowron et al., 2012).

2.3 Methods

Data collection took place from May 2012 to June 2013 with nine deployments to represent seasonal variation. A transect was set up perpendicular to the creek with four stations representing differences in vegetated conditions (Figure 2.1) and position within the tidal frame. The location of this transect was chosen to be representative of the creeks in the Kingsport marsh system. These included the un-vegetated creek thalweg, the marsh bank (tall *S. alterniflora*), the marsh edge, and the marsh surface (dominated by *S. patens*). The transect was positioned across the creek 100 m from the entry of the creek with 112 000 m^3 of the bankfull creek volume on the headward side of the transect. In order to collect data at four locations concurrently, spring tides were chosen because on neap tides the high marsh is often not inundated by water. One exception to the spring tide data collection is the deployment of June 2013 which was during neap tides.

Figure 2.2: Four sampling stations.

Deposition was measured with surface mounted sediment traps which consisted of an exposed preweighed Whatman 5 filter paper between two aluminum plates for sediment to be weighed for deposition and obtain $g{\cdot}m^{-2}$ values (Reed, 1989; van Proosdij et al., 2006a). Three of these traps were deployed per station, per tidal cycle. A shallow water Nortek acoustic Doppler current profiler (ADCP) was deployed on the creek bed to measure velocity in the water column. For 8 of the 9 deployments, it was set in high resolution mode, measuring 98 cells of 3 cm each in order to achieve detailed profiles of the water column. Three Nortek acoustic Doppler velocimeters (ADVs) were used to measure velocity at the marsh stations at a sampling frequency of 16 Hz, for 5-minute intervals every 10 minutes. The ADVs at the marsh surface and marsh edge measured 15 cm above the bed while the ADV at the marsh bank measured 10 cm above the bed. Horizontal velocity (RHV) was calculated using

$$RHV = \sqrt{u^2 + v^2} \qquad (2.1)$$

for the acoustic Doppler velocimeter data where u and v are the two instantaneous horizontal components.

Suspended sediment concentrations were measured with optical backscatter sensors at the marsh surface and marsh bank. Both optical backscatter sensors were calibrated in the field during three tidal cycles of measurements. An RBR data logger was used to measure turbidity, temperature, and salinity in the creek.

An ISCO automated water sampler was deployed at the marsh bank. The perforated nozzle of the ISCO sampler measured 5-20 cm above the bed and sampled 200 mL samples every 15 minutes. Rising stage bottles collected 500 mL samples at 20 cm and 50 cm above the bed at all stations. Rising stage bottles have a tube at the elevation desired to intake water and a second tube at a higher elevation to permit air to leave the bottle when filling (Nolte et al, 2013).

To determine suspended sediment concentration from the water samples, the samples were filtered through preweighed 8.0 µm SCWP Millipore membrane filters which have been shown to have an effective pore size below 1µm (Sheldon, 1972; Hill et al., 2000).

A Campbell-Scientific weather station was installed on site to measure hourly precipitation, air temperature, wind speed, and wind direction. Vegetation biomass samples at the three marsh stations were collected during each deployment with a 20 cm diameter metal ring (Poirier, 2012). The methodology from Neumeier (2005) was followed to determine vertical biomass.

During the study, five high resolution automated terrestrial surveys of the main creek and feeder creek system were conducted using a Trimble VX total station. Two larger surveys were done in May of 2012 and 2013 and three smaller surveys were done in October 2012, February 2013, and July 2013. A mean of 84 093 points per survey were collected with cm level accuracy; the total error of the survey was ± 0.08 m. The larger surveys were done to capture the entire creek network to see how it changed over the one year study period. The smaller surveys were done to capture seasonal changes in surface elevation in the main portion of the creek where the regular deployments were being conducted. The difference in the bankfull volume between these surveys was calculated for each time interval to show the change in volume between different seasons correlating to either net import or export of sediment. Using ArcGIS 10.0, change maps were made by calculating the difference in surface elevation between two time periods to represent the areas of the creek which had positive elevation change and the areas of the creek which had negative elevation change. Positive elevation change is then considered to be accretion and negative elevation change is considered to be erosion.

Instantaneous suspended sediment flux in the creek was calculated using

$$Q_{st(xsa)} = Q_{wt} \cdot SSC_t \qquad (2.2)$$

(Murphy and Voulgaris, 2006), where $Q_{st(xsa)}$ represents the instantaneous suspended flux, SSC_t (g·m^{-3}) is the suspended sediment concentration from the RBR in 10 minute means and Q_{wt} is the 10 minute mean of water discharge through the creek calculated by

$$Q_{wt} = \overline{U}_t \cdot A(h_t) \qquad (2.3)$$

(Murphy and Voulgaris, 2006), where $\overline{U}_t$ (m·s^{-1}) is the 10 minute mean of velocity and $A(h_t)$ is the cross-sectional area calculated using an ArcGIS hydraulic toolbox developed by Graham (2012). For the cross-sectional area during the middle portion of the tide where the banks were overtopped, only the area directly above the creek was considered, and not the area over the marsh surface adjacent to the creek.

Instantaneous suspended sediment flux at the two marsh stations with continuous suspended sediment concentration measurements (the marsh surface and the marsh bank) and also at the creek was calculated using

$$Q_{st(column)} = SSC_t \cdot \overline{U}_t \cdot W \cdot h_t \qquad (2.4)$$

(van Proosdij, 2001). Q_{st}(g·s^{-1}) is the mean instantaneous sediment flux which was calculated for every 10 minute mean throughout the tidal cycle. SSC_t (g·m^{-3}) is the 10 minute mean of suspended sediment concentration while $\overline{U}_t$ (m·s^{-1}) is the 10 minute mean of velocity. W is a 1 m wide portion of the water column and h_t (m) is the height of the water depth during the 10 minutes. Because suspended sediment concentrations and marsh velocities were point measurements at 10 cm above the bed for the marsh bank and at 15 cm above the bed for the marsh surface, using the water depth in the sediment flux calculations assumes that the conditions are the same throughout the water column.

The total sediment flux over the tidal cycle, Q_s (kg), was then obtained by

$$Q_s = \sum_{i=1}^{n-1} \frac{y_i + y_{i+1}}{2} (x_{i+1} - x_i) \qquad (2.5)$$

(van Proosdij, 2001) where y_i is the instantaneous suspended flux at time x. Calculating sediment flux is complicated by the assumption that all sediment supply on the flood is input material and all sediment supply on the ebb is output material (Coco et al., 2013). The net Q_s is therefore the rough mass balance (van Proosdij, 2001).

For seasonal analysis, tides were divided into three groups: spring, summer, and winter, to represent similarities in vegetative and meteorological conditions. Spring includes May 2012, May 2013, and June 2013; summer includes July 2012, August 2012, and September 2012; and winter includes November 2012, January 2013, and March 2013.

2.4 Results

Nine deployments resulted in data collection over 62 tides. A summary of data collected during these tides is presented in Table 2.1. These tides were divided into three categories of 'spring', 'summer', and 'winter'. 720 trap samples were collected however 156 of these were collected during tides in which rain occurred, and therefore are not included in the statistical analysis of the deposition or the mean deposition results but will be considered in the discussion.

2.4.1 Sediment Deposition

Sediment deposition was highest at the creek thalweg (C4) with a mean value of 56.4 $g \cdot m^{-2}$, intermediate on the marsh bank (M3) with a mean value of 30.9 $g \cdot m^{-2}$ and lowest at both the marsh edge (M2) and marsh surface (M1) which were similar with values of 15.5 $g \cdot m^{-2}$ and 15.3 $g \cdot m^{-2}$ respectively. A Kolmogorov-Smirnov test run on the depositional data showed the data to be non-normal, therefore the Kruskal-Wallis test was used for further analysis. A Kruskal-Wallis test rejects the null hypothesis that the deposition rates do not differ among sites (p=0). The creek thalweg was significantly different from all other stations and the marsh bank was significantly different from all other stations while the marsh edge and the marsh surface were not significant between each other and experienced similar deposition values (Figure 2.3).

Table 2.1: Summary of data collection for a) 'Spring' (n=25), b) 'summer' (n=15), and c) 'winter' (n=22) category tides. ✓ indicates the samples were good to use for all intended purposes, ⊗ indicates data were collected but not complete or ideal (rain on traps, incomplete time series), and × indicates that the data were unable to be used or not collected.

a) Spring Tide	ADCP Max Height (m)	V1	V2	V3	IS-CO	AD-CP	RBR	Level logger	M1 Trap	M2 Trap	M3 Trap	C4 Trap	Daily scrape
May5am '12	7.9	✓	✓	×	×	✓	✓	✓	✓	✓	✓	✓	✓
May5pm '12	7.6	✓	✓	✓	✓	⊗	✓	✓	✓	✓	✓	✓	
May6am '12	8.3	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
May6pm '12	7.8	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
May7am '12	8.4	✓	✓	✓	×	✓	✓	✓	⊗	⊗	⊗	⊗	✓
May7pm '12	7.9	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
May8am '12	8.4	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
May8pm '12	7.8	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
May9am '12	8.1	✓	✓	✓	✓	✓	✓	✓	⊗	⊗	⊗	⊗	✓
May25am '13	8.0	✓	✓	✓	✓	✓	✓	✓	⊗	⊗	⊗	⊗	✓
May25pm '13	7.5	✓	✓	✓	⊗	✓	✓	✓	✓	✓	✓	✓	
May26am '13	8.3	✓	✓	✓	✓	✓	✓	✓	⊗	⊗	⊗	⊗	✓
May26pm '13	7.7	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
May27am '13		✓	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	✓
May27pm '13		✓	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	
May28am '13	8.1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Jun8am '13	6.8	✓	✓	✓	✓	✓	✓	✓	⊗	⊗	⊗	⊗	✓
Jun8pm '13	6.4	×	✓	✓	✓	✓	✓	×	⊗	⊗	⊗	⊗	
Jun9am '13	6.8	✓	✓	✓	✓	✓	✓	✓	⊗	⊗	⊗	⊗	✓
Jun9pm '13	6.3	×	✓	✓	✓	✓	✓	×	×	✓	✓	✓	
Jun10am '13	6.9	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Jun10pm '13	6.3	×	✓	✓	✓	✓	✓	×	×	✓	✓	✓	
Jun11am '13	6.7	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Jun11pm '13	6.3	×	✓	✓	✓	⊗	✓	×	×	✓	✓	✓	
Jun12am '13	6.5	✓	✓	✓	✓	✓	✓	✓	⊗	⊗	⊗	⊗	✓

b) Summer Tide	ADCP Max Height (m)	V1	V2	V3	IS-CO	AD-CP	RBR	Level logger	M1 Trap	M2 Trap	M3 Trap	C4 Trap	Daily scrape
July4am '12	8.1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
July4pm '12	7.5	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
July5am '12	8.1	✓	✓	✓	✓	✓	✓	✓	⊗	⊗	⊗	⊗	
July5pm '12	7.5	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×
July6am '12	7.8	✓	✓	✓	✓	✓	✓	✓	⊗	⊗	⊗	⊗	
Aug4am '12	7.8	✓	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Aug4pm '12	7.4	✓	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Aug5am '12	7.5	✓	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Sep17am '12	7.6	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sep17pm '12	7.8	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sep18am '12		✓	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	
Sep18pm '12	8.0	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sep19am '12	7.6	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Sep19pm '12	7.9	✓	✓	✓	✓	✓	✓	✓	⊗	⊗	⊗	⊗	✓
Sep20am '12	7.4	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	

c) Winter Tide	ADCP Max Height (m)	V1	V2	V3	IS-CO	AD-CP	RBR	Level logger	M1 Trap	M2 Trap	M3 Trap	C4 Trap	Daily scrape
Nov14am '12	7.6	✓	✓	✓	✓	✓	✓	×	⊗	⊗	⊗	⊗	✓
Nov14pm '12	8.3	✓	✓	✓	×	✓	✓	×	⊗	⊗	⊗	⊗	
Nov15am '12	7.8	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	✓
Nov15pm '12	8.3	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	
Nov16am '12	7.8	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	✓
Nov16pm '12	8.2	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	
Nov17am '12	7.6	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	✓
Jan11pm '13	8.3	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	✓
Jan12pm '13	8.4	✓	✓	✓	✓	✓	×	×	✓	✓	✓	✓	✓
Jan13am '13	7.9	✓	✓	✓	×	✓	×	×	✓	✓	✓	✓	✓
Jan13pm '13	8.3	✓	✓	✓	✓	✓	×	×	✓	✓	✓	✓	
Jan14am '13	7.9	✓	✓	✓	×	✓	×	×	×	×	×	×	✓
Jan14pm '13	8.1	✓	✓	✓	✓	✓	×	×	✓	✓	✓	✓	
Jan15am '13	7.6	✓	✓	✓	✓	✓	×	×	✓	✓	✓	✓	✓
Mar27pm '13	7.7	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Mar28am '13	7.9	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Mar28pm '13	7.9	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Mar29am '13	8.2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Mar29pm '13	8.0	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Mar30am '13	8.3	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Mar30pm '13	7.8	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Mar31am '13	8.1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

On average, there was 2.7 times more sediment deposited in the creek thalweg compared to the mean of the three marsh stations. When taking all stations into account, the highest deposition occurred in November, January, and March, the three deployments with the colder temperatures. The higher mean value of deposition during these deployments was mostly attributable to increases in deposition at the creek thalweg and marsh bank stations. When considering individual tides rather than seasonal groups, the creek thalweg and the marsh bank were also much more variable than the marsh edge and the marsh surface. This can be observed by the outliers indicated with the red plus symbols in Figure 2.3 as well as the error bars in Figure 2.4. Outliers in Figure 2.3 are present at the four stations, and are all, with the exception of one point for the marsh edge, on the greater side of the median. That shows that abnormal deposition events are events of greater deposition, and not of less deposition. An exception to that, of course, is when the area is not inundated by water because of low tidal amplitude.

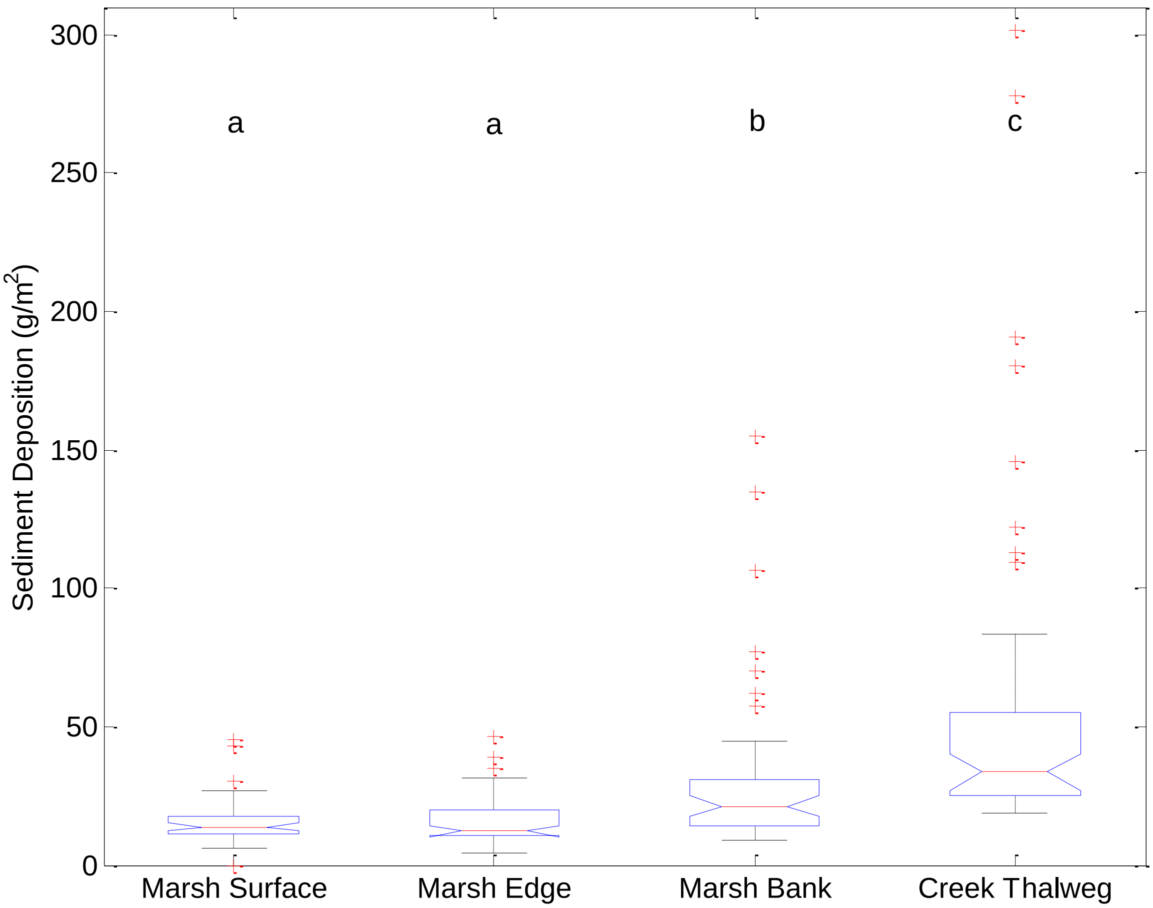

Figure 2.3: Boxplot of sediment deposition per station. The red line is the median, the edges of the blue box are the 25th and 75th percentiles, the black whiskers extend to the extreme data points not considered outliers, and the red plusses are outliers. Outliers are determined if data points are > q3+w(q3-q1) or <q1-w(q3-q1) where w is the whisker length, q1 is the 25th percentile and q3 is the 75th percentile. The letters (a, b, and c) represent a significant difference between groups without a common letter from Kruskal-Wallis tests being run on only two groups at a time.

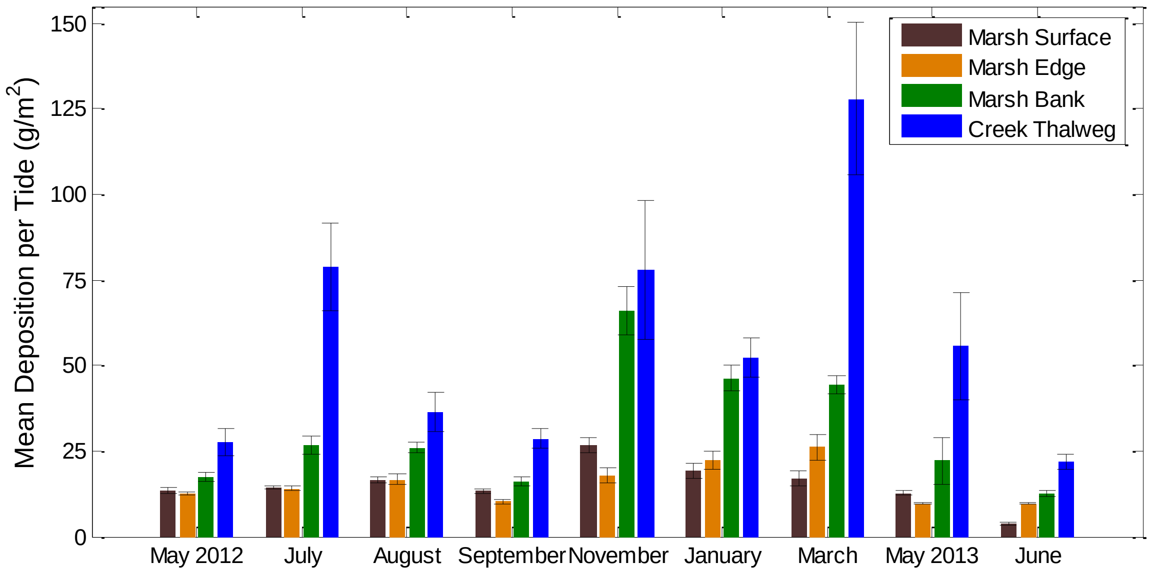

Figure 2.4: Mean sediment deposition per tide per deployment. Error bars are indicating standard error. 567 trap samples are included.

At the marsh edge and marsh bank stations, a Kruskal-Wallis test shows the winter season to be significantly different from the spring and summer seasons while the spring and summer share similarities in deposition values (Figure 2.5b,c). At the marsh surface and the creek thalweg, the spring and winter are the only two seasons that are significantly different from each other. The variability of values is greatest at the marsh bank and creek thalweg, while the marsh edge and marsh surface do not experience extreme values and values are all lower than 50 $g \cdot m^{-2}$. Figure 2.5 also shows that the variability in the marsh bank and creek thalweg includes more extreme values of greater deposition rather than lower deposition.

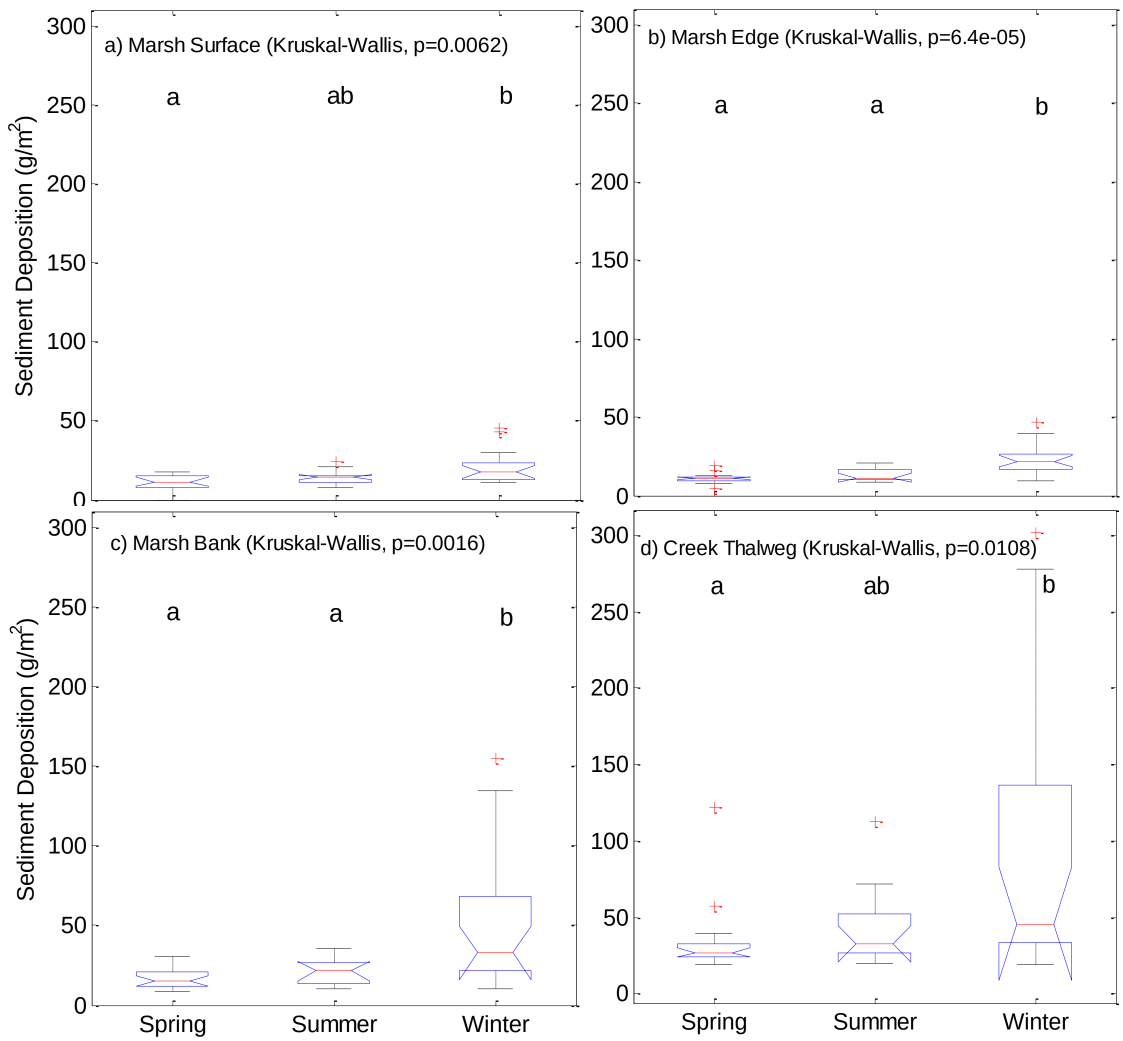

Figure 2.5: Boxplots of sediment deposition at the four stations. (a)Marsh surface, b) marsh edge, c) marsh bank, and d) creek thalweg. The red line is the median, the edges of the blue box are the 25th and 75th percentiles, the black whiskers extend to the extreme data points not considered outliers, and the red plusses are outliers. Outliers are determined if data points are > q3+w(q3-q1) or <q1-w(q3-q1) where w is the whisker length, q1 is the 25th percentile and q3 is the 75th percentile. The letters (a and b) represent a significant difference between groups without a common letter from Kruskal-Wallis tests being run on only two groups at a time.

2.4.2 Surface Elevation Change

From the five topographic surveys, elevation change maps were produced (Figure 2.6), to determine areas with positive net elevation change and areas with negative net elevation change. Areas of positive elevation change and a decrease in water volume represent a period of deposition. Areas of negative elevation change and an increase in water volume represent a period of erosion. These elevation change maps include the surface area of the creek below the vegetation, as the vegetation was a barrier to surveying the marsh surface. Data points which were taken where vegetation or water was present were omitted. Overall, there was a net loss of material when considering the entire creek system from the larger surveys which were conducted only twice, in May 2012 and May 2013. There was also a net loss when considering only the main part of the study creek. When considering the entire creek system below bankfull level on the upcreek side of the transect, the volume of water filling that creek system increased by 1279 m^3. When considering only the main creek data and excluding the tributary creeks, there was a net change of an additional 79 m^3 of water to fill the creek to bankfull. The source of this gain of volume in the specific creek comes mainly for the period of October 2012 to February 2013. This was the period with the most net negative elevation change and the largest change in volume with a value of 131 m^3 more in February than October. The period from October to February had the most winds above 10 $m \cdot s^{-1}$ (Figure 2.6). The two time periods between February and July both had a negative change in volume therefore positive elevation change. The positive elevation change values seen in the VX survey change maps (Figure 2.6) throughout most of the creek agree with the high deposition values on the creek traps, such as the traps during the March deployment.

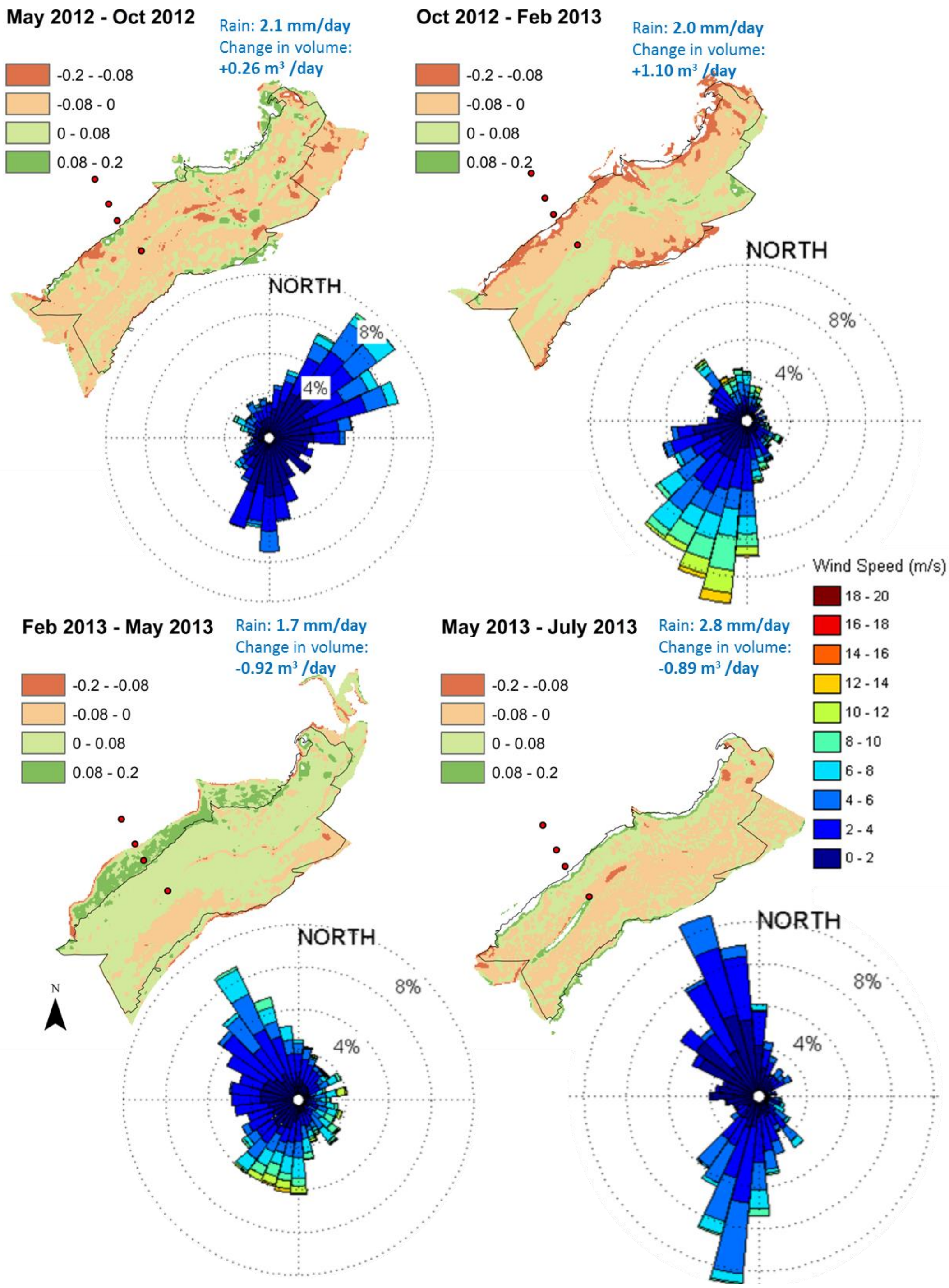

Figure 2.6: Change in elevation in metres between different surveying periods from the elevation maps for the indicated intervals. Negative elevation change (red) and positive change in volume represent erosion while positive elevation change (green) and negative change in volume represent accretion. The wind roses represent the corresponding dates included in the change maps. The black outline represents the area that is common between all surveys and was used for the volume calculations. The four red dots represent the four sampling stations.

2.4.3 Suspended Sediment Concentration

Suspended sediment concentration was highest at the creek thalweg with a mean value of 275 $mg \cdot l^{-1}$ from the RBR, intermediate at the marsh bank with a mean value of 106 $mg \cdot l^{-1}$ from OBS measurements, and lowest at the marsh surface with a mean value of 53 $mg \cdot l^{-1}$ also from OBS measurements.

This trend is seen in the RBR and OBS data as well as with the incoming suspended sediment concentration data from the rising stage bottles. A Kruskal-Wallis test on the rising stage bottles show the creek thalweg and the marsh bank to each be significantly different ($p<0.05$) from all other stations while the marsh surface and the marsh edge were not significantly statistically different from each other. Running Kruskal-Wallis tests on each station for seasonal variability in rising stage bottles, only the creek thalweg shows the winter to be significantly higher ($p<0.05$) than both spring and summer**.** The time series concentration agrees slightly more with the deposition data, with the creek thalweg and the marsh surface showing that the winter is significantly higher than the spring and summer. The marsh edge did not have an optical backscatter sensor but with other parameters (deposition, incoming suspended sediment concentration) being so similar, the marsh edge can be thought of as a proxy of the marsh surface.

The suspended sediment concentrations at the creek thalweg showed pronounced peaks on the initial flood period of the tide as well as at the final ebb stage (Figure 2.7) (Dyer et al., 2000a; Voulgaris and Meyers, 2004; van Proosdij et al., 2006a; Hill et al., 2013). In the creek thalweg, November and January had the highest concentrations both in their incoming and outgoing peaks as well as in the sustained concentration during the middle of the tide. At the marsh bank and the marsh surface, the colder temperature months were not significantly different from the other deployments. Concentration at the marsh bank was more variable than at the marsh surface.

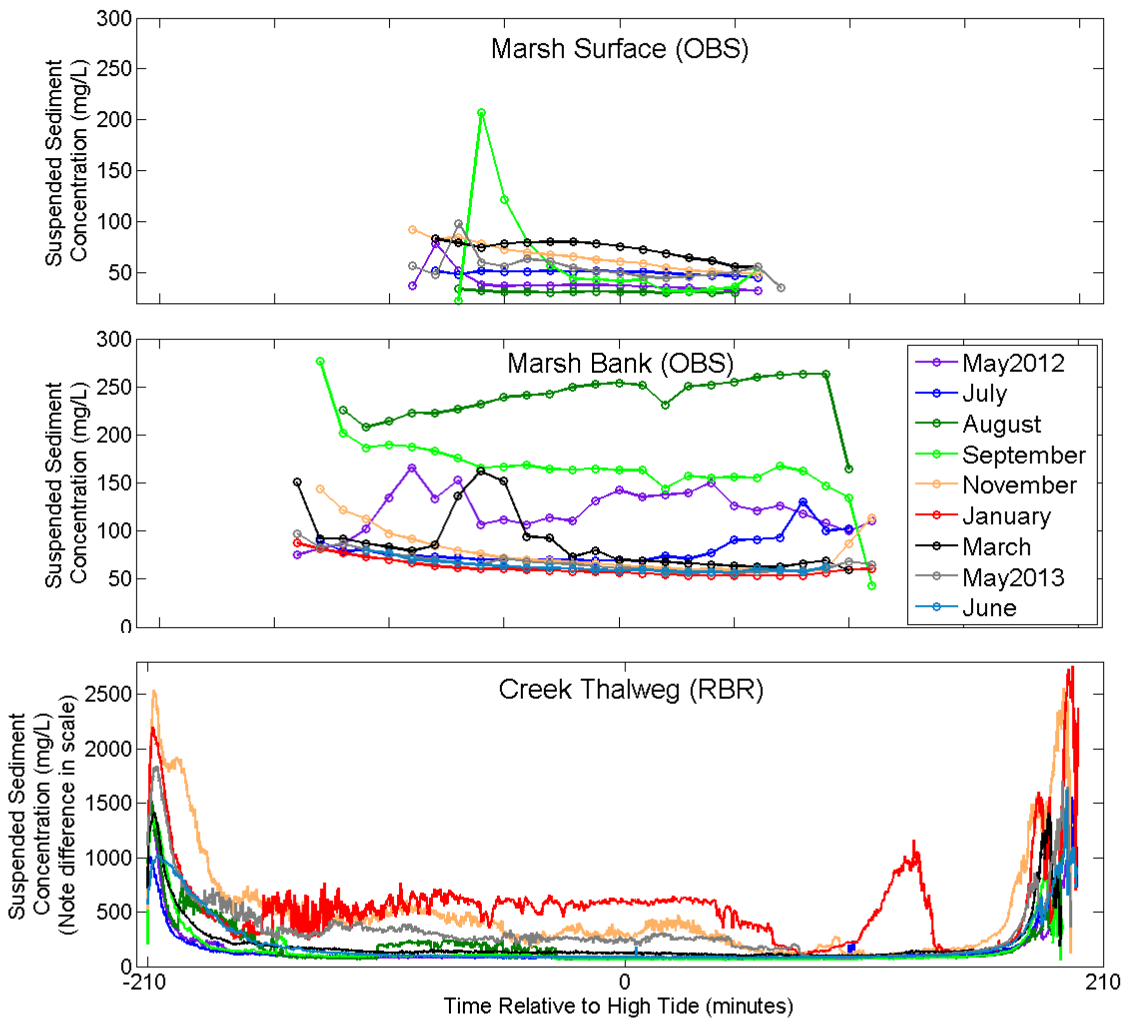

Figure 2.7: Suspended sediment concentration at the marsh surface, marsh bank and creek thalweg. Each line represents a mean of all tides during that deployment. Note difference in scale.

In fact, at the marsh bank concentrations were high during summer deployments. Suspended sediment concentrations from the rising stage bottles at 20 cm above the bed in November, January and March were high with values of 1656 $mg \cdot l^{-1}$, 777 $mg \cdot l^{-1}$ and 536 $mg \cdot l^{-1}$. Other than May 2013 with an incoming suspended sediment concentration of

1512 mg·l^{-1}, all other deployments had incoming suspended sediment concentrations lower than 500 mg·l^{-1}.

On several tides, there was more rainfall than others. The days where rain occurred are presented in Table 2.2. June 8th was the day of post tropical storm Andrea which brought 62.4 mm of rain. The period of May to July experienced the most intensive rainfall with a mean of 2.8 mm per day. Other notable days are September 19th, November 14th, and May 25th. The suspended sediment concentration in the creek thalweg following rainfall increased. This was seen in the ADCP backscatter during the tides following a rain event. The suspended sediment concentration on the marsh was not as influenced, perhaps because of the protective influence of the vegetated canopy when the rainfall hit the bed.

*Table 2.2: Precipitation totals on deployment days with precipitation occurring. *June 8th was the passing of post tropical storm Andrea.*

Date	Precipitation (mm)
May 9	1.3
July 5	4.3
Sep 19	8.0
Nov 14	16.4
Mar 27	4.7
May 25	11.9
June 8*	62.4

2.4.4 Water velocity

Magnitudes of velocities were flood dominant at the marsh bank, and were more symmetrical with increasing distance from the creek thalweg. The marsh surface, the furthest station from the creek, had certain tides which showed slight ebb dominance as can be seen in September and November in Figure 2.8a. At the three marsh stations, most magnitudes of velocities are in the range of 1-3 $cm \cdot s^{-1}$. There is no significant difference between the time-averaged speeds at these three marsh stations with a Kruskal-Wallis p value of 0.549. There were some exceptions to this range, one being the flood velocities on the marsh bank which reached 9 $cm \cdot s^{-1}$ at their maximum. Magnitudes of depth averaged velocities peaked at 25 $cm \cdot s^{-1}$ with a larger portion of the tides being around 15 $cm \cdot s^{-1}$ (Figure 2.8d). Magnitudes of velocities in the thalweg were depth averaged because they were collected with the ADCP which measured 3 m of the water column.

The marsh bank is the station that showed the most tidal asymmetry with clear flood dominance (Figure 2.8c). Magnitudes of depth averaged velocities in the creek thalweg (Figure 2.8d) experienced two high peaks during the flood and one high peak during the ebb. This made for overall higher magnitudes of velocities on the flood than on the ebb for the two stations in the confined creek. Above the creek on the marsh edge and marsh surface there was no flood dominance, and at the marsh surface station there was slight ebb dominance.

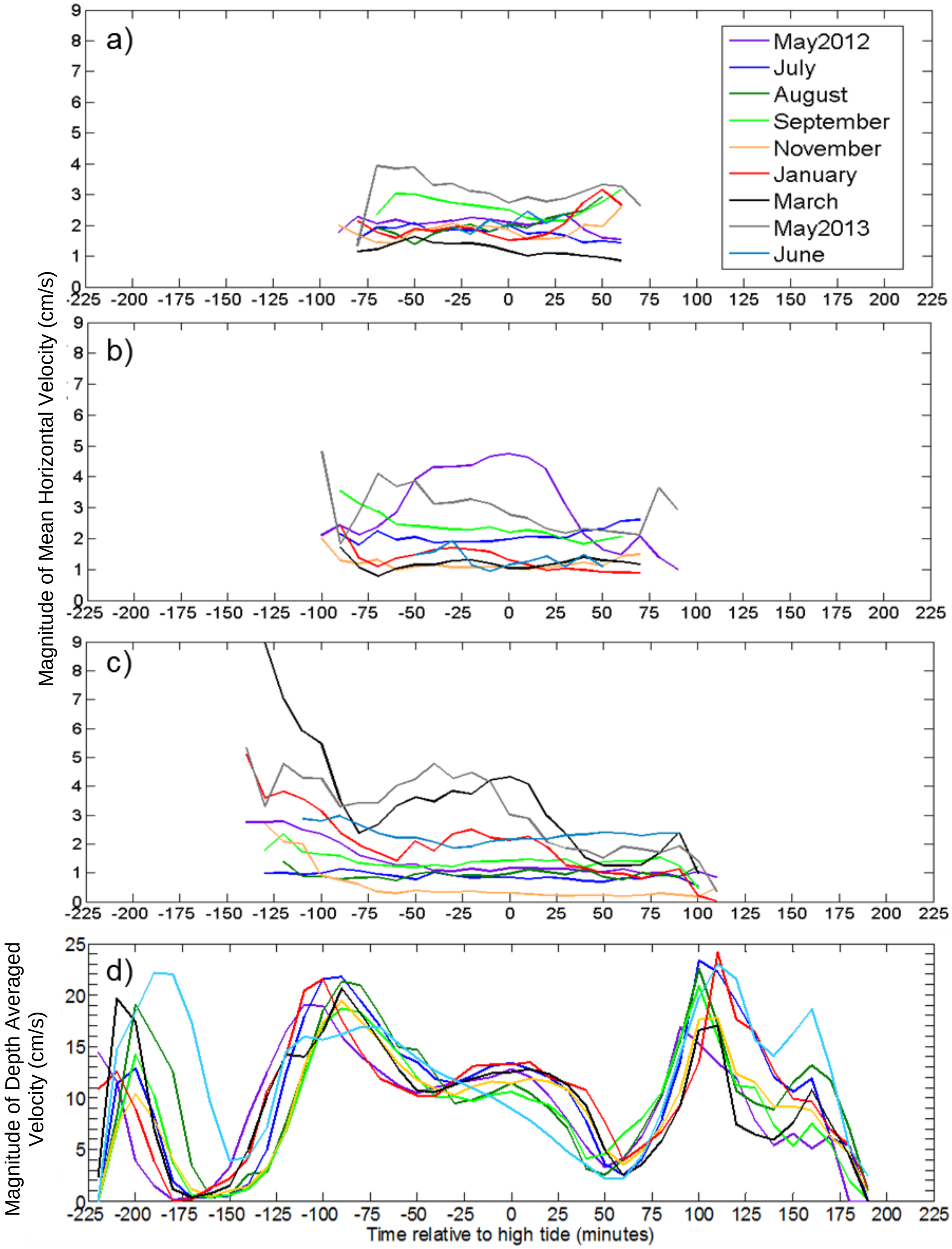

Figure 2.8: Magnitudes of mean horizontal velocity per deployment at a) the marsh surface, b) the marsh edge, c) the marsh bank, and d) the depth averaged velocity per deployment at the creek thalweg (note difference in scale).

2.4.5 Sediment Flux

Magnitudes of sediment flux values were much higher in the creek thalweg than on the marsh, resulting primarily from the higher suspended sediment concentrations as well as the deeper water levels. Figure 2.9a and 2.8b represent $Q_{st(column)}$ which is the instantaneous suspended sediment flux for a 1-m wide water column of depth h, while Figure 2.10 represents $Q_{st(xsa)}$ which is the instantaneous suspended sediment flux for the entire cross sectional area. The flux values for $Q_{st(xsa)}$ are much higher than those of $Q_{st(column)}$ if the same velocity and concentration parameters are used. In either case the suspended sediment flux in the creek is much higher than the marsh bank or marsh surface.

At the creek, magnitudes of suspended sediment flux values were highest in November and January, with March having slightly higher values than the spring and summer deployments. At the marsh bank, magnitudes of sediment flux values from March, September, and May 2013 were the highest with a few tides in May 2012 being high. At the marsh surface, the few tides that had high magnitudes of suspended sediment flux values were May26pm, Sep19am, and Sep19pm.

The creek thalweg had a more regular pattern of magnitudes of sediment flux throughout the tidal cycle than did the marsh edge and marsh surface, with the majority of the tides in the creek thalweg having peaks and lows at the same time periods. In the thalweg, one instance of peak flux occurs 90-100 minutes after high tide when the water level is once again confined to the creek. This increase occurs approximately 20-30 minutes after the change in flow direction measured by the ADCP.

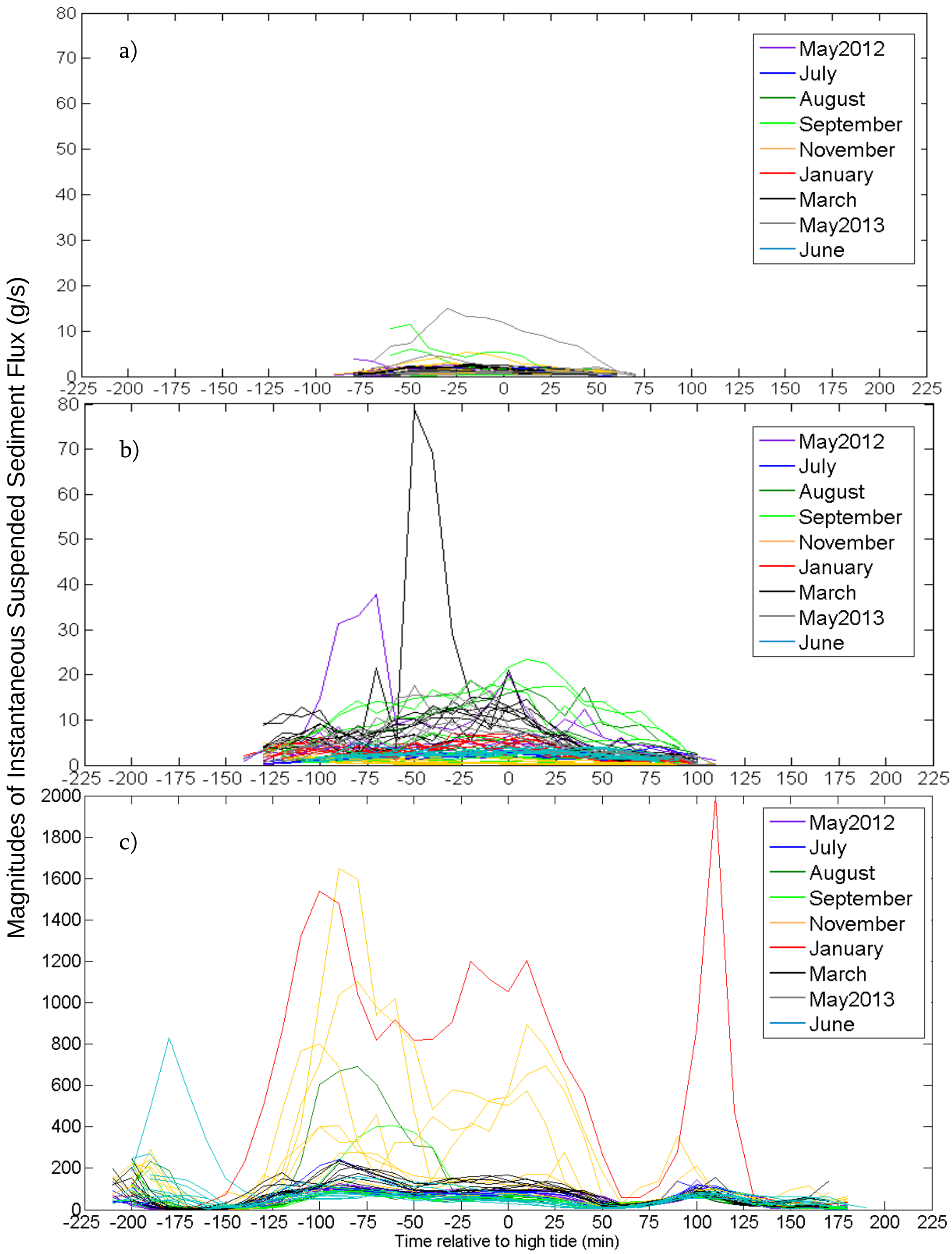

Figure 2.9: Magnitudes of instantaneous suspended sediment flux $Q_{st(column)}$ *at a) the marsh surface, b) the marsh bank, and c) in the creek per tide (note difference in scale). These figures represent the flux calculated with a 1* m^2 *column of water.*

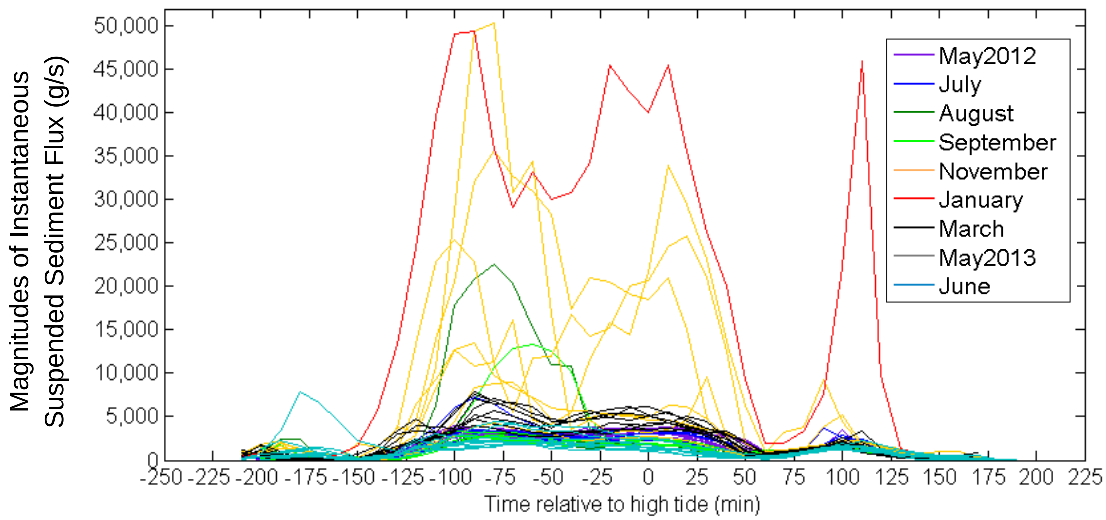

Figure 2.10: Magnitudes of instantaneous suspended sediment flux $Q_{st(xsa)}$ *in the creek. This figure represents the flux when using the cross sectional area of water at different depths.*

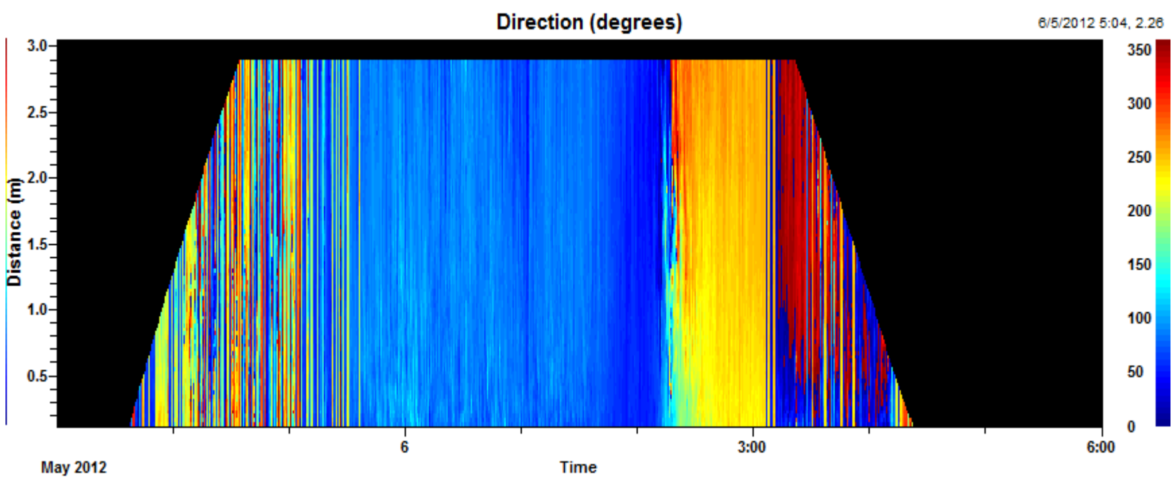

Figure 2.11: Direction of water current in the creek during May6am tide, of which the pattern is characteristic of most tides sampled. High tide on May6am was at 1:12.

The total sediment flux Q_s in the creek was positive for all tides. High import tides corresponded to tides with the high instantaneous suspended sediment flux (Figure 2.9c). All tides have higher peaks of instantaneous suspended sediment flux before high tide than they do after high tide.

With the sediment flux and the surface area known, the residual flux of sediment which would be left in this creek system can be extrapolated to an estimated mass of sediment deposited in the creek system over set time periods. To compare it to the time periods examined with the topographic surveys, residual fluxes of the tides collected were extrapolated to the time intervals between the topographic surveys (Table 2.3). Using the density of a silt sized particle of quartz, 2.798 $g \cdot cm^{-3}$, a sediment layer thickness was also estimated (van Proosdij et al., 2014). Table 2.3 is presented with the assumption that all tides within the set intervals have the same sediment flux values as the tides for which data were collected. Therefore, Table 2.3 is only a theoretical representation and an estimation because of the conditions assumed. A sediment layer thickness was also calculated with the values of volumes calculated from the topographic surveys (Table 2.4). The reason that Table 2.3 and Table 2.4 are contradictory is that Table 2.3 only considers the tides for which velocity and concentration data were collected, and these tides do not represent the entire time intervals. For example, the time period of October to February was the time period with the strongest winds, but the tides for which data were collected during this interval were uncharacteristically calm.

Table 2.3: Imported sediment from sediment flux calculations extrapolated to cover creek surface area based on tidal cycle data. The estimated depth of sediment layer is calculated using a silt particle density of 2.798 g·cm^{-3}.

Interval (between surveys)	Mean residual flux per tide (kg)	Days in interval	Total import (kg) based on tides collected	Surface area at bankfull (5.75m) (m^2)	Imported sediment covering creek banks (kg·m^{-2})	Estimated depth of sediment layer (cm)
May 2012 to Oct 2012	16882	145	4 895 763	76 124	64	2.3
Oct 2012 to Feb 2013	76091	120	18 261 888		240	8.6
Feb 2013 to May 2013	21404	100	4 280 764		56	2.0
May 2013 to July 2013	14259	47	1 340 356		18	0.6

Table 2.4: Estimated depth of sediment layer based on topographic survey elevation changes.

Interval (between surveys)	Change in volume of water (m^3)	Surface area common for all surveys (m^2)	Estimated depth of sediment layer (cm)
May 2012 to Oct 2012	40	4812	-0.83
Oct 2012 to Feb 2013	131		-2.74
Feb 2013 to May 2013	-92		1.91
May 2013 to July 2013	-42		0.87

2.4.6 Biomass

The months of August and September were the months with most vegetation present. Total biomass of the vegetated stations is presented in Figure 2.12. Living vegetation biomass varies considerably more than dead vegetation biomass. The marsh bank, the station where *Spartina alterniflora* is dominant, was the station with the most biomass. Over the whole study period, the marsh bank had the highest mean living biomass with 214 g·cm^{-2}, while the same station had the lowest mean dead biomass with 111 g·cm^{-2}.

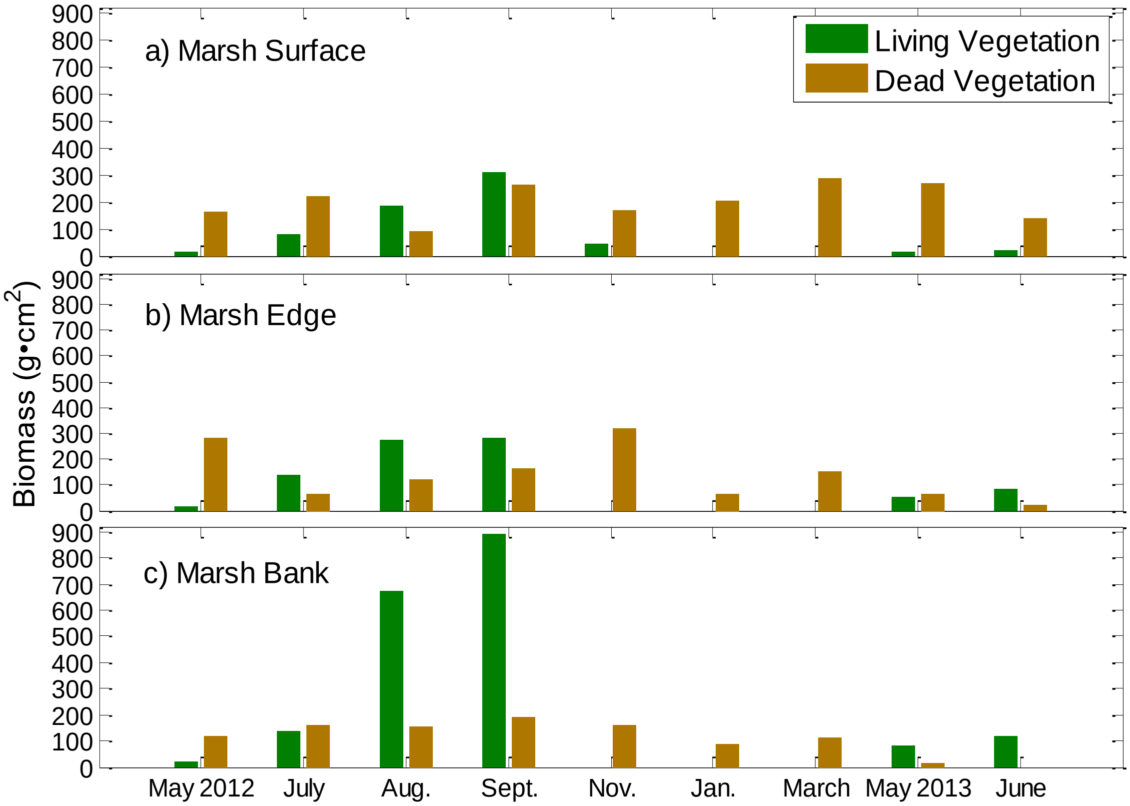

Figure 2.12: Biomass of living and dead vegetation per deployment for a) marsh surface, b) marsh edge, and c) marsh bank.

2.5 Discussion

Seasonal ecomorphodynamics were examined both in the creek and on the marsh surface as the interplay between the biological and the physical processes are crucial to salt marsh functioning and evolution (Fagherazzi et al., 2012). Over the time frame and portion of the Kingsport creek studied, although there is high seasonal variability, the system appears to be near equilibrium, with a volume change of only 79 m^3 for the amount of water it would take to fill the creek to bankfull. Both sediment deposition and erosion were higher in the winter with more sediment available in the system because of increased storm activity and higher suspended sediment concentrations. In the winter, vegetation was also lower, therefore causing an increase in erosion because of lack of bed protection from the vegetation.

The seasonal component was large enough to influence the deposition at all stations, but the difference in the winter deposition and the spring and summer deposition was greatest in the creek thalweg and on the marsh bank. The extra sediment in the system, caused by increased erosion of the creeks and flats in the winter, stayed confined to the creeks. Although the marsh edge and marsh surface did show increased deposition in the winter as well, the deposition values were not as variable. This can be observed in Figure 2.4 showing the deposition by station between deployments. This is contradictory to results from Leonard (1997) who demonstrated that the lack of vegetation or less vegetation in the winter should cause lower rates of deposition. The results from this study may differ from the Leonard (1997) study for two reasons. Firstly, the study was conducted in North Carolina where the winter conditions are different from the Bay of Fundy and the vegetation may play a larger role there because of the lack of ice. Because meteorological conditions are more similar year round in Leonard (1997), the seasonal differences in above ground biomass are lower. Secondly, the tidal amplitude is smaller at the Leonard (1997) site and the vegetation occupied more of the water column. Although there was no ice during the March deployment of the present study, a site visit in February confirmed many large ice blocks containing sediment were present on the marsh surface (Figure 2.13). Although the flow velocities were dampened by the dense vegetation canopy and slowed down by not being restricted by the tidal creek, as the water flowed over the marsh surface (Davidson-Arnott et al., 2002), even these slow velocities alone were not enough to promote sediment deposition on a comparable level to the sediment being deposited in the creek thalweg.

Figure 2.13: Evidence of ice being present on the marsh between the January and March deployments. Photo was taken February 19th 2013, with a 1.5 m rod for scale.

Because suspended sediment concentrations are high before sediment reaches the areas of dense vegetation canopy, and lower on the marsh surface itself, this implies sediment is depositing before it reaches the dense vegetation, agreeing with observations by with Neumeier and Ciavola (2004) in Portugal. As shown by the rising stage bottles, this clearing of sediment occurs in the tidal creek and does not leave enough sediment supply to the marsh for the vegetation to be a major factor in causing sedimentation. High incoming suspended sediment concentrations are of high importance for deposition in proximity to the creek thalweg. The cause of this is that high suspended sediment concentrations lead to rapid deposition of sediment, as Kranck (1980) and Milligan et al. (2007) explain and show in a laboratory experiment. When the incoming suspended sediment concentrations were high, sediment deposited earlier during the tide, which leads to more deposition at the creek thalweg and at the marsh bank. As more sediment had deposited during the earlier portion of the tide, the concentration had returned to a value typical of any other tide once the water had reached the marsh edge and marsh surface. Therefore, there was no large increase in deposition at the marsh edge and marsh surface. Effectively, processes on the marsh are being controlled by the preceding processes occurring in the creek. This situation was most prominent during the deployments which occurred in the colder temperatures (November, January, and March).

These winter tides brought higher suspended sediment into the creek thalweg because of stronger winds, therefore likely leading to stronger wave activity disturbing the material on the bed (Christie et al., 1999; Mulligan et al., *submitted*) as well as the winter having the additional mobilization of sediment by ice (van Proosdij et al., 2006b). The increase in incoming suspended sediment concentration during the months of October to March was also seen by Temmerman et al. (2003a) in the Scheldt estuary, where a positive correlation was recorded between incoming suspended sediment concentration and duration of tidal inundation. Christiansen et al. (2000) also saw a positive correlation between suspended sediment concentration in the creek thalweg and tidal inundation. Temmerman et al. (2003a) saw this correlation stronger in the winter than in the summer. In the study here, although incoming suspended sediment concentration varies and is higher in the winter, it does not correlate with tidal inundation. This may be because this site is hypertidal which means that the relative difference in tidal inundation between tides is not as great. A likely contributor to the absence of correlation between tidal inundation and deposition is that most of the tides sampled at Kingsport were spring tides in order to allow for data to be collected on the high marsh. The tides sampled, therefore, with the exception of June, represent only the higher portion of the natural tidal height distribution that occurs over the months. The smallest net sediment flux values on the marsh bank occurred in June, which indicates that less sediment gets to the marsh on these tides of lower amplitude.

Similar deposition rates at the marsh surface and marsh edge stations ($p=0.747$), demonstrates that beyond the beginning of the high marsh, the distance from the creek is not a controlling factor for deposition. This is primarily because most of the sediment has already deposited once the water gets to the high marsh, as already mentioned. Moreover, high suspended sediment concentration on the incoming portion of the tide was highly correlated with sediment deposition at the creek thalweg and marsh bank stations.

The spatial deposition pattern is that there is more deposition closer to the sediment source, agreeing with Christiansen et al. (2000). As the source of sediment was lower in elevation, there was less deposition at the marsh edge and the marsh surface (Richard, 1978; Chmura et al., 2001). This spatial deposition pattern, showing that deposition occurs lower in the tidal frame, also agrees with research from Allen and Duffy (1998) who found this to occur in the Severn estuary. The two high marsh stations also receive similar inundation times although the marsh edge is covered by water for slightly longer because it is 41 cm lower in elevation than the marsh station.

The seasonal trend shown in the depositional values differs from the pattern of Leonard (1997) which showed higher deposition during the summer months. At Kingsport marsh, greater biomass did not lead to higher deposition on the bed. This is inconsistent with other studies (Neumeier and Amos, 2006a; Mudd et al., 2010), where the vegetation acted as an aid to reduce the turbulence therefore enhancing sediment deposition. The fact that the vegetation was always fully submerged (with the exception of the lower tidal amplitude tides during the June 2013 deployment) may be the reason that it was not as effective at trapping and depositing sediment (Yang et al., 2008). Mean values of relative roughness ratios, of the maximum height of the vegetation to the maximum water depth, were 0.41, 0.22, and 0.13 for the marsh surface, marsh edge, and marsh bank respectively. These values show that the marsh bank is inundated by deeper water, and that all three marsh stations are inundated with water more than double their height.

Higher sediment concentrations in May 2013 can be attributed to the high flood velocities which exceeded 6 $cm \cdot s^{-1}$ for four of the seven tides at the marsh bank. This is well above the typical values of 1 – 3 $cm \cdot s^{-1}$ seen in most deployments. As a result, bed shear stress values were higher and would have had greater potential to suspend material from the bed on the flood tide (O'Laughlin and van Proosdij, 2012). These high velocities and shear stresses may have been due to strong winds during these tides.

March also had high incoming velocities at the marsh bank but May 2013 was the only deployment that had high flood velocities at all three marsh stations. No seasonal trend in velocity was found. The tides with the highest magnitudes of velocities were not clearly correlated with tidal height as found in previous research in the Bay of Fundy and elsewhere (Friedrichs and Perry, 2001; Bouma et al., 2005).

The lowest velocities occurred at the marsh bank during the November deployment. These low velocities allowed for the sediment to settle, leading to the highest amounts of deposition.

Velocities in the creek thalweg were much higher than at the marsh stations, which is typical behaviour of narrow creeks (Wargo and Styles, 2007), and is also explained by the presence of vegetation at the three marsh stations and the absence of vegetation in the creek thalweg (Leonard and Reed, 2002).

Kingsport experienced flood dominance at stations below bankfull, but once the marsh platform has been overtopped, the currents change from being controlled by the creek to a larger scale pressure gradient control (Torres and Styles, 2007; Davidson-Arnott et al., 2002). This larger scale circulation of currents eliminates the flood dominance effect on the marsh, as the two marsh stations do not experience the high flood velocities seen on the marsh bank.

Suspended sediment concentration patterns on the marsh bank showed the greatest variability, with highest suspended sediment concentration occurring in August and September. The marsh bank experiences more annual change in vegetation as it is occupied by *Spartina alterniflora* rather than *Spartina patens* which dominate the high marsh. With *Spartina alterniflora*, the majority of the new growth is removed during the winter whereas *Spartina patens*, after die off, leaves behind a mat of dead vegetation that stays on the marsh surface. *Spartina alterniflora* is effective at retaining sediment on its stems because of its naturally high biomass (Stumpf, 1983; Yang et al., 2008). With suspended sediment concentration being high during the greater portion of the tide and no increased deposition, this indicates that there is availability of sediment but no opportunity for it to settle. At the marsh bank, the living biomass values were highest in August and September with values of 671 $g \cdot cm^{-2}$ and 891 $g \cdot cm^{-2}$ respectively (Figure 2.12). Since *Spartina alterniflora* changes suspended sediment concentrations because of its ability to reduce flow and therefore allow more sediment to settle through the water column (Leonard and Luther, 1995; D'Alpaos et al., 2006), the high living biomass values in August and September lead to high sediment concentrations on the marsh bank. Leonard and Luther (1995) found that velocities in a *Spartina alterniflora* canopy were lowest at 7-12 cm above the bed. The OBS measuring suspended sediment concentration at the marsh bank was within that elevation at 10 cm, suggesting that the highest concentrations of the water column are being captured by the optical backscatter sensors but there is not enough opportunity for this sediment to deposit on the bed and on the traps. As sediment is adhered to the plants in the marsh, less sediment is available for deposition at the marsh surface in August and September (Mudd et al., 2004). The fact that the sediment deposited on the plants is not being captured by the surface mounted sediment traps is one of the disadvantages of measuring deposition with surface traps (Nolte et al., 2013).

The seasonal pattern of deposition and concentration was reflected in the seasonal sediment flux values with both the highest values and the greatest variability occurring in the winter months (Figure 2.9; Figure 2.10). The seasonal pattern is that the sediment supply and sediment deposition are highest in the colder temperature months of November, January, and March. Because the net sediment flux values are higher in

November and January than March, it is plausible that this early winter period, represented with the period of October to February in the surface change maps (Figure 2.6), is influenced more by the incoming suspended sediment concentration while the later winter/spring period, represented by February to July in the surface change maps (Figure 2.6), stems from other contributions. One other source of sediment that needs to be considered is ice blocks, as they can carry sediment within them that could account for some of the positive elevation change in the later winter period (van Proosdij and Townsend, 2006; Argow et al., 2007). The presence of ice in the winter can also cause sediment erosion with ice scour. Although there is no sediment flux calculated for the marsh edge station, it is expected that flux in that area would be similar to what was occurring on the marsh surface since the values for deposition, concentration, and velocity for these two stations were very similar and not statistically significant from each other, with the addition that they are at almost the same elevation within the tidal frame.

The period from October 2012 to February 2013, which experienced the greatest erosion rate in surface elevation from the surveys (Figure 2.6), was also the period with the strongest winds, which likely caused sediment resuspension by wind-derived waves (de Jonge and van Beusekom, 1995; Booth et al., 2000). Winds during this period were also oriented at an angle (from the south-southwest) that would facilitate the waves entering the creek. The time interval of October to February had the most winds over 10 $m \cdot s^{-1}$, which is the threshold that Christiansen et al. (1992) found for wind-induced waves to resuspend sediment. Another explanation for the high erosion rate from October to February in the surface elevation change surveys (Figure 2.6), but something that is not being represented by the suspended flux or trap values, is the possibility of density underflow (Hill et al., 2007), which would mean the sediment travelling downslope very close to the bed. While this is a possibility for the creek where the slope has a grade of 27%, equivalent to 15 degrees, measurements closer to the surface would be necessary to confirm this process.

The period of May to July, having the most rainfall, was also influenced by the passing of post tropical storm Andrea which occurred on June 8th 2013 and brought 62 mm of rain on that day alone (Table 2.2). As the heaviest of the rain fell during low tide, it mobilized the sediment from the bed, which increased the suspended sediment concentrations, and it may have been contributing to the increase in sediment during that time period, because rain-resuspended sediment would have been carried up on the bank with the incoming tide after the high intensity rain event during low tide on June 8th.

Total flux $Q_s$values in the creek, representing the rough mass balance, were positive for all the tides, indicating sediment import on every tide. This was influenced by the fact that high tide occurs slightly past half way throughout the period of time which the creek is inundated by water, and with the assumption that the flood is the importing phase and the ebb is the exporting phase, there is more material during the flood phase. The fact that suspended sediment concentration peaks are similar at the beginning of the tide and the end of the tide but that the resulting sediment flux is flood dominant agrees with previous observations by Dyer et al. (2000a) in the Netherlands.

For evaluating sediment budget and equilibrium, a larger scale perspective must be adopted. When comparing estimated layers of sediment calculated with the two different methods (Table 2.3 and Table 2.4), the results show significant contrasts. The topographic change maps show the greatest export in sediment during the period of October to February, with an estimated net lowering of 2.74 cm. This is also the period with the greatest residual flux (Table 2.3). A possible explanation for this is that the assumption of having incoming flows during the flood tide and outgoing flows during the ebb tide is invalid. As can be seen in Figure 2.11, there is an abrupt change in flow that occurs beyond high tide, and no change in direction occurs directly at high tide. Because the flow is still directed into the creek after high tide, the net flux values would still all be positive if using another parameter than high tide to divide between flood and ebb. A better way to calculate suspended sediment flux would be to use the directional component of the velocities and associate the material in suspension to be going in the direction of the instantaneous velocity. Topographic controls are therefore controlling the direction of the flow and the inundation of the marsh surface has a great influence. Figure 2.11 only shows the flow pattern for the bottom 3 m of the water column, therefore the flux could be an underestimation if the over marsh flow is incoming for a longer period, or the flux could be an overestimation if the over marsh flow reverses before high tide. As the second option is not likely to occur, flux values are likely underestimates.

At Kingsport, the sediment flux is higher when the concentrations are higher, both of which peak in the winter deployments. French et al. (2008) found high import of sediment in the late summer and fall, along with high exports in the winter and spring time periods, although they had higher suspended sediment concentrations in the winter. Christie et al. (1999) also found the winter period to be exporting sediment and the summer period to be importing material although the suspended sediment concentrations were higher in the winter.

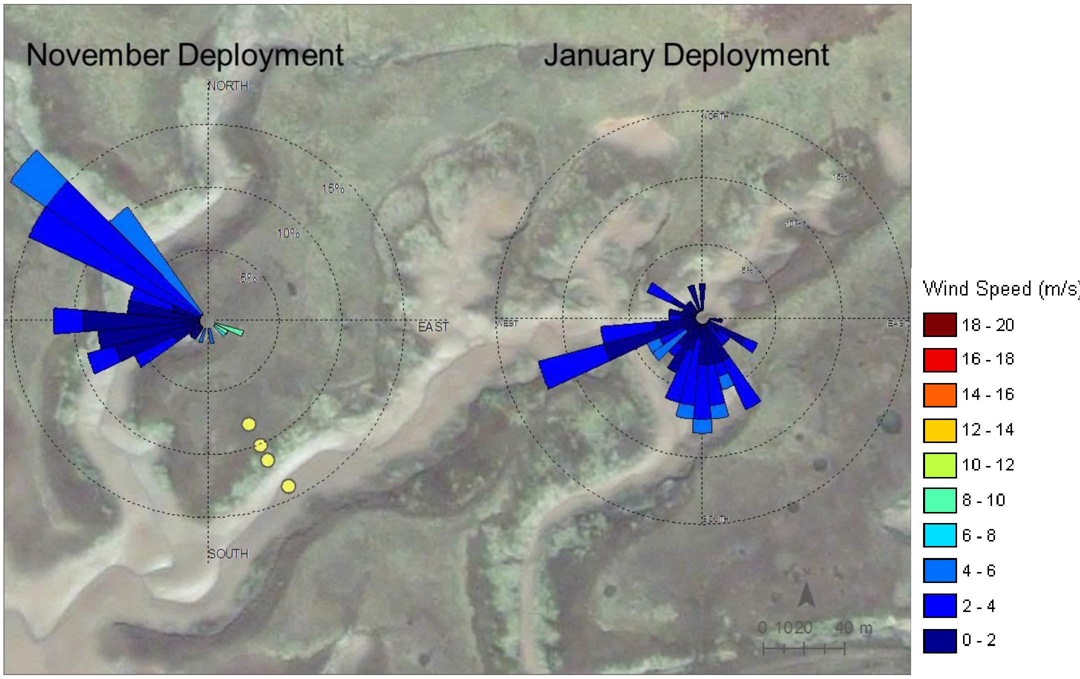

Figure 2.14: Wind roses for the weak winds during the deployments of November 2013 and January 2014. Aerial imagery of the creek is seen in the background for reference.

Magnitudes of velocities in the creek were much higher than any magnitudes of velocities seen on the marsh, agreeing with research of Christiansen et al. (2000). Magnitudes of velocities in the creek also followed a much more consistent pattern than magnitudes of velocities on the marsh. This is reflected in the sediment flux time series. When the winter seasonal characteristics are prominent in the creek zone, it has a noticeable impact because it varies from the consistent pattern of the regular creek sediment flux values. Because the marsh does not have such a consistent pattern, a variation in sediment flux on the marsh does not make for as clear a difference.

A limitation of this study was that it only measured spring tides. This was necessary to collect data on the marsh, but the variation between spring and neap was then not captured. With large changes in the tidal amplitude on a scale of neap to spring, there will be changes in sedimentation. O'Laughlin and van Proosdij (2012) showed the difference in behaviour of channel-restricted and over-marsh tides to be significant. With a change in tidal amplitude that would cause less tides to cover the marsh fully, we would see a decrease of sedimentation on the marsh during those tides, but the high variability in deposition particularly in the creek indicate that the area will probably not be impacted as much by changes in tidal amplitude. Although not the goal of this study because of focus on the marsh surface dynamics as well as the creek dynamics, exploring neap tides at Kingsport would allow us to see if tides of lower tidal amplitude would result in net negative total flux values. If neap tides result in an export of material, that would be an additional explanation to why Table 2.3 and Table 2.4 are so different, because Table 2.3 only represents spring tides while Table 2.4 represents both spring and neap tides equally.

Rainfall (Table 2.2) did have an effect on sediment deposition, because rain during low tide created the opportunity for sediment to be resuspended from the bed of the flats and the creek, and therefore be available for distribution in the marsh system. While wind is known to have a temporal lag on resulting higher incoming suspended sediment concentrations into estuarine systems (French et al., 2008), it is apparent that rain in this case did the same thing and led to high incoming supply of sediment several tides after the rain event, such as on September 19th and May 25th. Although rainfall is sometimes considered as a seasonal factor, the rain accumulation at this site was not dominated by one particular season and heavy rainfall events were capable of occurring throughout the year, as the two greatest events were in November and June.

Data collected in this study show that suspended sediment concentration is the leading control on sediment dynamics at Kingsport, and it interacts with many other components to result in deposition or erosion. Equilibrium is maintained with frequent flushing of the sediment through the creek system during storms with deposition and erosion of the same material. The link between suspended sediment concentration and deposition is seen on the tidal cycle scale where certain tides (November and March, for example) of higher concentration led to high deposition. The link between suspended sediment concentration to both deposition and erosion is seen in the sediment budget analysis (Table 2.3 and Table 2.4). Times with high concentration led to deposition on a short time scale and erosion on the long time scale, the erosion then, in turn, leading to increased concentrations. The season with the greater dynamics between deposition and erosion was late fall to winter (including the deployments of November and January) when the creek had highest concentrations incoming, during the middle of the tide, and outgoing. This reiterates the importance of the increased sediment availability in the winter in the Bay of Fundy as presented by Tao (2013).

The period of October to February is the time interval with the strongest winds, although the tides that were chosen for data collection did not experience exceptionally strong winds on those days (Figure 2.14). The late fall and winter period is therefore a period with increased wind activity, and increased sediment in suspension leading to both removal and deposition of material. This shows the importance of collecting data at different scales for long temporal periods. With only certain tidal cycles sampled, major patterns can be missed, a concern also argued by French and Spencer (1993) and French et al. (1995). For example, if the topographic surveys of the present study were not completed, the erosional phases in the winter would not have been recognized because there was little evidence of it in the trap data alone. With coupling of small and large temporal scales, a more complete picture is able to be derived.

2.6 Conclusion

The seasonal control on deposition at Kingsport was strongest in the creek thalweg and at the marsh bank. At these two stations, with the creek thalweg having the effect more than the marsh bank, deposition and suspended sediment concentrations were both higher and this occurred in the winter. Deposition was higher because of the rapid deposition from the high concentration suspension. At the marsh edge and marsh surface locations, sediment supply in suspension was depleted before inundation therefore reducing the influence of seasonal variations there. Stations on the high marsh did not receive increased sedimentation by vegetation-reduced flows, because most of the sediment deposited before it reached the marsh surface.

The seasonal impact on sediment supply and sediment deposition became weaker furthest away from the creek and from the sediment source. Fagherazzi and Priestas (2010) found that tides of lower tidal amplitude were more likely to export sediment from the tidal creek.

The period of October to February proved to be the most active period in terms of high suspended sediment concentrations and sediment resuspension. It was evident that this late fall to winter period experienced both high deposition and high erosion rates and that more sediment was available in the creek system during this period. The higher winds during the winter lead to resuspension and that sediment is then made available to be deposited. Even with the large amount of sediment being transported, deposited and resuspended, this portion of the Kingsport creek remains in relatively balanced equilibrium at the temporal scale of just over a year. The ability of this system to stay in equilibrium with such high variability in sediment dynamics demonstrates the resilience of tidal creek and salt marsh systems. This study also demonstrates the necessity of performing data collection on two different temporal scales to attain a complete characterization of the seasonal ecomorphodynamics.

<u>Chapter 3</u>:

Seasonal sediment characteristics and flocculation in a tidal creek and salt marsh ecosystem

To be submitted to: Estuarine, Coastal and Shelf Science

3.1 Introduction

Sediment grain size reflects the depositional environment that particles settled in and the mechanisms that transported the sediment to its current location (Kranck and Milligan, 1985; Boggs, 2001). This makes grain size an ideal measure to use in the study of tidal flat and marsh sediment dynamics. The development and retention of marshes is highly dependent on the supply of sediment from creeks (Bouma et al., 2005; Temmerman et al., 2003b). Sediment grain size also affects how wetlands retain certain elements and is important when considering contaminant transport (Milligan and Loring, 1997; Yang et al., 2008). Salt marshes play a role in lowering pollution levels because they remove certain contaminants from the water. The invertebrate community is particularly important for the strength of substrate of creeks and adjacent tidal flats (Paarlberg et al., 2005).

In many coastal systems, grain size changes seasonally (Komar, 1976; Davidson-Arnott, 2010). As the winter brings more energy into the coast with low pressure systems and high wave activity, there is more opportunity for coarse grains to be transported

(Davidson-Arnott, 2010). In salt marsh systems, the relationship is not clear (Reed et al., 1999; O'Laughlin, 2012). There is a general consensus that there is a change in grain size between summer and winter (Callaghan et al., 2010; Law et al, 2013b) and that coarser particles have more potential to be resuspended and transported further within the creeks and marsh surface during the winter (Yang et al., 2008). Coarse sediments from further offshore can be brought to the marsh by larger wave energy (Yang et al., 2008). The winter period is also associated with stronger currents (Mulligan et al., *submitted*), increasing the potential for larger grains to be transported (Allen, 2000). Callaghan et al. (2010), in a study in the Netherlands, show that during the summer period finer sediments can be found in the bed, having been deposited there during the transition from winter to summer, and that during the winter, fine sediments are more prominent in the vegetated areas that have not died off, and in the water column. Increased water viscosity in winter has been hypothesized to generally result in coarser sediments, with finer sediments in the summer (Allen, 2000).

Among the many factors controlling grain size on tidal flats and marshes, sediment dynamics in these environments are complicated by flocculation of the fine-grained, cohesive sediment found there. Flocculation occurs when grains which are in suspension collide and adhere forming large, fast-sinking particle agglomerates (Kranck, 1975; Eisma, 1986; Milligan et al., 2007). The flocculation of sediment is largely controlled by particle concentration, particle composition, and turbulence, all of which can vary seasonally on tidal flats (Milligan and Hill, 1998; Hill et al., 2013; Law et al., 2013)

The rate and extent of aggregation of particles is strongly related to the amount of suspended sediment in the water column, with higher concentrations leading to greater floc formation (Kranck, 1980; Milligan and Hill, 1998; Milligan et al., 2007). Because of their aggregated structure, flocculated sediments have a settling rate faster than their constituent single grains (Kranck, 1975; Sternberg et al., 1999). The faster settling of flocs therefore has the potential to lead to greater amounts of deposition for a given depth of water as it is deposited rapidly (Fox et al., 2004). Greater flocculation leads to more rapid deposition to the bed (Kranck, 1980; Milligan et al., 2007).

Particle composition will affect how well particles adhere to one another when they collide (Milligan and Hill, 1998). Organic coatings on particles have been shown to increase flocculation rate and the ability for flocs to withstand higher stresses (Kranck and Milligan, 1980). On tidal flats and in salt marshes, organic matter varies greatly as a result of diatom growth, bacterial activity, and the establishment of grasses (van de Koppel et al., 2001; Carrière-Garwood 2013; Fagherazzi et al., 2013; Wheatcroft et al., 2013).

High levels of turbulence will act to disaggregate flocs. Below a certain threshold turbulence enhances floc build-up because of the increased opportunity for grains to collide and stick together (Milligan et al., 2001; Manning, 2004). Beyond this threshold, an increase in turbulence will be too high for the flocs to withstand and they will be broken up. Bed shear stresses that exceed 0.1-0.2 $N \cdot m^{-2}$ can disrupt flocs (Hill et al., 2013), therefore at higher turbulence levels there is less potential for flocculated sediment to form (Hill et al., 2001; Mietta et al., 2009).

The extent of flocculation can vary from summer to winter (Chen et al., 2005; Bartholomä et al., 2009; van der Lee et al., 2009; Law et al., 2013b). Chen et al. (2005), in a study in the Sheldt estuary, conclude that because of flocs being compact and dense, deposition is greater during the winter and spring period. In the summer the flocs are looser and more easily resuspended. Bartholomä et al. (2009) observed flocs of larger sizes in the spring and summer because of increased organic material. van der Lee et al. (2009), in a remote sensing study in the Irish Sea with lower concentrations than at Kingsport, also found flocs of larger diameters in the summer, and finer individual grains. In a mudflat study from Washington State, Law et al. (2013b) found less floc deposited sediment within a creek in the summer due to reduced concentrations of suspended sediment and that the highest concentrations and floc fractions occurred in the winter.

The purpose of the present research is to associate how the variations in grain size characteristics in a hypertidal creek and adjacent salt marsh are linked to both physical forcing and flocculation. Although individual flocs cannot be differentiated from single grains once the sediment has settled (Syvitski, 1991), the deposited sediment can give an interpretation of the degree of flocculation in the overlying suspension (Kranck and Milligan, 1975; Curran et al., 2004). The specific objectives of this research were (1) to determine the seasonal variability in grain size across the creek cross section, (2) to determine the extent of flocculation and its seasonal variability, and (3) to determine what factors are influencing the change in both grain size and proportion of material deposited in floc form.

3.2 Methods

The study area was located on a salt marsh, in Kingsport, Nova Scotia, in the Minas Basin of the Bay of Fundy (Figure 3.1). The site has a relatively large second order tidal creek which feeds five first order tidal creeks (Strahler, 1957). For this study, 62 high amplitude overbank tides were chosen to include the marsh surface. Four main sampling stations were positioned along a transect from the creek thalweg into the marsh interior to capture the different spatial zones of the marsh and creek system: the creek thalweg, marsh bank, marsh edge, and marsh surface (Figure 3.1). The marsh surface and marsh edge are on the high marsh, in vegetation dominated by *Spartina patens*, at 5.89 m and 5.47 m elevation relative to CGVD28 respectively. The marsh bank, at an elevation of 3.67 m, is in the low marsh dominated by *Spartina alterniflora*, and the creek thalweg is bare of any vegetation at -0.51 m relative to CGVD28. Meteorological data were collected with a Campbell-Scientific weather station installed on site sampling hourly means for precipitation amount, wind direction, wind speed, and temperature.

At the four main stations, sediment trap samples were collected every tide. Sediment deposited on a tide was collected using surface mounted sediment traps consisting of a preweighed 90 mm diameter Whatman #5 filter paper held between two aluminum plates which allowed the upper filter surface to be exposed (Reed, 1989; van Proosdij et al., 2006a). The filters were air dried and then reweighed to obtain sediment deposition in $g \cdot m^{-2}$. At the same locations, surface scrape samples consisting of the top 5 mm at the four main stations were collected once per day. In addition, surface scrape samples from two other transects perpendicular to the creek, labelled down creek and up creek with 1 being closest to the thalweg and 4 being highest on the bank, were collected once per deployment (Figure 3.1).

For suspended sediment samples, rising stage bottle samples were collected at the four stations along the main transect. There were two bottles at each location, at 20 cm and 50 cm above the bed, capturing 500 mL samples (Nolte et al., 2013). While these only measure incoming flood tides, they can provide an interesting comparison of the material available at each station. An ISCO water sampler collected 200 mL samples every 15 minutes at the marsh bank station. The 15 cm intake nozzle was situated at 5-20 cm above the bed. Samples were collected for each tide during the deployment.

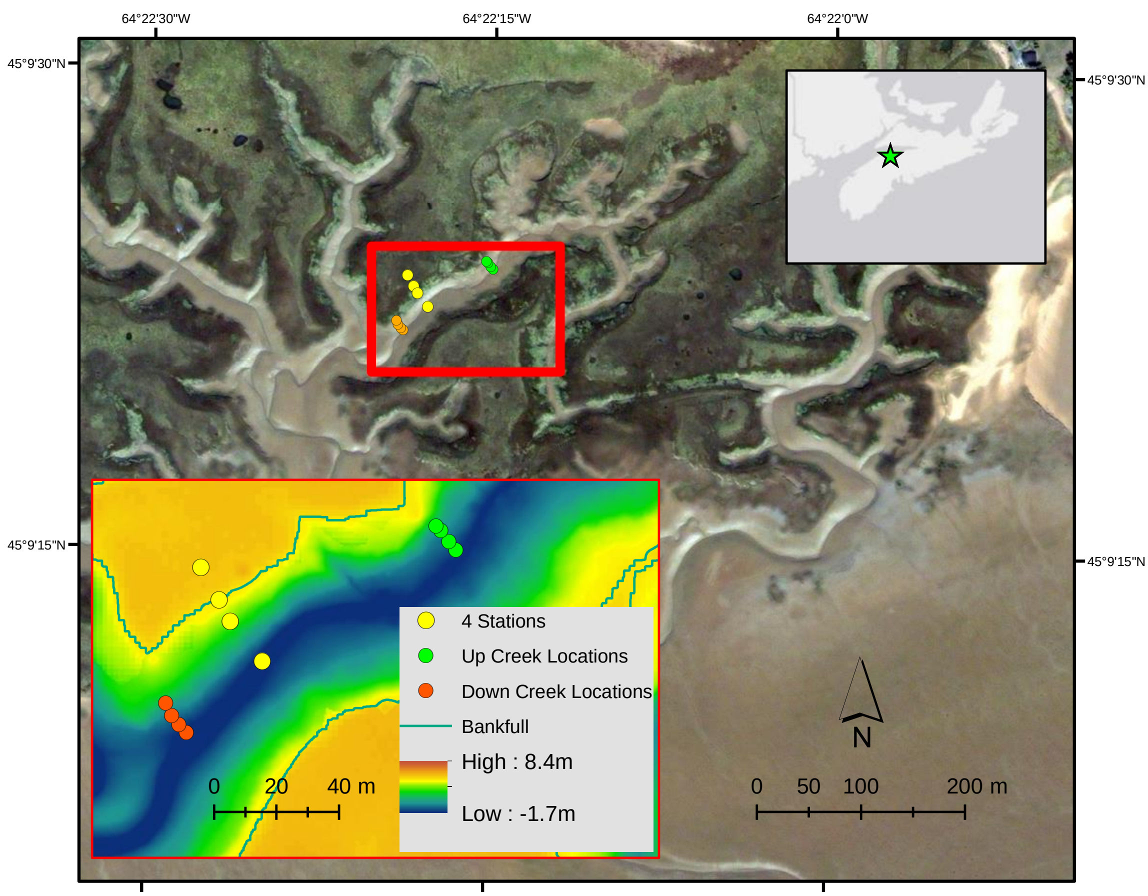

Figure 3.1: Study area and sampling locations. Inset map is a combination of LiDAR and elevation data from the automated total station.

For the scrape samples, water content was calculated using the difference in weights before and after drying at 60°C. Organic matter was calculated from the difference in weights before and after the samples were combusted at 550°C (Howard and Howard, 1990).

Disaggregated inorganic grain size (DIGS) was determined for sediment samples using a Beckman Coulter Multisizer™ III electro-resistance particle size analyser using the method described in Milligan and Krank (1991). Before processing samples for grain size, all organics were removed with a solution of 30% H_2O_2. Sediments were put into a 1% NaCl solution and sonicated prior to processing through the Multisizer™. Aperture tubes of 30 µm and 200 µm were used. Results were expressed as equivalent weight percent in each channel for the scrapes, trap samples, rising stage bottles, and mean of ISCO samples and as volume of sediment per sample volume as ppm in each channel for the 15-minute interval ISCO samples (Milligan and Kranck, 1991).

Gradistat, a program developed by Blott and Pye (2001), was used to determine descriptive grain size statistics, and the results are expressed using the Folk and Ward method (Blott and Pye, 2001). The d50, d75, and d90 values were also calculated. The d50 values represent the median, d75 and d90 represent the 75^{th} and 90^{th} percentile of the distribution.

To determine the fraction of the sediment deposited as flocs, the inverse floc model developed by Curran et al. (2004) following Kranck et al. (1996) was used. This model parameterizes the DIGS to describe its depositional characteristics. It evaluates the relative contribution of flocculated sediment in the bed. This is determined by the floc fraction, which represents the proportion of material deposited in floc form. A second parameter considered is the floc limit, which is the diameter at which the flux of single grains to the bed is equal to the flux of flocs to the bed. It also examines the source of sediment in terms of the slope of parent suspension, represented as m (Curran et al., 2004).

For seasonal analysis, tides were divided into the three categories of spring, summer, and winter. Spring includes May 2012, May 2013, and June 2013; summer includes July 2012, August 2012, and September 2012; and winter includes November 2012, January 2013, and March 2013.

In addition to the sediment samples, a Nortek acoustic Doppler current profiler (ADCP) was deployed in the creek thalweg to measure water velocity throughout the water column and for water velocity on the marsh, three Nortek acoustic Doppler velocimeters (ADV) were deployed measuring for 5 minute burst intervals every 10 minutes. These ADVs were set at 16 Hz frequency, with the instrument at the marsh bank at 10 cm above the bed and the instruments at the marsh edge and marsh surface at 15 cm above the bed. For suspended sediment concentration measurements, the marsh surface and marsh bank stations had an optical backscatter sensor (OBS) co-located with the ADVs. In the creek thalweg, an RBR data logger was deployed which measured turbidity, water temperature and salinity. Samples from the rising stage bottles and ISCO water sampler at the marsh bank were for DIGS of the suspended sediment concentrations.

From the ADV data, bed shear stress was measured with

$$\tau_0 = \rho {u_*}^2 \qquad (3.1)$$

where u_* is the shear velocity (Middleton and Southard, 1984) which was measured using the Reynolds stress method

$$u_* = \sqrt{-\overline{u'w'}}. \qquad (3.2)$$

3.3 Results

All sediments sampled at this site were categorized as muds, which are classified as having a diameter less than 63 μm. Several thresholds have been proposed for the diameter below which particles behave cohesively: 50 μm (Partheniades, 2009), 16 μm when greater than 7.5% is 4 μm or smaller (Law et al., 2008), and 10 μm (McCave, 2008). Sediments at this site fit in all of these categories. Table 3.1 presents a summary of sediment characteristics at the main four stations, showing d50 (the median), d75, d90 values as well as the floc parameters for floc fraction, floc limit, and source slope.

Table 3.1: Summary (mean values per season) of sediment characteristics on the main transect.

	Station		d50	d75	d90	Floc Fraction	Floc Limit (μm)	Source Slope
Daily Scrapes n=155	Marsh Surface	Spring	9.3	19.8	33.3	0.82	37.6	0.42
		Summer	8.2	17.2	28.5	0.75	23.0	0.41
		Winter	9.0	19.2	32.1	0.81	34.7	0.45
	Marsh Edge	Spring	9.5	19.8	32.4	0.83	37.4	0.46
		Summer	8.9	18.6	30.7	0.81	33.1	0.40
		Winter	8.6	17.8	29.4	0.80	31.1	0.45
	Marsh Bank	Spring	9.9	20.7	34.1	0.83	38.3	0.48
		Summer	9.5	19.5	30.6	0.84	34.9	0.45
		Winter	9.2	18.8	30.9	0.82	34.3	0.45
	Creek Thalweg	Spring	11.8	24.8	38.7	0.80	38.7	0.45
		Summer	14.0	27.6	40.7	0.70	28.3	0.43
		Winter	11.4	23.5	36.6	0.77	32.4	0.46
Traps n=108	Marsh Surface	Spring	8.1	16.6	27.8	0.81	27.9	0.45
		Summer	9.2	19.7	31.3	0.80	29.7	0.35
		Winter	8.4	16.7	26.9	0.85	35.0	0.46
	Marsh Edge	Spring	8.8	19.3	31.5	0.76	28.8	0.29
		Summer	9.0	19.9	32.1	0.85	38.7	0.32
		Winter	8.5	17.3	28.2	0.84	36.3	0.43
	Marsh Bank	Spring	10.2	21.4	34.7	0.80	35.7	0.39
		Summer	9.5	19.9	31.8	0.86	40.0	0.39
		Winter	8.7	17.4	28.2	0.85	36.6	0.47
	Creek Thalweg	Spring	10.7	21.3	33.3	0.77	30.2	0.44
		Summer	14.4	27.6	41.4	0.75	36.1	0.47
		Winter	12.9	23.4	34.1	0.76	31.4	0.45
Rising Stage Bottles (20 cm) n=102	Marsh Surface	Spring	5.1	10.1	17.5	-	-	-
		Summer	5.0	10.3	17.8	-	-	-
		Winter	5.0	10.1	16.9	-	-	-
	Marsh Edge	Spring	4.9	9.8	17.4	-	-	-
		Summer	5.2	10.5	18.2	-	-	-
		Winter	5.2	10.3	17.3	-	-	-
	Marsh Bank	Spring	5.6	11.0	19.3	-	-	-
		Summer	5.7	11.6	20.0	-	-	-
		Winter	5.9	11.6	19.4	-	-	-
	Creek Thalweg	Spring	7.2	14.0	22.9	-	-	-
		Summer	7.1	14.0	23.3	-	-	-
		Winter	6.4	12.5	21.1	-	-	-
ISCO n=140	Marsh Bank	Spring	5.2	10.5	18.9	-	-	-
		Summer	5.6	12.2	21.2	-	-	-
		Winter	6.4	12.7	21.2	-	-	-

3.3.1 Surface Scrape Bed Sediments

Mean DIGS of the surface scrape samples for each deployment along the main transect are shown in Figure 3.2. The coarsest sediments were the ones in the creek thalweg, with a fining of sediments with increasing distance from creek (Figure 3.3). This trend was persistent in both bed samples and suspended samples. It is clear by looking at Figure 3.3 that the creek thalweg, being the data points at 0 metres from the creek, has markedly larger sediments than anywhere on the marsh. Mean size distribution of the spring, summer, and winter categories do not vary greatly from each other. As can be seen in Figure 3.3, the d75 in the winter is coarser at the marsh surface, which is 36.04 m from the creek thalweg, than at the marsh edge and marsh bank, in closer proximity to the creek thalweg. This is the only point contrary to the trend of fining of sediments with distance from the creek and higher elevation.

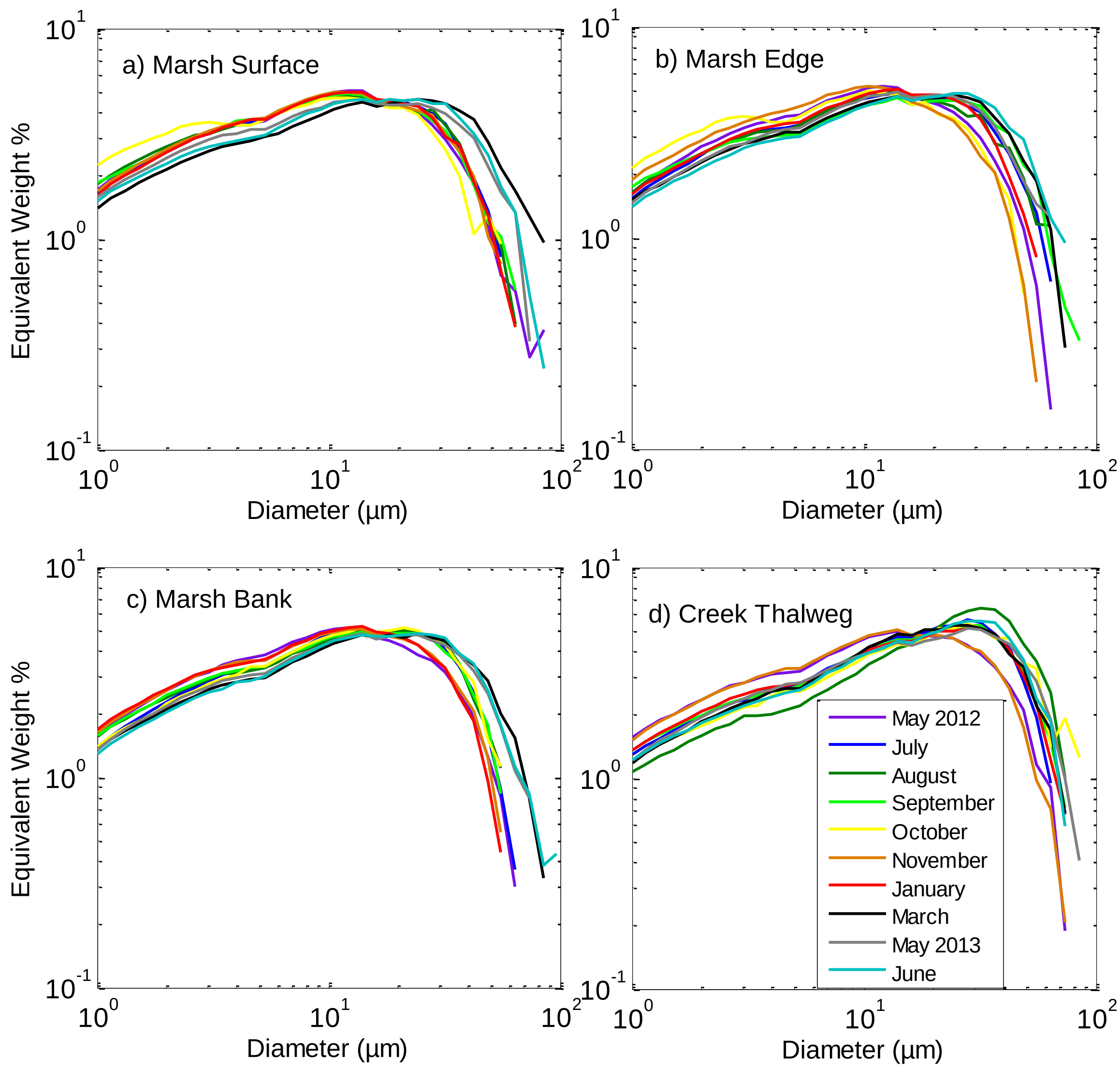

Figure 3.2: Deployment means of DIGS of daily scrape samples at the a) marsh surface, b) marsh edge, c) marsh bank, and d) creek thalweg.

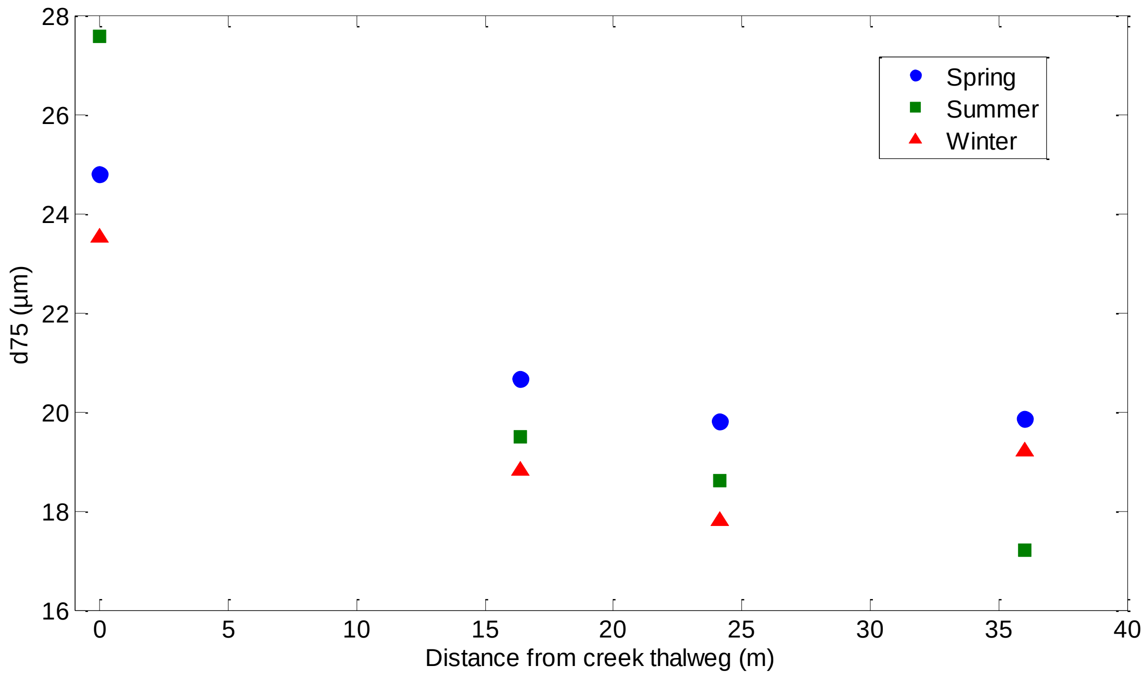

Figure 3.3: Mean d75 (µm) of daily scrapes at the four main stations for the three seasons plotted vs. the distance from creek thalweg. n=155.

For the daily scrape samples, the mean d50 values per station were 8.8 µm at the marsh surface, 9.0 µm at the marsh edge, 9.5 µm at the marsh bank, and 12.4 µm at the creek thalweg. A Kolmogorov-Smirnov test run on the daily scrape d50 data showed the data to be non-normal, therefore the Kruskal-Wallis test was used for further analysis. The creek thalweg was significantly coarser ($p<0.05$) than all marsh stations, while all marsh stations were not statistically significant from each other. For d75, mean values per station were 18.9 µm at the marsh surface, 19.3 µm at the marsh edge, 19.6 µm at the marsh bank, and 24.7 µm at the creek thalweg. With further division of the samples and plotting individual deployments (Figure 3.4, Figure 3.5), it can be seen that the three marsh stations were of similar size and had similar seasonal patterns, with the three deployments of March, May 2013, and June, being the coarsest for the marsh stations. The seasonal pattern in the creek thalweg was different than the one seen at the marsh stations. At the creek thalweg, the two months with the finest sediments were May 2012 and November, and the month with the coarsest sediments was August.

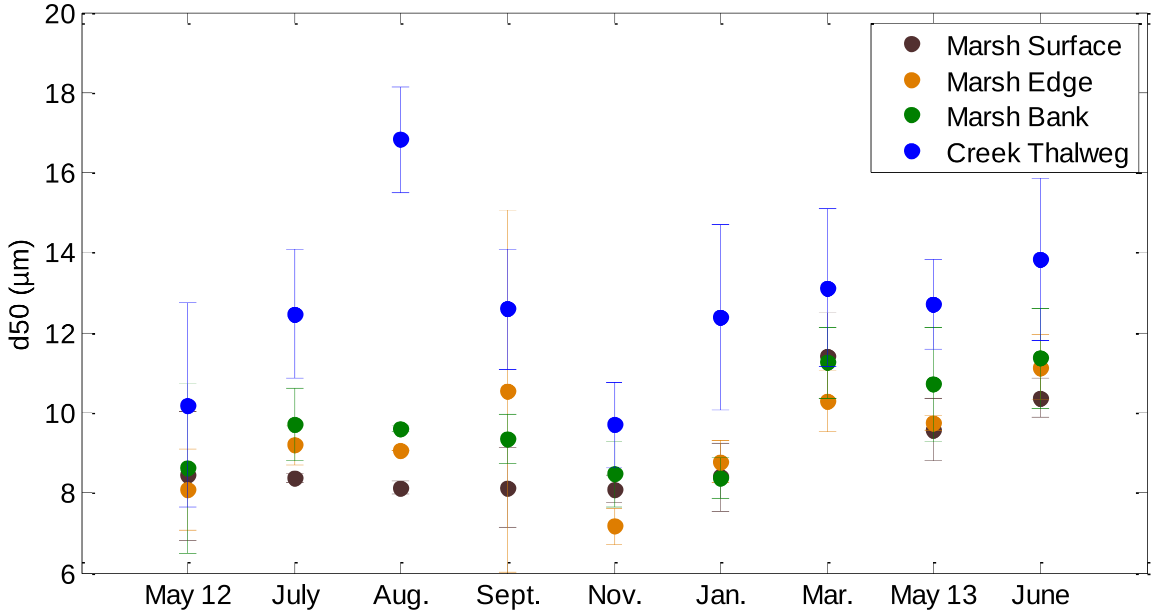

Figure 3.4: d50 (µm) of daily surface scrapes (mean per deployment). Error bars represent standard deviation. n=248.

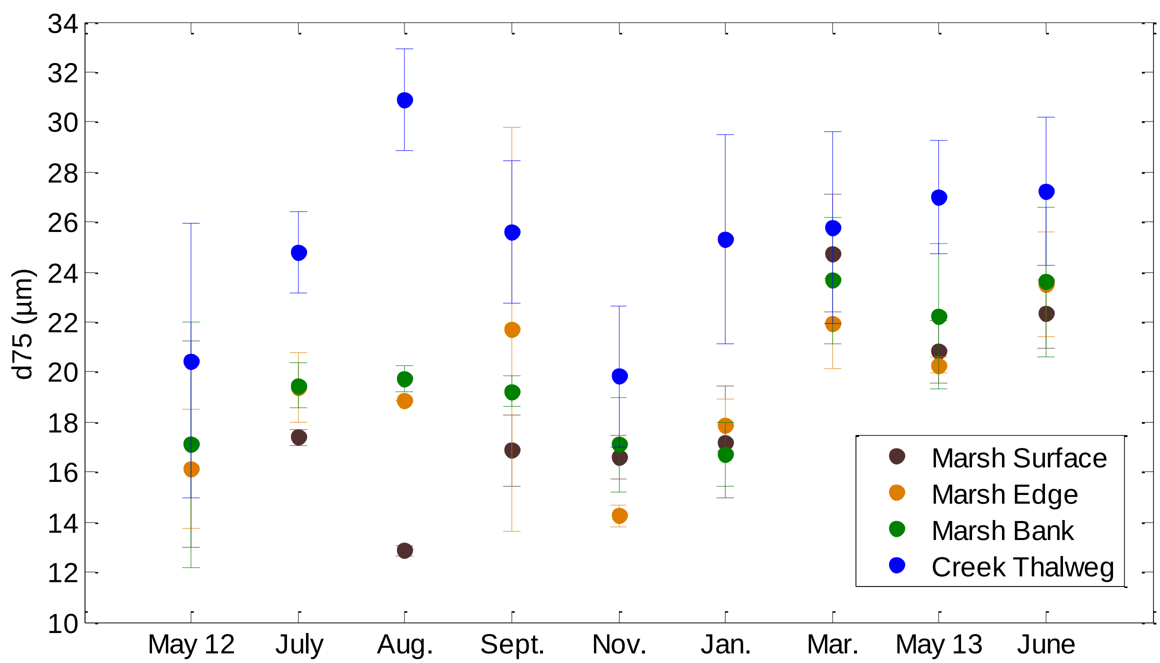

Figure 3.5: d75 (µm) of daily surface scrapes (mean per deployment). Error bars represent standard deviation. n=248.

Figure 3.6 shows the mean floc fraction per station per deployment. The mean values per station were 0.79 at the marsh surface, 0.82 at the marsh edge, 0.83 at the marsh bank and 0.76 at the creek thalweg. A Kolmogorov-Smirnov test run on these floc fraction data showed the data to be non-normal, therefore the Kruskal-Wallis test was used for further analysis. The creek thalweg is statistically significant from all other stations ($p<0.05$), while all of the marsh stations are not significant from each other.

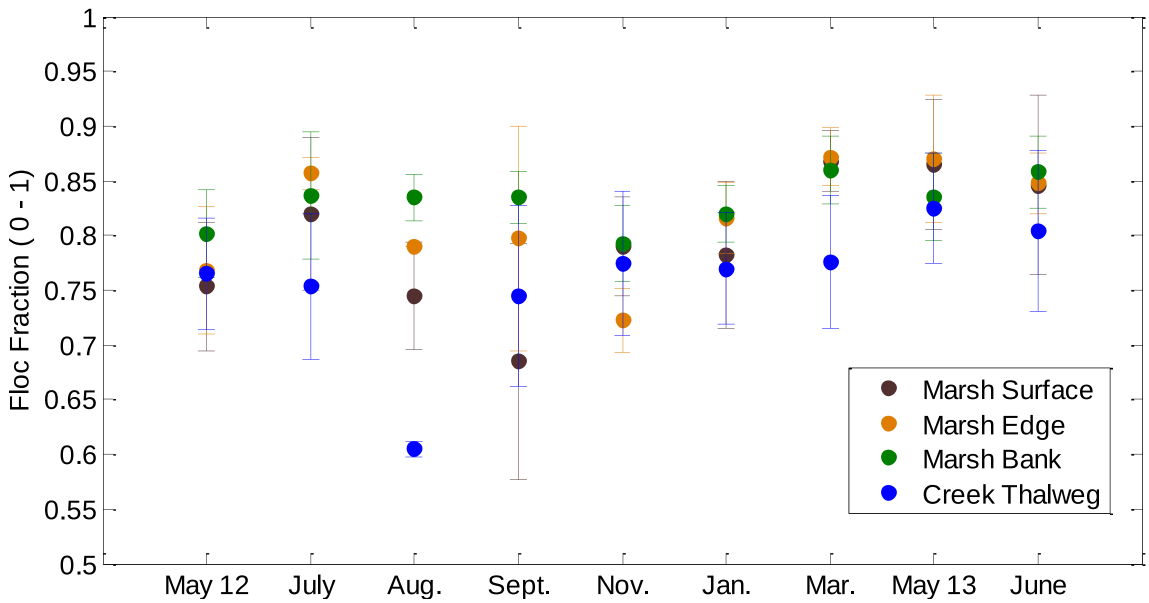

Figure 3.6: Floc fraction of daily surface scrapes (mean per deployment). Error bars represent standard deviation. n=248.

In the surface samples that were taken along the two additional transects up and down creek of the main sampling transect, August had fine sediments (as can be seen with a high floc fraction value in Figure 3.8). This is in contrast with the surface scrapes in the creek thalweg station which were coarsest in August (Figure 3.4).

The grain size distribution of the bank surface scrape samples (Figure 3.7) show two things: 1) a fining of sediment from the bottom of the bank (sample 1) to the top of the bank (sample 4), and 2) a fining of sediment from down creek to up creek. 82% of the bank surface samples from this dataset were classified as medium silt, with the remaining being classified as coarse silt. All of the samples were classified as poorly sorted by the Folk and Ward method. A seasonal trend from the down creek and up creek bank samples is not clearly evident. There is also no seasonal trend in the floc fraction of the down creek and up creek bank samples as can be seen in Figure 3.8 where floc fraction values increase and decrease multiple times throughout the sampling duration.

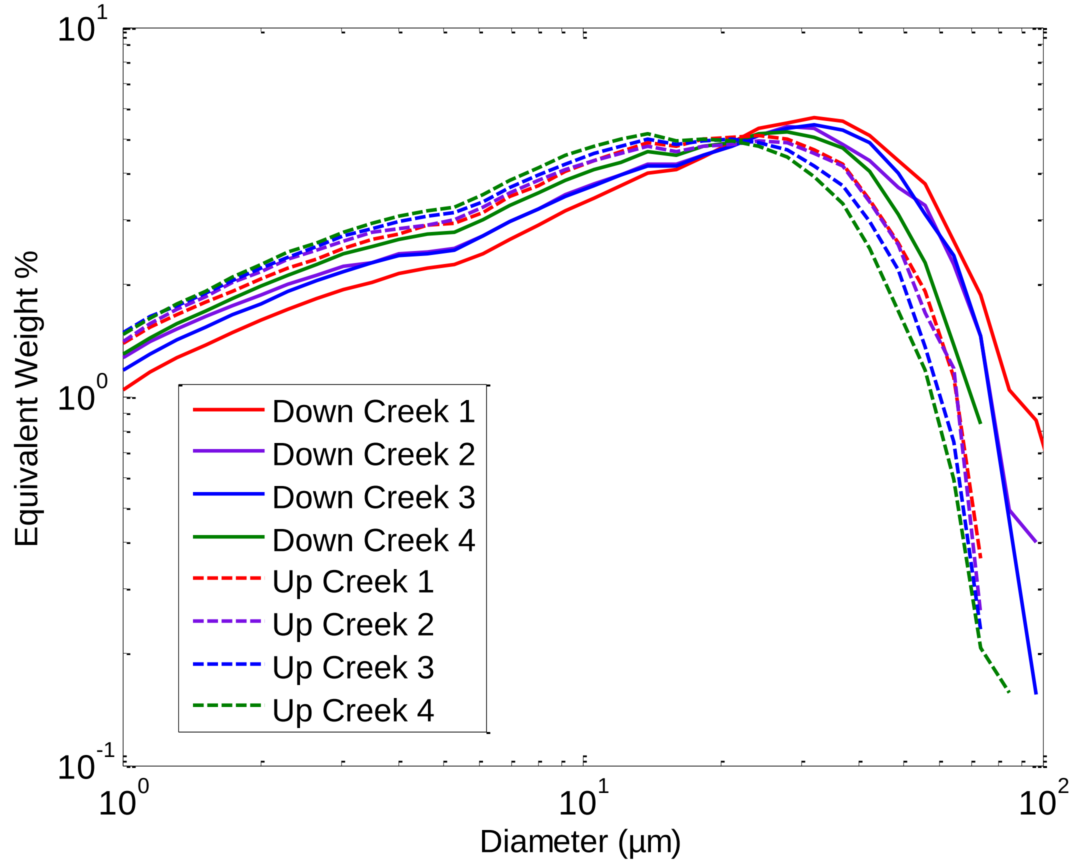

Figure 3.7: Mean DIGS of scrape samples on the bank at the down creek and up creek transects including samples of all deployments, plotted per sampling location.

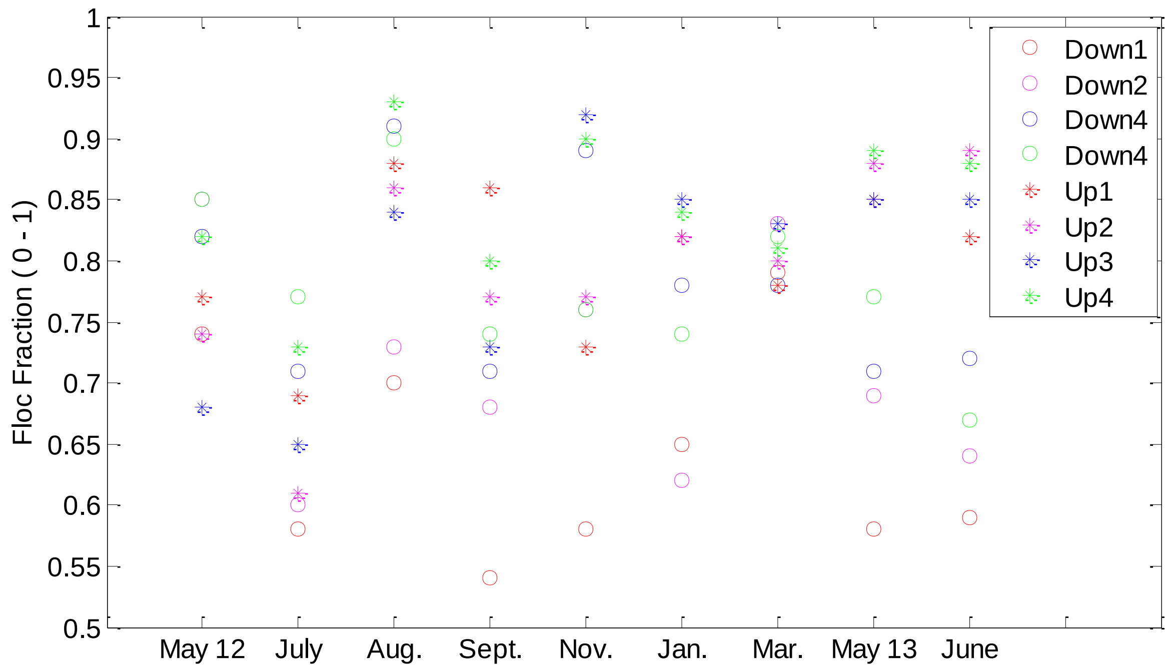

Figure 3.8: Floc fraction of down creek and up creek surface scrape samples per deployment. n=72.

The thalweg samples (thalweg station of the daily scrape samples, Down Creek 1, and Up Creek 1) show a decrease in grain size with elevation and with distance from the sediment source (Figure 3.9).

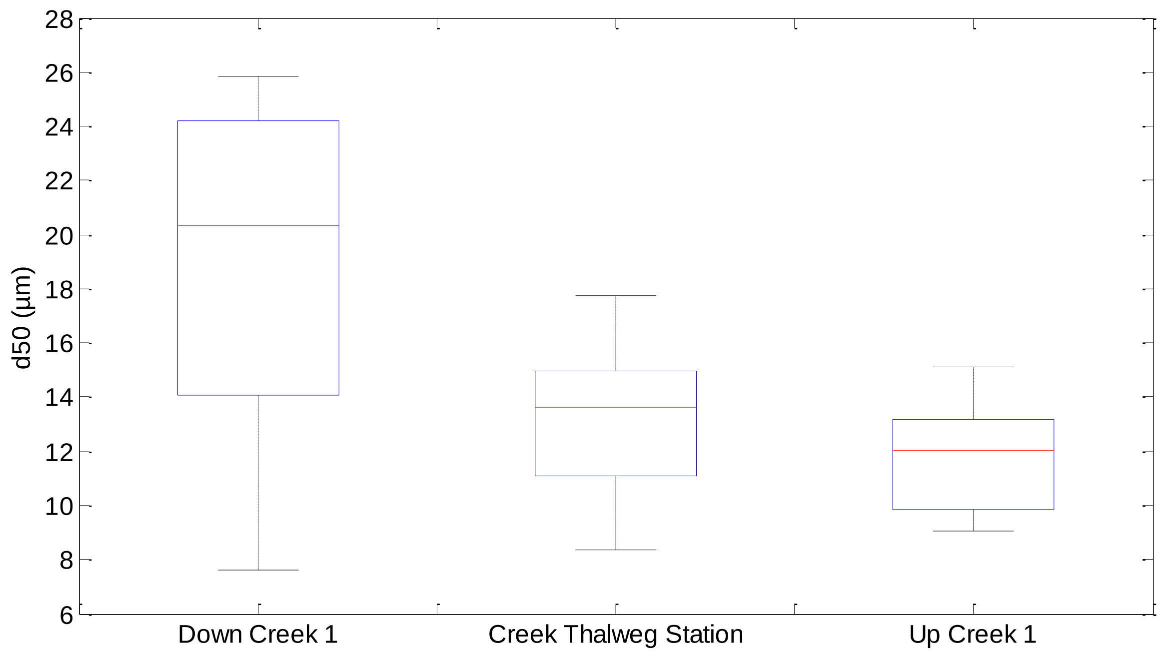

Figure 3.9: Box plot of d50 (µm) of Down Creek 1 samples, Creek Thalweg Station samples, and Up Creek 1 samples, which are all along the thalweg, with n=9 for each station (1 sample per deployment).

3.3.2 Deposited Sediments on Traps

Sediments deposited on traps have mean d50 values of 8.4 µm at the marsh surface, 8.7 µm at the marsh edge, 9.4 µm at the marsh bank, and 12.6 µm at the creek thalweg. The sediment deposited on the traps exhibit the most variability in grain size between samples from the five sampling techniques (traps, surface scrapes, bank scrapes, ISCO, and rising stage bottles). This variability can be seen in Figure 3.10. At the three marsh stations, there are certain tides which appear to have a much coarser signature than the others. Sep19pm is an example of a tide where no rain was experienced while the traps were deployed and coarse sediment distributions are present at the marsh stations. Because Figure 3.10 raised the question of whether these coarse grain size spectra were indeed representative of the sediment deposited, the grain sizes were then redimensionalised by weight of sediment deposited (Figure 3.11) to examine if the traps of less deposition were the traps with the coarsest sediment. It can be seen that most of the traps with the coarse distributions were amongst the traps with the lowest deposition values. Therefore, the coarse distributions are likely an artefact of the traps and they have been removed from further analysis. Discussion of these filters can be found in Appendix B.

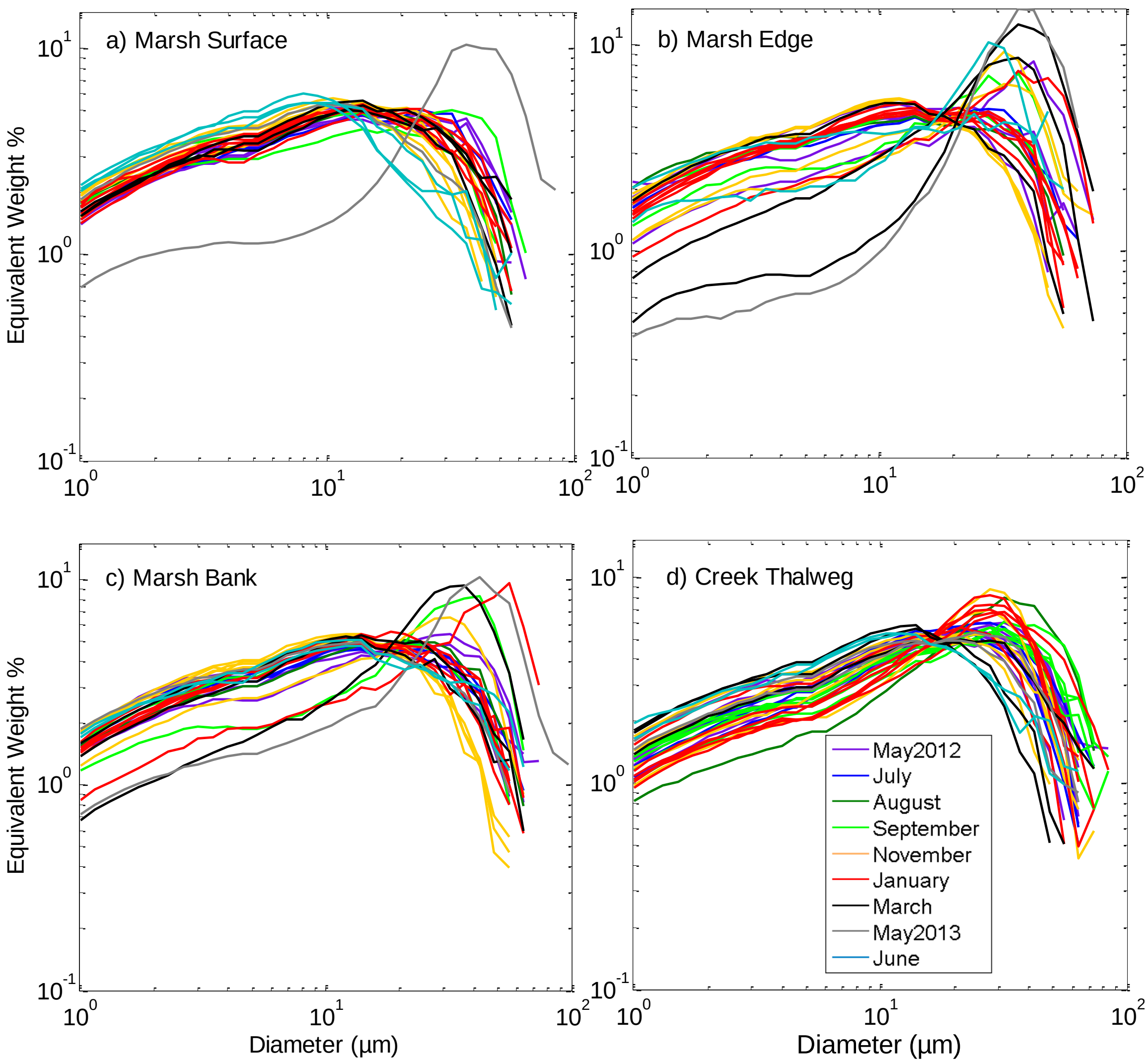

Figure 3.10: DIGS of sediment deposited on traps at a) the marsh surface, b) the marsh edge, c) the marsh bank, and d) the creek thalweg. Each line represents one tide. Traps directly impacted by rain are not shown.

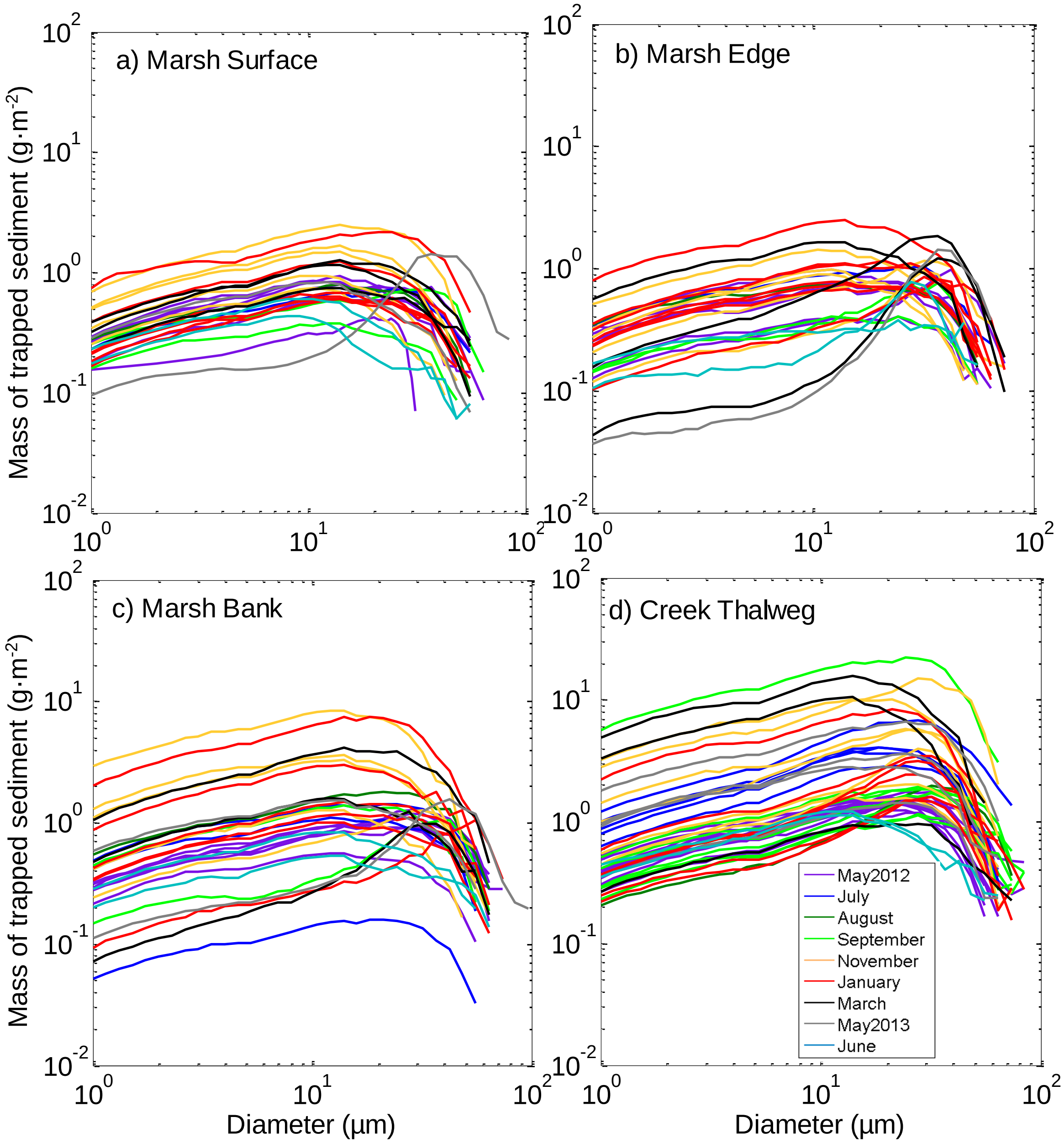

Figure 3.11: DIGS of sediment deposited on traps at the a) marsh surface, b) marsh edge, c) marsh bank, and d) creek thalweg redimensionalised by the equivalent weight of the sediment deposited on each sample's respective trap. Each line represents one tide. Traps directly impacted by rain are not shown.

The fraction of sediment deposited as flocs on the traps do not show a consistent seasonal trend (Figure 3.12). The August deployment does have the lowest floc fraction which agrees with the corresponding floc fraction of the daily scrape sediments.

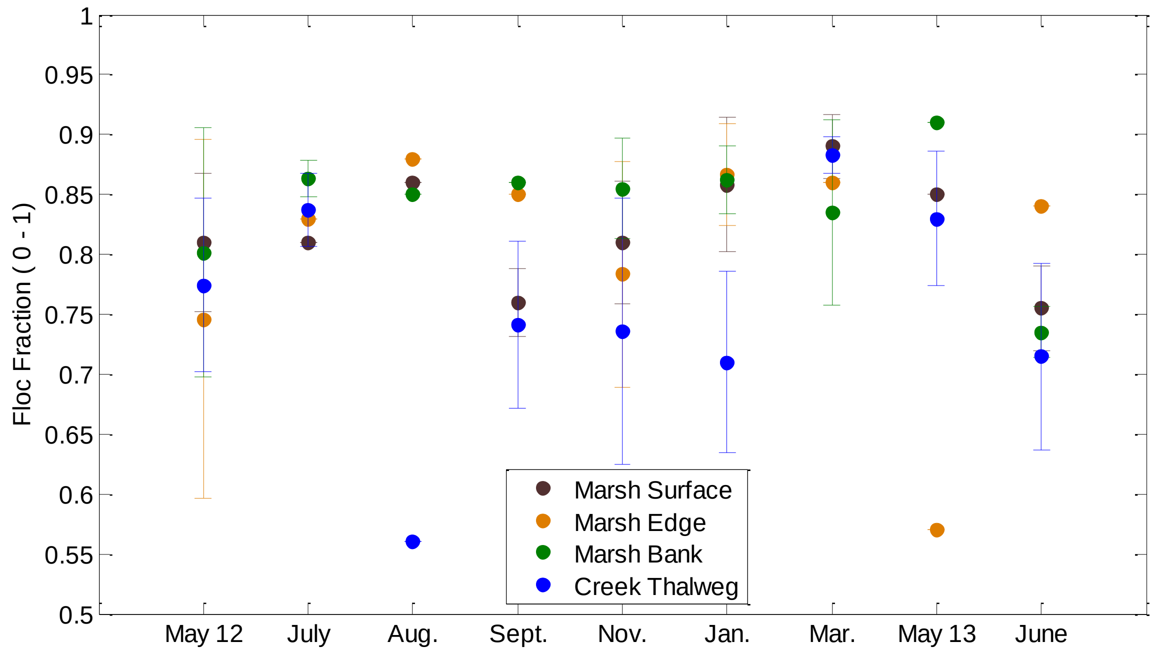

Figure 3.12: Floc fraction of sediment deposited on traps per deployment. Samples with anomalous DIGS distributions were not included in these mean values.

Floc limit, which is the particle diameter where flux to the bed is equal for floc and single settling, is represented in Figure 3.13. The marsh bank, at a distance of 16.37 m from the creek thalweg, which is the station with the overall highest floc fraction in the scrapes, is the station with the least variation in the floc limit (Figure 3.13). The floc limit is most variable at the marsh surface, the station furthest from the creek thalweg. This pattern is present with the scrape samples, mainly because of a very low summer floc limit value.

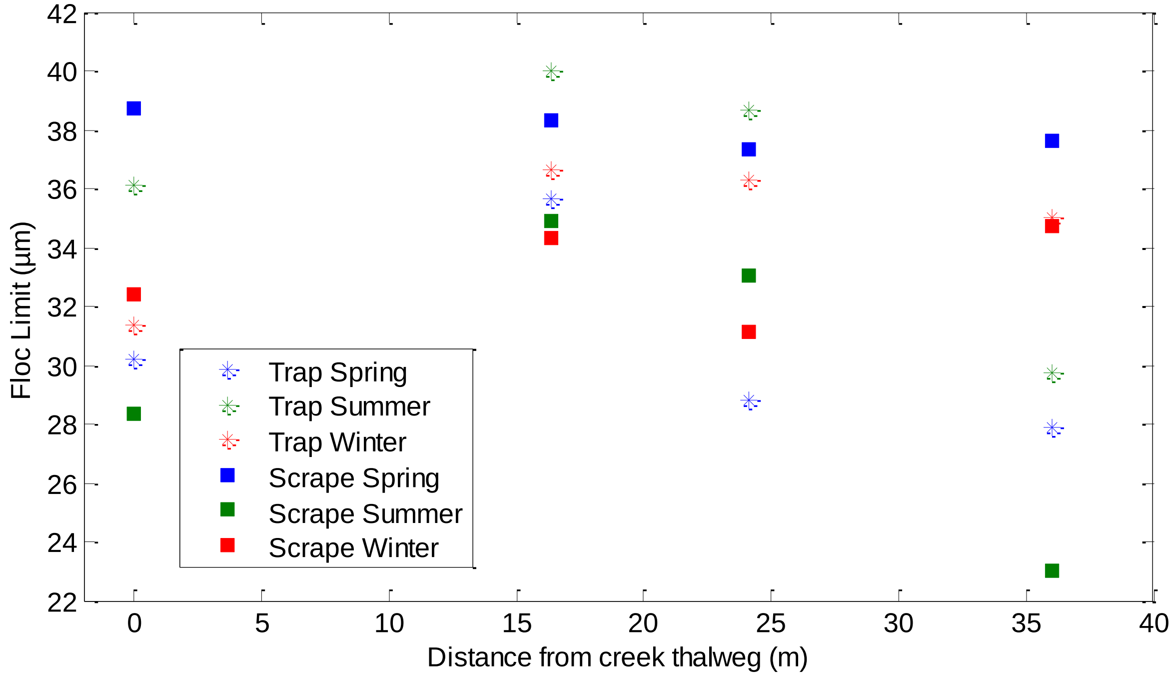

Figure 3.13: Floc limit (µm) of both trap and surface scrape sediments divided by seasonal categories, vs distance from the creek thalweg. Trap samples with anomalous DIGS distributions were not included in these mean values.

3.3.3 Suspended Sediments

For suspended sediments from the automated water sampler at the marsh bank, values of the June tides were much finer than all the other months (Figure 3.14), while the means of all the other months did not vary extensively. The June10am tide representing the month of June is the most notable tide as it is finer than all the others. The ISCO samples for June8pm were also processed and their grain size distribution is similar to June10am, finer than the ISCO samples of all other deployments, as can be seen in Figure 3.14. Finer grain size distributions were also seen on some June traps (Figure 3.11).

In Figure 3.15, which shows the grain size distributions at 15-minute intervals within each of the tides displayed, both the concentrations and the size of the sediments change throughout the tide. This is especially true in the tides with high concentrations, such as July5am and Nov15am which experience a fining of suspended sediments on the final ebb. July5am also shows the first sample of the tide to be finer than the samples during the middle of the tide. The first and last samples, being the finest, are also the most concentrated samples in the tide. Sep18am experiences a different scenario where the first sample of the tide is in contrast coarser than all the remaining 15-minute interval samples of that tide. In another scenario, Jan11pm does not experience a change in grain size during the entirety of the tide. As can be seen by the colours in Figure 3.15, most tides show that the samples on the initial flood were amongst the most concentrated. Some tides (July5am, Nov15pm, and Mar28am) also show the samples on the final ebb being amongst the most concentrated while other tides (Aug4pm, Jan11pm, and Jun10am) show a progression towards lesser concentration throughout the tide.

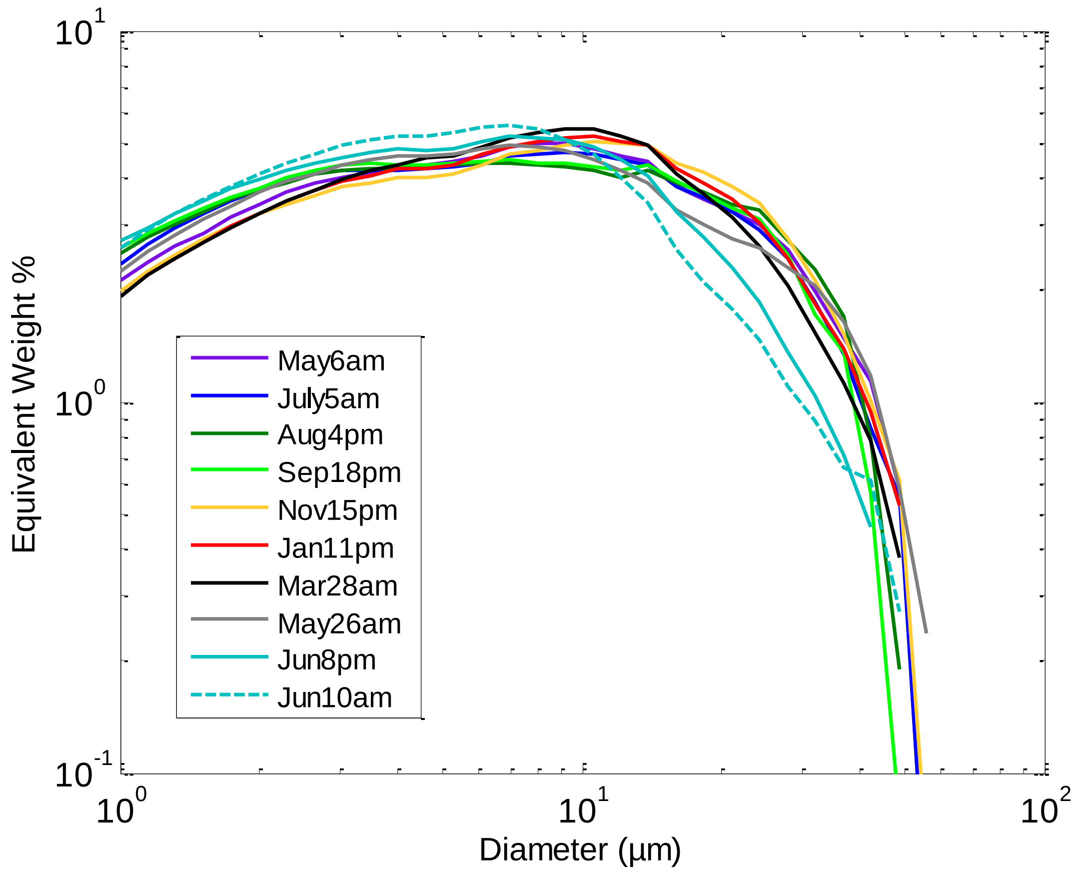

Figure 3.14: Mean DIGS per tide of suspended sediments from the ISCO water sampler at the marsh bank.

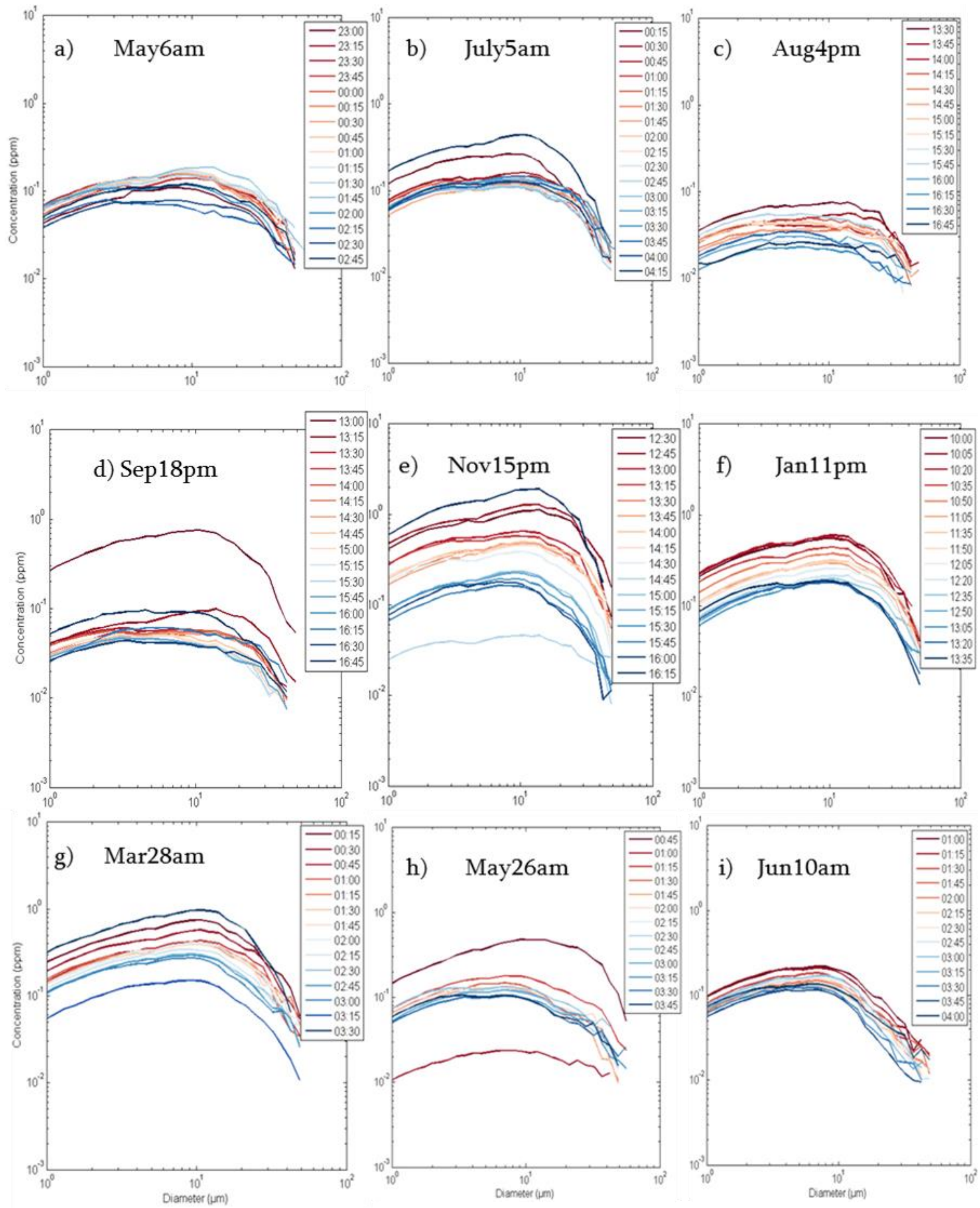

Figure 3.15: Concentration (ppm) of grain size from the water sampler samples at the marsh bank for one tide per deployment: a) May6am, b) July5am, c) Aug4pm, d) Sep18pm, e) Nov15pm, f) Jan11pm, g) Mar28am, h) May26am, and i) Jun10am. The 16:00 sample from Sep18pm is not shown because of likely contamination.

The total sum of volume concentrations from each ISCO sample collected at 15-minute intervals over one tide from each deployment are shown in Figure 3.16. Approximately 3 hours after the water has initially entered the creek (~45 minutes after high tide), concentrations for all tides are reduced to low values. Tides from the three deployments of the winter category start with a high concentration and decline at a similar rate. The slopes of the time series for November, January, and March are -5.83, -2.32, and -3.47 $ppm \cdot hr^{-1}$ respectively. Tides from September and May 2013, which are the two deployments that experienced high wind events leading to high shear stresses, start with an initially high concentration but decline much faster than the winter tides. The slopes for September and May 2013 are -4.54 and -2.43 $ppm \cdot hr^{-1}$ respectively. The abrupt drop in concentration in the first 15 minutes of the tide during these two deployments results in slopes of -48.09 and -36.02 $ppm \cdot hr^{-1}$ respectively between the time of the first ISCO sample to the second sample 15 minutes after the water has reached the nozzle. This implies that the sediment is settling during the very beginning of the tide. All slopes of the other deployments for the first 15-minute interval are less than 12. The remaining tides, which group the tides of spring and summer which have no notable episodic wind event and high shear stresses during the sampling deployment, begin at low concentrations. These tides, being July, August, September, and June, do not decrease in concentration by a large amount because of their low initial concentration, but they decrease at a similar rate nonetheless. This rate has a slope between -0.66 and 0.26 $ppm \cdot hr^{-1}$ for the four deployments of calm and non-winter conditions. The large increase in total concentration at the end of the tide is caused by an ebb pulse carrying suspended sediment passed the marsh bank as the tide is receding. This final peak is notably higher in the two tides during the months of November and March.

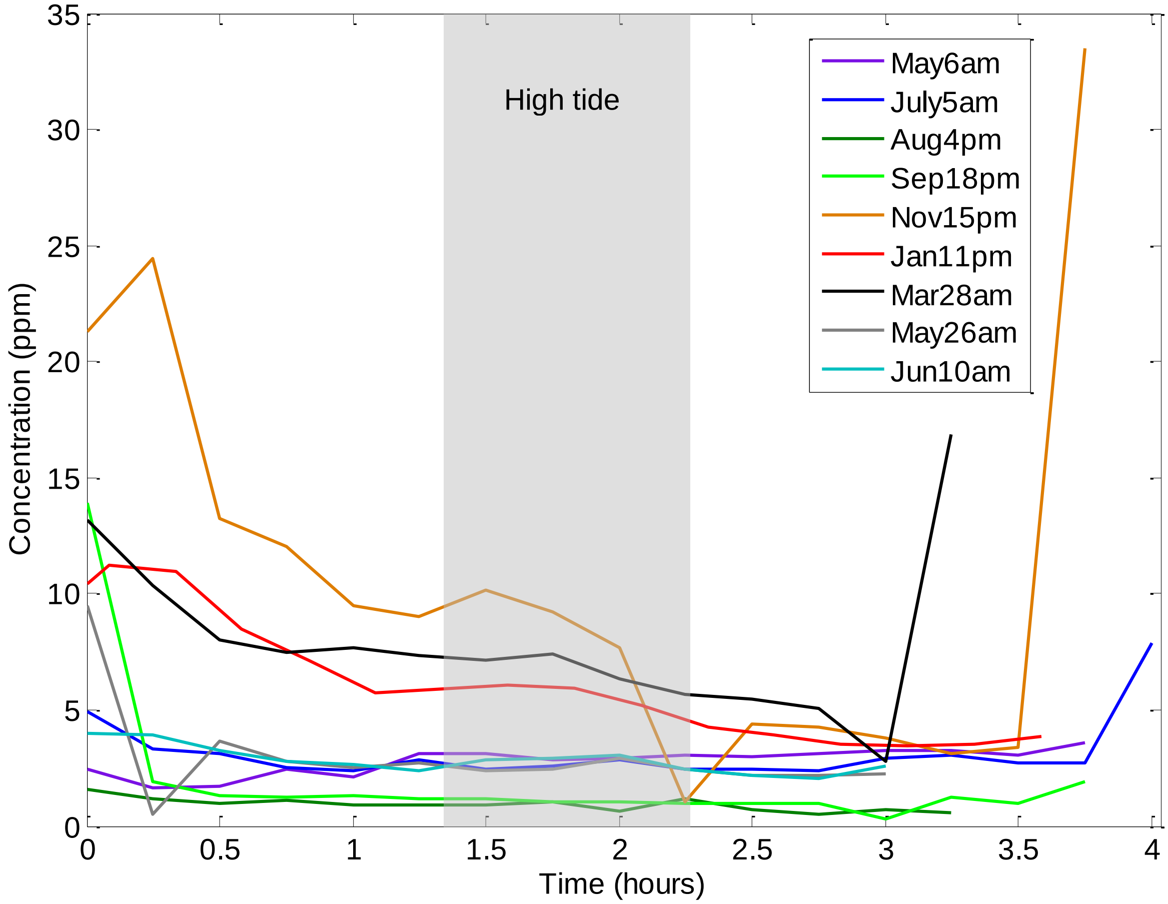

Figure 3.16: Total concentration (ppm), as the sum of all size classes, of each ISCO sample at 15-minute intervals for one tide per deployment plotted with time on the x axis. 0 on the x axis represents the time at which the water first inundates the ISCO nozzle, which is at 3.7 m relative to CGVD28 and spans 5-20 cm above the bed. The grey area is the time interval in which the high tide times of all the tides represented occur.

The mean grain size of the daily scrape samples show enrichment in single grains when compared to the rising stage bottles (Figure 3.17). Similar to the bed samples, the DIGS in the rising stage bottles is coarsest in the thalweg and fines upwards to the marsh surface. When dividing these samples by deployment per station (Figure 3.18), it is evident also with this dataset that the three marsh stations share characteristics that differ greatly from the creek thalweg. On the marsh, the June deployment has finer sediments, which agrees with the sediments from the ISCO water sampler and some of the traps. In the creek thalweg, the March deployment has the coarsest sediments.

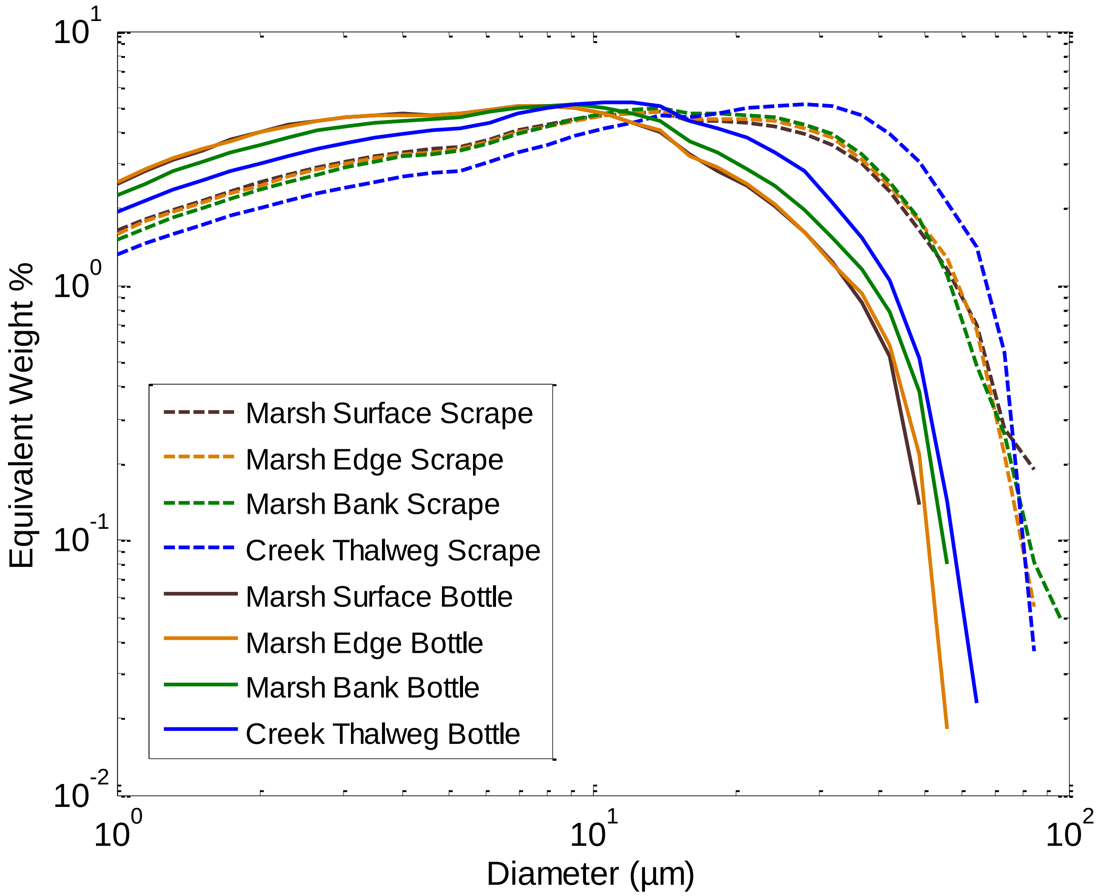

Figure 3.17: Mean DIGS per station of rising stage bottles 20 cm above the bed in the solid lines with the mean DIGS per stations of the surface scrape samples in the dashed lines for comparison.

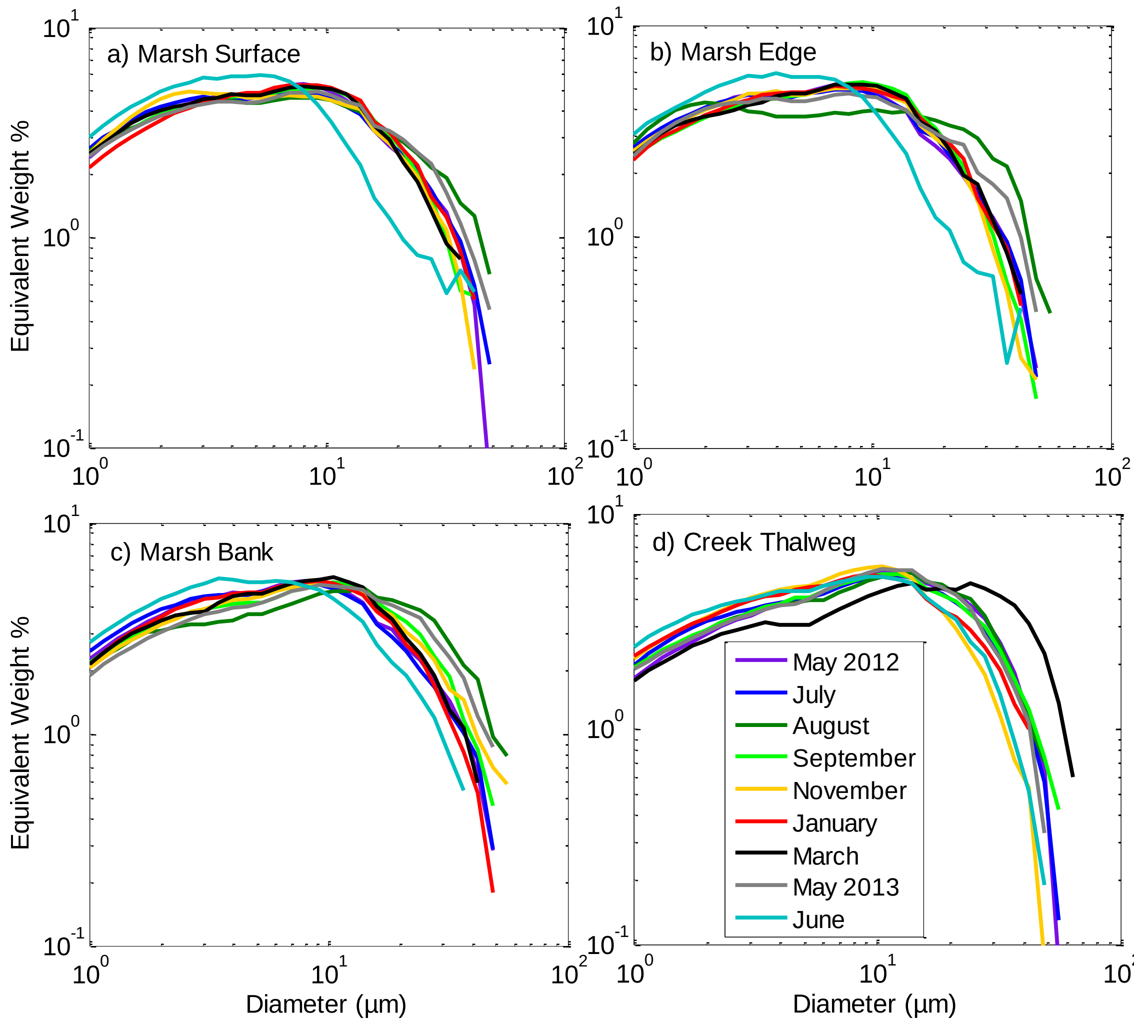

Figure 3.18: DIGS of the rising stage bottles at 20 cm above the bed per deployment at the a) marsh surface, b) marsh edge, c) marsh bank and d) creek thalweg. These are means of the tides per deployment but not all tides were run: means include between 1 and 8 tides.

3.3.4 Shear Stress

Mean shear stress values were 0.159 $N \cdot m^{-2}$ at the marsh surface, 0.137 $N \cdot m^{-2}$ at the marsh edge, and 0.045 $N \cdot m^{-2}$ at the marsh bank (Figure 3.19). At the marsh surface, the four tides with the highest shear stress values, May26pm, May25am, Sep19am, and Sep19pm were four of the five tides with the coarse signatures on the marsh surface. The fifth tide, Jun8pm, did not have enough tidal amplitude to cover the ADV at the marsh surface. May26pm is the tide with highest shear stresses at all three marsh stations. The sediments on these traps at the marsh surface and marsh bank were coarse, and the marsh edge trap sediment was not processed because of lack of deposited material, which is the same scenario for May25am. Sep19pm, a set of traps not having been influenced by rain, also having shear stresses exceeding 1 $N{\cdot}m^{-2}$ at the three marsh stations, had a coarse grain size distribution, and were lacking fine sediments at all three stations. Tides which have elevated shear stress values in the beginning of the tide are tides which also had elevated wind values (Figure 3.21).

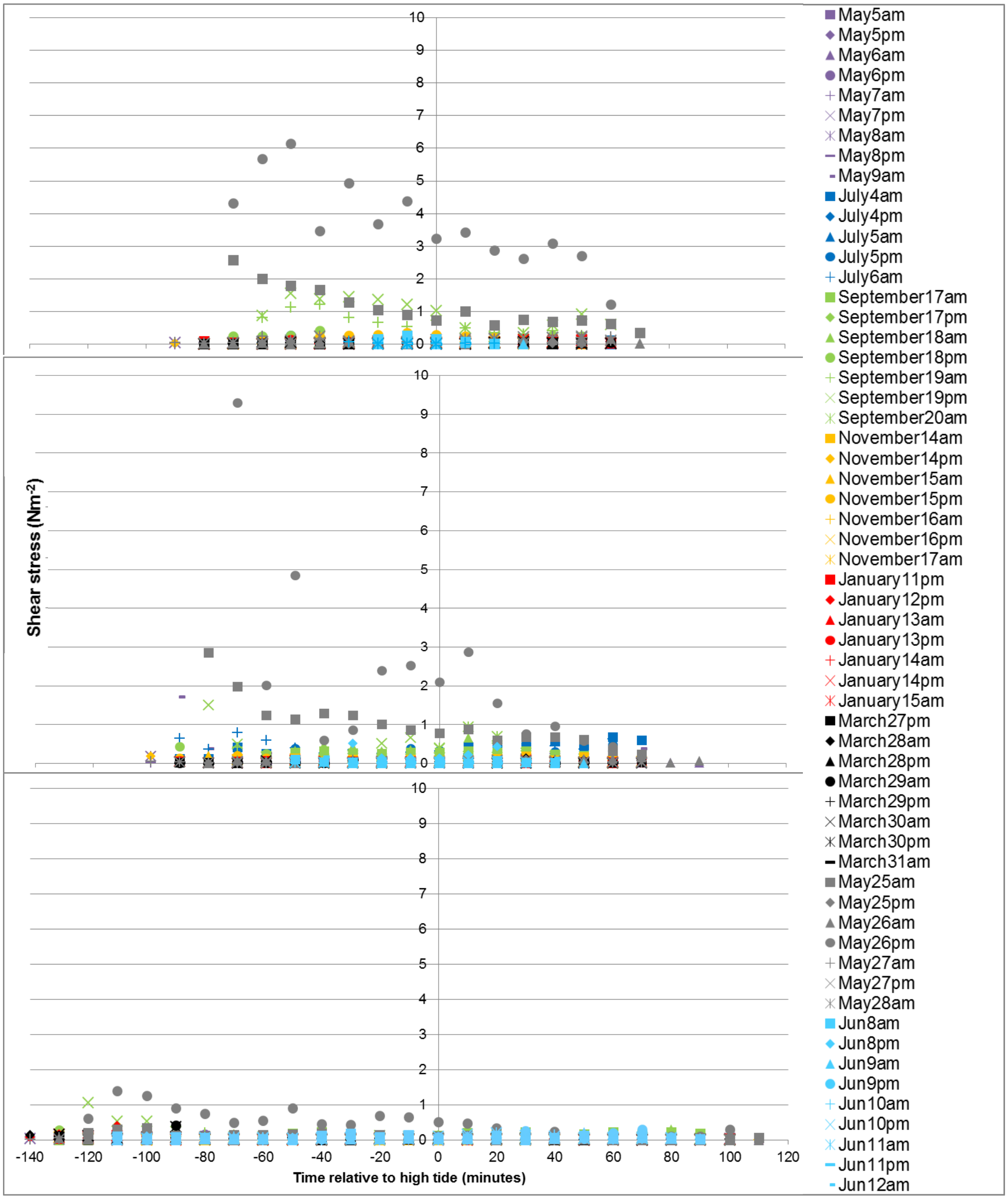

Figure 3.19: Shear stress values per tide at the a) marsh surface, b) marsh edge, and c) marsh bank.

3.3.5 Meteorological Conditions

Figure 3.20 shows that the May 2013 deployment was the deployment with the strongest winds, in fact the only deployment with winds in the 10-12 $m \cdot s^{-1}$ and 12-14 $m \cdot s^{-1}$ categories. Although there are no wind data for the September deployment because the anemometer was being repaired, field notes report very strong winds the morning of September 19th. Environment Canada wind data for Kentville, NS show 9 hours of September 19th having hourly mean wind speeds of 4.2-5.3 $m \cdot s^{-1}$ (Environment Canada, 2014), and Kingsport is much more exposed than Kentville. Therefore, high winds are promoting high shear stresses.

In Figure 3.21, it can be seen that the hourly wind speeds were highest before high tide on the May25am and May26pm tidal cycles. With the peak wind speeds closest to high tide on May26pm, higher shear stresses are present. Although shear stress results (Figure 3.19) were not differentiated between tidal stress and wave stress, it is likely that the increased stress values are because of wave stress as they occur on windy days (Mulligan et al., *in press*). The station with highest increase in shear stress on windy days is the marsh surface, with the marsh edge being second. Because the marsh surface is of higher elevation and experiences shallower inundation, it has greater potential for wave stress to influence sediments on the bed.

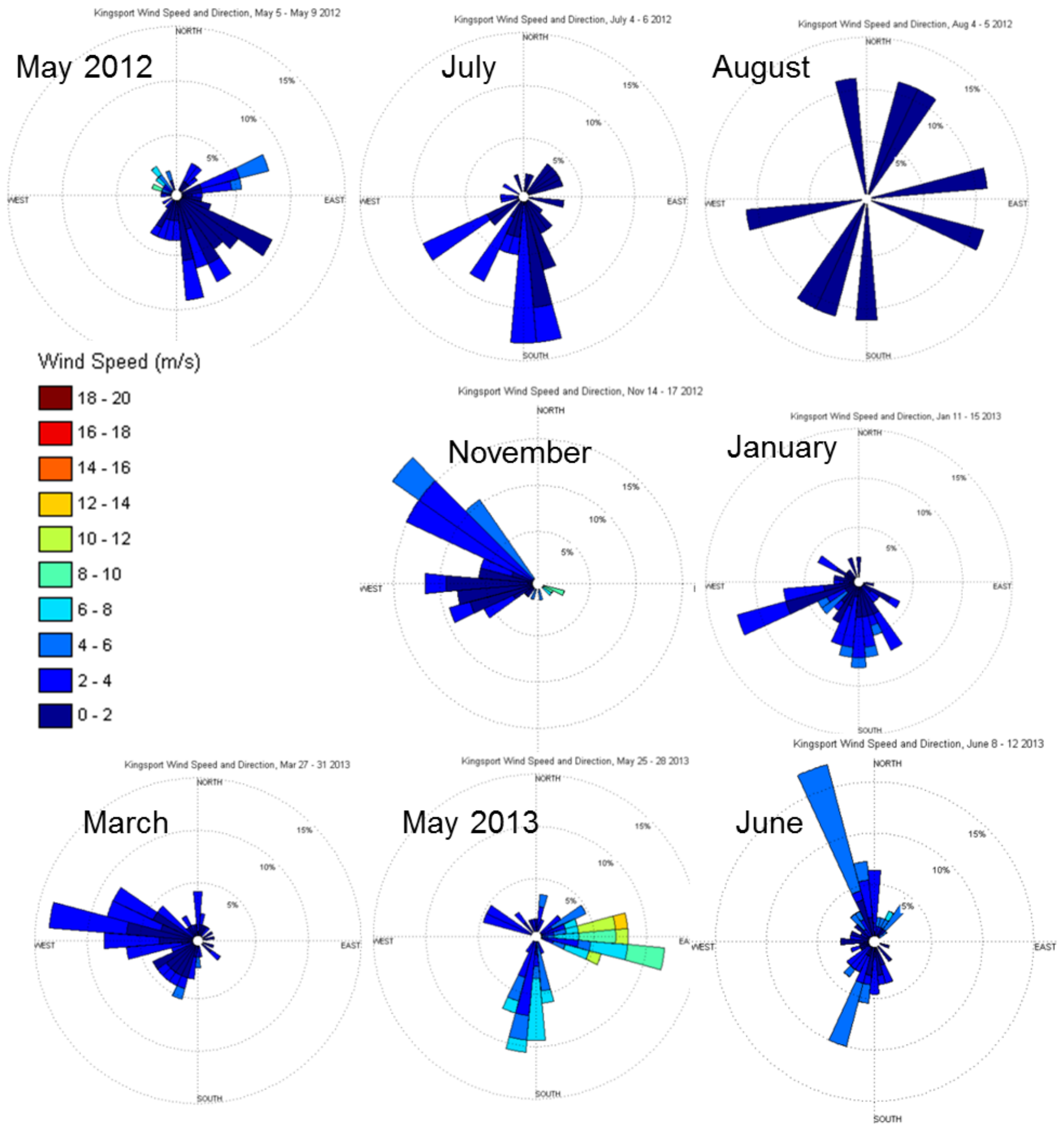

Figure 3.20: Wind roses for each deployment (September is not included because the anemometer was being repaired during that period).

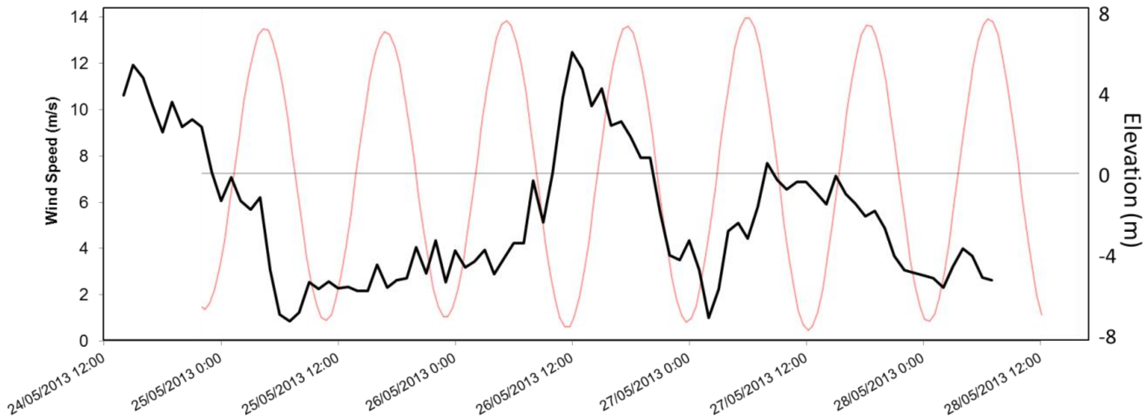

Figure 3.21: Hourly wind speeds for the May 2013 deployment. Red line represents the tidal cycle (data obtained with Webtide software, Dupont et al., 2005).

3.4 Discussion

Grain size characteristics were examined for spatial variability from a creek to a salt marsh surface, and for temporal variability over a 13 month period. Spatial variability in both the grain size and the floc fraction, the portion of sediment deposited in floc form, were evident both along the creek and from the creek to the marsh surface. Seasonally, there was no strong pattern for either grain size or floc fraction.

Due to the high concentration of fine-grained sediment in the Upper Bay of Fundy the relative amount of material being deposited on the bed in floc form is consistently high (Figure 3.6, Figure 3.12). Increase in suspended sediment concentration for a given floc fraction leads to a faster clearance rate and therefore more sediment deposition (Kranck, 1980). The higher suspended sediment concentrations occurred in the winter and they led to larger amounts of sediment deposition. It is the increase in suspended sediment concentration that controls the increase in settling and therefore deposition.

Because it is highly flocculated, more deposition does not lead to a great increase in sediment being deposited in floc form rather than single grain form for that winter period. This finding further builds on the results of O'Laughlin et al. (2014), showing that floc fraction is routinely high in Upper Bay of Fundy tidal creeks.

Daily surface scrape samples integrate sediment deposition over multiple tides. The marsh bank is the area where most sediment deposited in floc form. The marsh bank is the station that had the highest mean floc fraction (83%). The area occupied by the marsh bank received the most material deposited in floc form because it is the most favourable zone for flocculated sediment to deposit. The location of the marsh bank is far enough from the source of sediment for the single grains to have already deposited because of reduced velocities from the creek thalweg to the marsh bank, yet it is close enough to the sediment supply for the suspended sediment concentration to still be high (Curran et al., 2004). The marsh bank represents this area in the main transect as the creek sees single grain settling, with the lowest floc fraction of 76%, and the marsh surface has low concentrations, which leads to this station having the second lowest floc fraction of 79%. Because of the reduced suspended sediment concentration on the high marsh, there is no pronounced rapid settling at these high elevations such as there is on the marsh bank. The marsh edge is the transition between the marsh bank and the marsh surface with a high floc fraction as well, being 82%, but at lower concentrations than the marsh bank. Rapid floc deposition on the rising tide led to decreased sediment deposited in floc form further from the source because the flocs deposited early as soon as the velocities were low enough to be suitable for rapid settling. Although this pattern is seen, the differences in the floc fraction values only span 7%, and the marsh bank is not statistically significant from the marsh edge or the marsh surface, therefore flocculation at all stations is high, and flocs are a major component of sediment deposition in this entire creek system.

There was a progressive fining of sediment with elevation and distance from the creek, from the creek thalweg to the marsh surface, supported by the surface scrapes, traps, and rising stage bottles along the main transect. This fining of sediment with increased elevation was also seen in the smaller scale bank transects. These results agree with the study of Yang et al. (2008). A fining of grains along the creek thalweg with increasing distance from the mouth of the creek was also prominent. Sediments deposited become finer with increasing elevation and increasing distance from the source. With a decrease in tidal amplitude from tidal energy extraction (Karsten et al., 2008), these locations would become higher in elevation relative to the tidal frame, and therefore coarse grains would deposit sooner and the areas further from the main creek, such as the marsh surface, would receive less coarse grains.

The pattern of decreasing grain size from the creek to the marsh surface with increasing elevation within the tidal frame and increasing distance from creek reflects the decreasing velocity being able to carry progressively less sediment as it travels through the marsh and deposits along the way. Although the effect of vegetation on the marsh to reduce velocity and increase deposition has been extensively researched (Bouma et al., 2005; D'Alpaos et al., 2006; Neumeier and Amos, 2006a; Neumeier and Amos, 2006b; Yang et al., 2008; Nolte et al., 2013), the increased biomass in the summer at this site did not lead to increased deposition, as shown in Chapter 2. The velocities are progressively diminished with higher elevations because the flow becomes less confined by the topography of the creek (Torres and Styles, 2007).

The June deployment had a lack of fine sediments on the traps for the tide of Jun8pm, directly following post tropical storm Andrea, but had an abundance of fines and lack of coarse material on those same traps after several tidal cycles had occurred, on June 10^{th}. Incoming suspended sediments were very fine for the June deployment. This indicates that there was abundant fine, flocculated sediment in the system, although it did not make it to the traps for that Jun8pm tide of heavy rain. This abundant fine material is likely because of rain resuspension during post tropical storm Andrea, and there was a several tide lag on that fine suspended sediment coming back into the creek and marsh system (Beuselinck et al., 2001; Yang et al., 2008). The fine signature is not seen in the surface scrapes, where the sediments seem in fact coarse, because the surface scrapes are a representation of a longer period of time, representing not only the June tides but sediment that would have previously deposited. The fact that the June suspended sediments are fine indicates that the coarseness in the June surface samples may be coming from sediment deposited when the suspended sediments were also coarse. The coarseness of the June surface scrapes may also be because many fines have been resuspended during the rain event and had not yet settled out.

Tides in the March deployment showed coarse sediments in the incoming suspended sediments caught by the rising stage bottles in the creek thalweg. Coarse sediments were then also seen deposited on the traps during that time, on March 27^{th} and March 28^{th}, further up from the creek thalweg, on the marsh bank and the marsh edge. Coarse materials during this time travelled further than they typically do. Sedimentation on the Bay of Fundy marshes is heavily affected by the formation and melting of ice blocks that contain sediment (van Proosdij and Townend, 2006). Melting of ice blocks both locally, and offshore to then be transported into the creek, could be the source of this coarser material.

Biological influences are more active in the summer, leading to differences in seasonal mobility of sediments (Amos et al., 2004; Andersen et al., 2007). In a study conducted on the adjacent tidal flat to this creek at Kingsport, Carrière-Garwood (2013), found fine grains <10 µm to be retained by biofilms at lower shear stress values of 0.08 $N{\cdot}m^{-2}$ and 0.16 $N{\cdot}m^{-2}$ while biofilms did not retain these fines at higher shear stress values up to 0.60 $N{\cdot}m^{-2}$. Carrière-Garwood (2013) found erodibility to decrease from April to November in the tidal flat, which differs from the creek which experienced considerable erosion from October to February as discussed in Chapter 2. Nevertheless, the fact that biofilms retain sediments less than 10 µm at low shear stresses leads to the possibility that there could be less fine sediment retention in the creek in the winter because of less abundant biofilms. With median shear stress values for the marsh over the entire study of 0.030 $N{\cdot}m^{-2}$ - 0.034 $N{\cdot}m^{-2}$, conditions are often in the range for biofilms to retain <10 µm sized sediments. The exception to that are the windy tides where shear stresses exceed 1 $N{\cdot}m^{-2}$, which are high enough to mobilize sediment of sizes present (McCave and Hall, 2006). The fact that the March deployment, not having experienced windy days, does see abundant coarse sediments could be because of lack of biofilms to retain the fines.

Increased bottom stress from winds has a strong effect on both concentration and DIGS in the study area. On windy tides, such as May25am and May26pm, the DIGS on the traps suggest that the floc settled material had been preferentially removed (Figure 3.11). Strong winds lead to high shear stresses which anomalously removed material from the traps. This disruption occurred when winds were above the threshold of 10 $m \cdot s^{-1}$ (Christiansen et al., 1992), and shear stresses exceeded 1 $N \cdot m^{-2}$.

Bed shear stress values were greater at the marsh surface and lowest at the marsh bank, which is opposite to that seen in the horizontal velocity data. Because the bed shear stress takes the *u* and *w* components which include one horizontal and one vertical component, there was more vertical movement in the water column at the marsh surface, which is likely the effect of waves in shallow water. The means of the bed shear stress values (0.159 $N \cdot m^{-2}$, 0.137 $N \cdot m^{-2}$, and 0.045 $N \cdot m^{-2}$ at the marsh surface, marsh edge, and marsh bank respectively) are highly influenced by the few tides that have very high values. The median values for bed shear stress are 0.034 $N \cdot m^{-2}$, 0.034 $N \cdot m^{-2}$, and 0.030 $N \cdot m^{-2}$ at the marsh surface, marsh edge, and marsh bank respectively, which spans much less of a range than the mean values. Because the marsh surface and the marsh edge are at higher elevations in the tidal frame and get inundated by a shorter height of water, this means that the rain and wind are able to have a greater influence on what is occurring at the bed. In contrast, the depth at the marsh bank reduced the influence of the rain and the wind; the exception being the period of wetting and drying at that location. For example, on the May26pm tide with a level of 7.7 m of water in the creek at high tide, the marsh bank had 4.0 m of water and the marsh surface 1.8 m. For wind-induced waves that have a relatively short fetch, which is the case in Kingsport for the orientation of the creek, the bed shear stresses decrease with increased water height (Fagherazzi et al., 2006; Mariotti and Fagherazzi, 2013). This agrees with the high marsh stations having higher bed shear stress values because they are the stations with the shallowest water depths. The high marsh stations therefore have more opportunity for flocs not to be retained, and instead to be resuspended, leading to a lower floc fraction. Floc fraction and grain size typically have a negative relationship, meaning that coarser sediment leads to less flocs deposited, because flocs are formed of fine material. Understanding that the high marsh stations are more capable of having flocs resuspended explains why the median grain size decreases from the marsh bank to the marsh surface while the floc fraction also decreases from the marsh bank to the marsh surface, as finer material is typically more flocculated.

Law et al. (2013a), in a study on the same Kingsport marsh system with a focus on the un-vegetated tidal flat, found that floc fraction was controlled by elevation. In summer, floc fraction decreased with elevation but in winter this trend was reversed and floc fraction was higher further up the flat. Sediment concentration was identified as the controlling factor with higher concentrations in March leading to more floc deposition higher up the flat. Floc fraction decreased with elevation in July when the concentration was lower. A similar trend was found at our study site to the extent of the marsh bank, but not beyond. The high marsh stations are understandably different from the flats because of the abundance of *Spartina patens* vegetation which acts as a barrier. Another reason why flocs are not seen on the higher elevations as much is because of the steeper slope in the creek. As it takes a long time for the water to reach the high marsh, the bulk of the flocs have already deposited and there is less sediment available once the water does reach it.

The total sum of the concentrations obtained from all the ISCO samples being run through the Multisizer™ show that certain tides begin with different concentrations, but the concentrations just after mid-tide are similar. Tides of different initial concentrations have different clearance rates but result in similar concentrations just after the middle of the tide. This agrees with the lab results of Kranck (1980) who concludes that the clearance rate of flocculated suspensions is dependent on initial concentration and that the concentration of the suspension will reach the final concentration at the same time. Figure 3.16 differentiates the suspensions on the marsh bank in three categories. One category includes the three winter deployments and is characteristic of suspensions which occur during regularly highly concentrated waters, and decrease at a similar rate. The second category includes the two deployments which had wind events and high shear stresses, which also have high initial concentrations but decrease at a faster rate. The third category includes the calm deployments of the spring and summer where the concentrations begin low, and stay low for the remainder of the tide. Samples with the highest concentrations will have the fastest clearance rate leading to the greatest flux to the bed (Kranck, 1980). Deposition on the Kingsport traps was highest on tides with the highest initial concentration. This rapid clearance depleted the water column of sediment before it could reach the marsh surface. Suspended sediment concentration fell to close to the same value on all tides regardless of the initial concentration (Figure 3.16). Similar to Kranck's (1980) study, in the high concentration environment of the Bay of Fundy, the water flooding the marsh surface had reached its equilibrium concentration.

At the marsh bank, both the concentration of sediment and the size of sediment changed throughout the tide (Figure 3.15). The samples at the very first portion of the flood tide and the samples at the very end of the ebb were the ones which experienced different grain sizes than most other samples during the middle of the tide. On the flooding tide, some tides showed high concentration and rapid clearing. This clearing resulted in deposition on the bed. In some cases, including the winter and on tides experiencing rainfall, there was a highly concentrated ebb pulse consisting of finer material than the rest of the tide. Jan11pm was an exception to this but the final ebb could have been missed by the 15-minute interval of the ISCO not capturing this pulse. This ebb pulse was resuspending some of the material that was deposited; therefore not all the material that was deposited stayed on the bed. While the final ebb was always either similar or finer than the remainder of the tidal cycle, the initial flood sample was not consistently different in grain size as July5am experienced a fine first flood sample while Sep18pm and May26pm experienced a coarse first flood sample. Sep18pm and May26pm were amongst the windiest of tides. High winds resulted in higher bed shear stress which led to erosion of sediments, which is why in these cases a high suspended sediment concentration is seen at the initial stage of the tide (Bartholomä et al., 2009). The suspended sediment concentration was elevated during the initial portion of the tide but the coarse sediments which were initially resuspended by the incoming tide did not stay in suspension once the bed was inundated by deeper water. Wave resuspension combined with the flood pulse was able to maintain higher concentrations of coarser particles at the intake nozzle. As water depth at the station increased, wave resuspension diminished, therefore grain size diminished.

While both deposited samples and suspended samples showed a strong trend of decreasing grain size with increasing distance from the creek, the deposited samples were all coarser than the suspended samples (Figure 3.17). Coarse grains are over-represented in the bed relative to the suspension because they sink faster than flocs. Another possibility is flocs being removed from the surface on the ebb. After studying the different concentrations and sizes at the marsh bank from the ISCO water sampler, it can be concluded that the removal of flocs from the surface is likely for the tides of July5am, Nov15pm, and Mar28am. This is because the ebb pulse in concentration consists of material that is finer than the material in suspension for the earlier portion of the tide.

With a decrease in tidal energy caused by energy extraction (Karsten et al., 2008), there is the possibility of a decrease in initial suspended sediment concentration for the locations considered in this study. This would lead to less rapid settling where it is mostly seen now, on the marsh bank. The settling could occur earlier, before the water reaches the marsh bank. This would lead to a shift of zones moving to lower elevations, and a new, less frequently inundated and therefore less saline zone at the uppermost marsh surface.

3.5 Conclusion

Flocculation played an important role in depositing sediments at all stations, and its role was maximized at the marsh bank. The fact that flocculation was critical to the settling of sediment led to the categorization of sediment settling at three different clearance rates yet resulting to the same low concentration approximately 3 hours after inundation (Kranck, 1980). These three different clearance rates were grouped in winter tides with high initial concentrations decreasing steadily, episodic windy tides with high initial concentrations and very rapid and immediate settling, and calm spring/summer tides which had low concentrations which remained low.

Sediments showed a decreasing size from the creek with increasing elevation in the tidal frame, as the marsh bank has intermediate grain size relative to other grains at the site, and the marsh edge and marsh surface were very similar with the finest sediments. A fining of sediment was also seen with increasing distance from the source, with the bank samples closer to the head of the creek being finer. While both deposited and suspended sediments showed this grain size trend, all the deposited samples were coarser than the suspended samples because of the faster sinking coarse material being over-represented in the bed.

The largest rainfall event captured, post tropical storm Andrea, had an abundance of fine sediments that were available to the system for several tides following the event, suggesting that many fines had been resuspended during the storm. Although the excessive rainfall led to a change in the grain size of the incoming suspended sediment as well as a change in the grain size of the sediment deposited on the trap for several tides, the marsh system was able to recover from this meteorological event within a few days. Because a change is also seen in the concentration, these episodic events are important to consider. In contrast to this episodic meteorological effect, the seasonal trend, although not pronounced, was different in the creek than on the marsh. On the marsh (at the three stations) a coarsening of grains was seen in March in the surface scrape samples. While the seasonal component, being mainly higher concentrations, is effective at increasing deposition, the episodic events are not.

The differences between the sediment characteristics in the creek and on the marsh are important because changes imposed to the intertidal system by tidal energy extraction will lead to lower tidal amplitudes and therefore less flooding of the marsh surface (Karsten et al., 2008; O'Laughlin and van Proosdij, 2012). Less water inundation and less sediment supply could lead to more changes on the marsh, not only to the grain sizes, but the interconnecting components such as plant communities and therefore invertebrates and other organisms using the salt marsh as their habitat.

Chapter 4:

Synthesis: Seasonal sediment dynamics

Both seasonal controls and episodic controls were present at Kingsport marsh. Chapter 2 showed a strong seasonal control in the creek, as the winter did have higher suspended sediment concentrations than the summer, and that led to more deposition. Chapter 2 also showed that these high winter depositions are more pronounced at the creek thalweg and the marsh bank while the high marsh is not as influenced because of lack of increased supply, the sediment having already largely deposited in the creek thalweg and marsh bank. Chapter 3 showed an episodic control on the clearance rate of sediment led by meteorological events with strong winds, and also showed that increased initial concentration led to increased settling. Chapter 3 also showed that flocculation is high throughout the system, while maximized at the marsh bank, that there is a consistent fining with both distance from the creek and distance from the downstream source along the creek, and that deposited sediments are consistently coarser than suspended sediments.

The seasonal pattern seen was that winter was the period with both the most deposition and erosion. More incoming suspended sediment, frequent strong winds, and less vegetation made more sediment available in the winter. This sediment stayed confined to the creek, as higher concentrations of regularly flocculated material led to rapid deposition. The ecomorphodynamics of the Kingsport creek remained in relative equilibrium because the tides with high incoming suspended sediment concentration also had high outgoing suspended sediment concentration.

The companion component to this project is hydrodynamic and sediment transport modelling of Kingsport marsh being done by Logan Ashall at Queen's University. In that component the Delft3D modelling suite is used, which calculates non-steady flow and transport phenomena that result from tidal and meteorological forcing on a curvilinear, boundary-fitted grid (Lesser et al., 2004; van Proosdij et al., 2014). The model has three grids, coarser in the Minas Basin and finest in Kingsport marsh with a resolution of 8 m. With this fine resolution, the Kingsport creek studied in this thesis and other nearby creeks are able to be resolved and represented. Vegetation was included in the model, and with appropriate vegetation characteristic inputs, the flows on the marsh were resolved very well (Ashall et al., *in prep*). This indicates that the vegetation and hydrodynamic feedback plays a great role in the ecomorphodynamics at this site.

A separate larger scale model encompassing the entire Minas Basin is presented in Mulligan et al. (*submitted*). From this model, van Proosdij et al. (2014) showed significant wave height occurring on the tidal mudflat adjacent to the tidal creek discussed in this thesis (Figure 4.1 and Figure 4.2). The data used for these wave height calculations were from an ADCP deployed by the Bedford Institute of Oceanography (BIO) during the January 2013 and June 2013 deployments, data courtesy of Brent Law. In January, significant wave heights were regularly 5-15 cm, while significant wave heights in June were regularly much lower, often less than 1cm. The one tide where this is an exception is Jun8pm (yearday 159.5), during tropical storm Andrea during which significant wave heights exceed 20 cm. Suspended sediment concentration was very high on that Jun8pm tide, suggesting that wave resuspension caused this increase in suspended sediment. Winter tides regularly have higher suspended sediment concentration but when episodic events such as tropical storm Andrea occur, summer tides experience increased suspended sediment concentration. The deposition values for these tides are shown in Figures 4.1 and 4.2. The evidence of increased winds causing larger waves with higher significant wave heights (van Proosdij et al., 2014) shows that this increased suspended sediment concentration is because of resuspension of sediment by waves, with high bed shear stress.

With this Minas Basin model (Mulligan et al., *submitted*), more wind during the winter period led to having more development of waves in the Minas Basin. In the intertidal areas, these waves are capable of causing greater shear stress values than are caused by only tidal influence. When wind is coming from a direction that allows a long fetch, waves have more opportunity to form. Long fetch also means that bed shear stress can be applied by waves in deeper waters than if the fetch was shorter (Mariotti and Fagherazzi, 2013). Mulligan et al. (*submitted*) found that in the Minas Basin, winds in the winter came primarily from a direction that allowed for fetch from the top of the Minas Basin to the intertidal areas such as Evangeline Beach and potentially Starr's Point, using data from the Debert Environment Canada weather station.

Fagherazzi et al. (2007) showed that waves are the most important factor for controlling suspended sediment concentration in a microtidal system. Even in a macrotidal system such as the Minas Basin, wind-wave shear stresses are able to exceed tidal shear stresses. In Mulligan et al. (*submitted*), the intertidal areas are the areas where the shear stress values increased when the wind was strong (with a long fetch from the top of the Bay of Fundy towards the coastal areas in proximity to Kingsport). The shear stresses were up to 1 $N \cdot m^{-2}$ higher with these wind-induced waves than the natural shear stresses imposed by the tidal forces only (Mulligan et al., *submitted*).

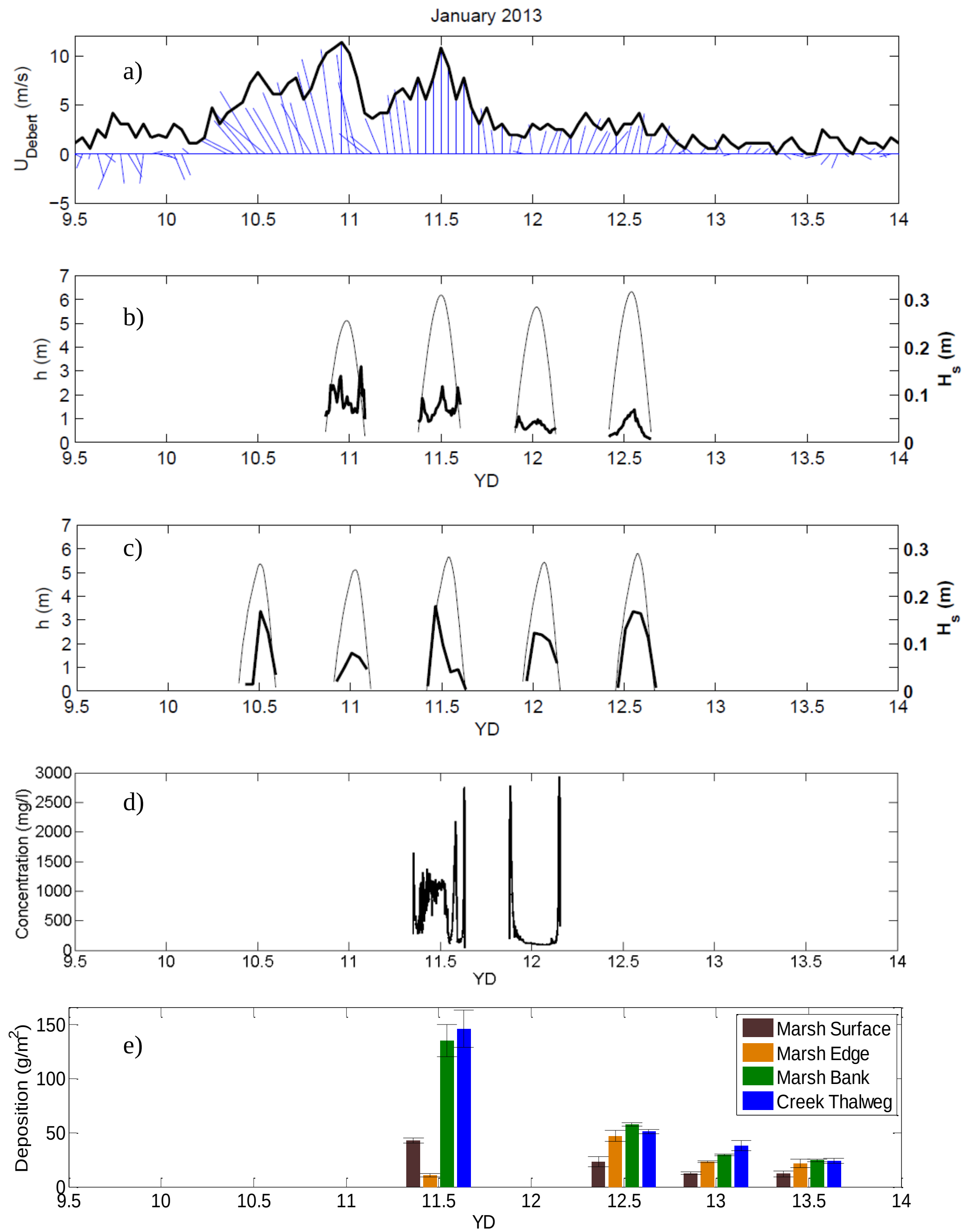

Figure 4.1 January 2013 winds, water levels and significant wave height on the adjacent mudflat, and suspended sediment concentrations and deposition in the creek. a) Winds observed at the Debert weather station, b) observations of water level and significant wave height on mudflat, c) predictions of water level and significant wave height on mudflat, d) suspended sediment concentration from the RBR at 10 cm above the bed in the creek and e) deposition per station for individual tides with error bars representing standard error. a),b), and c) are from van Proosdij et al. (2014) and are from collaboration with Fisheries and Oceans and Queen's University.

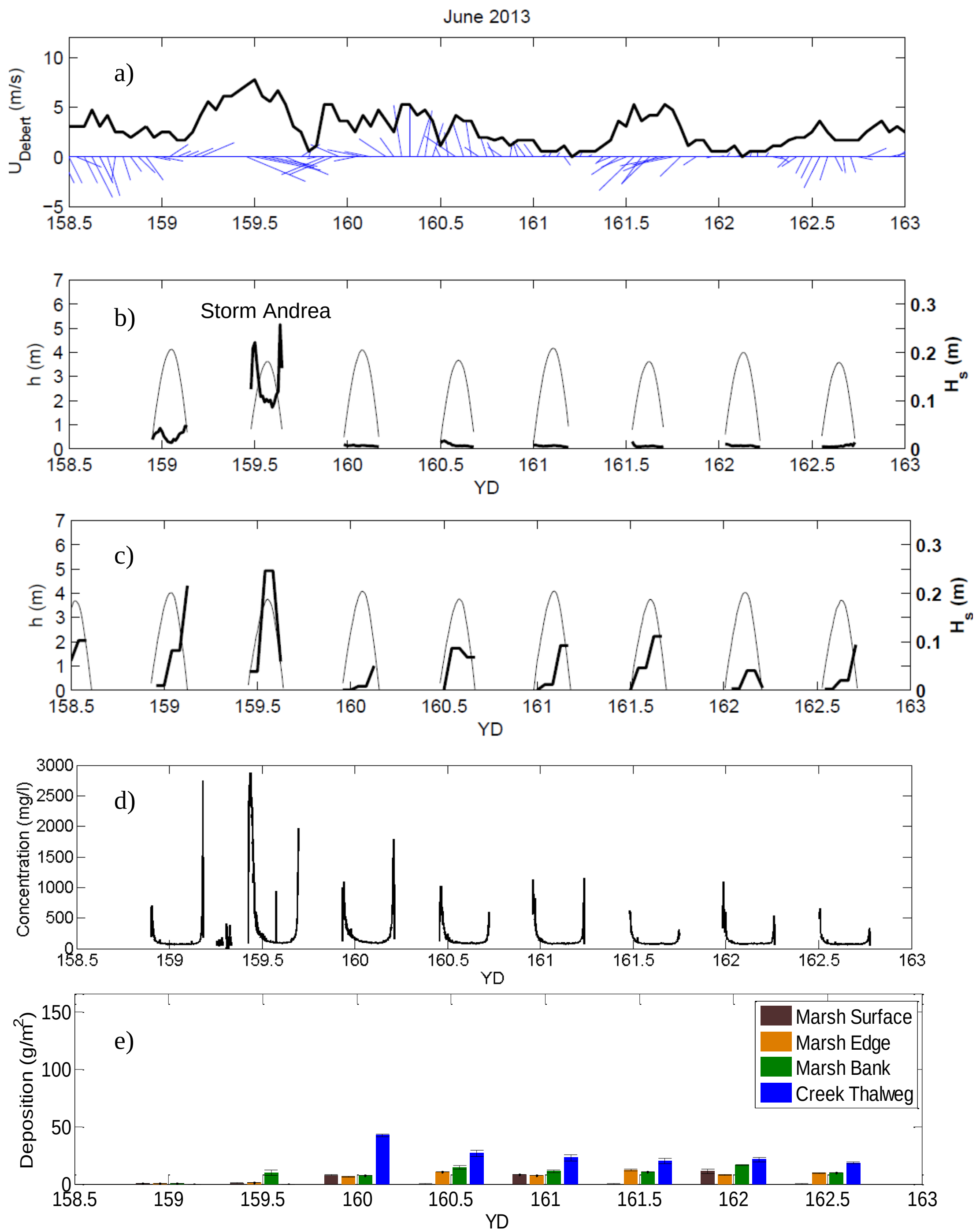

Figure 4.2 June 2013 winds, water levels and significant wave height on the adjacent mudflat, and suspended sediment concentrations and deposition in the creek. a) Winds observed at the Debert weather station, b) observations of water level and significant wave height on mudflat, c) predictions of water level and significant wave height on mudflat, d) suspended sediment concentration from the RBR at 10 cm above the bed in the creek and e) deposition per station for individual tides with error bars representing standard error. a),b), and c) are from van Proosdij et al. (2014) and are from collaboration with Fisheries and Oceans and Queen's University.

When episodic storm events occur in the winter, their outcomes may go less noticed in terms of suspended sediment concentration because the regular tidal cycle in the winter will carry more suspended sediment than a regular tidal cycle during the summer. Because there are typically more storms during the winter seasons, these episodic events will amplify the resuspension and the suspended load of sediment in the water. When storm events such as heavy rainfall and high wind occurs in the summer, they will have a pronounced impact that will last for several tidal cycles before things return to background conditions as the salt marsh and creek surfaces adapt.

When considering the impact that energy extraction will have on the far field sediment dynamics of the intertidal zones, it is necessary to consider how much energy will be taken out of the system to be converted. Because of the high natural variability of the system, and its ability to adapt to storm events, a small amount of energy extraction from the Minas Passage would likely be something that the marsh system could adapt to with relatively minor changes compared to the normal, natural variability. With a large scale field of turbines with a high number of turbines, the hydrodynamic changes are likely to increase because of the larger amount of energy being removed from the water. For a case of 15 turbines in the Minas Passage, the model of Ashall et al. (*in prep)* indicates a 0.2 m decrease in maximum water level (Figure 4.3).

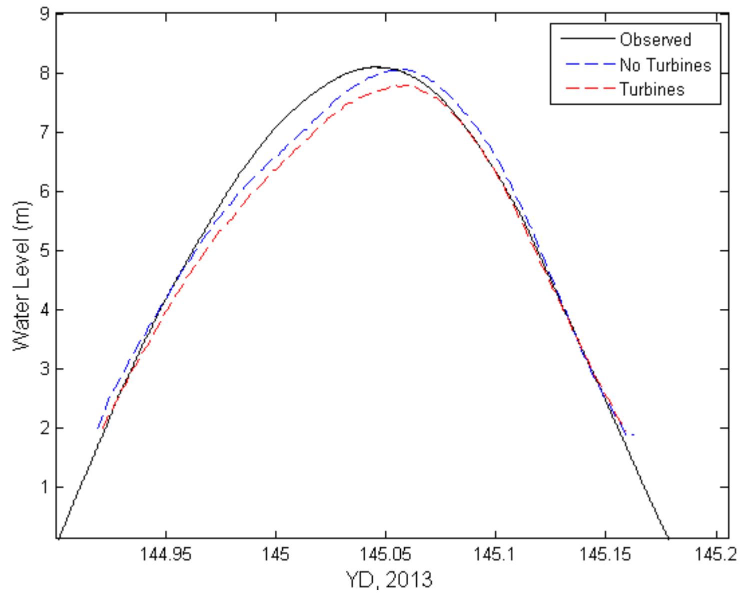

Figure 4.3 Water levels at the creek thalweg station in the Kingsport creek showing a 0.2 m decrease in water level with an array of 15 turbines. This figure is from van Proosdij et al. (2014).

Karsten et al. (2008) predicts that the intertidal zones of the Minas Basin areas would receive a 3.5% change in amplitude with a 2.0 GW energy extraction, which for an area such as Kingsport that would mean a decrease in water elevation by 20-30 cm. van Proosdij et al. (2014) used this 3.5% change in amplitude from Karsten et al. (2008) with a finer resolution model of the Kingsport marsh itself and found an amplitude change of 20 cm (Figure 4.3). Although this change in tidal amplitude was seen which could lead to restructuring of vegetation communities and creeks, there was no significant change is the water currents flowing through Kingsport resulting from this 2.0 GW energy extraction (van Proosdij et al., 2014).

Because sea level is rising in Nova Scotia, both still from isostatic rebound and more recently from current climate change, a decrease in water elevation from energy extraction could be dampened by the rising sea level, as sea level rise in Nova Scotia is projected to rise a minimum of 43 cm in the next century. While energy extraction would mean a decrease in tidal amplitude for the Upper Bay of Fundy, in other areas such as Massachusetts, the change in tidal amplitude is predicted to be amplified (Karsten et al., 2008), meaning that they would undergo a greater rise in water level. For those locations, a rise in water level from energy extraction and sea level rise from climate change would greatly compound the increase in water levels.

Although differences in velocity did not translate to differences in sediment deposition, variability in velocity was higher on the marsh than in the creek. Variability was also higher on the marsh for grain size characteristics. With energy extraction from tidal power, we will see a decrease in velocity, and a smaller tidal amplitude. A smaller tidal amplitude means less inundation of the high marsh, and less tidal cycles which overtop the banks and provide material to feed the marsh. Relative to the distance of the site of the turbines to the sampling stations, the four sampling stations in this thesis are relatively close in proximity to each other. The decrease in water level from energy extraction, at the Kingsport site, can be considered as the same at these four stations, but the consecutive changes caused by a relatively similar water level decrease will be different. On the marsh surface, the slope is very gentle; therefore a slight decrease in water level will mean a larger portion of the marsh not being inundated. On the marsh bank, the slope is steeper; therefore a slight decrease in water level will lead to only a smaller surface area being inundated less frequently. In the long term, the marsh surface plant community could be changed to less saline plants. This shows the importance of the feedbacks between hydrodynamics and plants in salt marshes, similarly emphasized in Wolner et al. (2013) for barrier island ecosystems.

In the case of the change of velocity, it is the creek that will see the most difference because it had such a repetitive velocity pattern to begin with. On the marsh, the velocity is so variable (Figure 2.8a,b,c) that a small alteration from that won't be outside the range of natural variability. In the creek, an alteration from Figure 2.8d would be more likely to cause a variation further from the norm. Therefore, the two initial things that would happen with energy extraction is less inundation of the marsh surface, and slower velocities in the creek. Decreased currents within the creek could likely lead to more deposition in the creek. As the single grains would deposit further down creek, the location most ideal for flocs to deposit, which is currently the marsh bank, would move to an area lower in elevation. The potential for more deposition in the creek and the filling in of the creeks would be possible. Infilling of creeks would cause more development of low marsh. The changes in velocities on the marsh would not alter the sediment transport processes directly, but these processes could be indirectly altered by the slowing of flow in the creek. Because most of the tides collected for the purposes of this thesis were in high tidal amplitude conditions, data of neap tides would be useful to examine the flow conditions in the creek under different tidal amplitudes. Tides from the June 2013 deployment, which were moderate tides, did seem to vary slightly from the regular pattern seen from the other deployments (Figure 2.8d). O'Laughlin and van Proosdij (2012) showed that channel-restricted tides behave differently than over-marsh tides, meaning tides that either overtop the creek banks or stay confined. In Figure 2.8d we are seeing the behaviour of the over-marsh tides and not of the channel-restricted tides. The addition of channel-restricted tides would likely increase the variability of Figure 2.8d and therefore the relative magnitude of the change in velocity introduced by energy extraction would be dampened. In addition, the creek thalweg was the station that saw by far the most variability in sediment deposition, therefore although consistently slower velocities might cause deposition; it is arguable that episodic events such as tropical storms and seasonal patterns such as high wind activity resuspending sediment would exceed the small changes.

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Appendix A: Geographical coordinates of sampling stations

Station	Latitude	Longitude	Z (CGVD28)	Instruments Deployed
Marsh Surface	45.156545	-64.371856	5.888	ADV, OBS, traps, bottles
Marsh Edge	45.156452	-64.371781	5.473	ADV, traps, bottles
Marsh Bank	45.156390	-64.371732	3.672	ADV, OBS, ISCO, traps, bottles
Creek Thalweg	45.156276	-64.371601	-0.507	ADCP, RBR, traps, bottles

Appendix B: The use of surface mounted sediment traps for sediment characteristics

The use of surface mounted sediment traps to collect sediment for DIGS analysis proved to be challenging under certain hydrodynamic and meteorological conditions. When influenced by rainfall or high shear stress conditions, grain size distributions were anomalously coarse. Although no clear threshold of deposition values is seen, most of the samples with the least amount of sediment deposition were among the anomalous samples showing coarse DIGS distributions. The fact that, for two of the sampling stations, being the marsh edge and the marsh bank, the median diameter of the sediments deposited on the traps are greater than the median of the daily scrapes, suggests that the traps are retaining the coarse sediments and the fine sediments are being preferentially removed during high energy conditions in a way that is different than how the bed is retaining sediments.

Variability in grain size on the traps was much greater on the marsh than in the creek thalweg, even with the tides which experienced rainfall removed. Coarse grains at all three marsh stations were found on tides 1-3 tidal cycles following the rain event. Out of 24 marsh trap samples which show a coarse size spectrum, 19 of these (79%) were on tides which saw rain in the previous 1-3 tidal cycles. Yang et al. (2008) also found a coarsening of sediments during storms on their vegetated surface and observed a lag of 1-2 days, and Beuselinck et al. (2001) found rainfall to enhance transport of coarse material over a larger area, but these samples, as can be seen in Figure B.1, appear to be anomalies.

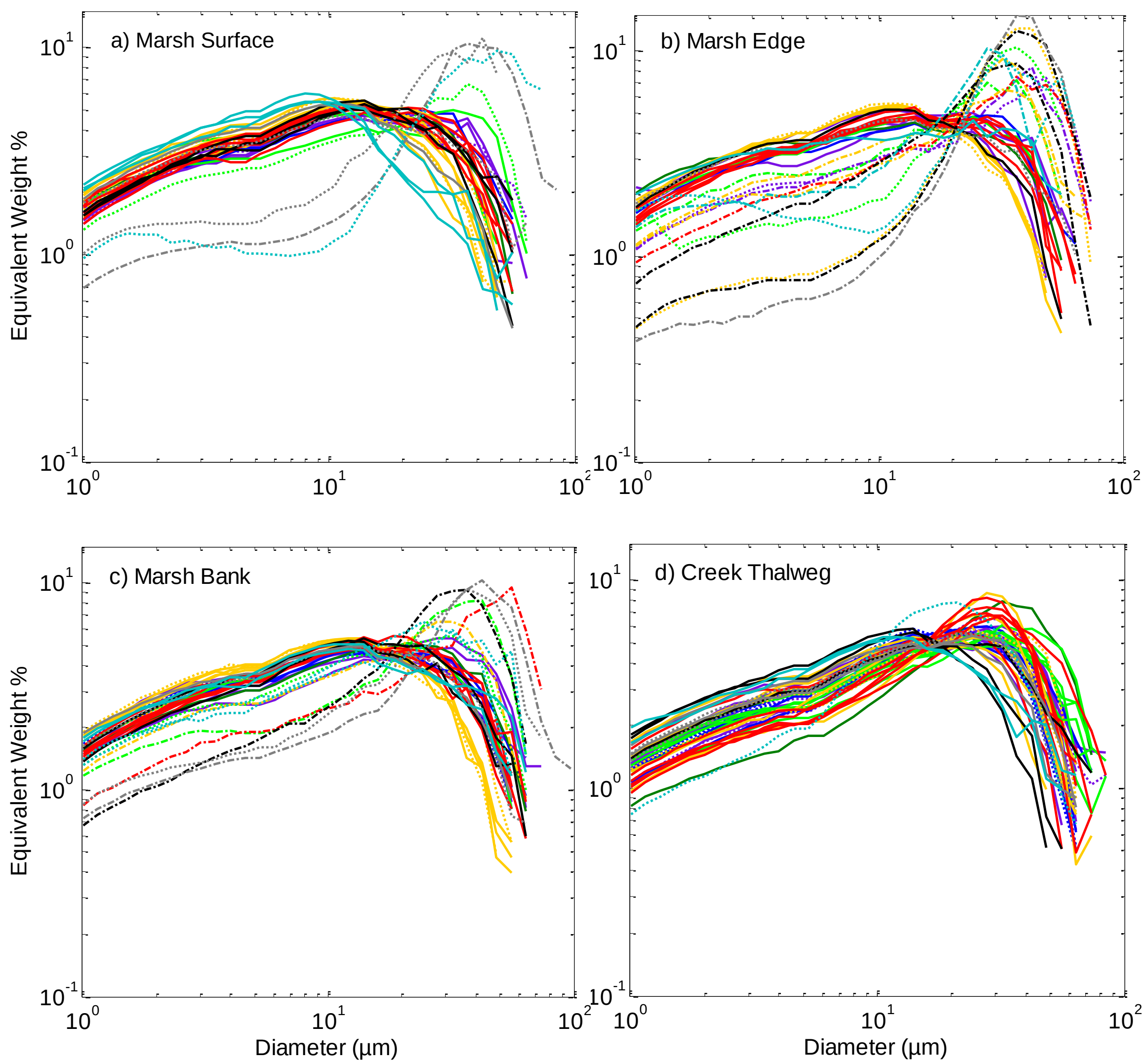

Figure B.1: All DIGS of sediment deposited on traps. Each line represents one tide, with all tides processed being shown. Dotted lines represent tides with rainfall and dash-dotted lines represented tides which were anomalous.

When a grain size spectrum is dominated by a coarse signal, there are two cases which could have occurred. Firstly, there could be more coarse grains present, or secondly, there could be a removal of fine grains. Therefore the influences of the rainfall and high shear stress could either be removing fine sediments or introducing coarse sediments. The mean floc fraction of the trap samples which present a coarse signature is

67%, while the mean floc fraction of all trap samples is 78%. Many of the samples with a coarse signature were also samples of low concentration, as could be determined when being run through the Coulter Counter Multisizer. Because of this low concentration, the grain size distributions of the trap samples were plotted against their respective weight of sediment which had deposited on the trap for that tide (Figure 3.11). In Figure 3.11 it is apparent that these particular tides with the coarse signature are mostly tides which have low amounts of deposition. This leads to the option that what differentiates these coarse size spectra is the lack of fine grains within the sample. High shear stresses are selectively removing the fine sediments from the traps. There was evidence in the field of wave resuspension from the traps as the water was on its final ebb and exposing the traps.

Shear stress values above 1 $N \cdot m^{-2}$, which are high enough to mobilize sediment of sizes present (McCave and Hall, 2006), were enough to influence the grain size. At Kingsport, Garwood (2013) found fine grains <10 µm to be retained by biofilms at lower shear stress values of 0.08 $N \cdot m^{-2}$ and 0.16 $N \cdot m^{-2}$ while biofilms did not retain these fines at higher shear stress values up to 0.60 $N \cdot m^{-2}$. Traps, with a filter paper catching the sediment, do not have the same biological characteristics as the bed. Preferential removal of flocs from the trap surface would result in coarsening of the deposited sediment in a manner consistent with sortable silts (McCave, 1984) and the erodibilty of cohesive sediment (Law et al, 2008). The shear stresses at which fine sediment was missing from the traps were typically, although not in every case, above 1 $N \cdot m^{-2}$, which is much higher than the shear stress values at which fines are retained.

This project has given insight for the use of surface mounted sediment traps. During days when it was raining, as well as during some high shear stress scenarios, rain preferentially removed fine sediments from the traps. This is the reason why trap samples directly impacted by rain as well as trap samples not directly impacted by rain but with anomalously coarse distributions were not included in the statistical analysis. The factor that makes surface mounted sediment traps potentially unreliable is that the filter paper catching the sediment is different than the natural bed and has a different drag coefficient than the bed because the drag coefficient relies on the bottom roughness (Wu et al., 2011). With a different drag coefficient, the shear stress required to resuspend sediment will vary.

While surface mounted sediment traps used in this project are very useful for certain conditions, specifically calm and dry conditions, there may be a better alternative for measuring sediment deposition on a tidal cycle scale during windy and rainy days. In addition to collecting sediment on a tidal cycle scale, surface mounted sediment traps do have the advantage of collecting the sediment on them for further analysis on the sediment itself. In this study, the analysis consisted of determining the weight of the sediment, the size distribution of the sediment, which could then be used to determine characteristics about how the sediment deposited, water content, and organic matter. Other additional analysis includes chemical and mineralogical analysis to determine what the sediment is built of (Nolte et al., 2013). When meteorological conditions cause preferential removal of sediments on the traps, this causes some of those parameters to be changed, which gives an inaccurate representation of the characteristics of the sediment deposited. An alternative sediment trap method that may yield more accurate results in changing meteorological conditions is the open cylinder type of traps (Nolte et al., 2013). These cylinder traps have walls preventing the material to be resuspended, therefore although it will prevent the fabricated preferential removal of rain and high shear stresses, it will also prevent the natural resuspension because the flow characteristics within the cylinder are different than the flow characteristics outside of the cylinder. Therefore, while cylinder traps may fix the problem which occurs with flat open traps, other problems arise with using them, for example changing the currents within the trap. It is recommended that the type of trap which will be most appropriate to each project be given greater consideration.

Appendix C: Sediment characteristics of daily scrape samples

	Folk & Ward (µm)						Inverse Floc Model			
	Mean	Sorting	Skewness	Kurtosis	d50	d90	Floc Fraction	Floc Limit	Source Slope	dhat
May4-M1	7.902	2.758	-0.132	0.914	8.631	27.18	0.78	21	0.54	17
May4-M2	8.196	2.795	-0.139	0.899	8.973	28.56	0.72	18	0.52	16
May4-M3	6.451	2.606	-0.123	0.876	7.061	21.04	0.85	24	0.53	16
May4-C4	7.545	2.793	-0.164	0.910	8.570	26.34	0.79	21	0.53	17
May5-M1	8.811	2.910	-0.119	0.853	9.410	33.08	0.7	18	0.52	17
May5-M2	7.582	2.833	-0.150	0.902	8.529	27.09	0.71	16	0.52	14
May5-M3	8.946	2.845	-0.118	0.827	9.584	33.12	0.77	24	0.53	20
May5-C4	9.857	2.977	-0.205	0.840	11.62	36.09	0.78	28	0.44	27
May6-M1	10.84	3.346	-0.117	0.874	12.13	47.26	0.8	37	0.38	33
May6-M2	8.941	2.909	-0.086	0.858	9.514	33.79	0.74	21	0.55	18
May6-M3	10.92	3.055	-0.176	0.843	12.32	38.56	0.82	37	0.5	31
May6-C4	10.74	3.084	-0.178	0.837	12.17	38.60	0.82	37	0.46	31
May7-M1	8.895	2.941	-0.123	0.834	9.526	33.82	0.83	32	0.44	25
May7-M2	9.749	2.965	-0.176	0.834	11.17	35.98	0.84	37	0.45	29
May7-M3	10.80	3.074	-0.170	0.833	12.14	38.53	0.82	37	0.46	32
May7-C4	13.11	3.088	-0.245	0.874	15.69	47.61	0.77	37	0.49	37
May8-M1	6.453	2.803	-0.061	0.862	6.732	22.48	0.73	14	0.31	14
May8-M2	7.639	2.899	-0.140	0.899	8.590	28.35	0.84	28	0.44	21
May8-M3	6.855	2.739	-0.092	0.826	7.254	22.49	0.74	16	0.48	14
May8-C4	7.259	2.850	-0.160	0.829	8.271	26.18	0.76	18	0.37	18
May9-M1	8.332	2.795	-0.160	0.862	9.305	28.70	0.68	16	0.5	17
May9-M2	7.007	2.830	-0.065	0.858	7.392	26.09	0.76	18	0.48	15
May9-M3	7.527	2.847	-0.133	0.928	8.416	27.61	0.81	24	0.52	17
May9-C4	10.79	3.228	-0.183	0.867	12.26	44.22	0.67	21	0.37	25
July4-M1	8.642	2.924	-0.106	0.841	9.130	33.15	0.82	28	0.45	22
July4-M2	9.753	3.005	-0.165	0.829	11.12	36.69	0.84	37	0.43	29
July4-M3	10.27	2.933	-0.200	0.852	11.94	36.50	0.77	28	0.53	25
July4-C4	12.75	3.030	-0.274	0.849	15.42	45.73	0.71	28	0.44	34
July5-M1	8.678	2.938	-0.115	0.833	9.218	33.30	0.75	21	0.45	19
July5-M2	9.510	3.065	-0.170	0.850	10.83	36.13	0.87	42	0.41	30
July5-M3	9.534	2.899	-0.191	0.809	10.90	34.87	0.88	42	0.47	29
July5-C4	12.46	2.997	-0.272	0.846	15.04	44.32	0.72	28	0.46	32
July6-M1	8.755	2.952	-0.108	0.836	9.265	33.67	0.89	42	0.41	29
July6-M2	8.864	2.991	-0.097	0.865	9.422	34.16	0.86	37	0.44	27
July6-M3	9.021	2.924	-0.128	0.851	9.681	33.96	0.86	37	0.48	26

July6-C4	10.15	2.997	-0.204	0.839	11.88	37.14	0.83	37	0.44	32
Aug4-M1	8.653	2.949	-0.104	0.844	9.121	33.39	0.78	24	0.45	20
Aug4-M3	9.570	3.048	-0.200	0.841	11.13	35.48	0.82	32	0.38	30
Aug4-C4	13.63	3.069	-0.301	0.897	17.08	47.39	0.6	21	0.39	34
Aug5-M1	8.215	3.093	-0.118	0.815	8.953	33.93	0.71	18	0.34	18
Aug5-M2	9.082	3.063	-0.100	0.867	9.715	35.92	0.79	28	0.43	23
Aug5-M3	9.580	2.892	-0.202	0.812	11.05	34.79	0.85	37	0.47	28
Aug5-C4	15.69	3.150	-0.341	0.915	20.21	51.58	0.61	24	0.44	36
Sep17-M1	9.114	2.878	-0.119	0.827	9.787	34.17	0.66	16	0.52	16
Sep17-M2	15.42	3.284	-0.322	0.884	19.81	58.94	0.65	28	0.39	39
Sep17-M3	9.895	2.884	-0.214	0.863	11.47	35.30	0.81	32	0.48	28
Sep17-C4	12.01	3.226	-0.261	0.870	15.05	46.31	0.67	24	0.37	32
Sep18-M1	7.126	3.020	-0.028	0.833	7.304	29.65	0.56	9	0.19	13
Sep18-M2	8.145	3.022	-0.136	0.828	8.979	29.44	0.85	32	0.37	26
Sep18-M3	9.461	2.945	-0.210	0.835	10.91	34.68	0.85	37	0.45	28
Sep18-C4	11.20	3.111	-0.193	0.843	12.86	39.76	0.77	32	0.43	33
Sep19-M1	8.759	2.956	-0.111	0.842	9.299	34.01	0.7	18	0.46	17
Sep19-M2	9.124	2.940	-0.129	0.842	9.784	34.48	0.88	42	0.47	29
Sep19-M3	9.476	3.003	-0.185	0.862	10.86	35.18	0.82	32	0.45	26
Sep19-C4	10.64	3.099	-0.175	0.845	12.07	38.45	0.85	42	0.45	33
Sep20-M1	8.502	2.934	-0.104	0.850	8.998	29.88	0.82	28	0.44	22
Sep20-M2	7.977	3.234	-0.097	0.769	8.735	34.53	0.81	28	0.17	29
Sep20-M3	8.494	3.139	-0.119	0.835	9.377	34.74	0.86	37	0.34	30
Sep20-C4	13.16	3.155	-0.254	0.878	15.96	48.60	0.69	28	0.41	34
Oct22-M1	7.380	2.973	-0.131	0.812	8.282	28.31	0.84	28	0.28	24
Oct22-M2	7.039	2.919	-0.063	0.815	7.405	27.36	0.69	14	0.3	15
Oct22-M3	9.801	2.930	-0.186	0.899	11.29	35.38	0.85	37	0.5	28
Oct22-C4	13.61	3.233	-0.210	0.888	15.75	49.78	0.76	37	0.47	36
Nov14-M1	8.762	2.948	-0.107	0.839	9.244	33.56	0.74	21	0.47	18
Nov14-M2	7.509	2.945	-0.122	0.897	8.323	28.85	0.68	14	0.34	16
Nov14-M3	9.080	3.001	-0.113	0.853	9.747	34.82	0.83	32	0.43	26
Nov14-C4	10.72	3.091	-0.168	0.842	12.04	38.51	0.85	42	0.46	33
Nov15-M1	8.662	2.919	-0.112	0.853	9.196	29.91	0.78	24	0.48	20
Nov15-M2	7.341	2.847	-0.137	0.904	8.204	26.79	0.73	16	0.47	14
Nov15-M3	8.866	2.941	-0.123	0.838	9.500	33.81	0.81	28	0.45	23
Nov15-C4	10.18	3.189	-0.167	0.799	11.41	37.95	0.77	28	0.38	27
Nov16-M1	7.793	2.891	-0.144	0.898	8.742	28.69	0.79	18	0.49	16
Nov16-M2	7.993	2.778	-0.135	0.901	8.731	27.66	0.74	18	0.52	16
Nov16-M3	7.467	2.845	-0.146	0.894	8.389	26.88	0.75	18	0.47	16
Nov16-C4	9.639	2.982	-0.169	0.852	11.04	35.96	0.79	28	0.48	23

Nov17-M1	8.100	3.007	-0.119	0.833	8.827	29.51	0.85	32	0.4	24
Nov17-M2	6.866	2.741	-0.080	0.826	7.199	25.00	0.74	16	0.52	14
Nov17-M3	8.784	2.904	-0.128	0.849	9.443	29.86	0.78	24	0.49	21
Nov17-C4	8.265	2.774	-0.161	0.850	9.182	28.13	0.69	16	0.51	16
Jan11-M1	7.409	2.806	-0.148	0.905	8.322	26.25	0.72	16	0.52	14
Jan11-M2	8.173	2.963	-0.131	0.837	8.948	28.96	0.76	21	0.47	18
Jan11-M3	8.217	2.786	-0.146	0.907	9.055	28.47	0.83	28	0.51	21
Jan11-C4	15.09	3.234	-0.315	0.879	19.17	51.98	0.7	32	0.43	41
Jan12-M1	8.608	2.883	-0.122	0.838	9.182	29.08	0.72	18	0.5	17
Jan12-M2	8.988	2.863	-0.124	0.812	9.687	33.28	0.83	32	0.48	25
Jan12-M3	8.879	2.904	-0.131	0.842	9.552	30.04	0.84	32	0.48	25
Jan12-C4	10.67	3.070	-0.184	0.834	12.13	38.11	0.79	32	0.45	29
Jan13-M1	9.721	2.998	-0.166	0.841	11.10	36.89	0.81	32	0.46	26
Jan13-M2	8.799	2.961	-0.121	0.829	9.401	33.84	0.84	32	0.4	26
Jan13-M3	7.644	2.839	-0.158	0.902	8.664	27.31	0.81	24	0.49	19
Jan13-C4	10.95	3.144	-0.165	0.844	12.35	44.46	0.84	42	0.45	34
Jan14-M1	8.671	2.939	-0.106	0.845	9.174	33.28	0.78	24	0.45	21
Jan14-M2	9.568	2.866	-0.196	0.824	10.97	34.39	0.82	32	0.51	25
Jan14-M3	8.875	2.921	-0.131	0.838	9.558	33.46	0.84	32	0.45	25
Jan14-C4	11.68	3.162	-0.267	0.812	14.42	44.88	0.76	32	0.37	37
Jan15-M1	8.816	3.037	-0.085	0.861	9.304	34.84	0.88	42	0.4	28
Jan15-M2	8.843	2.975	-0.130	0.826	9.523	33.98	0.83	32	0.39	27
Jan15-M3	8.162	3.065	-0.158	0.803	9.208	29.99	0.78	24	0.28	26
Jan15-C4	10.50	3.153	-0.206	0.841	12.12	37.47	0.76	28	0.37	31
Mar27-M1	10.95	3.210	-0.135	0.869	12.22	45.23	0.86	49	0.44	35
Mar27-M2	11.06	3.226	-0.136	0.869	12.35	45.79	0.83	42	0.44	34
Mar27-M3	12.66	3.392	-0.177	0.878	14.59	51.03	0.86	56	0.43	42
Mar27-C4	10.31	2.951	-0.202	0.868	12.06	36.90	0.83	37	0.53	29
Mar28-M1	11.89	3.308	-0.210	0.868	14.33	48.86	0.84	49	0.41	40
Mar28-M2	9.533	3.027	-0.188	0.851	10.96	35.30	0.87	42	0.43	30
Mar28-M3	10.52	3.090	-0.175	0.840	11.92	38.05	0.9	56	0.46	35
Mar28-C4	11.04	3.093	-0.184	0.848	12.62	39.50	0.78	32	0.47	30
Mar29-M1	10.26	3.148	-0.124	0.803	11.24	39.04	0.88	49	0.41	33
Mar29-M2	10.64	3.108	-0.163	0.842	11.94	38.83	0.9	56	0.45	36
Mar29-M3	10.82	3.188	-0.148	0.833	12.06	45.51	0.83	42	0.41	34
Mar29-C4	12.47	2.986	-0.271	0.866	15.02	43.99	0.72	28	0.49	31
Mar30-M1	11.13	3.306	-0.130	0.867	12.47	47.34	0.85	49	0.4	37
Mar30-M2	9.681	3.080	-0.178	0.849	11.08	36.69	0.89	49	0.41	33
Mar30-M3	10.14	2.974	-0.187	0.905	11.73	36.92	0.83	37	0.49	29
Mar30-C4	14.37	3.184	-0.246	0.887	17.03	50.34	0.71	32	0.47	37

Mar31-M1	11.97	3.302	-0.224	0.855	14.57	48.24	0.91	74	0.43	44
Mar31-M2	10.54	3.154	-0.148	0.833	11.74	39.75	0.87	49	0.4	36
Mar31-M3	11.21	3.192	-0.152	0.873	12.66	45.76	0.88	56	0.46	38
Mar31-C4	13.31	3.062	-0.239	0.896	15.80	48.00	0.84	49	0.54	40
May25-M1	9.127	3.088	-0.086	0.862	9.639	36.83	0.87	42	0.39	30
May25-M2	9.799	2.974	-0.177	0.849	11.27	36.23	0.89	49	0.47	31
May25-M3	11.92	3.226	-0.219	0.875	14.38	47.40	0.85	49	0.46	37
May25-C4	12.35	3.089	-0.215	0.877	14.48	45.76	0.82	42	0.49	35
May26-M1	9.264	3.154	-0.076	0.851	9.732	39.18	0.83	37	0.36	29
May26-M2	9.862	3.007	-0.172	0.839	11.33	37.09	0.89	49	0.45	32
May26-M3	10.61	3.102	-0.145	0.862	11.77	39.15	0.85	42	0.47	31
May26-C4	11.05	3.253	-0.138	0.852	12.34	46.58	0.88	56	0.4	41
May27-M1	10.58	3.145	-0.161	0.836	11.92	39.12	0.87	49	0.42	35
May27-M2	9.765	2.987	-0.167	0.854	11.17	36.54	0.86	42	0.47	29
May27-M3	9.025	3.049	-0.091	0.861	9.586	35.87	0.82	32	0.43	25
May27-C4	13.57	3.287	-0.188	0.818	15.45	51.26	0.82	49	0.44	43
May28-M1	9.763	3.091	-0.169	0.848	11.08	37.82	0.89	49	0.41	33
May28-M2	9.678	3.084	-0.169	0.861	11.01	36.88	0.84	37	0.41	30
May28-M3	10.85	3.061	-0.181	0.840	12.29	38.16	0.82	37	0.47	32
May28-C4	12.85	3.102	-0.239	0.819	15.33	46.83	0.78	37	0.46	38
Jun8-M1	10.78	3.301	-0.107	0.861	11.80	46.76	0.71	24	0.43	22
Jun8-M2	9.733	2.969	-0.179	0.839	11.19	35.85	0.89	49	0.46	32
Jun8-M3	10.69	3.068	-0.151	0.859	11.86	38.48	0.9	56	0.49	34
Jun8-C4	13.30	3.001	-0.299	0.867	16.33	46.37	0.77	37	0.48	42
Jun9-M1	10.61	3.114	-0.164	0.844	11.95	38.41	0.85	42	0.45	32
Jun9-M2	11.06	3.131	-0.173	0.837	12.52	44.29	0.83	42	0.45	35
Jun9-M3	10.75	3.045	-0.159	0.860	11.99	38.34	0.88	49	0.53	32
Jun9-C4	10.99	3.075	-0.188	0.842	12.52	38.78	0.89	56	0.51	35
Jun10-M1	9.598	3.106	-0.175	0.859	11.00	37.30	0.92	64	0.37	38
Jun10-M2	10.95	3.145	-0.163	0.846	12.32	44.33	0.84	42	0.45	33
Jun10-M3	12.92	3.516	-0.158	0.881	15.03	59.24	0.82	49	0.45	37
Jun10-C4	11.98	3.200	-0.232	0.874	14.53	46.45	0.85	49	0.47	38
Jun11-M1	10.59	3.128	-0.153	0.838	11.83	39.27	0.85	42	0.44	33
Jun11-M2	11.15	3.281	-0.151	0.855	12.67	47.23	0.82	42	0.39	36
Jun11-M3	9.975	3.012	-0.181	0.836	11.51	37.30	0.83	37	0.44	30
Jun11-C4	12.86	3.043	-0.263	0.859	15.37	46.58	0.81	42	0.48	39
Jun12-M1	10.47	3.215	-0.175	0.807	11.83	39.09	0.9	56	0.4	38
Jun12-M2	11.15	3.178	-0.161	0.839	12.51	45.73	0.86	49	0.43	38
Jun12-M3	11.35	3.103	-0.189	0.851	12.97	44.59	0.86	49	0.49	36
Jun12-C4	15.01	3.196	-0.331	0.895	19.36	49.97	0.7	32	0.41	48

Appendix D: Summary of deposition, concentration from RBR, ISCO, and creek thalweg rising stage bottle at 20 cm

Tide	Marsh surface deposition (g·m⁻²)	Marsh edge deposition (g·m⁻²)	Marsh bank deposition (g·m⁻²)	Creek thalweg deposition (g·m⁻²)	ISCO mean concentration (mg·l⁻¹)	RBR mean concentration (mg·l⁻¹)	Creek thalweg rising stage bottle concentration at 20cm (mg·l⁻¹)
May5am	9.3	8.8	11.9	29.3		119	155
May5pm	16.2	15.6	21.7	29.1	64	121	246
May6am	12.7	11.6	18.9	25.2	50	121	233
May6pm	17.7	11.2	19.5	24.9	59	138	334
May7am	12.7	10.7	17.6	20.4		129	311
May7pm	14.9	11.4	14.5	31.7	61	136	404
May8am	10.7	18.9	20.2	26.0	49	134	320
May8pm	12.2	10.3	14.3	27.3	48	142	327
May9am	9.2	3.2	14.4	24.6	49	145	251
July4am	14.4	21.1	30.9	112.6	37	129	108
July4pm	15.4	12.2	23.2	51.9	42	116	143
July5am	3.1	3.8	3.2	64.4	42	139	184
July5pm	13.5	9.1	26.5	72.0	30	150	170
July6am	9.0	6.5	23.4	69.7	32	142	215
Aug4am	15.4	16.9	35.5	25.1	67	273	292
Aug4pm	20.7	16.5	19.8	53.1	65	101	129
Aug5am	14.0	16.8	22.8	31.0		123	275
Sep17am	10.8	10.2	13.0	28.5	38	116	297
Sep17pm	10.6	10.4	20.0	21.2	37	105	292
Sep18am	11.9	11.5	10.5	34.1	36	120	450
Sep18pm	24.3	10.9	13.9	37.9	53	97	259
Sep19am	14.5	10.5	12.7	30.6	56	161	583
Sep19pm	7.4	6.8	9.4	410.3	42	154	138
Sep20am	7.7	8.5	27.4	19.7	50	235	410
Nov14am	3.1	2.0	21.3	224.7	37	532	1094
Nov14pm	23.9	3.9	77.2	99.4		366	3238
Nov15am	30.2	10.5	19.2	190.6	74	655	2209
Nov15pm	45.4	17.9	70.2	45.6	53	526	1140
Nov16am	17.5	17.9	155.2	83.4	23	395	2116
Nov16pm	27.1	26.7	61.8	38.1	16	483	526
Nov17am	12.8	16.3	23.4	32.2	26	294	1270
Jan11pm	42.7	10.9	134.6	145.6	35	783	348
Jan12pm	23.1	46.7	57.5	51.0	46		669

Jan13am	12.2	23.1	29.5	38.2			1441
Jan13pm	11.7	21.7	24.3	23.7	36		540
Jan14am							1169
Jan14pm	13.5	16.0	11.1	20.3	37		485
Jan15am	11.8	16.5	20.8	35.2	33		785
Mar27pm	20.8	9.6	10.6	180.7	61	222	662
Mar28am	23.6	21.3	76.9	278.0	61	286	480
Mar28pm	21.6	39.2	106.6	301.8	62	256	647
Mar29am	16.9	22.6	17.2	109.3	53	213	685
Mar29pm	17.6	26.7	44.8	59.7	50	174	493
Mar30am	11.0	35.2	36.3	33.1	47	142	603
Mar30pm	11.0	22.4	32.9	41.7	46	130	323
Mar31am	14.9	31.6	30.0	19.3	46	116	397
May25am	2.1	2.3	6.3	25.6	95	197	875
May25pm	6.3	4.3	8.7	34.6	97	254	3136
May26am	13.0	13.3	40.7	65.7	55	166	1089
May26pm	13.7	11.2	15.3	122.3	79	415	1398
May27am	15.5	9.5	30.9	57.0	71	723	1357
May27pm	17.1	10.8	30.4	39.5	28	237	1475
May28am	11.4	12.2	25.6	25.2	19	218	1251
Jun8am	0.6	0.4	0.6		49	123	368
Jun8pm	0.8	1.1	9.9		60	406	694
Jun9am	7.6	6.3	7.6	42.5	57	220	370
Jun9pm	0.0	10.4	14.6	26.8	55	159	335
Jun10am	7.9	7.5	11.2	22.7	38	145	424
Jun10pm	0.0	12.3	10.7	20.0	43	105	334
Jun11am	11.0	8.1	16.5	21.3	48	116	449
Jun11pm	0.0	9.5	9.8	18.7	46	97	326
Jun12am	1.8	1.7	2.8	19.6	50	229	934

Appendix E: Summary of magnitude of horizontal velocity and bed shear stress at the three marsh stations

Tide	Magnitude of Horizontal Velocity mean ($cm \cdot s^{-1}$)			Bed Shear Stress mean ($N \cdot m^{-2}$)		
	Marsh Surface	Marsh Edge	Marsh Bank	Marsh Surface	Marsh Edge	Marsh Bank
May5am	1.651	3.333	2.307	0.027	0.029	0.066
May5pm	1.748	2.978	0.545	0.023	0.026	0.002
May6am	2.328	3.963	1.427	0.029	0.034	0.024
May6pm	1.747	2.899	1.229	0.024	0.026	0.029
May7am	2.541	4.270	1.384	0.063	0.034	0.026
May7pm	1.525	2.964	1.404	0.013	0.020	0.020
May8am	2.465	4.234	1.427	0.028	0.046	0.018
May8pm	1.472	2.630	1.462	0.023	0.030	0.025
May9am	2.729	2.343	1.428	0.092	0.219	0.089
July4am	2.220	2.210	0.947	0.035	0.338	0.004
July4pm	2.040	2.066	0.837	0.033	0.264	0.006
July5am	0.847	1.847	0.951	0.019	0.155	0.005
July5pm	1.744	2.099	0.908	0.084	0.331	0.003
July6am	2.055	2.185	0.681	0.019	0.392	0.003
Aug4am	2.019		1.091	0.065		0.004
Aug4pm	2.115		0.566	0.097		0.002
Aug5am	1.649		1.110	0.050		0.005
Sep17am		2.587	1.767		0.238	0.138
Sep17pm		1.487	1.992		0.084	0.113
Sep18am	1.412	2.252	1.345	0.021	0.282	0.073
Sep18pm	2.380	2.262	1.400	0.209	0.178	0.077
Sep19am	3.247	2.642	0.809	0.640	0.112	0.075
Sep19pm	4.075	3.255	1.541	0.927	0.338	0.145
Sep20am	1.300	1.597	1.038	0.031	0.253	0.034
Nov14am	1.363	1.322	0.899	0.024	0.097	0.008
Nov14pm	2.230	1.326	0.396	0.113	0.055	0.006
Nov15am	1.768	1.310	0.353	0.064	0.078	0.007
Nov15pm	2.179	1.383	0.581	0.156	0.070	0.011
Nov16am	1.421	0.860	0.374	0.033	0.031	0.003
Nov16pm	1.977	0.939	0.551	0.040	0.030	0.007
Nov17am	1.430	0.902	0.487	0.024	0.054	0.007
Jan11pm	1.886	1.744	1.530	0.044	0.037	0.040
Jan12pm	1.836	1.374	2.028	0.031	0.016	0.047
Jan13am	1.973	1.309	2.036	0.017	0.022	0.019
Jan13pm	1.985	1.329	1.968	0.035	0.025	0.033

Jan14am	1.898	1.116	1.853	0.030	0.029	0.029
Jan14pm	2.267	1.125	2.179	0.042	0.027	0.032
Jan15am	2.011	1.050	1.868	0.026	0.026	0.025
Mar27pm	0.939	1.196	3.279	0.019	0.013	0.029
Mar28am	1.425	1.247	3.649	0.040	0.043	0.039
Mar28pm	1.418	1.211	3.462	0.038	0.013	0.027
Mar29am	1.326	1.322	3.460	0.027	0.020	0.055
Mar29pm	1.178	1.097	3.279	0.039	0.009	0.030
Mar30am	1.380	1.212	3.305	0.024	0.015	0.035
Mar30pm	1.077	0.966	3.250	0.027	0.009	0.040
Mar31am	1.135	1.158	3.320	0.019	0.020	0.036
May25am	4.560	4.620	3.220	1.109	1.019	0.110
May25pm	1.425	1.693	2.871	0.036	0.033	0.022
May26am	1.642	2.066	3.278	0.047	0.045	0.035
May26pm	8.445	6.870	3.665	3.692	2.266	0.504
May27am	1.920	2.150	3.476	0.109	0.037	0.029
May27pm	2.357	1.795	2.525	0.095	0.034	0.019
May28am	1.840	1.689	2.560	0.114	0.027	0.023
Jun8am	2.120	1.250	2.663	0.131	0.039	0.068
Jun8pm		2.326	1.681		0.258	0.052
Jun9am	2.409	1.179	2.212	0.026	0.011	0.040
Jun9pm		0.730	2.300		0.008	0.081
Jun10am	1.670	1.043	2.204	0.033	0.004	0.038
Jun10pm		1.606	2.571		0.031	0.053
Jun11am	0.953	0.863	2.282	0.009	0.010	0.062
Jun11pm		1.323	2.420		0.018	0.054
Jun12am	3.306	1.713	2.469	0.015	0.054	0.046

Appendix F: DIGS of scrape samples on the bank at the down creek and up creek transects.