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The hydrodynamics of surface tidal flow exchange in saltmarshes

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ABSTRACT

Modeling studies of estuary circulation show great sensitivity to the water exchange into and out of adjacent marshes, yet there is significant uncertainty in resolving the processes governing marsh surface flow. The objective of this study is to measure the estuary channel-to-saltmarsh pressure gradient and to guide parameterization for how it affects the surface flow in the high marsh. Current meters and high-resolution pressure transducers were deployed along a transect perpendicular to the nearby Little Ogeechee River in a saltmarsh adjacent to Rose Dhu Island near Savannah, Georgia, USA. The vertical elevations of the transducers were surveyed with static GPS to yield high accuracy water surface elevation data. It is found that water level differences between the Little Ogeechee River and neighboring saltmarsh are up to 15 *cm* and pressure gradients are up to 0.0017 *m* of water surface elevation change per *m* of linear distance during rising and falling tides. The resulting Little-Ogeechee-River-to-saltmarsh pressure gradient substantially affects tidal velocities at all current meter locations. At the velocity measurement station located closest to the Little Ogeechee River bank, the tidal velocity is nearly perpendicular to the bank. At this location, surface flow is effectively modeled as a balance between the pressure gradient force and the drag force due to marsh vegetation and bottom stress using the Darcy–Weisbach/Lindner's equations developed for flow-through-vegetation analysis in open channel flow. The study thus provides a direct connection between the pressure gradient and surface flow velocity in the high marsh, thereby overcoming a long-standing barrier in directly relating flow-through-saltmarsh studies to flow-through-vegetation studies in the open channel flow literature.

1. Introduction

Saltmarshes are valuable and productive ecosystems that serve as storm buffers, fish nurseries, and nutrient sources, and they play a significant role in the dynamics of estuary circulation. The limited amount of precise field data on the spatial variation of water surface elevation in estuarine creeks, channels, and in particular high marshes, is a critical gap in the understanding of saltmarsh hydrodynamics. The lack of data negatively impacts our ability to assess the effect of vegetation on surface water flow and accurately estimate the bottom stress in these settings. For instance, modeling results show that a channel-to-saltmarsh pressure gradient (i.e., differential water levels between the estuary main channel and the adjacent saltmarsh) is responsible for surface transport of water between the saltmarsh and the channel at high spring tide (Bruder et al., 2014). However, the modeling results are based on non-validated assumptions and the resulting pressure-gradient-driven surface flows show great sensitivity to the parameterization of the bottom stress, in agreement with earlier modeling results (Kjerfve et al., 1991). Therefore, detailed measurements of the pressure gradient and corresponding surface flows, together with application of appropriate hydrodynamic models, are needed to improve our understanding of the flow into and out of the high marsh.

In an effort to determine the effect of vegetation on the transition from channelized flow to sheet flow on the marsh platform, Vandenbruwaene et al. (2015) directly measured the velocity of the surface flow and estimated the water surface elevation in a high marsh. Their study is the only published field measurements we are aware of that show the presence of differential water levels between the high marsh and the adjacent main channel in a saltmarsh. No study to our knowledge has attempted to quantitatively relate the corresponding pressure gradient to the sheet flow

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through the high marsh vegetation.

Analyses of the effects of variable marsh friction (i.e., variable marsh vegetation) on the mean flow in tidal creeks and deeper estuary channels are predominantly restricted to modeling studies (Kjerfve et al., 1991; Rinaldo et al., 1999a, 1999b; Bruder et al., 2014). Attempts to quantify water surface elevations on high marsh platforms (and thus quantify the pressure gradient between the high marsh and the creeks and channels) are also chiefly limited to modeling studies (Kjerfve et al., 1991; Rinaldo et al., 1999a, 1999b). Unfortunately, due to the paucity of available field data, these models were unable to validate their results in the high marsh. The principal gaps in current knowledge are the lack of available water surface elevation measurements, the lack of directly observed flow patterns (although see Temmerman et al., 2012; Vandenbruwaene et al., 2015), and an inability to verify the model's parameterization of the bed/vegetation friction (e.g., through Manning's n or drag-coefficient formulations; Kjerfve et al., 1991; Huang et al., 2008; Bruder et al., 2014). We note that several recent studies have focused on the dissipation of wave energy by the marsh vegetation rather than addressing the relationship between the mean surface flow and bed/vegetation friction (Lowe et al., 2005; Augustin et al., 2009; Riffe et al., 2011; Wu, 2014). Thus, the objective of this study is to determine the estuary channel-to-saltmarsh pressure gradient and to evaluate how it affects the surface flow in the high marsh.

1.1. Background

Studies on water movement in saltmarshes generally have focused on one of three areas: the surface flow in the network of branching tidal creeks (e.g., Bayliss-Smith et al., 1979; French and Stoddart, 1992; Allen, 1994), the surface flow high in the marsh platform (Eiser and Kjerfve, 1986; Leonard and Luther, 1995), and the groundwater flow (Howes and Goehringer, 1994; Gardner et al., 2002; Gardner, 2005; Wilson and Gardner, 2006). The flow in tidal creeks depends on the water surface elevation relative to the marsh bathymetry. For low relative water surface elevation, the creeks remain below bankfull and the flow velocity is small, $\sim 0.1 - 0.2\ m/s$ (Bayliss-Smith et al., 1979; Pethick, 1980; Healey et al., 1981; Dankers et al., 1984; French and Stoddart, 1992; Leopold et al., 1993; Allen, 1994; Pringle, 1995). The water surface elevation (i.e., pressure gradient) slopes into the tidal creek during flood and towards the ocean during ebb (Leopold et al., 1993). For high relative water surface elevation, the flow velocity in the creeks remains small while the creek is below bankfull and peaks at much larger values ($\sim 1\ m/s$) once the marsh is flooded (Bayliss-Smith et al., 1979; Pethick, 1980; Healey et al., 1981; Dankers et al., 1984; French and Stoddart, 1992; Allen, 1994; Pringle, 1995; Rinaldo et al., 1999a, 1999b). Some studies observed “pulses” in the tidal creek velocity, which correspond to sudden changes in velocity as the marsh is flooded (e.g., Temmerman et al., 2005b; Torres and Styles, 2007). Similar pulses also have been observed as the creek itself initially flooded or became dry (Hazelden and Boorman, 1999). Consistent with low relative water surface elevation conditions, the pressure gradient in high relative water surface elevation conditions slopes into the tidal creek during flood and towards the ocean during ebb (Healey et al., 1981; French and Stoddart, 1992).

Regarding the hydrodynamics on the high marsh platform, Allen (2000) writes, “the local hydraulics of channels has undoubtedly been over-emphasized at the expense of what are in effect tidal floodplains.” Allen (2000) acknowledges that studies considering flow on the high marsh platform face formidable challenges due to the difficulty in accurately measuring small gradients in the water surface elevation (Horstman et al., 2013) and the difficulty in making direct flow measurements in dense vegetation (Mazda et al., 2007). Flow velocities across the high marsh surface are much smaller than in the creeks ($\sim 0.01 - 0.1\ m/s$) and decrease in proximity of bathymetric obstacles (Eiser and Kjerfve, 1986; Wang et al., 1993; Allen, 1994). The flow is generally governed by the bathymetry of the high marsh (Eiser and Kjerfve, 1986; Davidson-Arnott et al., 2002; Temmerman et al., 2005a), the pressure gradient from the slope in the water surface elevation (Kjerfve et al., 1991; Bruder et al., 2014), and the vegetation characteristics (Leonard and Luther, 1995; Temmerman et al., 2012). At low relative water surface elevation, the flow essentially follows the high marsh bathymetry (Eiser and Kjerfve, 1986; Davidson-Arnott et al., 2002). As the relative water surface elevation becomes higher, currents in the high marsh begin to behave more analogously to sheet flow (Temmerman et al., 2005b; Vandenbruwaene et al., 2015) and are effectively forced by the water surface elevation slope between neighboring positions (Kjerfve et al., 1991; Bruder et al., 2014; Vandenbruwaene et al., 2015). This interplay between bathymetry-driven flow and sheet flow is also observed in estuaries dominated by mangrove swamps (e.g., Aucan and Ridd, 2000; Mazda et al., 2005; Horstman et al., 2013). In all cases, the flow is mediated by the characteristics of the vegetation and the relative water surface elevation (Leonard and Luther, 1995; Temmerman et al., 2012; Vandenbruwaene et al., 2015). When vegetation is partially submerged, the mean velocity depends on the plant morphology and density (Leonard and Luther, 1995). For deeply submerged vegetation, the flow is characterized by a two-layer velocity profile (Leonard and Luther, 1995). The bottom layer extends from the bed to the approximate height of the vegetation stems, and the flow characteristics are similar to the partially-submerged case. The upper layer is a logarithmic-law turbulent boundary layer that extends from essentially the top of the vegetation to the free surface (Leonard and Luther, 1995).

Groundwater flow rates in marshes are typically substantially smaller than flow rates on the surface (Wolanski and Elliott, 2015). However, the authors noted that groundwater flow is a critical area of study because it influences the soil properties and fluid salinity. Salinity is governed by a combination of marsh soil porosity, upland groundwater level, and tidal inundation (Wolanski and Elliott, 2015). The water table and salinity respond rapidly to precipitation and tidal inundation, as groundwater moves rapidly through saltmarshes (Gardner et al., 2002; Gardner, 2005; Wolanski and Elliott, 2015). It is important to note that rapid changes occur in response to the tide in areas that are not inundated due to tidal effects on subsurface pore pressure gradients (Gardner et al., 2002; Gardner, 2005; Wilson and Gardner, 2006). Model results suggest that the majority of the direct groundwater interaction with seawater occurs during the recharge and drainage of groundwater along the banks of tidal creeks that branch into the marsh (Gardner, 2005; Wilson and Gardner, 2006).

2. Materials and methods

A field experiment was conducted in the tidal marsh adjacent to Rose Dhu Island near Savannah, Georgia, USA (Fig. 1) from November 2nd to November 6th, 2014, coinciding with the largest spring tide in November 2014. The project site was selected due to the availability of numerical model data of water levels (Bomminayuni et al., 2012; Bruder et al., 2014) and previously-collected bathymetric/topographic and vegetation data.

Three Onset HOBO pressure transducers (PTs), two Acoustic Doppler Velocimeters (ADVs, Nortek Vector – Nortek AS, Rud, Norway) and a current profiler (Nortek Aquadopp HR-profiler) were deployed along a transect perpendicular to the Little Ogeechee River in the tidal marsh. The ADVs measure the fluid velocity at essentially a point in the flow, whereas the Aquadopp measures