Journal of Hydrology 542 (2016) 552–563

Contents lists available at ScienceDirect

Journal of Hydrology

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

Research papers

Tidal reversal and flow velocities using temperature and specific conductance in a small wetland creek

Timothy T. Eaton

School of Earth and Environmental Sciences, Queens College CUNY, 6530 Kissena Blvd, Flushing, NY 11355, United States

A R T I C L E I N F O

Article history:
Received 16 March 2016
Received in revised form 26 August 2016
Accepted 9 September 2016
Available online 10 September 2016
This manuscript was handled by K. Georgakakos, Editor-in-Chief, with the assistance of Marco Toffolon, Associate Editor

Keywords:
Wetland creek
Tidal intrusion
Low cost
Advection
Heat and specific conductance tracers

A B S T R A C T

Characterizing flow dynamics in very small tidal creeks is complicated and not well suited to methods developed for upland streams or coastal estuaries, due to low flows, bidirectionality and shallow waters. Simple instrumentation enables thermal and salinity signals to be used to observe flow directions and estimate velocities in these settings. Using multiple inexpensive sensors over 500 m along a tidally influenced wetland creek, I demonstrate how advection of temperature and specific conductance pulses reveal flood and ebb tides and the temporary reversal of flow by warmer, estuarine water from the receiving embayment. The sequential rise of temperature upstream was most evident under hot and dry conditions, after daily peak air temperatures of 25 °C or above, and was subdued or disrupted under cooler or rainy conditions in summertime. Changes in specific conductance at successive sites upstream were less susceptible to environmental influences and confirm tidal flood velocity of between 0.07 and 0.37 m/s. The tidally-induced flow reversal suggests that periodic high tide conditions can interfere with rapid dispersal of pollution discharges, such as from the combined sewer overflow (CSO) located upstream of the studied creek reach. This low-cost approach of temperature and specific conductance sensing in vegetated coastal wetlands where access, precise elevation control and creek discharge measurements are difficult, provides a simple way of tracking water masses when sufficient contrast exists between water sources.

Published by Elsevier B.V.

1. Introduction

In both terrestrial freshwater streams and marine estuaries, hydrologic observation and measurement techniques have been well established, however their interface often includes small tidal wetland creeks, which are ill-suited to such approaches. Measurement of water temperature and specific conductance provides a straightforward means to investigate tidal dynamics, particularly tidal pumping, which may impede pollution dispersal and adversely affect water quality (Sousa et al., 2013). While saltwater intrusion is well known in tidally affected rivers and streams, the simplicity of methods in this study make them well suited to analysis of very small tidal creeks. Here, temperature and specific conductance sensing is analyzed to show tidal intrusion in a very small wetland creek, a common setting in coastal urban areas where water quality is of concern.

Both temperature and specific conductance have different advantages. Water specific conductance is a measure of the amount of dissolved minerals. It is a sensitive tracer of mixing saline with freshwaters and is easy to measure, hence is useful as a tidal indicator and screening tool for water quality (Jones and Graziano, 2013; Kawanisi et al., 2010). However, water temperature also reveals ecological health of upland streams (Kelleher et al., 2012; Poole and Berman, 2001) and allows characterization of groundwater exchange (Boano et al., 2014; Moffett et al., 2008; Keery et al., 2007). Temperature of larger streams and rivers has been used to investigate global climate change (Wu et al., 2012; Wagener et al., 2010); as well as specific anthropogenic impacts such as wastewater and dam releases (Xin and Kinouchi, 2013; Kinouchi et al., 2007). Temperature measurements are also beginning to be used in coastal settings where the dynamics of shallow flow and sediment transport in channels and over tidal flats is of interest (Rinehimer et al., 2013). A broad review of how water temperature responds over many timescales to meteorology, tidal marsh morphology and tidal harmonics in sloughs in the San Francisco Estuary is given by Enright et al. (2013).

Small stream temperature is more susceptible than specific conductance to variability from local environmental conditions: specifically, net solar radiation dominates latent and sensible heat fluxes (Kelleher et al., 2012; Leach and Moore, 2010). Local heat fluxes from the atmosphere and streambed should also be

E-mail address: Timothy.Eaton@qc.cuny.edu

http://dx.doi.org/10.1016/j.jhydrol.2016.09.030
0022-1694/Published by Elsevier B.V.

considered in specific circumstances: for example, shading can limit atmospheric heat flux. Computations based on heat budgeting in marsh creeks (McKay and Di Iorio, 2008) have been used to study hydrodynamic flows throughout tidally-influenced coastal wetlands using particle tracking to determine residence time (Arega, 2013). The modeling approach is constrained in many cases by the sheer amount of data required (Benyahya et al., 2007), particularly on the stream itself (geometry, flow, substrate) (Westhoff et al., 2011) and simple unidirectional flow models are not applicable in tidal settings.

Some authors take an oceanographic perspective to study hydrologic flows in coastal wetlands (Rinehimer et al., 2013; Mariotti and Fagherazzi, 2011). These studies and others (Enright et al., 2013; McKay and Di Iorio, 2008; Leopold et al., 1993) that address the hydrology of tidal creeks, largely neglect terrestrial inflows, and discuss primarily tidal residual flow (or dispersion), a reasonable focus when creeks lack freshwater input. New acoustic technologies have revolutionized tidal bore measurements in large or wide estuaries (Razaz et al., 2013; Zhu et al., 2012). However, discharges through small tidal sloughs are still generally quantified with reference to average velocities and cross-sectional areas and assumed to equal zero when integrated over the tidal cycle, without regard to terrestrial input, but tidal cycling introduces a lag time between velocity changes and stage heights (Leopold et al., 1993).

From a terrestrial hydrology perspective, coastal wetland creeks may be important conveyances of freshwater from runoff, and groundwater discharge in these settings can be significant (Michot et al., 2011). Creeks in tidal wetlands often serve as discharge points for wastewater from combined sewer overflows (CSO), which are among the largest contaminant sources to coastal waters (Phillips et al., 2012; Eaton et al., 2013; Rouff et al., 2013). Flows in tidal rivers present severe complexities for measurement because of bidirectional flow (Chen et al., 2012) and smaller creeks are more sensitive to terrestrial inputs and meteorological events as well as the tidal cycle. Compared to upland creeks where a fixed stage-discharge relationship, unidirectional flow and gaging stations are fundamental to flow characterization, the poorly known hydrodynamics of tidally-influenced wetland creeks presents significant challenges, and has been called "a major limitation to the understanding of salt marsh hydrology" (Fagherazzi et al., 2008).

Much of the difficulty lies in the lack of easily-deployed instrumentation to study tidally influenced small wetland creeks. While specific conductance is often used by the U.S. Geological Survey to monitor tidal stage, general hydrologic instrumentation in both upland streams and coastal settings is increasingly sophisticated and specialized. For example, distributed temperature sensing (DTS), a high resolution continuous cable technology developed recently (Briggs et al., 2012; Moffett et al., 2008), has been used for evaluating hyporheic heat and groundwater fluxes. Modern Doppler-based area-velocity flow meters use ultrasonic beams to track particles in channel flows, including reversing flows, but data quality can quickly be degraded by excessive suspended sediment (Nord et al., 2014), or accumulation on sensors at the bottom of wetland creeks of uncertain and changing geometry. In coastal channels and tidal flat settings, Conductivity Temperature Depth (CTD) sondes and Acoustic Doppler Current Profilers (ADCP) are methods of choice for surface flows (Rinehimer et al., 2013; Mariotti and Fagherazzi, 2011), however these instruments can usually be deployed in only one or two locations on specially-built platforms, or are not particularly suited to shallow water ($\ll$1 m). Many field and hydrologic settings are not conducive to such data-intensive approaches due to inaccessibility and logistical challenges in coastal wetland creeks, which are usually surrounded by dense marsh vegetation and even muddy tidal flats at low tide. Costs of conventional instrumentation (US$100-$2500/month not including mobilization) can be prohibitive for individual investigators, which is why consortia have been established for general hydrologic (CUAHSI, 2016) and oceanographic (WHOI, 2016) instrument sharing.

Hence, there is a need for simpler, cost-effective techniques and instrumentation not limited to high frequency, high resolution data gathering at one or two locations. The objective of this work was to test how inexpensive sensors deployed at multiple sites over the length of wetland creek channels can provide meaningful information on flow velocities and directions. Data from such spatially distributed sensors provides a different perspective and means to study processes using a tracer-based approach (Mudge et al., 2008), allowing point to point characterization of fundamental parameters such as flow velocity or detection of ephemeral flow (Constantz et al., 2001). Unlike upland streamflow that may be nonuniform, but can be assumed to be unidirectional, the hydrodynamics of tidally influenced creeks are even more temporally and spatially variable – variability that is not well captured by flow averaging techniques at single locations. Therefore temperature and conductivity provide sensitive, but underutilized tools to detect subtle hydrodynamic processes as long as major forcing factors are well understood. In particular, in such small tidal creeks that serve as discharge points for urban stormwater and possibly sewage, water quality monitoring efforts at any distance from outfalls need to take into account how tidal reversals affect mixing and control pollution dispersal.

2. Study site and methods

2.1. Hydrologic setting

The Alley Pond wetlands surround a small groundwater-fed creek at the head of an embayment of Long Island Sound in the New York City area (Fig. 1). The embayment, Little Neck Bay, has mesotidal-semidiurnal tides with a mean range of about 2.4 m measured at the NOAA Kings Point station at its mouth, approximately 6 km N of the study site. Previous work (Eaton et al., 2013; Rouff et al., 2013) has shown that a combined sewer overflow outfall (CSO) discharges upstream from the present study site and adversely affects the water quality in the creek. Unlike purely tidal creeks, Alley Creek originates as groundwater at a flowing (artesian) well with a relatively low constant temperature ($\sim$12–13 °C) and low specific conductance (<10 μS cm^{-1}). Many other natural springs and flowing wells were reported in the wetland (Veatch, 1906), however all but one of the wells no longer exist. The work reported here focused on an area downstream from (northwest of) the CSO site, along a 550 m stretch of a creek channel. In the study area, the V-shaped stream channel width of 1 m at mean tide enlarges downstream to about 10 m, and dense stands of tall (3 m) *Phragmites* reeds line the entire channel, preferentially shading the upper reaches of the creek as the day advances. The channel further widens downstream towards the Bay, and is underlain by soft mud and tidal flats exposed at low tide. Depth of water in the channel ranges from <0.1 m in parts of the channel at low water to over 2 m downstream at high water. Discharge is highly variable depending on tide stage, however it was measured at 0.036 m^3 s^{-1} at low ebb-phase tide (representing order-of-magnitude discharge) in dry weather at the upstream end of the channel (Eaton et al., 2013). Maximum flood tide in the creek was observed to slow downstream velocity to zero but the extent of salinity intrusion was unclear.

2.2. Sensor deployment and data processing

Different types of sensors were deployed at locations along the creek in summers 2014 and 2015 (Fig. 1). In 2014, at Sites 10–16