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A novel approach for direct estimation of fresh groundwater discharge to an estuary

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[1] Coastal groundwater discharge is an important source of freshwater and nutrients to coastal and estuarine systems. Directly quantifying the spatially integrated discharge of fresh groundwater over a coastline is difficult due to spatial variability and limited observational methods. In this study, I applied a novel approach to estimate net freshwater discharge from a groundwater-fed tidal creek over a spring-neap cycle, with high temporal resolution. Acoustic velocity instruments measured tidal water fluxes while other sensors measured vertical and lateral salinity to estimate cross-sectionally averaged salinity. These measurements were used in a time-dependent version of Knudsen's salt balance calculation to estimate the fresh groundwater contribution to the tidal creek. The time-series of fresh groundwater discharge shows the dependence of fresh groundwater discharge on tidal pumping, and the large difference between monthly mean discharge and instantaneous discharge over shorter timescales. The approach developed here can be implemented over timescales from days to years, in any size estuary with dominant groundwater inputs and well-defined cross-sections. The approach also directly links delivery of groundwater from the watershed with fluxes to the coastal environment.

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1. Introduction

[2] Quantifying fresh groundwater discharge to the coastal margin is confounded by spatial and temporal variability and the inherent difficulty of observing the discharge. While many eutrophic estuaries receive the majority of their freshwater and nutrient loads from rivers, the effects of coastal groundwater discharge can also be large depending on biogeochemistry and the transformation of nutrients during transit time in the aquifer. *Valiela et al.* [1990] highlighted the importance of coastal groundwater discharge as a large overlooked source of nutrients to coastal ecosystems and addressed the potential biogeochemical significance. *Slomp and Van Cappellen* [2004], highlighting the higher nitrogen/phosphorus ratio in groundwater, explored possible shifts in nutrient limitation and primary productivity as the ratio of groundwater to riverine water is changed. There are instances in which the riverine freshwater and nutrient load is rivaled or exceeded by the coastal groundwater portion. In Tampa Bay, *Kroeger et al.* [2007] found that submarine groundwater discharge accounted for up to 33% of the freshwater discharge, and 50% of nutrient loads. *Valiela et al.* [1990] estimated that over 70% of the nitrogen load to eight New England bays resulted from direct coastal groundwater discharge.

[3] Several methods to measure fresh coastal groundwater discharge have been used with varying success dependent on the system and the assumptions. Radiochemical tracer methods [e.g., *Moore*, 1996; *Cable et al.*, 1996] which sample estuarine water for constituents such as radon and radium, trace total groundwater discharge (i.e. fresh and saline) rather than specifically freshwater discharge. Seepage meters [*Lee*, 1977] can be used to estimate flows but spatial variability in groundwater seepage confounds extrapolation of those measurements to entire basins. Advanced techniques such as the eddy-correlation method [*Crusius et al.*, 2008] avoid some complications of seepage meters and cover somewhat larger footprints. Remote sensing methods can identify spatial variability [*Portnoy et al.*, 1998], but cannot readily resolve the total mass transport. Watershed water-balance methods [*Kroeger et al.*, 2006] yield whole system estimates of fresh groundwater discharge over longer time-periods (e.g. annual to decadal), but cannot resolve the temporal variability that may be caused by tidal fluctuations, discrete rainfall events, or enhanced evapotranspiration. *Lee and Kim* [2007] used intensive salinity sampling to estimate freshwater budgets and the submarine groundwater discharge in a coastal system where the oceanic end member was relatively constant. There is a clear need for independent measurements of fresh groundwater discharge, separate from saline discharge, as only the fresh discharge carries new land-derived materials including nutrient loads.

[4] In contrast to the difficulty in measuring groundwater discharge, quantifying tidal water fluxes through estuarine cross-sections is relatively straightforward. *Simpson and Bland* [2000] first detailed the use of shipboard ADCPs to calculate tidally varying discharge in estuarine channels; *Ruhl and Simpson* [2005] further described methods to generate continuous time-series of tidal flows in tidally affected channels. While these methods are accurate (±5%) for instantaneous tidal flows, extracting the mean (residual flow due to freshwater) can be difficult due to the small ratio of freshwater flow to instantaneous tidal flow. *Ganju and Schoellhamer* [2006] found that a tidal velocity bias of 0.01 m/s was enough to reduce net freshwater flow estimates by 50% through a large channel in San Francisco Bay. Quantifying net freshwater discharge with flow measurements can be improved by measurement of mean salinity in the channel: as a conservative constituent, the flux of salt through the cross-section must balance. This article presents direct estimates of fresh groundwater discharge to a groundwater-fed tidal creek and seaward estuary using acoustic measurements of velocity, spatially intensive salinity measurements, and salt

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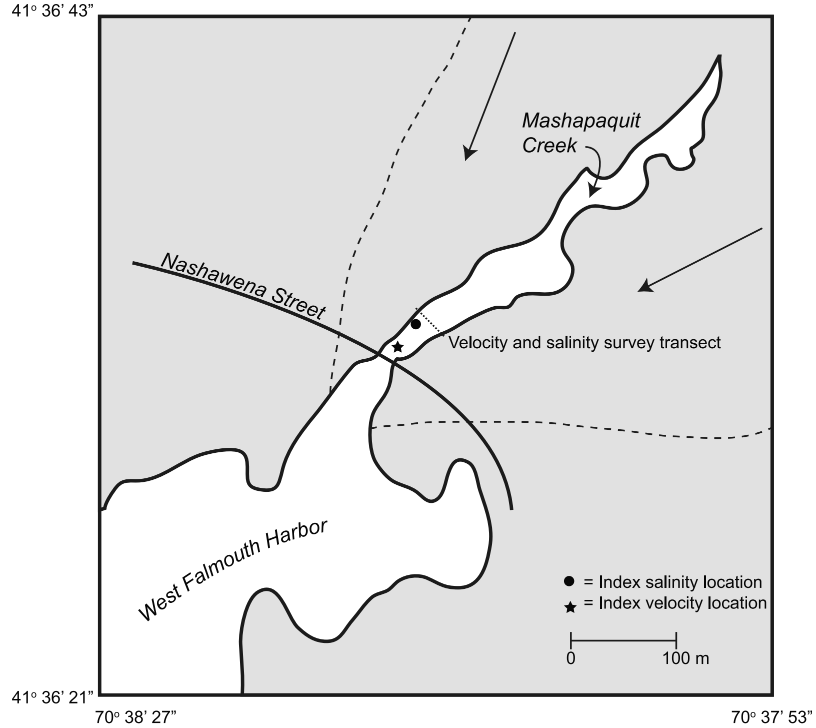

Figure 1. Mashapaquit Creek and the landward portion of West Falmouth Harbor, Massachusetts. Dashed lines indicate watershed delineation reported by *Kroeger et al.* [2006], and arrows denote general direction of groundwater flow.

balance calculations. The mechanisms and implications of the temporal variability are discussed as well as the sensitivity of the salt balance calculation.

2. Methods

2.1. Site Description

[5] Mashapaquit Creek (Figure 1) is a small tidal creek (~1.5 m deep at mean sea level) that drains into West Falmouth Harbor, Massachusetts, located on Upper Cape Cod. The creek is bordered by marsh and residential areas. Groundwater is the largest source of freshwater to coastal margins on Cape Cod [*Valiela et al.*, 1992]; the largest lens of the aquifer is centered 15 km northeast of West Falmouth Harbor. Prior estimates of freshwater loading to Mashapaquit Creek by *Kroeger et al.* [2006] used a mass-balance approach over delineated water table contours (Figure 1), using average annual hydrological conditions. In that study the groundwater discharge to Mashapaquit Creek was estimated to be 0.019 m^3/s. During the summer of 2010 a suite of instruments was deployed in Mashapaquit Creek, with the goal of measuring tidal water fluxes, cross-sectionally averaged salinity, and fresh groundwater discharge over a spring-neap cycle.

2.2. Tidal Water Fluxes

[6] Computing water fluxes in tidally affected channels requires a continuous record of index velocity (v_i) and water level (h) and a less-frequent record of channel-average velocity (v_{ca}) and channel area (A) over some representative period [*Ruhl and Simpson*, 2005]. A complete record of v_{ca} is computed using the correlation between v_i and v_{ca}, and a complete record of A is computed using h and the channel geometry. The product of v_{ca} and A from the complete record yields a continuous record of tidal water fluxes (Q). A Nortek Aquadopp ADCP and Seabird 39 pressure/temperature (PT) sensor were deployed approximately 0.1 m above the bed to measure v_i and h respectively from 22 July 2010 to 9 September 2010. The package was deployed in the center of the channel just landward of the outlet to West Falmouth Harbor (Figure 1), approximately 400 m seaward of the termination of the creek. Measurements of v_{ca} and A were collected on 11 August 2010 using a 1200 kHz RD Instruments Rio Grande ADCP operated from an OceanSciences River Surveyor catamaran with radio modems and a tagline secured from bank-to-bank (Figure 1). At all sites U.S. Geological Survey protocols [*Mueller and Wagner*, 2009] were followed for ADCP settings, compass calibration, and edge estimates (due to the inability to measure near banks). The survey was performed on a spring tide (11 August 2010) when the largest range of conditions was expected. The index velocity method relies on the assumption that the relationship between the index measurement and cross-sectionally averaged value during the tidal-cycle survey is steady over the entire period. This is true for the index salinity method described below.

2.3. Cross-Sectionally Averaged Salinity

[7] Generating a continuous record of cross-sectionally averaged salinity (s_{ca}) requires an index salinity (s_i) measurement and a less-frequent record of cross-sectionally averaged salinity over some representative time period; the correlation between the two can be used to estimate continuous cross-sectionally averaged salinity. A YSI 6-series multi-parameter sonde was deployed from a floating dock (depth approximately 1.25 m at mean high water), with the measurement volume approximately 0.1 m below the water surface. The instrument was deployed in this fashion due to prior observations of strong vertical stratification in the shallow, groundwater-fed creek. Vertical stratification was

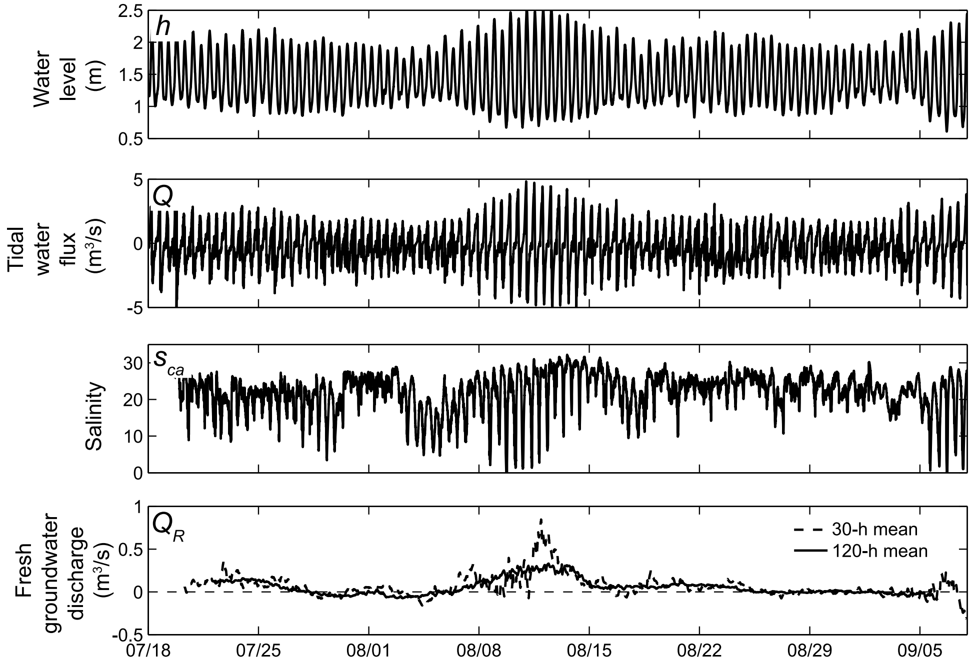

Figure 2. Time-series measurements of water level, tidal water flux, cross-sectionally averaged salinity, and calculated fresh groundwater discharge (over varying averaging windows). Negative freshwater fluxes may arise from error or more landward transport of fresh groundwater from other areas of the harbor.

accounted for by deploying a vertical array of three Seabird Microcat conductivity/temperature (CT) sensors adjacent to the dock at 0.33, 0.55, and 0.77 mab. The dock is located approximately 30 m landward of the ADCP/PT package (Figure 1). The multi-parameter sonde was downloaded and serviced weekly following the guidelines of *Wagner et al.* [2006]. The vertical salinity profiles obtained from the floating dock and vertical array were interpolated to a uniform depth coordinate (due to variable locations in the water column relative to each other) and averaged to yield a depth-averaged salinity at the edge of the creek. Cross-sectionally averaged salinity was estimated by vertical profiling with a multi-parameter sonde at five equally spaced locations in the cross-section. The sonde sampled at 1 Hz, and downcast data were interpolated to a uniform vertical coordinate, weighted by total depth of the profile, and averaged. Profiles along a transect (Figure 1) were collected from a canoe secured to the tagline, intermittently during the ADCP surveys on 11 August 2010.

2.4. Time-Dependent Salt Balance and Freshwater Discharge Calculation

[8] *MacCready and Geyer* [2010] describe the steady salt balance of *Knudsen* [1900] as

$$Q_{out} = \frac{s_{in}}{\Delta s} Q_R \text{ and } Q_{in} = \frac{s_{out}}{\Delta s} Q_R \tag{1}$$

where Q_{out} is the net water flux on ebb tides, s_{out} is the cross-sectionally averaged salinity on ebb tides, Q_{in} is the net water flux on flood tides, s_{in} is the cross-sectionally averaged salinity on flood tides, Δs is the difference between s_{in} and s_{out}, and Q_R is the total freshwater discharge to the estuary. Equation (1) is typically applied as a spatially varying description of tidally averaged quantities; *MacCready* [2011] derived the analogous time-dependent version of equation (1)

$$\begin{aligned} Q_{out}(t) &= \frac{s_{in}(t)}{\Delta s} Q_R(t) + \frac{1}{\Delta s} V \frac{ds}{dt} \text{ and} \\ Q_{in}(t) &= \frac{s_{out}(t)}{\Delta s} Q_R(t) + \frac{1}{\Delta s} V \frac{ds}{dt} \end{aligned} \tag{2}$$

where the last term on the right hand sides accounts for storage of salt or freshwater within an estuary of volume V. Rearranging the first relationship to solve for the freshwater discharge gives

$$Q_R(t) = \frac{\Delta s}{s_{in}(t)} Q_{out}(t) - \frac{1}{s_{in}(t)} V \frac{ds}{dt} \tag{3}$$

Assuming zero net salt flux eliminates the last term in equation (3) and allows for the calculation of Q_R using instantaneous tidal water flux and cross-sectionally averaged salinity data. The tidal water flux and salinity merely need to be separated based on whether the water and salt flux are landward or seaward.

3. Results

3.1. Tidal Water Fluxes

[9] An index velocity relationship between v_i and v_{ca} was successfully developed with the continuous and cross-sectional ADCP data (Figure S1 of the auxiliary material); the stage-area relationship was constructed with a high-water channel geometry cross-section and the continuous water level data (Figure S2 of the auxiliary material and Figure 2).[1]

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL047718.

Table 1. Sensitivity Analyses for Salt Balance Calculation[a]

Perturbed Variable	Time-mean Q_R (m^3/s)	Error	Max Q_R (m^3/s)	Error
$Q_{in,out}$ + 5% random error	0.020	0%	0.85	0%
$Q_{in,out}$ + 5% seaward bias	0.045	125%	0.90	6%
$s_{in,out}$ + 5% random error	0.020	0%	0.84	1%
$s_{in,out}$ + 5% fresh bias	0.021	5%	0.89	5%
$Q_{in,out}$, $s_{in,out}$ + 5% random error	0.021	5%	0.85	0%
$Q_{in,out}$, $s_{in,out}$ + 5% seaward/fresh bias	0.047	135%	0.95	12%

[a]Original value of Q_R was 0.02 m^3/s, maximum Q_R was 0.85 m^3/s.

The computed tidal water flux (Figure 2) shows a maximum tidal water flux of 5 m^3/s, with a pronounced spring-neap signal. Maximum neap tidal water flux was about half the spring tide magnitude. The time-mean of this tidal water flux is 0.2 m^3/s (in the seaward direction), which equates to a representative water velocity of 0.007 m/s (using the average channel area) and is approximately the same as the error of the index velocity relationship. The average tidal excursion at the site was approximately 1 km, larger than the distance to the creek terminus.

3.2. Cross-Sectionally Averaged Salinity

[10] The continuous vertical profile data showed that the creek was strongly stratified on ebb tides, with vertical salinity gradients exceeding 25 m^{-1} on neap tides. Stratification was less on spring tides, due to greater tidal energy and mixing. The relationship between the creek-edge, depth-averaged salinity and the cross-sectionally averaged salinity during the 11 August 2010 survey was linear (Figure S3 of the auxiliary material).The time-series of computed continuous cross-sectionally averaged salinity (Figure 2) shows the largest fluctuations in tidal-timescale salinity occur during the spring tide (8 August 2010 – 15 August 2010), when the salinity difference between flood and ebb tide is maximized.

3.3. Freshwater Discharge Calculation

[11] The tidal water flux and cross-sectionally averaged salinity data were used in equation (3) by separating the data depending on whether the current was flooding or ebbing (to separate Q_{in} from Q_{out}, and s_{in} from s_{out}). This separation was first performed over the entire time-series resulting in a groundwater flux of 0.02 m^3/s; separation was then applied in moving windows of 30 and 120 h, to evaluate the temporal variation of groundwater discharge over varying timescales (Figure 2). With the shortest 30-h averaging window (which essentially represents a "tidally averaged" window), the peak fresh groundwater discharge was 0.85 m^3/s during the spring tide, which is an order of magnitude larger than the period mean. During neap tides groundwater flux was closer to the period mean. Rainfall during this period was minimal (http://www.emc.ncep.noaa.gov) and cannot account for the large variations in freshwater discharge. Small negative values may be due to error or landward transport of fresh groundwater from elsewhere in the harbor.

4. Discussion

4.1. Sensitivity of Salt Balance

[12] The salt balance calculation is most sensitive to systematic bias in tidal water flux measurements (Table 1), and is largely insensitive to random errors and biases in salinity measurement. The sensitivity to tidal water flux bias is due to the tight coupling between near-slack tide (i.e. zero tidal water flux) and maximum fresh groundwater input to the creek. Synthetically biasing the tidal water flux measurements with a sensitivity analysis essentially shifts the phasing between slack tide and minimum salinity such that ebb tide carries fresher water seaward, thus resulting in larger calculated fresh groundwater discharge. However, identifying slack tide with acoustic velocity measurements is relatively reliable in a small channel. Biases in salinity are less critical due to the Δs term in equation (3) which is unaffected by bias. Random errors are minor as they do not shift the phasing of tidal water flux and salinity, nor alter the net water transport on flood and ebb tides.

4.2. Fresh Groundwater Discharge and Tidal Pumping

[13] The temporal variability in fresh groundwater discharge is highly correlated with tidal range (Figure 3). Correlations were tested between the fresh groundwater discharge and tidal range (r^2 = 0.79), low-tide level (r^2 = 0.51), and time below a range of arbitrary tide levels (r^2 < 0.4). The 120-h mean fresh groundwater discharge was used to reduce scatter in the relationship and highlight the lower frequency variation with tidal range. The stronger correlation with tidal range as opposed to low tide level supports the "tidal pumping" mechanism elucidated by others [*Nielsen*, 1990; *Moore*, 1999] whereby increased tidal action extracts more ground-

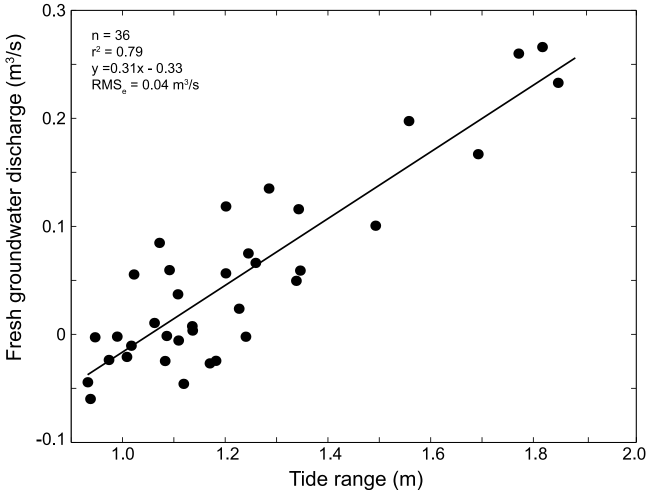

Figure 3. Relationship between daily tidal range and mean fresh groundwater discharge over a full spring-neap cycle.

water from the aquifer. Those studies apply to the total submarine groundwater discharge (i.e. fresh and recirculated saline groundwater); the results of this study show that the mechanism applies for the fresh groundwater component alone as well. The large temporal variability over spring-neap timescales (from virtually no net discharge to peak discharge in a few days) has major implications for ecosystems. The delivery of "new" nutrients in fresh groundwater fluctuates over short timescales and may confound ecological observations (e.g. primary production estimates) that are not as temporally resolved.

4.3. Steady Salt Balance Assumption

[14] The steady salt balance assumption which simplifies equation (3) is supported by two calculations. Firstly, the salt storage term in equation (3) can be calculated using representative values of estuarine volume landward of the cross-section (V), the variation in subtidal salinity (ds/dt), and flood tide salinity (s_{in}) for comparison with Q_R. V is calculated as 6.25×10^4 m^3 assuming an area that includes the channel and adjacent marsh plain (1.25×10^5 m^2) and an average depth of 0.5 m; over the neap-to-spring transition from 4 August 2010 to 11 August 2010 ds/dt is approximately 1 d^{-1}, and s_{in} is approximately 20, giving a value of 3.125×10^3 m^3/d or 0.036 m^3/s. This is an order of magnitude less than the calculated peak Q_R using either the 30-h or 120-h averaging windows. Secondly, the increased fresh groundwater discharge on spring tides is not caused by storage of freshwater during neap tide periods (when flushing is reduced) and subsequent export on spring tides with greater flushing ability. The total volume of exported freshwater between 6 August 2010 and 17 August 2010 was 1.4×10^5 m^3; over the area of Mashapaquit Creek's channel and marsh plain (~1.25×10^5 m^2) this would require a subtidal water level increase of 1 m which is not supported by the data (Figure 2). In systems with larger embayments, however, storage of freshwater on neap tides could be an important mechanism controlling the temporal variability of freshwater export at the estuary mouth. In this case the data support storage within the coastal aquifer on neap tides, and enhanced extraction on spring tides.

5. Conclusion

[15] This study presents a new robust approach to quantifying the fresh portion of coastal groundwater discharge to estuarine systems. The methods require careful acoustic velocity and salinity surveys, but rely on a simple time-dependent salt balance which can be applied over multiple timescales. The approach was implemented in a groundwater-fed tidal creek and quantified the large temporal variability in fresh groundwater discharge over the spring-neap timescale. The variability was highly correlated with tidal range, supporting the tidal pumping mechanism for sequentially increasing and decreasing pressure gradients within the coastal aquifer leading to increased discharge of fresh groundwater. The method is most sensitive to the phasing of tidal water flux and salinity, though this sensitivity ultimately depends on the nature of the tidal wave (i.e. standing vs. progressive) at the estuarine cross-section. This approach can be used to complement other methods (gas tracer, high-resolution models) by quantifying specifically the fresh portion of coastal groundwater discharge. The approach can be applied in any estuarine cross-section where groundwater is the dominant source of freshwater, and provides a foundation for estimating loads of watershed-derived constituents to coastal margins.

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