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# Eddy correlation measurements of submarine groundwater discharge

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## Abstract

This paper presents a new, non-invasive means of quantifying groundwater discharge into marine waters using an eddy correlation approach. The method takes advantage of the fact that, in virtually all aquatic environments, the dominant mode of vertical transport near the sediment–water interface is turbulent mixing. The technique thus relies on measuring simultaneously the fluctuating vertical velocity using an acoustic Doppler velocimeter and the fluctuating salinity and/or temperature using rapid-response conductivity and/or temperature sensors. The measurements are typically done at a height of 5–15 cm above the sediment surface, at a frequency of 16 to 64 Hz, and for a period of 15 to 60 min. If the groundwater salinity and/or temperature differ from that of the water column, the groundwater specific discharge ( $\text{cm d}^{-1}$ ) can be quantified from either a heat or salt balance. Groundwater discharge was estimated with this new approach in Salt Pond, a small estuary on Cape Cod (MA, USA). Estimates agreed well with previous estimates of discharge measured using seepage meters and  $^{222}\text{Rn}$  as a tracer. The eddy correlation technique has several desirable characteristics: 1) discharge is quantified under *in-situ* hydrodynamic conditions; 2) salinity and temperature can serve as two semi-independent tracers of discharge; 3) discharge can be quantified at high temporal resolution, and 4) long-term records of discharge may be possible, due to the low power requirements of the instrumentation.

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## 1. Introduction

Flow of water through permeable sediments is increasingly recognized as an important process that can impact the fluxes of many dissolved substances to the marine environment. Fresh groundwater delivers a significant flux of nutrients to many coastal waters, thus contributing to eutrophication (e.g. Valiela et al., 1990; Giblin and Gaines, 1990). Recent studies have also suggested a possible important contribution of advective

fluxes through sediments to the coastal marine budgets of iron (Windom et al., 2006), mercury (Bone et al., 2007), and barium and uranium (Charette and Sholkovitz, 2006). Such fluxes are likely important for other elements as well. Yet, quantifying and characterizing these advective fluxes of water across the sediment–water interface remains a challenge because: 1) discharge is slow, spread out over a large area, and spatially variable (e.g. Michael et al., 2003); 2) discharge often occurs below the water surface, where it is difficult to observe and to measure; 3) most established techniques for measuring chemical fluxes to or from sediments (e.g. benthic chambers, concentration profile interpretations)

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are not appropriate for sediments where advection is the dominant means of transport.

The term “submarine groundwater discharge” (SGD) has often been used to describe flow through permeable sediments, regardless of the driving mechanism (e.g. Burnett et al., 2003). Many processes can contribute to this flow, including movement of fresh groundwater from land, discharge of brackish water resulting from mixing of fresh groundwater with seawater below the sediment–water interface, and recirculation of seawater through sediments via tidal pumping, wave pumping, and bio-irrigation (the transport caused by pumping activity of tube-dwelling animals). This grouping of multiple processes under a single label occurs in part because many of the methods currently available for quantifying this discharge do not readily distinguish among the different phenomena. These methods include: 1) site-calibrated groundwater flow models; 2) hydrologic balance approaches; 3) seepage meters; and 4) tracers. Each of these approaches most likely quantifies a subset of the above-mentioned transport processes, and each has limitations. Neither groundwater flow models nor hydrologic balance approaches, for example, can determine whether discharge occurs at the coastline or farther offshore, yet the impacts of introduced nutrients depend heavily on the discharge locations.

Seepage meters have the potential to provide an accurate estimate of discharge through the area covered by the seepage meter. However, because such fluxes are often very heterogeneous spatially (e.g. Michael et al., 2003; Crusius et al., 2005) and temporally (e.g. Sholkovitz et al., 2003; Taniguchi et al., 2003), estimates from a single seepage meter over a limited time may not be representative of the average discharge. Furthermore, seepage meters are frequently thought to quantify discharge that includes seawater recirculation through sediments, not just fresh groundwater discharge (e.g. Taniguchi et al., 2006). Finally, the degree to which seepage meters can be subject to a variety of artifacts due to the presence of an enclosure over the sediment is not fully resolved (Shinn et al., 2002; Corbett and Cable, 2003).

Natural geochemical tracers represent a relatively new approach for quantifying SGD. Among the commonly used tracers are  $^{222}\text{Rn}$  and radium isotopes. SGD is estimated in each case from the measured radionuclide fluxes to the water column and from the radionuclide content of groundwater, which is typically greatly enriched relative to the water column (Ellins et al., 1990; Burnett and Dulaiova, 2003; Moore, 1996). These tracers often track advective pore water exchange that includes both fresh groundwater discharge and various mechanisms of seawater exchange, as well (Burnett et al., 2006).

Given the limitations of existing approaches reviewed briefly above, there is clearly a need for new means of quantifying the various processes referred to as SGD. With this background in mind, we developed and tested an eddy correlation approach for estimating discharge of fresh groundwater to the coastal environment. The “specific discharge” ( $q$ ) of groundwater is defined as:

$$q = Q/A, \quad (1)$$

where

$Q$  groundwater discharge ( $\text{cm}^3 \text{d}^{-1}$ )  
 $A$  cross sectional area ( $\text{cm}^2$ ).

The specific discharge therefore is the volumetric rate of groundwater discharge normalized to cross sectional area, and is typically expressed in units of  $\text{cm}^3 \text{cm}^{-2} \text{d}^{-1}$  (abbreviated as  $\text{cm d}^{-1}$ ). We point out that the specific discharge is an “apparent” velocity of the water immediately above the sediment–water interface; it is not the same as the true velocity of porewater (or groundwater) traveling through the porous medium of the subsurface. This subsurface velocity equals  $q/\phi$ , where  $\phi$  is the porosity of the sediment ( $\text{cm}^3 \text{porewater cm}^{-3} \text{sediment}$ ).

Water-column temperature and vertical velocity data help to give an intuitive sense of how the eddy correlation method can be used to quantify SGD. In this example, we consider the discharge of groundwater which is colder than the overlying water column. Sensors positioned a few centimeters above a sediment surface, where cold groundwater is discharging into a warmer water column, will typically record colder water moving upwards and warmer water moving downwards (Fig. 1). The groundwater discharge across the sediment–water interface can be inferred from a heat balance, in this example, if the groundwater and water column temperatures are known. The same can be done from a salt balance if salinity is measured. It should be noted that the method will work as long as there is a temperature and/or salinity difference between groundwater and the water above the sediment–water interface. Obviously, the sensitivity of the approach will depend on the magnitude of this difference.

This work represents the first application of eddy correlation for quantifying SGD. However, eddy correlation-based approaches have become the most widely accepted method for measuring land–atmosphere and air–sea exchanges of  $\text{CO}_2$ , heat, and moisture (i.e. Wyngaard, 1989; Goulden et al., 1996), and are in use in continuous monitoring systems worldwide. The eddy correlation technique has only been applied recently in the aquatic benthic environment to

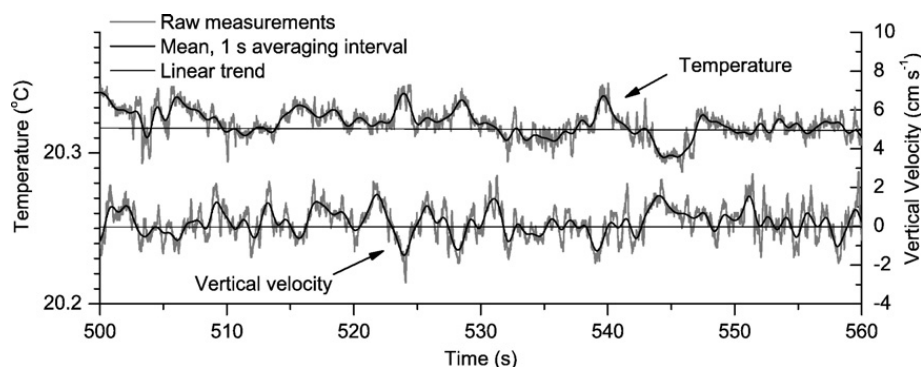


Fig. 1. Water-column temperature and vertical velocity data collected in Salt Pond on Cape Cod (USA) using the PME conductivity/temperature sensor interfaced with the Nortek acoustic Doppler velocimeter (Vector). The figure includes the raw data (64-Hz; thin grey line), a one-second running average (thick line), and a linear trend (black line). Negative velocities reflect water movement downward, toward the sediment.

measure the dissolved oxygen flux (Berg et al., 2003; Kuwae et al., 2006; Berg et al., 2007).

## 2. Methods

The velocity measurements were carried out using an acoustic Doppler velocimeter (the Vector) made by Nortek™, which gives the 3 dimensional velocity field for a measuring volume of  $\sim 1 \text{ cm}^3$  located  $\sim 15 \text{ cm}$  below the Vector's sensor arms (Fig. 2). Salinity and temperature measurements were made using a rapid-response conductivity/temperature sensor made by Precision Measurement Engineering (PME) of Carlsbad, CA. The temperature sensor is a GE type FP07 thermistor and consists of small-diameter glass-coated thermistor beads hermetically sealed at the tips of shock-resistant glass rods. The beads are exposed at the top of the glass rod to yield a faster time response. The conductivity sensor is a four-electrode cell, consisting of four platinum wires supported by a tapered glass structure, with a sub-millimeter size measuring volume (Head, 1983). The Vector powered the conductivity/temperature sensor and also recorded all data at a frequency of 64 Hz. This setup guarantees that all data are fully synchronized in time, a critical issue here where short-term fluctuations are important. While carrying out measurements at a frequency of 64 Hz is not required for the SGD estimate, capturing data at such high resolution allows time-averaging to reduce noise. Data acquisition was performed using existing software from Nortek and software developed as part of this work. Both the ADV and the conductivity/temperature sensor were mounted on a tripod for initial lab tests and field deployments. The tip of the conductivity/temperature sensor was positioned immediately ( $\sim 5 \text{ mm}$ ) downstream of the measuring volume of the ADV (Fig. 2).

Field measurements were carried out in the channel between Salt Pond and Nauset Marsh (henceforth referred to as Salt Pond Channel; Fig. 3), at the Cape Cod National Seashore. This site has been the subject of a previous SGD study based on a  $^{222}\text{Rn}$  mass balance and on seepage meter data (Crusius et al., 2005). For this field deployment, the conductivity/temperature sensor and ADV were deployed 6 m from shore in a  $\sim 40\text{-m}$ -wide channel ( $41.8342^\circ \text{ N}$ ,  $69.9698^\circ \text{ W}$ ) during a falling tide, with the Vector's measuring volume and the conductivity/temperature sensor tip positioned  $\sim 5 \text{ cm}$  above the sediment surface. The field deployment was intentionally designed to span an interval of low tide, when the greatest discharge might be expected, based on previous research (Paulsen et al., 2001; Sholkovitz et al., 2003). To eliminate any influence of solar heating of sediments, measurements were carried out at night, from 21:00 to 01:30. Groundwater temperatures and salinities



Fig. 2. Eddy correlation instrumentation used in lab tests and field deployments, with the tip of the conductivity/temperature sensor (left) positioned adjacent to the measuring volume of the acoustic doppler velocimeter, right. The instruments were deployed in this orientation when the current direction was from the right.



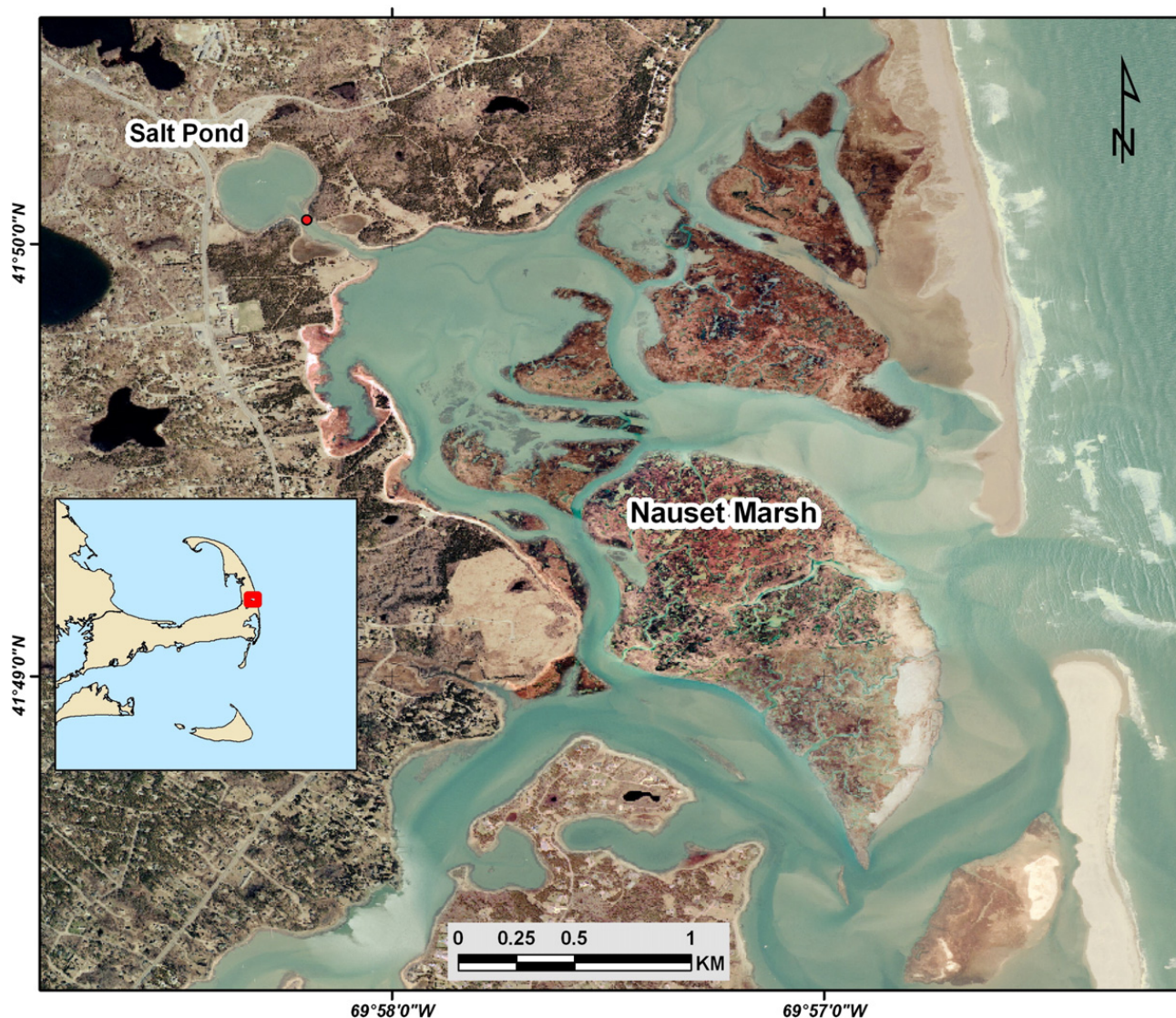


Fig. 3. Aerial photo of Salt Pond and Nauset Marsh system (Cape Cod, USA location on inset), showing the NW end of “Salt Pond Channel” as a red dot, where we deployed our instruments.

were determined, after eddy flux data collection was complete, by sampling below the sediment–water interface with a small drive-point piezometer with an embedded thermistor. Salinity was determined using a YSI multiparameter water quality probe.

### 2.1. Eddy correlation theory

The eddy correlation technique for estimating sediment–water fluxes takes advantage of the fact that turbulent mixing is the dominant vertical transport mechanism in the water column near the sediment–water interface. If turbulent fluctuations of the vertical velocity ( $u_z$ ) and temperature ( $T$ ) can be measured here with adequate temporal resolution and for a period long enough to obtain a statistically sound representation of

their variations, then the vertical eddy flux of heat can be derived. This flux can then be used to estimate the groundwater specific discharge, if there is a clear temperature difference between the groundwater and the water column. In other words, the groundwater temperature is simply used as a tracer of the incoming or seeping groundwater. A similar estimate can be made if high frequency salinity ( $S$ ) data are recorded instead of temperature. If both  $T$  and  $S$  are measured, two semi-independent calculations of the groundwater specific discharge can be obtained. Below we present the calculation in which temperature is used as the groundwater tracer.

Consider a heat balance for a control volume, with fixed boundaries, that straddles the sediment–water interface where groundwater is discharging and stretches

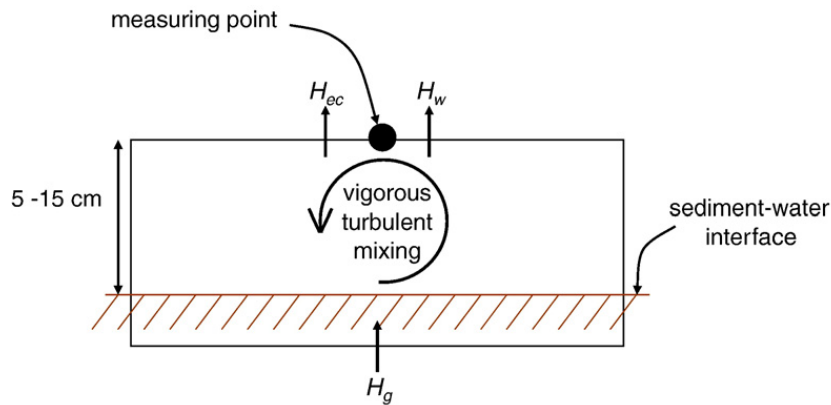


Fig. 4. Schematic illustrating the heat fluxes for a control volume boundary covering the sediment–water interface.  $H_g$  is the heat flow due to discharging groundwater,  $H_w$  is the heat flow tied to the water in the control volume being displaced by groundwater inflow, and  $H_{ec}$  is the heat flow associated with the eddy flux of heat across the upper control volume (see text). The salt balance can be portrayed similarly.

up into the water column above, where vigorous turbulent mixing creates a near-uniform water mass (Fig. 4). Assuming steady state, this balance yields

$$H_g - H_w - H_{ec} = 0 \quad (2)$$

where  $H_g$  is the heat flow into the control volume due to discharging groundwater,  $H_w$  is the heat flow tied to the water in the control volume being displaced by groundwater inflow, and  $H_{ec}$  is the heat flow associated with the eddy flux of heat across the upper control volume boundary. In this heat balance we have neglected any heat flow contributions associated with horizontal temperature differences. This is a common assumption in eddy correlation flux extractions (see Lee et al., 2004, for a detailed evaluation of this simplification).

The three terms in Eq. (2) are defined as follows:

$$H_g = T_g C_{p_g} \rho_g q_g \quad (3)$$

$$H_w = T_w C_{p_w} \rho_w q_g \quad (4)$$

$$H_{ec} = \overline{u'_z T'_w} C_{p_w} \rho_w \quad (5)$$

where

- $T_g$  the mean groundwater temperature ( $^{\circ}\text{C}$ ),
- $C_{p_g}$  the specific heat of groundwater ( $\text{J g}^{-1} \text{ } ^{\circ}\text{C}^{-1}$ ),
- $\rho_g$  the groundwater density ( $\text{g cm}^{-3}$ ),
- $q_g$  the groundwater specific discharge ( $\text{cm s}^{-1}$ ),
- $T_w$  the mean water-column temperature ( $^{\circ}\text{C}$ ),
- $C_{p_w}$  the specific heat of the water column ( $\text{J g}^{-1} \text{ } ^{\circ}\text{C}^{-1}$ ),
- $u'_z$  the fluctuating vertical water velocity ( $\text{cm s}^{-1}$ ),
- $T'_w$  the fluctuating water-column temperature ( $^{\circ}\text{C}$ ),

- $\overline{u'_z T'_w}$  the time-averaged eddy temperature flux ( $\text{cm } ^{\circ}\text{C s}^{-1}$ ; for additional details on eddy flux calculations see Berg et al., 2003),
- $\rho_w$  water-column density ( $\text{g cm}^{-3}$ ).

Inserting Eqs. (3–5) into Eq. (2), and rearranging, yields an expression for  $q_g$ :

$$q_g = \frac{\overline{u'_z T'_w} C_{p_w} \rho_w}{\rho_g (T_g C_{p_g} - T_w C_{p_w})} \quad (6)$$

The similar calculation can be carried out to estimate the groundwater specific discharge based on the salt balance, according to:

$$q_g = \frac{\overline{u'_z S'_w} \rho_w}{\rho_g (S_g - S_w)} \quad (7)$$

In the interests of brevity, the derivation of this will not be presented. Additional definitions for Eq. (7) are:

- $S_w$  the mean salinity of the water column,
- $S_g$  the mean salinity of the groundwater,
- $S'_w$  the fluctuating water-column salinity,
- $\overline{u'_z S'_w}$  time-averaged eddy salt flux ( $\text{cm s}^{-1}$ ).

### 3. Results

Lab tests and field deployments were performed to assess the accuracy, precision, stability and response time of the temperature and salinity sensors. A critical requirement of these sensors when used in eddy correlation is that the reaction time of the sensors be sufficiently short ( $<0.2\text{--}1$  s) to resolve the fast fluctuations around the mean. The conductivity/temperature



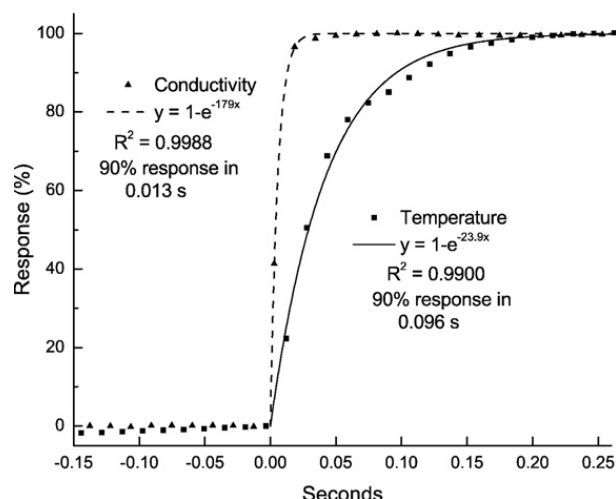


Fig. 5. The response of the conductivity and temperature sensors to a rapid change in both salinity and temperature. Both salinity and temperature data were normalized so that the full change is portrayed as 100%, to facilitate intercomparison and observation of the 90% response time (see text).

sensor provided data that were free of significant noise in the laboratory (mean amplitude of temperature noise = 0.00085 °C; mean amplitude of salinity noise =

0.0042 psu). In the field the temperature signal was also consistently stable (mean amplitude of temperature noise = 0.00084 °C), whereas the conductivity signal contained abrupt spikes and abrupt changes of the mean. We believe that these problems are caused by particles in natural waters becoming lodged in the electrodes at the sensor tip (M. Head, personal communication, 2006), given that the tests of the conductivity sensor in seawater in the lab showed no such instability. This problem might be overcome by re-designing the sensor head.

The response time of the conductivity and temperature sensors was evaluated in the laboratory by rapidly transferring the sensor from a warm fresh water bath ( $T=22$  °C,  $S=0$ ) to a cooler, saline bath ( $T=16$  °C,  $S=25$ ). The signals were logged at a frequency of 64 Hz during this test. The responses of the conductivity and temperature sensors were normalized so that the full change in response equals 100%. Further, the response times were quantified by fitting the normalized data with an exponential function (Fig. 5). The 90% response time of the conductivity sensor was shorter (0.013 s) than that of the temperature sensor (0.096 s). The response time estimate for the temperature sensor is longer than that stated by the manufacturer (63% response time of

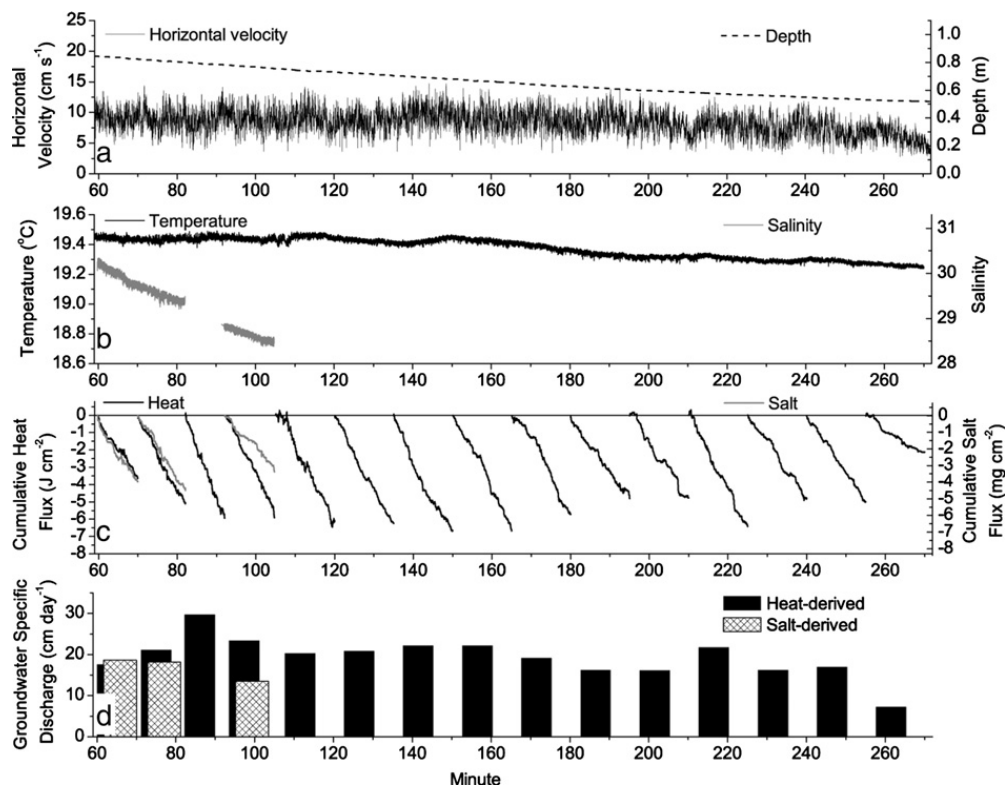


Fig. 6. Data used to estimate groundwater specific discharge at Salt Pond Channel, Cape Cod (MA), on September 28–29, 2006 (9:45 p.m.–1:40 a.m.): a) Horizontal current velocities (1 s running average) and water depth; b) Temperature and salinity (64 Hz); c) Cumulative heat and salt fluxes; d) Groundwater specific discharge inferred from the heat and salt flux data (see text). Note that the heat and salt fluxes were quantified over identical time intervals, but the columns in the figure are offset for ease of viewing.

0.007 s; M. Head, personal communication, 2006), perhaps due to our simple experimental setup that includes the transfer time from one bath to another. However, the response times are sufficiently small to be used in eddy correlation measurements, which require response times of  $\sim 0.2$ – $1$  s, or less (Berg et al., 2003).

Field measurements were carried out at Salt Pond channel (Fig. 3) in September, 2006, in a first attempt to estimate the specific discharge of groundwater using eddy correlation. Measurements were carried out during a  $\sim 3.5$ -hour interval just prior to slack low tide. The temperature and salinity of the groundwater were estimated at a number of locations and times ( $n=16$ ) (Eqs. (6) and (7)). During the velocity and conductivity/temperature measurements, groundwater salinity and temperature were measured slightly downstream from the location of the data recording to avoid disturbing the natural flow. Immediately prior to and after making the ADV and conductivity/temperature measurements, groundwater/porewater salinity and temperature were measured upstream of the ADV. All these data spanned a range, from the lowest temperature and salinity values of  $T=12.0$  °C and  $S=0$ , to values close to the bottom-water values of  $T\approx 19.4$  °C and  $S\approx 29$ . We assumed that these higher values reflect mixing of groundwater and water-column water, and for the purpose of estimating groundwater fluxes, we used the lowest temperature and salinity values. We evaluate this assumption further below.

Horizontal mean current velocity was fairly constant ( $\sim 10$  cm  $s^{-1}$ ) through most of the deployment, but decreased at the end ( $\sim 2$  cm  $s^{-1}$ ) (Fig. 6a), while the water depth at the site diminished gradually from  $\sim 0.8$  m to  $\sim 0.6$  m. Water-column temperature deviated little from  $\sim 19.3$  °C, while salinity decreased from  $\sim 30.2$  to  $28.5$  for the period of reliable measurements (Fig. 6b). Note that the salinity data span a shorter time period than the temperature data because of problems with the conductivity/temperature sensor (see results section). Water-column salinity, temperature and current velocity were recorded continuously at 64 Hz, but interpreted as fifteen successive time-series, each  $\sim 15$  min long, to allow assessing the temporal variability of the fluxes. The cumulative heat fluxes were fairly consistent during the  $\sim 3.5$  h deployment (Fig. 6c) which indicate a strong eddy correlation signal. The cumulative salt fluxes were also fairly consistent during the periods of reliable conductivity measurements (Fig. 6c).

The groundwater specific discharge derived from the cumulative heat flux (using Eq. (6)) was  $19.4\pm 4.9$  cm  $day^{-1}$  (Fig. 6d;  $n=15$ ; note that the reported uncertainties are the standard deviation (SD) of the estimated values). The cumulative salt flux data,

spanning the 0.75 h of reliable conductivity data (Fig. 6b), yielded a mean groundwater specific discharge of  $16.9\pm 2.9$  cm  $day^{-1}$  ( $n=3$ , SD), indistinguishable from the heat flux-derived estimate of  $20.7\pm 2.9$  cm  $day^{-1}$  ( $n=3$ , SD) over the same brief time interval for which we had reliable salinity data. It should be noted that the instruments were deployed so that the measuring volume of the ADV, and the tip of the conductivity/temperature sensor, were  $\sim 5$  cm above the sediment surface. The footprint (the upstream area that contributes 90% of the measured flux) is a function of this measurement height and the sediment surface roughness (Berg et al., 2007) and was approximately nine meters long and one half meter wide.

#### 4. Discussion

These groundwater specific discharge estimates, derived here using the eddy correlation approach for the first time, warrant comment on a number of fronts. With respect to validation of this approach, it is important to note that these specific discharge estimates are similar to seepage meter-derived estimates measured nearby within Salt Pond ( $16\pm 9$  cm  $d^{-1}$ ) and also similar to the specific discharge to Salt Pond Channel inferred by modeling radon data ( $25\pm 9$  cm  $d^{-1}$ ) during an earlier field study (Crusius et al., 2005). Despite these other two estimates being made at different times, and over slightly different areas, this agreement gives us some confidence in the rates estimated by eddy correlation. We derive additional confidence in these results from the good agreement of the specific discharge estimates derived from the two semi-independent tracers (salinity and temperature). While it is unfortunate that the conductivity measurements were not always reliable, we point out that having two such tracers is unusual in eddy flux measurements, and is therefore a strength of this approach. We plan in future work to further increase our confidence in eddy correlation specific discharge estimates by comparing them with estimates made simultaneously using other approaches, including radioisotopes and seepage meters.

As discussed above, our groundwater specific discharge estimates critically depend upon the measured temperature and salinity of the discharging groundwater, much as radioisotope-based flux estimates depend upon an estimate of the activity of a groundwater endmember (e.g. Moore, 1996; Burnett and Dulaiova, 2003). In this study, we used the lowest measured temperature and salinity ( $12$  °C,  $S=0$ ), and therefore, our estimates represent the cold, freshwater component of the groundwater. Obviously, if the groundwater was mixing



with warmer, saline water (e.g. brackish porewater or groundwater) prior to discharge, the total groundwater specific discharge would be larger than our estimates. In previous work at the same location, we attempted to quantify the relative proportions of fresh versus saline groundwater discharging, based on observed sharp increases in water-column radon activity at low tide that were synchronous with decreases in water-column salinity (Crusius et al., 2005). That analysis concluded that the freshwater proportion of the discharge represented between 50 and 100% of the total discharge, which would imply that the total specific discharge could be no more than two times higher than estimated in this work.

Additional work will be needed to assess the minimum groundwater specific discharge that can be estimated using this new method. However, we note that the clear and consistent linear trends in the cumulative flux data obtained in this work (Fig. 6c) indicate statistically sound discharge estimates. We further conclude that significantly smaller linear trends, representing smaller discharge rates, easily can be inferred from data such as these. Furthermore, if needed, the cumulative fluxes could be measured over a longer time interval than the fifteen minutes used here, which would improve our ability to quantify much smaller trends of the cumulative flux. We are thus confident that it will be possible to estimate specific discharge values that are at least an order of magnitude smaller than obtained here.

A goal for future work will be to carry out tests to better understand the environments where this eddy correlation approach will yield reliable groundwater specific discharge estimates. More specifically, we need to test the method in shallow, open-coastline environments where waves exhibit a major influence on near-bottom currents. We need to assess how well the approach will work in quiescent settings where current speeds are small and variable and we also need to evaluate the method in settings where solar radiation may warm the sediment surface and thereby influence the heat balance. Determining when the heat balance approach fails to accurately quantify groundwater advection will, of course, benefit from using salinity as an independent tracer. In addition, we need to evaluate the extent to which vertical heat conduction and salt diffusion in surficial sediments influence the heat and salt balances, likely a problem only at very low discharge. Finally, we need to evaluate how well this method will work at shallow water depths. The minimum water depth is likely to be in the range of 20 cm, both because the Vector must be positioned ~15 cm above the measuring volume and because transport processes may differ at extremely shallow

depths. The set of tests outlined above are obviously on our agenda, given the promise and potential of this new eddy correlation approach for measuring SGD.

## 5. Conclusions

Rapid, simultaneous measurements of near-bottom velocities, temperature and salinity were used to quantify groundwater specific discharge by a new non-invasive eddy correlation approach. Based on lab tests and field deployments in Salt Pond Channel (Cape Cod, USA), we conclude that the method will be viable in other locations when the temperature and/or salinity of the groundwater differ from that of the water column. Groundwater specific discharge determined from 15-minute time-series using temperature and salinity as independent tracers, were consistent with previous estimates based on a  $^{222}\text{Rn}$  mass balance and on seepage-meter measurements. The eddy correlation method has several desirable characteristics as a tool for quantifying discharge: 1) discharge is quantified under *in-situ* hydrodynamic conditions; 2) salinity and temperature can serve as two semi-independent tracers of discharge; 3) discharge can be quantified at high temporal resolution, and 4) long-term records of discharge may be possible, due to the low power requirements of the instrumentation. Given the promise of this approach, we have outlined additional work to better understand the environments and conditions where this eddy correlation approach will yield reliable groundwater specific discharge measurements.

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