Spatial and temporal patterns of salinity and temperature at an intertidal groundwater seep

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Abstract

Spatial and temporal patterns at an intertidal groundwater seep at Cape Henlopen, Delaware, were characterized using a combination of pore water salinity and sediment temperature measurements. Pore water salinity maps, both on a small scale (resolution of 0.1 m over a 1.25 m² area) and large scale (1–5 m over a 1710 m² area) showed reduced pore water salinities to as low as one-sixth seawater strength in a region 0–6 m from the intertidal beach slope break. In this region, there was substantial spatial variability in pore water salinity at all measured scales (0.1–90 m) alongshore. At −10 cm sediment depth, pore water salinity ranged from 6 to 24 in less than 1 m horizontally. To further characterize spatial patterns in discharge, we used novel temperature probes during summer low tides and found temperatures were much lower in a groundwater seep than the nearby sediment, as much as 8−9 °C cooler at −30 cm sediment depth. Measurements over time using temperature loggers showed that despite strong tidal and diel forcing on surficial sediment temperatures, thermal anomalies due to groundwater discharge persisted over several-day sampling periods and were strongest at −20 and −30 cm depth. Over a seasonal time scale, monthly sediment temperatures in or near a seep were cooler in the summer (by 3−4 °C) and warmer in the winter (by 5−6 °C) compared to a nearby non-seep location. In an ecological context, these temperature differences are equivalent to ~250 km latitudinal shift northward in summer and ~380 km southward in winter, a change important in relation to recognized biogeographical boundaries. Our results have substantial implications for hydrological measurements made at sandy intertidal sites like Cape Henlopen. Existing methods such as mass-balance and geochemical tracer techniques integrate over the scales of variability we observed, but are unable to resolve small-scale patterns of groundwater discharge that may be biologically important. Seepage meters can capture spatial variability at the meter scale, but results will be subject to high inherent variability unless spatial patterns are considered in sampling design and replication. Intertidal temperature profile measurements for point discharge estimates will be complicated by varying boundary conditions such as the interaction of insolation and tidal exposure. In addition to these methodological implications, the observed spatial and temporal variability suggests a thermal and salinity habitat envelope that must be considered when attempting to interpret biological productivity, faunal abundance and community composition of benthic species living in and around groundwater seeps.

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1. Introduction

Discharge of fresh groundwater into surface water can occur wherever an aquifer with an elevated water table is hydraulically connected to surface water (Emery and Foster, 1948; Johannes, 1980). Since such geological conditions are widespread on many coasts (Issacs and Bascom, 1949; Kudelin et al., 1971; Zektzer et al., 1973; Bokuniewicz et al., 2003), submarine groundwater seeps are common features of shorelines. While numerous studies have quantified groundwater discharge (Burnett et al., 2001), the spatial patterns and variability of these seeps — that is, their orientation towards shore, magnitude and scale of spatial variability, and total

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extent — are less well understood. Studies have typically examined the spatial patterns over large (100 m to >2 km) scales (Cable et al., 1997a; Smith and Zawadzki, 2003; Taniguchi et al., 2005), yet direct SCUBA observations of groundwater escaping fissures only a few centimeters wide have demonstrated significant small-scale heterogeneity (Bussmann et al., 1999). Small-scale spatial heterogeneity at a single site has been shown to affect groundwater discharge measurements in lake systems (Shaw and Prepas, 1990a,b). As is typical of many geophysical processes, variability is likely to span a wide range of scales, but unfortunately there are relatively few specific studies of small-scale variability (here defined as 1—100 m in a horizontal dimension) in submarine groundwater discharge. Urish and McKenna (2004) showed that temporal (over tidal cycles) and spatial (over tens of meters) patterns of groundwater discharge from a sandy beach are highly site-specific and within one site can vary greatly. On an intertidal sandflat, Miller and Ullman (2004) revealed significant spatial variability in groundwater discharge in the cross-shore direction along a 16—24 m transect.

We argue that any appreciable pattern of groundwater discharge on the scale of 1—100 m is critical to quantifying and interpreting groundwater discharge estimates at any given site. Small-scale spatial variability in discharge could lead to variable results between two nearby or “replicate” seepage meters and thus, a priori knowledge of the spatial and temporal patterns of intertidal groundwater discharge should lead to more accurate discharge measurements and greater appreciation of their inherent variability. While discharge estimates using integrative methods would be unaffected, smaller-scale point measurement techniques such as seepage meters may yield a biased rate when discharge is variable in space or time.

2. Previous work

2.1. Salinity

Seepage areas can be detected and their variablity quantified by several methods. In a groundwater seep, pore water ion concentration (as measured by pore water salinity) is a conservative property since groundwater discharge only dilutes ions present in seawater. At Cape Henlopen, near the mouth of Delaware Bay, surface water salinity ranges between 25 and 30. Values below this range result from dilution by groundwater (Hayes, 2005) and therefore indicate proximity to a groundwater seep. Mass-balance approaches typically use conservation of water and salt to calculate groundwater discharge (Millham and Howes, 1994; Burnett et al., 2001).

Miller and Ullman (2004) characterized the salinity patterns on the meter scale along a single 16- to 24-m transect over 3 years at our study site. They found high spatial variability of pore water salinity along a cross-shore transect. During each sampling period, the lowest pore water salinity was found in the region 5—10 m seaward from the break in slope. A second region with slightly higher pore water salinity was found 13—17 m seaward from the break in slope. They attributed these spatial variations to differences in sediment permeability possibly caused by a historical tidal creek. Over the 3-year study, the two regions of reduced salinity persisted along the transect, but the magnitude of the signal changed with season. Pore water salinity was lower in the winter (0—8 in the 5—10 m region, 8—16 in the 13—17 m region) and higher in the summer (12—25 in the 5—10 m region, 16—30 in the 13—17 m region), indicating greater groundwater discharge in winter. This monthly variation in pore water salinity was interpreted as seasonal changes in water table height due to reduced evapotranspiration in winter. Our present study extends the cross-shore patterns observed by Miller and Ullman (2004) by expanding the spatial coverage to include alongshore patterns, and refines temporal coverage to include variations over time scales from hours to years.

2.2. Temperature

Temperature has been used to study groundwater discharge by comparing the relatively constant temperature of groundwater with that of surface waters, which fluctuate with season. Techniques such as infrared imagery address spatial variability of groundwater discharge by expanding spatial coverage at the expense of temporal coverage. Fig. 1, modified from Miller and Ullman (2004), shows an aerial infrared image of the Cape Henlopen sandflat surface exposed at night in winter, when the largest expected temperature contrast would be expected. A narrow band of warmer temperatures, indicating groundwater discharge, was identified alongshore and this pattern becomes more complex farther out toward the tip of Cape Henlopen. This large-scale (10 m—1 km) pattern has been confirmed by subsequent measurements (Dale, 2006).

In subtidal systems, temperature profiles of sediment can be used to calculate the rate of groundwater discharge (Land and Paull, 2001). This technique assumes constant boundary conditions and employs heat flow probes or temperature loggers to obtain thermal profiles of the sediment, which can then be used to estimate the ratio of heat transport by bulk fluid flow to transport by conduction (Peclet number). Essentially, any non-linearity in the thermal gradient is attributed to advective flow, which is in turn attributed to groundwater discharge.

![Fig. 1. Georectified aerial thermal infrared image, modified from Miller and Ullman (2004), of field site on the southern shoreline of Delaware Bay near its juncture with the Atlantic Ocean. Light features along shoreline are thermal anomalies due to groundwater discharge. All data presented in this paper were collected in the area inside box (a).](image-url)
In intertidal systems, however, temperature is a non-conservative property of pore water since at low tide heat can diffuse between sediment, water, and air independent of water movement. Varying surface boundary conditions are at work as well: vertical temperature gradients are typical for intertidal sediments and variations in surface temperatures are driven by the interaction of solar radiation and tidal exposure (Wilson, 1983; Harrison and Phizacklea, 1987; Harrison and Morrison, 1993). Without knowing in detail the thermal conductive properties of the sediment or pore water and the magnitude of external heat exchange, intertidal temperature measurements can only serve as an indicator of the location of groundwater discharge, not as a measure. Thermal anomalies in intertidal sediments can, however, be easily and rapidly measured on small scales in order to characterize the spatial and temporal variability of groundwater discharge.

2.3. Ecological effects

Groundwater discharge measurement techniques employing large-scale spatial integration can obscure small-scale patterns that may be important to the benthic organisms living in and around groundwater seeps. Seeps can be biologically productive sites (Kohout and Kolipinski, 1967; Johannes, 1980; Kamermans et al., 2002; Zipperle and Reise, 2005), and spatial variability on the scale of 1–10 m has the potential to affect the benthic community by modifying environmental parameters such as salinity, temperature, and nitrogen and phosphorus input. For example, Zipperle and Reise (2005) showed that on the north German sandflats there was a change in dominant polychaetes from Arenicola marina outside groundwater seeps to Nereis diversicolor inside the seeps. This faunal shift occurred within several meters and was attributed to changes in salinity. Dale (2006) found an evidence that the diversity of benthic macrofauna increased with increasing distance from a seep, and further work is underway to elucidate this pattern (Dale and Miller, in preparation). Thermal anomalies at small scales can be ecologically important as well; for example, spatial temperature differences on the meter scale in rivers have been shown to be important thermal refugia for fishes (Power et al., 1999; Ebersole et al., 2001; Hayashi and Rosenberry, 2002; Ebersole et al., 2003). Worm burrows can also influence sediment characteristics (Jones and Jago, 1993; Dale, 2006), contributing to spatial variability in hydraulic conductivity.

On a larger scale (over 1 km), groundwater discharge alters the distribution of organisms in Biscayne Bay, FL (Kohout and Kolipinski, 1967), restricting brackish water species to within 400 m from shore where groundwater discharge is greatest. Also near Biscayne Bay, salinity regimes partially driven by groundwater discharge have a negative effect on coral density and coral reef species richness (Lirman et al., 2003). Nutrient input due to groundwater discharge can be important as well. Previous studies have found that groundwater has greater nutrient concentrations than surface water (Johannes and Hearn, 1985; Valiela et al., 1990; Reay et al., 1992; Uchiyama et al., 2000), and Johannes (1980) estimated that nutrient concentrations may be up to three times higher in groundwater than in surface water. Nutrients in groundwater discharge have been linked to a decrease in seagrass community diversity (Kamermans et al., 2002), and nutrient input via groundwater discharge likely affects benthic primary production by benthic diatoms and attached macroalgae (Ullman et al., 2003; Miller and Ullman, 2004). Given the potential for groundwater discharge to modify important parameters like salinity, temperature, and nutrient availability, the spatial and temporal patterns of discharge must be considered when attempting to interpret faunal abundance, biological productivity or community composition of organisms living in and around groundwater seeps.

The goal of our research was to determine spatial and temporal patterns in groundwater discharge from days to months in the time dimension and from 1 to 100 m in the spatial dimension by using a combination of thermal mapping techniques and pore water salinity measurements. The term “seep” will be used to identify regions that have strong thermal anomalies as well as low pore water salinities, which are indicative of groundwater discharge. In contrast, the term “non-seep” refers to locations that have weak or no thermal anomalies (aside from diel forcing) as well as pore water salinity near that of surface seawater. These terms are used relatively and only apply for the timeframe observed, particularly the seasonality of sampling. Indeed, one conclusion from our study is that we find enough seasonal variability in salinity and temperature (and presumably point discharge) that it may be necessary to observe a given location over several months to a full year in order to confirm that it is unaffected by groundwater seepage.

3. Methods

3.1. Study site

All data presented here were collected on the bay side of Cape Henlopen, Delaware, USA near the mouth of Delaware Bay at a site that has been previously described by Ullman et al. (2003) and Miller and Ullman (2004). The beach profile is typical of a mesotidal estuarine beach with a large tidal range relative to wave height (Nordstrom, 1992). The morphology consists of a dune, a foreshore with relatively steep slope, a break in slope (also termed slope break), and a low tide terrace or sandflat (Fig. 2). All sampling occurred on the sandflat. This field site is a popular recreational destination in summer and installing benchmarks that would remain undisturbed was not practical. Instead, cross-shore distances are referenced to the break in slope. The position of the break in slope does not vary greatly, with cross-shore movements of only +/-1 m over a year (W.J. Ullman 2004, unpublished data). Since there was no permanent benchmark, no conclusions were made about the absolute distance in the cross-shore or alongshore directions, and comparisons between sampling efforts were based on relative patterns only. All sampling was conducted in the area indicated by box (a) in Fig. 1, near 38° 47.2’ N, 75° 06.2’ W. Air and water temperatures as well as observed water levels were downloaded from
NOAA CO-OPS station number 8557380 (http://co-ops.nos.noaa.gov/data_res.html) which is located in Lewes, Delaware at 38° 46.9' N, 75° 07.2' W, 2 km west of the Cape Henlopen field site.

3.2. Pore water sampling for salinity maps and variation over a tidal cycle

To measure pore water salinity, pore water piezometers—termed “wells” herein after Miller and Ullman (2004)—were constructed using 2.5-cm diameter PVC pipe attached to a 50-ml centrifuge tube. Five equally spaced holes were machined 1 cm from the bottom of the centrifuge tube to allow pore water into the well. At low tide, wells were inserted until the holes were 10 cm below the exposed sediment surface. The wells were purged with a syringe and tubing to remove any water that entered the well from the surface or any other depth during insertion. Pore water from −10 cm was allowed to fill into the well, drawn into a syringe, and the salinity was measured using a YSI Model 30 handheld salinity meter.

Using these pore water wells, a salinity map was generated during a single low tide on 19 September 2005. A 19-m shore-normal transect was laid out every 5 m over a straight, 90 m stretch of beach. From pilot studies (Miller and Ullman, 2004, personal observation, 2005), it was known that most of the groundwater discharge was close to the slope break, so each transect started at the slope break, had 1-m spacing from 1 to 9 m offshore, then 2-m spacing from 9 to 19 m offshore. Wells were inserted at each point in a single transect, all wells were purged, then all wells were sampled. Wells were then removed before starting the process again in the next transect 5 m away alongshore. Beach topography was surveyed using the Emery (1961) method of sighting to the horizon, and relative elevations among transects were measured by sighting from the shore across adjacent transects to the horizon.

A smaller map of pore water salinity at −10 cm sediment depth was generated in February 1996 using 29 wells inserted in a radial grid pattern that covered an area of ~1.25 m². Well positions are indicated in Fig. 5. The area measured was 5–10 m from the slope break in a region known to be influenced by groundwater discharge. Wells were inserted 10 cm apart in lines crisscrossing an easily visible patch of Marenzelleria viridis, the red-gilled mudworm, where burrows and fecal pellets were evident on the surface and at the center but less apparent or absent at the margins of the grid. At this site, this species is typically found associated with low pore water salinity (Miller and Ullman, 2004).

To determine whether pore water salinity changed during inundation, pore water salinity at −20 cm and tide pool water salinity (~5 cm above sediment surface) were measured at ~40 min intervals over an entire 12-h tidal cycle on 5 July 1997. The salinity was measured using a pore water well (as described above) modified to allow for complete submergence using an internal stopper allowing entry of a 3-mm I.D. sampling tube for this ~3 cm sealed section. After inserting the well to −20 cm, a second sampling tube for sampling seawater ~5 cm above the sediment surface was fastened to the exposed portion of the well. The well was placed in a tide pool with ~5 cm of standing water at low tide 5–10 m from the slope break in an area determined to be a “seep” area. The tide pool was connected to the bay via a channel between sandbars, allowing some exchange with the bay surface water. Both sampling tubes were run about 30 m from the well to shore, and to collect a sample, enough water was drawn through each tube with a syringe to flush the tubing before each sample was taken. Salinity was measured directly from the syringe with a YSI Model 30 handheld conductivity meter, and tidal height (water depth against a marked post) at the well was simultaneously recorded.

3.3. Thermistor probe design, temperature mapping and monthly temperature differences

We designed and constructed novel thermistor probes to rapidly measure sediment temperatures at multiple depths. The goal of the design was to have a small-diameter, rugged probe with low thermal mass that could detect thermal gradients in the sediment caused by groundwater discharge. This was achieved with thermistors arranged at four different depths inside a 7-mm diameter hollow anodized aluminum shaft (Fig. 3A). Depths of −5, −10, −20, and −30 cm sediment depth were selected as biologically relevant depths (Dale, 2006) to determine the environmental parameters experienced by organisms living in and around the groundwater seeps. Three probes, each with thermistors at four depths, were connected to a switch box and meter and were calibrated in the laboratory to 0.1°C. Laboratory tests showed that when transferred from 20°C water to 5°C water, the probes equilibrated to within ±0.25°C of the final temperature within 120 s. Other laboratory tests simulating field use of the probes as well as actual field testing showed that minimally exposing probes to air temperatures between measurements allowed the probes to equilibrate within 90 s.

During the summers of 2004 and 2005, three thermal maps were generated on spring low tides when the sandflat was...
exposed. The location of each map was selected to include both low salinity/low temperature (seep) and high salinity/high temperature (non-seep) sediment to ensure the map would include a range of temperatures. The landward extent for each map was the slope break (cross-shore meter 0), and extended perpendicular to the slope break toward the bay. Elevation changes across each thermal map were less than 10 cm, corresponding to differences in tidal exposure of about 15–30 min. All maps were located within the 20°C × 100 m box outlined in Fig. 1. For each thermal map, an area of sandflat (14°C × 7 m on 24 June 2005, 11 × 9 m on 5 July 2004 and 11 × 10 m on 30 July 2004) was marked with a grid. To begin sampling the first sediment temperature measurements of each map, the thermistor probes were inserted into the sediment, and all were allowed to equilibrate for at least 120 s. Temperatures were then read off the meter from 0, 10, 20, to 30 cm depths. Consecutive measurements were made by quickly removing and then reinserting the probes at the next three points in the grid and allowing them to equilibrate. The ~90 s equilibration time measured in the laboratory for probes minimally exposed to air was confirmed in the field, and readings remained stable even after longer equilibration times of 5–7 min.

In order to validate the use of temperature to map the location of intertidal groundwater seeps, −20 cm sediment temperatures were recorded on 7 different days in summer 2005 with a Fluke Model 52 meter and thermocouple probe (Fluke Corporation, Everett, WA). Temperatures were measured along transects crossing regions of known discharge, and pore water salinity at −10 cm depth was simultaneously measured <5 cm away.

Seasonal temperature variations were recorded at the same site using the single-depth Fluke thermocouple probe over a 3-year-period beginning in November 2002. Each month during spring tides, one “seep” and one “non-seep” location were selected for sampling at low tide. Typically five separate temperature measurements at −20 cm depth were made at haphazardly chosen locations within a 1-m² area at each location, and these temperatures were averaged. The “seep” temperatures were taken at −20 cm sediment depth 2–4 m from the slope break in patches of Marenzelleria viridis, where burrows and fecal pellets are evident on the surface, and pore water salinity is generally low (Miller and Ullman, 2004). These locations were often noticeable by reddish-colored surficial sediments from the oxidation of iron-rich groundwater. The “non-seep” temperatures were roughly 10–20 m offshore near the crest of the first sandbar (Fig. 2) where there were no visible M. viridis burrows nor fecal pellets and no evidence of iron oxide on the sediment surface. Pore water salinity measurements were made initially to confirm that the chosen location was a “seep” or “non-seep”. All measurements were taken within a roughly 400-m² area of the beach within the sampling area shown in Fig. 1, but since the sandflat surface and sandbars moved naturally over the 3 years of sampling (e.g., Muir, 2002), the exact locations varied from month to month.

3.4. Temperature logger stacks and time-series deployments

iButton® (http://www.ibutton.com) temperature loggers are a cost-effective solution for determining general temperature patterns in hydrological applications (Hubbart et al., 2005). Here, we used a vertical housing or “stack” designed for deploying the iButtons® at predetermined depths on the sandflat. Each temperature logger stack consisted of a PVC outer
sleeve, the iButtons® themselves, internal spacers, and end caps (Fig. 3B). The sleeves were made out of Schedule 30 PVC (17 mm I.D., 21 mm O.D.) and were approximately 35 cm long. Three evenly spaced 7 mm × 4 mm slots were machined in the wall of the sleeve to allow the pore water to directly contact the iButtons® at each desired depth. The bottom end of the sleeve was fixed with a blunt point for insertion into the sediment. Spacers were made out of CPVC pieces (12 mm I.D., 16 mm O.D.) joined together with 28-mm long copper couplings (16 mm I.D., 17 mm O.D.) and capped with #00 rubber stoppers. The copper couplings on the spacers enabled a tight fit into the PVC sleeve to prevent the sleeve from acting as a conduit for pore water, and the copper did not contact the iButtons® (thereby limiting corrosion and thermal conductivity). The ends of the spacers were also capped to prevent pore water movement within the stack. The spacers were sized so that when loaded into the sleeve they positioned the temperature loggers flush with the slots machined in the sleeve. The completed stack was capped with a rubber septum nested inside an elbow joint to prevent water from entering the stack from the top. The temperature loggers were calibrated in the laboratory prior to each deployment. To deploy a stack, TMEX-iButton software (Dallas—Maxim Semiconductors) was used to launch the iButtons® with a sampling interval of 12 min. In the field, the stacks were inserted into the sediment so the slot for the surface logger was flush with the surface of the sediment. The stacks were left in the field for several days to record temperature with 0.125 °C resolution.

Two temperature logger deployments are presented here, one in winter and one in summer. In winter, two temperature logger stacks were deployed from 2 December 2004 to 7 December 2004 in “seep” and “non-seep” locations determined as outlined above. The loggers recorded temperature at the surface, −10 cm, −20 cm, and −30 cm. On 25 June 2005, five temperature logger stacks were deployed, spaced 2 m apart across the thermal anomaly detected in the thermal map generated the previous day. The loggers sampled temperature for 3 days at 5 cm above the surface (+5 cm), surface, −10 cm and −20 cm. Autocorrelation was used to determine periodicity in the temperature signals and cross-correlation was used to determine the phase lag between pairs of temperature signals (Chatfield, 1984).

4. Results

4.1. Salinity maps

Measurements taken on 19 September 2005 were used to generate a map of pore water salinity at −10 cm (Fig. 4). This map extends 19 m out from the break in slope (Fig. 2) across a swale and ends at two sandbars. Two regions are evident in these salinity maps: within 6 m of the break in slope, pore water salinity is low and variable, while farther from the break in slope, salinity is high and relatively uniform. Isolated intermediate salinity values were also measured 10–19 m offshore. Within the nearshore seepage region, these salinity data indicate variations in salinity at essentially all scales from many meters alongshore to the 1-m spacing of our wells.

A smaller salinity map of −10 cm pore water, with 10-cm horizontal spacing over a 1.25 m² area, is shown in Fig. 5. Two small patches of lower salinity, 20–40 cm in diameter, are evident on this scale. Salinity varies as much as 10 in distances as small as 20 cm, and lower salinity pore water appears to coincide with burrows and fecal pellets of Marenzelleria viridis.

4.2. Salinity over a tidal cycle

Fig. 6 shows the salinity of tide pool water and pore water salinity at −20 cm during a flood—ebb tide cycle in an intertidal seep. The pore water salinity in the seep stays relatively low (14–17) throughout the tidal cycle, while tide pool water salinity is intermediate (21–24) at low tide and increases to over 28 during inundation. This small variation in tide pool water salinity is likely due to groundwater discharge diluting the tide pool at low tide (Hays and Ullman, in press) and inundation by bay surface water at high tide. There is some increase in −20 cm pore water salinity (=3, from 14 to 17) that is lagged behind the increase in tidal height.

4.3. Thermal maps

From July through September, there is a weak but significant correlation between sediment temperature at −20 cm and pore water salinity at −10 cm when all days are pooled together (Pearson’s $r = 0.511, P < 0.001$, Fig. 7H). On any individual day, the pattern is more robust (Fig. 7, A–G). Within this figure, 5 of the 7 days show significant correlations between temperature and salinity when evaluated using a Bonferroni-adjusted $\alpha = 0.007$ to reduce Type I error in multiple comparisons (Sokal and Rohlf, 1995). We found that even though temperature is non-conservative in the intertidal, thermal anomalies correspond with low pore water salinity during this season. This verified that by measuring temperature rapidly and at multiple depths, thermal anomalies could be used as an indicator of groundwater discharge and a reflection of its spatial pattern.

There are three general patterns common to the three thermal maps (Figs. 8–10). First, mean sediment temperature decreases with depth. Second, localized thermal anomalies become more distinct with depth. Third, the isotherms are quite variable on the surface, but converge to be parallel to shore at −20 cm and −30 cm. In each of the thermal maps there is a distinct band of cooler sediment between 2 and 7 m from the slope break. This is consistent with the salinity map, where lower pore water salinity was found within the first 6 m from the slope break.

There are patterns unique to each of the thermal maps. In comparison to the other dates, Fig. 8 (24 June 2005) shows relatively cooler −5 cm temperatures. This is probably due to less surface heating (cooler air temperatures and cloud cover during
sampling), and as a result, the mean temperature at each depth is lower than that of the other two thermal maps. There appears to be a seasonal pattern, as well, since the mean temperatures at each depth in Figs. 8–10 increase with the progression through summer. Another difference can be found in the −5 cm depths: Fig. 10 has contour lines on the surface oriented perpendicular to shore. This is most likely due to continued solar heating during the mapping, since the order in which the measurements were taken was moving from bottom right to top left. Over the course of the mapping, solar heating and warm flooding surface water elevated the temperatures at −5 cm.

Local and offshore wind patterns produced low tides that did not expose the field site (<0 m MLLW) in winter 2005 during the week-long spring tide windows. However, we would expect that temperature differences would be greater than those measured in the summer due to increased groundwater discharge in winter (Miller and Ullman, 2004; Dale, 2006).

4.4. Diel temperature variations

The winter deployment time series are shown in Fig. 11. Non-seep temperatures (Fig. 11A) and seep temperatures
Fig. 6. Salinity over a single tidal cycle of tide pool water (asterisks) and at ≈20 cm sediment depth (closed circles) and tidal height (open circles) in a groundwater seep. The tide pool was flooded at time point A, and re-exposed by the falling tide at time point B.

Fig. 7. Correlation of temperature at ≈20 cm and pore water salinity at ≈10 cm. Panels A through G show the relationship for individual days; panel H shows the pooled data ($r = 0.511$, $P < 0.001$, $N = 110$).
Temperature minima are evident during exposed low tides and sediment temperatures were consistently warmer with increasing sediment depth, although this pattern was stronger in the seep. When temperatures were averaged over time (Fig. 11D), the surface temperatures were nearly the same but at −10 cm and deeper, the seep was warmer in the winter than the non-seep. At −30 cm the seep was warmer than the non-seep by an average of 1.7 °C (range, 1.1−2.2 °C). Cross-correlations on detrended time series data (Chatfield, 1984) showed that there were lags between temperature events on the surface and at depth. Temperature pulses due to exposure at low tide propagated downward at a rate of approximately 1.5−2.0 h per −10 cm in the non-seep and 2.0−3.0 h per −10 cm in the seep (Dale, 2006). The longer phase lags in the seep time series could be due to upward advective flow counteracting downward heat diffusion, however, longer time series would provide more confidence to these approximate lag times.

The summer deployment of a five-stack transect permitted a more detailed analysis of the persistence of the thermal anomaly measured in the 24 June 2005 thermal map (shown in Fig. 8). Time series of two of the five stacks are shown in Fig. 12. Non-seep (Fig. 12A) and seep (Fig. 12C) time series show that, in contrast to winter, summer temperatures are consistently cooler at depth in the seep than the non-seep (Fig. 12D) by an average of 1.0 °C at −10 cm and 1.1 °C at −20 cm. Note that only 0, −10, and −20 cm depths are shown in Fig. 12; a limited number of temperature loggers constrained the possible depths for this deployment. Cross-correlations were more difficult to interpret due to the shorter 3-day-time series, but lag times appear to be similar to those in winter, around 1−3 h per −10 cm.

The plots of temperature over time, space, and depth for all five stacks show that the thermal anomaly measured at low tide in the 24 June 2005 thermal map (Fig. 8) remained consistent over 3 days, between 5 and 7 m from break in slope (see also Dale, 2006). The persistence means that the temperature differences measured during low tide, such as those measured in the thermal maps or during the monthly sediment temperature measurements, are representative of temperature differences at other points in the tidal cycle. While the magnitude of differences may not be consistent throughout the tidal cycles due to varying air and water temperature, the position of the thermal anomaly at any one time remains the same. This is important, since at this site water levels low enough to expose the sandflat (below 0.0 m MLLW) occur less than 10% of the time (Dale, 2006).
4.5. Monthly sediment temperatures

Monthly sediment temperatures at −20 cm inside a seep and outside a seep for 3 years are shown in Fig. 13. Over the 3 years, the seep is consistently warmer in the winter and cooler in the summer than surrounding sediment. The maximum temperature difference occurs in the coldest winter months; during this time it can be 2–3 °C outside the seep while inside the seep the temperature remains around 8–10 °C at a depth of −20 cm. There is little to no temperature difference between the two locations in spring (mid-May) and autumn (mid-October). There appears to be an asymmetry in the difference between seep and non-seep locations. During the winter, the difference between the seep and non-seep has an inverted V-shape while during the summer the difference has more of a broader U-shape. The difference has its greatest magnitude (5–7 °C warmer) in the winter, but this occurs only briefly in early January. In contrast, the summer difference between the two locations stays near its maximum for 3–4 months although the absolute magnitude of the difference (3–4 °C) is less than in winter. This pattern in seep temperatures (warmer in the winter, cooler in the summer) is expected since groundwater tends to remain at the mean annual temperature. Similar to salinity, the largest differences between seep and non-seep are in the winter. Additionally, seep temperatures over seasonal time scales are less variable than non-seep temperatures.

5. Discussion

5.1. Synthesis of spatial and temporal patterns

The salinity time series (Fig. 6) shows that tide pool water salinity was consistently higher than pore water salinity and fluctuated with the tide. In contrast, pore water salinity remained relatively low and constant throughout the tidal cycle. Small changes in pore water salinity lagged behind the tide, consistent with observations that water table height lags behind the tide (Emery and Foster, 1948; Valiela et al., 1990). Other studies have shown variable but changing groundwater discharge rates over tidal cycles (Lee, 1977; Taniguchi et al., 2002; Burnett et al., 2003), but at some sites the pattern is more strongly affected by water table level than sea level (Taniguchi et al., 2003b).
the small change in pore water salinity we observed over a tidal cycle is much less than the range of spatial variability of 10 or greater per meter observed in the salinity maps (Figs. 4 and 5) and shows that the low pore water salinities measured in the salinity maps will remain consistently low at this site throughout the tidal cycle. While the temporal pattern of discharge may change due to tides and water table levels over longer time periods than we measured, these data show that the spatial pattern we observed in the salinity map is representative over a tidal cycle at this field site and is likely to be robust as long as there is a detectable difference in salinity between “seep” and “non-seep” areas. Over seasonal time scales, Miller and Ullman (2004) show that low salinity areas grow in the cross-shore direction during winter and shrink again in summer, suggesting that low salinity areas measured in our summer two-dimensional salinity map will similarly expand in the winter.

The temperature time series show that over time scales of 3–7 days, groundwater discharge dampens the effect of variable surface temperatures on subsurface sediment and creates sharper vertical temperature gradients in both summer and winter (Figs. 11 and 12). The periodicity in temperature patterns both inside and outside a seep appeared to be mostly affected by the interaction of tides and solar radiation; this is consistent with the literature and indicates that intertidal surface temperatures are strongly influenced by the phase difference between solar radiation and tidal cycles. Similar lag times (4–6 h between surface and −20 cm on a sandy beach in summer) have been observed before in sediment temperatures (Wilson, 1983). Land and Paull (2001) note that it may take weeks for cold surface temperatures in the winter to propagate meters downward into muddy sediment.

The seasonal temperature time series shows that the temperature difference between “seep” and “non-seep” locations varies over time, reversing with season and becoming zero in mid-October and mid-May (Fig. 13). The temperature differences observed in the seasonal time series during summer and winter correspond with differences between “seep” and “non-seep” locations during the summer and winter temperature logger deployments. The thermistor probe data over space and the temperature logger data over time are consistent with each other, both in terms of vertical gradients as well as the trend of reduced temperature variability with depth. Importantly, the temperature and salinity data presented here show that even though the thermal maps and salinity maps were generated at low tide, the low salinities and thermal anomalies due
to groundwater discharge are present at all points in the tidal cycle.

As would be expected from the correlation between temperature and salinity in groundwater seeps (Fig. 7), the alongshore band of low salinity pore water in the large salinity map (Fig. 4) matches the alongshore band of thermal anomalies in the thermal maps (Figs. 8–10). This feature corresponds with the band of anomalous temperatures identified in aerial infrared imagery by Miller and Ullman (2004) (Fig. 1). However, the salinity and thermal maps, which were sampled at higher resolution than the aerial imagery, show alongshore-spatial variability where the same area of the beach in the aerial imagery showed a relatively uniform band of anomalous temperatures.

Groundwater discharge does not always create lower pore water salinity or temperature anomalies; these signals may be diminished or absent entirely depending on the degree of mixing between fresh groundwater and surface water. It is reasonable to assume the opposite, however, that reduced salinity or a temperature anomaly is indicative of groundwater discharge (e.g., Land and Paull, 2001; Taniguchi et al., 2003b; Bendjoudi et al., 2005). Despite this relationship, directly relating the salinity and temperature patterns to discharge rate at our site would require additional sampling and detailed subsurface flow modeling, as well as precise estimates of hydraulic conductivity at the same spatial scale — all beyond the scope of this study.

5.2. Mechanisms for spatial variation in groundwater discharge

The salinity and thermal maps describe patterns in salinity and temperature, but defining the boundary of a seep is not a straightforward task. At any one point in time, a boundary defined by salinity is dependent on advection and mixing processes, while a boundary defined by temperature depends on advection and mixing but also the additional variable of thermal conduction through sediment, water, and air. Our data indicate that there are changing gradients in groundwater discharge over time and space rather than discrete patches that can be delineated by clear boundaries.

There are general patterns, however, such as reduced salinity and thermal anomalies near the break in slope that could be caused by the beach topography. At this site, the water table outcrops at the sharp change in topography that occurs at the break in slope, causing visible discharge in the form of rivulets on the foreshore (Ullman et al., 2003). This likely contributes to the band of fresh groundwater discharge visible in the salinity and thermal maps less than 10 m from the slope break.

Cross-shore differences in sediment grain size and resulting differences in hydraulic conductivity may also contribute to the discharge being restricted to near the break in slope. Estuarine beaches typically have coarser surface sediments than ocean beaches, especially in the lower foreshore and break in slope. This is due to the absence of swell waves that
typically deliver fine sediment from offshore (Nordstrom, 1977) as well as the interaction of low-energy waves with beach topography that preferentially erode fine sediment from the base of the foreshore (Nordstrom, 1992). These physical processes determine sediment grain size which may in turn cause the patterns we see in groundwater discharge by affecting the hydraulic conductivity of the sediment close to the slope break.

Spatial variation in sediment hydraulic conductivity may work in combination with the effects of cross-shore beach topography to generate the alongshore patterns that we observed. The state of the sediment at any one point in time depends on the previous hydrodynamic conditions set up by wave action and offshore sandbars and troughs, which move over time at this site (Muir, 2002) and would cause changing flow conditions. However, the depth of the actively
reworked beach is relatively small at this site, where the average seasonal change is ±2.0 cm vertical on the sandflat, with extremes of up to 22.0 cm (Muir, 2002). Other mechanisms may affect the hydraulic conductivity of deeper sediment. Since the Cape Henlopen field site was once the location of a tidal creek which has since been converted into a containment pond (Miller and Ullman, 2004), the alongshore-spatial variability may be in part due to remnant layers of higher hydraulic conductivity left over from the tidal creek, and sediment cores at this site sometimes reveal a layer of coarse sand at -20 to 40 cm sediment depth. Biological factors may also contribute to heterogeneity in groundwater discharge. The highly abundant red-gilled mudworm, *Marenzelleria viridis*, burrows as deep as 50 cm at this site (personal observation 2006, Dale and Miller, in preparation) and these burrows increase the hydraulic conductivity of the sediment (Jones and Jago, 1993; Dale, 2006; Dale and Miller, in preparation).

The interaction of beach topography with the water table combined with differences in sediment size due to local hydrodynamics, historical morphology, and sediment transport, as well as bioturbation by macroinvertebrates may all contribute to the spatial variability observed at this site. The salinity map and the thermal maps presented here only covered the first 19 m from the break in slope, and it is possible that subtidal groundwater discharge occurs beyond the coverage of these maps: Ullman et al. (2003) found evidence of vertical flow, presumably discharge of salty subsurface water, about 20 m from the break in slope.

5.3. Implications for benthic communities

Salinity plays a large role in structuring biological communities in estuaries (Remane and Schlieper, 1971; Barnes, 1989; Little, 2000). The gradient of pore water salinities we measured in the intertidal sandflat (0.1–28 over several meters) is at least an order of magnitude sharper than the salinity gradient (0–30 in >100 km) found in a typical estuary (Remane and Schlieper, 1971; Dauer et al., 1987), and these sharp gradients may determine the types of organisms that can be found in and around groundwater seeps. In addition to sharp spatial salinity gradients, seasonal variation in pore water salinity at a single location is likely to be physiologically stressful to benthic organisms (Little, 2000). Salinity changes due to groundwater discharge are correlated with changes in benthic communities in such disparate habitats as sandflats (Zipperle and Reise, 2005), seagrass beds (Kamermans et al., 2002), and coral reefs (Lirman et al., 2003). Recent work at the Cape Henlopen field site indicates similar correlations exist there in sandflat communities (Dale, 2006; Dale and Miller, in preparation).

Temporal salinity and temperature variations have implications for population ecology of benthic fauna. Species that settle at a certain time of year may become established uniformly across the sandflat, but later pore water salinity or sediment temperature patterns may create differential patterns of feeding or growth between seep and non-seep locations. For a species that can tolerate a wide range of salinities, such as the red-gilled mudworm *Marenzelleria viridis* found at Cape Henlopen, temperature in groundwater seeps may play a part in structuring populations. For example, Sarda et al. (1995) notes a die-off of *M. viridis* from freezing winter temperatures in a New England salt marsh; worms living in a groundwater seep would potentially be buffered by 5–7°C from such seasonal extremes (Fig. 13).

To place the monthly temperature results in an ecological perspective, we compared the difference between seep and non-seep temperatures to geographical temperature differences found along the east coast of the United States. Coastal water temperatures obtained from the NODC Coastal Water Temperature Guide (http://www.nodc.noaa.gov/dsdt/cwtg/) indicate that winter water temperatures in Delaware are ~3–5°C, consistent with the ~20 cm non-seep temperatures in Fig. 13. Summer coastal water temperatures in Delaware are ~22–24°C, also consistent with the ~20 cm non-seep temperatures in Fig. 13. When compared to the seep ~20 cm temperatures, however, winter seep temperatures are around 8–10°C—equivalent to a ~380 km shift southward where water temperatures at Cape Hatteras, North Carolina are ~8–10°C. Conversely, in summer, seep ~20 cm temperatures are 18–20°C, equivalent to a ~250 km northward shift where Montauk, New York summer water temperatures are 18–20°C. Expressed in these terms, the impact of the seep on sediment temperatures on the Delaware sandflat is equivalent to a several hundred kilometer geographical shift northward in summer and southward in winter.

In a study of latitudinal gradients in estuarine benthic communities, Engle and Summers (1999) place Cape Henlopen at the boundary of the Lower Virginian biogeographical province. Although the provinces were empirically determined using multivariate analysis on benthic communities, the mean summer temperature was a significant factor explaining the differences between these latitudinal groups. Since the north or south shifts represented by our seep–non-seep temperature differences correspond to identified differences in benthic communities among biogeographical provinces, it is reasonable to infer that such temperature differences may alter macroinfaunal populations and species assemblages within a single biogeographical province. Clearly, further study is required to determine if temperature, especially shifts in temperature range or extremes, in groundwater discharge are strong enough to shift community structure in and around these areas.

5.4. Implications for groundwater discharge measurements

Our results also have implications for hydrological measurements made at sites like Cape Henlopen. Mass-balance (e.g., Hays and Ullman, 2007) and geochemical tracer methods (Moore, 1996; Burnett et al., 2001) integrate over the scales of variability we observed, but in doing so are unable to resolve significant physical, geological, hydrological and biological factors causing heterogeneity in groundwater discharge. Seepage meters (e.g., Cable et al., 1997b) can be
used to capture variability at the meter scale, but results will be subject to high measurement uncertainty unless spatial patterns are considered in sampling design and replication. Intertidal point discharge estimates that depend on temperature gradients (Land and Paull, 2001; Taniguchi et al., 2003a) will be complicated by varying boundary conditions as well as substantial sub-meter horizontal variability at sites similar in structure to Cape Henlopen. Thermal infrared techniques (e.g., Miller and Ullman, 2004; Duarte et al., 2006) can take advantage of thermal anomalies and cover the widest range of scales of any methods described here. However, they can only be used where circumstances allow groundwater-forced temperature differences to exist at the surface and the resulting data must be interpreted in light of seasonal and diel forcings that may be several times larger in magnitude.

The spatial patterns in the thermal and salinity maps suggest that two seepage meters spaced as little as one or two meters apart at Cape Henlopen may or may not record the same discharge rates, depending on their exact positions relative to the patches visible in Fig. 4. To compensate for this variability, Burnett et al. (2001) suggest using tracer methods; other studies have used integrative methods at the Cape Henlopen site to calculate flux based on length of shoreline instead of on a per area basis (Hays, 2005). Prior to deploying seepage meters at a site like Cape Henlopen, it may be beneficial to first map the area at 1-m resolution using the methods described here, i.e., pore water salinity or thermal maps, as appropriate for the season. This would allow for a stratified sampling design with the placement of seepage meters in a range of recognized patches of groundwater discharge. Scaling up these measurements to calculate discharge for the entire nearshore zone may be possible, but would depend strongly on the extent of knowledge of the patterns and scale of spatial variability, especially those within which the samplers are embedded. The derived discharge estimates would ideally be verified by measurement with techniques integrating over relevant scales.

6. Conclusions

Using a combination of temperature and salinity measurements, we found intertidal fresh groundwater discharge at Cape Henlopen, Delaware to be confined to less than 10 m from the slope break. The spatial distribution of the discharge was variable down to 0.1 m, the smallest scale measured. Thermal maps revealed high variability in sediment temperature within seeps, but with far more detail than pore water sampling alone. Although our spatial measurements were made during low tide, continuous measurements over a tidal cycle show that these spatial patterns in both temperature and salinity persist even at high tide. Temperature logger deployments showed temperature variations strongly driven by diel and tidal forcing, with strong vertical gradients and substantial lags, but the temperature contrast associated with seepage was still strong at all stages of the tide.

The methods described here can be used to supplement and guide direct discharge rate measurements. Temperature or salinity maps can indicate where the highest relative fresh groundwater discharge rate is likely to occur. If this spatial variability in groundwater discharge is not taken into account, then point discharge measurement techniques, even two replicate seepage meters spaced as little as a meter apart, could yield different results. Further, the spatial and temporal variability in temperature and salinity suggest a highly variable thermal and salinity envelope that must be considered when attempting to interpret abundance, productivity or community composition of benthic organisms living in and around groundwater seeps.

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