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Exonerating Bernoulli? On evaluating the physical and biological processes affecting marine seepage meter measurements

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Abstract

Seepage meters, like most benthic flux chamber techniques, come with inherent concerns about how their presence may alter the environment and flow regimen of the benthic boundary layer and underlying sediments. Flow due to wave and current movement across topographic features induces a downward and upward flow field within the sediments surrounding the feature. We found this Bernoulli-induced flow is a real, but maybe minor, component of measured advection using seepage meters. This study was conducted in a Florida coastal lagoon to test the physical forcing mechanisms that may influence seepage measurements from sediments. Calculated Bernoulli seepage was within the measured background (~1 to 2 cm day^{-1}) expected from seepage meters when a plastic barrier beneath the device is used to inhibit natural seepage contributions. Nearby seepage measurements made with Lee-type seepage meters placed directly in the sediments ranged from 1 to 12 cm day^{-1}. Thus, when seepage flow is very slow from sediments, Bernoulli-induced seepage may obscure the measurement. However, this study demonstrates that seepage in the Indian River Lagoon must be driven by forces other than Bernoulli-induced (pumped) flow. Suggestions for these forcing mechanisms highlight the uncertainty of the water source(s) in seepage measurements. In these Florida lagoon sediments, bioirrigation and terrestrial groundwater inputs are the most likely drivers, depending on distance from shore, benthic community composition, and continental recharge. Seepage measurements can be an excellent measure of advection in shallow-water marine sediments if Bernoulli-induced seepage is taken into account either experimentally or calculated based on local hydrographic and meteorological data.

Introduction

Seepage meters provide the most widely applied direct measurements of water advection to or from sediments in marine and lacustrine systems. Seepage meters were developed originally by engineers studying leakage of canal bank linings (Israelson and Reeve 1944) but were largely ignored by the scientific research community until the 1970s when Lee (1977) demonstrated their effectiveness in evaluating groundwater seepage along shorelines. Since then, different forms of the seepage meter have been used with varying degrees of success in many freshwater and marine environments (e.g., Bokuniewicz 1980, 1992; Shaw and Prepas 1989, 1990; Belanger and Montgomery 1992; Reay et al. 1992; Libelo and MacIntyre 1994; Cable et al. 1996; Gallagher et al. 1996; Taniguchi and Fukuo 1996; Cable et al. 1997a,b; Corbett et al. 2000; Chanton et al. 2003; Cable et al. 2004). The simplicity of seepage meter design and deployment makes the device simultaneously attractive for field work and the bane of the researcher. The conventional seepage meter is constructed from the top or bottom section of a 208-L drum with an open port placed near the rim to attach a plastic collection bag (Figure 1). This design can be inexpensive to build, but sampling is labor intensive. Other designs have been developed to improve measurement accuracy, increase sampling frequency, reduce manual labor, and automate sampling through a variety of sensors, including a heat-pulse approach (Taniguchi and Fukuo 1993), acoustic Doppler technologies (Paulsen et al. 2001; Krupa et al. 1998), dye-dilution methods (Sholkovitz et al. 2003), and an electromagnetic flow meter approach (Rosenberry and Morin 2004). For all seepage meter designs, however, heterogeneity of bottom sediment compositions may make the devices subject to large variations in measured seepage over short distances.

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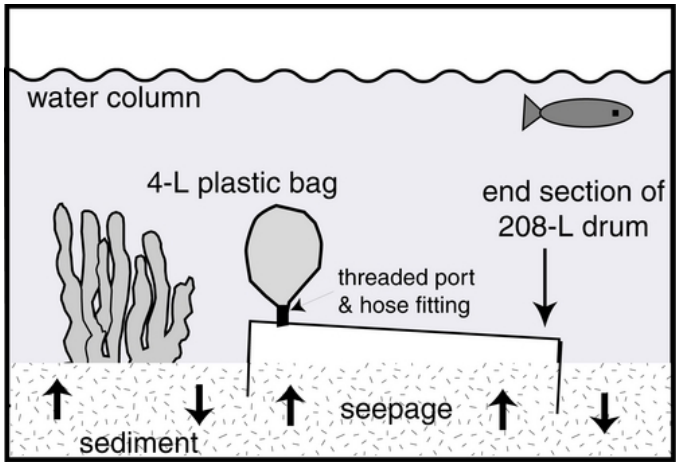

Fig. 1. Traditional seepage meter design is simply an open-ended chamber inverted over the sediments where a plastic bag is used to collect interstitial water as it is advected from the sediments.

Field or laboratory experiments are often needed with each new application to quantify potential impacts on these measurements. These impacts include hydrostatic pressure differences between the flexible bag and the rigid underlying sediments (Shaw and Prepas 1989; Cable et al. 1997a), bioirrigation/bioturbation effects (Aller 1980; Martin et al. 2004), spatial heterogeneity and low-flow conditions (Rosenberry 2005), and effects from physical forces such as winds, waves, currents, and tides that move water across the sediments and the seepage meters (e.g., Huettel et al. 1996; Li et al. 1999; Shinn et al. 2002). These potential impacts have produced concerns about artifacts in the measured seepage rates, and researchers have refined the methodology in an attempt to improve the accuracy of the seepage measurements. For example, prefilling the seepage collection bag with 1000 mL water was found to alleviate an anomalous influx of water associated with the mechanical properties of an empty flexible plastic bag attached to a meter (Shaw and Prepas 1989; Cable et al. 1997a). The potential for artifacts of measurements has been evaluated by comparing seepage rates measured from meters with a standard deployment and a nearby seepage "blank," where a seepage meter is deployed within a child's plastic swimming pool filled with local sediment (Cable et al. 1997a; Chanton et al. 2003). Belanger and Montgomery (1992) used test-tank evaluations to compare measured seepage rates to the actual (calculated) seepage flowing through tank sand and found a 0.77 ratio between measured and actual flux. Their discrepancy was attributed to flow field deflection and frictional resistance along the inner walls of in situ seepage meters (Erickson 1981; Belanger and Montgomery 1992).

Seepage from marine sediments can consist of several sources, including meteoric water derived from continental-based aquifers and recirculated seawater driven by various biological and physical processes. Additionally, the temporal and spatial variability in seepage measurements makes understanding its sources and magnitudes complex. However, accurate assessment of seepage rates is critical to understanding the relative magnitudes of pore water sources, fluxes, and reactive solute contributions to cycling within estuarine and coastal systems. Consequently, this article evaluates the impact of external biological and physical forcing of seepage, including wind speed, maximum wave height, and current velocity, on the variability in seepage meter measurements. Some plausible suggestions are presented for the source of seepage water in the Indian River Lagoon, eastern Florida.

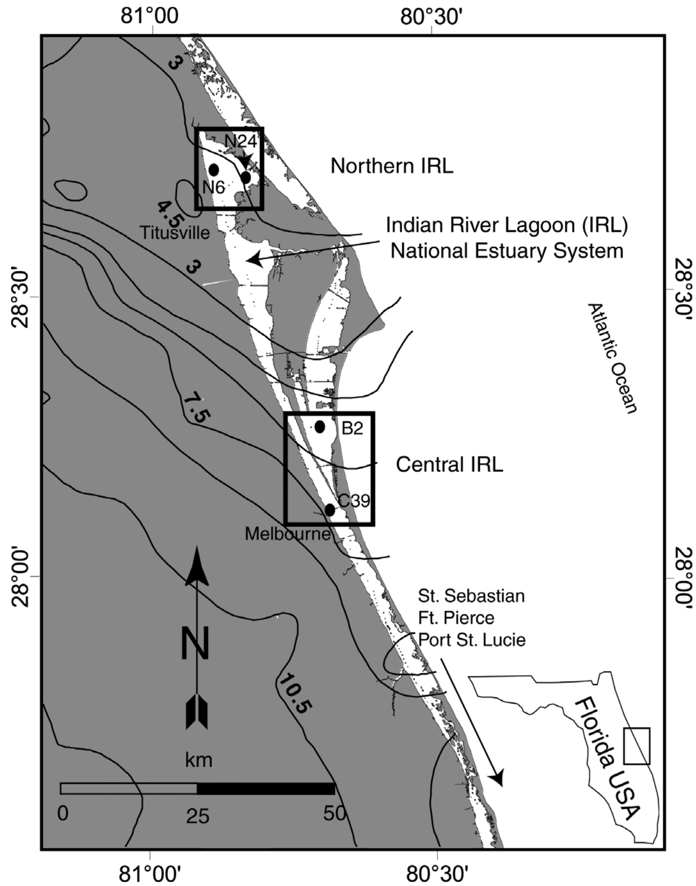

Fig. 2. The field site is located on the eastern coast of Florida. Four sites were occupied, BRL2 (B2) and CIRL39 (C39) in the central lagoon and NIRL6 (N6) and NIRL24 (N24) in the northern lagoon. Potentiometric surface lines of the Floridan Aquifer are shown at 1.5-m intervals.

Materials and procedures

The Indian River Lagoon (IRL) National Estuary system is a 250-km long series of lagoons located along the east coast of Florida, with an average lagoonal width of 2 to 4 km and depth of about 1.5 m (Figure 2). The estuary as a whole is microtidal (< 10 cm tidal range). Within the study area, a nearby datalogger recorded a tidal range of about 2 to 5 cm. Annual precipitation ranges from 111 to 130 cm between Melbourne and Titusville,

Table 1. Average seepage rates (±1σ, n = 3) for 4 stations in the Indian River Lagoon.

	Average Seepage (cm/day)									
	11-12 May 2003		11-12 June 2003		12-14 July 2003		25-27 Sept 2003		24-26 May 2004	
Station	rate	±	rate	±	rate	±	rate	±	rate	±
BRL2										
East #1	1.57	0.07	3.45	1.66	0.78	1.34	2.91	0.96	3.96	1.96
West #2	1.51	0.54	2.89	0.77	3.31	0.78	1.29	0.75	4.26	3.99
CIRL39										
South #1	7.07	2.24	8.27	3.15	7.39	1.22	4.12	0.54	7.19	1.34
North #2	8.11	0.81	8.43	2.43	7.75	3.41	3.56	1.78	5.76	1.94
NIRL6										
North #1	7.25	2.22	3.64	0.36	9.71	2.43	0.45	2.32	1.85	1.17
South #2	12.61	1.14	6.05	2.99	6.28	2.59	-0.17	3.40	3.49	0.87
NIRL24[2]										
West #1	—	—	—	—	12.06	2.47	2.38	2.96	3.42	0.19
East #2	—	—	—	—	11.34	2.19	10.26	1.93	6.26	1.33

[1]Seepage meter installed July 2003.

Florida, respectively (NCDC 2004). Direct surface water exchange with the Atlantic Ocean is limited to three inlets (St. Sebastian, Ft. Pierce, and St. Lucie) located > 72 km south of the central field site. Sediments vary along the length of the lagoon but are generally moderate-porosity (~ 0.40) medium to fine sands and shell hash with interstitial fine-grained sediment and organic matter. Three main aquifers, the Floridan, Intermediate, and Surficial aquifers, underlie this coastal region. In the central IRL, the Floridan aquifer is completely confined by the Hawthorn Group (~30 m thickness), and the Surficial Aquifer is the principal source of groundwater to the lagoon, whereas in the northern IRL the Hawthorn Group confining unit is absent, resulting in a direct connection between the Floridan Aquifer and the lagoon (Scott 1988, 1992).

Seepage meters used in this study were modified slightly from Lee (1977; see Figure 1). Meters were twisted and pushed into the sediment, with sediment packed firmly around the sides to inhibit leaking. The meters were allowed to equilibrate at least 24 h before measurements were initiated. A small (1.1 cm ID) threaded port attached to the top of the meter allowed a 4-L plastic bag to be connected via a matching hose fitting attached to the plastic bag. Seepage bags were prefilled with 1000 mL ambient lagoon water before deploying on the seepage meter. Net measured water volumes (minus the prefill volume) collected in the bag over a known time (~ 1 h) and area (0.255 m^2) yielded a seepage rate (cm/day) for that location.

Four field stations were established, two stations in the northern IRL and two about 45 km south in the central IRL. Two seepage meters were deployed about 2 m apart at each site and left for the duration of the project with the ports open to flow when not in use. During each field trip (May, June, July, and September 2003 and May 2004), seepage measurements were collected concurrently with hydrographic and meteorological measurements. Three sequential seepage measurements were collected from each device during each site visit. The reported seepage rates are the mean (± 1σ, n = 3 1-h measurements) of each meter for any given field trip at each site. Occasionally, a faulty seepage measurement occurred due to problems with the bag, the hose fitting, or organisms nesting along the device sides, and those measurements were omitted from the mean.

Astronomical tides with ranges between 2 and 10 cm are not likely to impact seepage, but wind-driven flow regimens created by coastal breezes and fronts were considered potentially important contributors to seepage measurements. At each station, wind speed, current velocity, and wave height and period were measured concurrently with seepage measurements. Instantaneous wind speeds (averaged over a 60-s interval) were measured with a hand-held Kestral 2000 model pocket wind meter about 2.5 m above the lagoon surface. Current velocities were measured at 2 depths, approximately 20 cm below the water surface and 30 cm above the sediment-water interface, with a Sontek FlowTracker hand-held acoustic Doppler velocimeter (ADV), which takes a 60-s mean of the current flow and reports velocities along the x- and y-coordinate planes. The ADV has a resolution of less than 1 cm s^{-1} and estimated error of ± 1% of the measured currents and is well suited for shallow waters (greater than 3 cm depth). Wave height and period were estimated using a stopwatch and a meter stick. Period was estimated from the number of wave crests to pass the meter stick in about 10 s. Wave height was estimated as the mean wave height to pass the stick in about 20 s.

Assessment

Seepage measurements are shown in Table 1. The lowest seepage overall was found at BRL2, which is the deepest station (2 m water depth), whereas the highest seepage rates occurred in the northern stations (NIRL6 and NIRL24), which

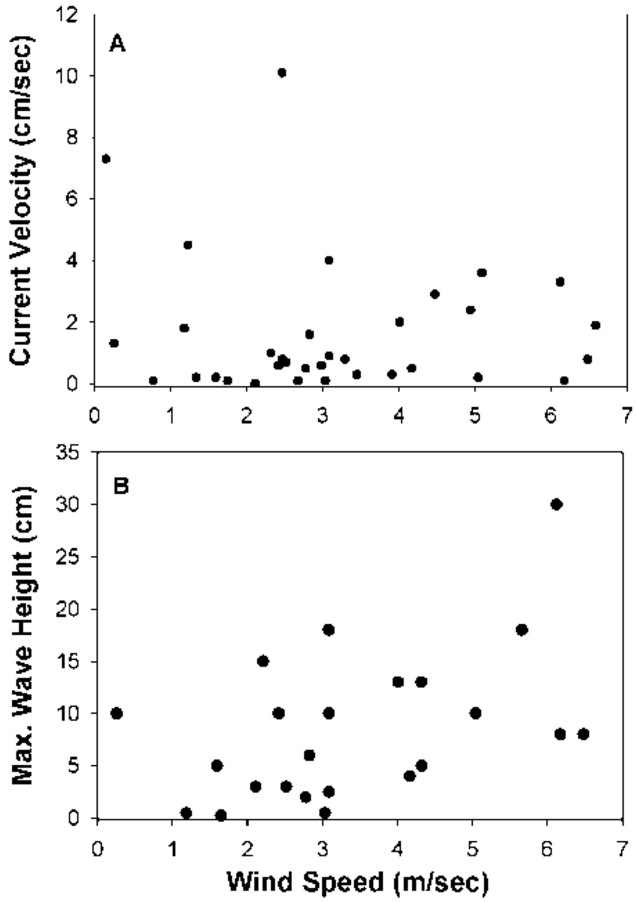

Fig. 3. Wind speeds versus current velocities (A) and maximum wave height (B) are shown to identify surface water responses to increasing wind speeds. No relationship is observed between current and wind, but 20% of the wave height variability could be explained by wind speed (r^2 = 0.21).

are the shallowest sites (< 0.7 m depth). Estimates of error are included as the standard deviation of the 3 sequential measurements. In most cases the coefficient of variation among individual measurements for a single site was greater than 20%. BRL2 showed the greatest variability through time, with a coefficient of variability of 55% over the project period. NIRL24 had the most consistent seepage measurements through time, with typical coefficients of variation of 16%. CIRL39 and NIRL6 were similar, with about 30% variability among measurements.

Winds, waves, and currents were used to evaluate physical environmental conditions that could affect seepage measurements. These parameters did not vary by much within the 3-h sampling period at each station but varied considerably between stations and sampling trips. Stations sampled in the afternoon typically had higher wind speeds than those sampled in the morning as a result of the onset of late afternoon coastal breezes. No apparent relationship was observed between time of day and current velocities or wave heights.

Measured current velocities were low in the lagoon near our stations. Current velocities are a function of the long-term water movement in the lagoon more than the instantaneous wind speeds, and consequently, changes in instantaneous wind speeds did not translate immediately to increased wave heights or current velocities (Figure 3). Flow in this microtidal lagoon is a function of boat wakes, longitudinal flow within the intracoastal waterway, and the relative fetch of cross-lagoon or down-lagoon wind. The lack of correlation between current velocities and instantaneous wind speeds at each site may be explained by several factors. Instantaneous wind speeds were measured each hour at the site, which do not capture the average daily wind speed or changes in direction of the wind. A comparison of our hand-held wind speed measurements to hourly and mean daily winds collected at an airport about 5 km inland from CIRL39 revealed a 1:1 slope with a negative y-intercept (r^2 = 0.6), indicating that our hand-held measurements slightly underestimated inland winds. Because airport meteorological data were available at only one site, we report our own wind measurements for all sites to examine spatial and temporal variability. Wave heights and period are a function of the fetch on the lagoon, which varies greatly depending on the direction of the wind at each location, and the length of time that the wind blows at a given wind speed. Instantaneous wind speeds reflect a minor, although still predictable, component of wave heights (r^2 = 0.21). These comparisons demonstrate the limits of our wind speed data interpretation on the fluid motion (waves and currents) that may impact seepage meter measurements.

Discussion

Spatial and temporal variability in seepage measurements can be attributed to several factors, including distance from shore, intensity of biological activity, types of burrowing organisms, hydraulic properties of regional sediments, seasonal and annual climate changes (i.e., aquifer recharge, aquifer hydraulic head), and sediment bed ripple height. Here we consider first the spatial variability due to aquifer type and regional benthic environment (sedimentology, seagrass beds versus sandy sediments). After this discussion we evaluate temporal variability in seepage due to potential aquifer recharge (i.e., using local precipitation as a proxy) and external physical forcing on seepage meters.

Spatial and temporal seepage distribution—In the Indian River Lagoon system, seepage rates measured with seepage meters ranged from less than 1 to 12 cm d^{-1} throughout the project period (Table 1). A comparison of all four stations shows that the highest seepage rates were more common at the northern than central stations, similar to earlier findings (Martin et al. 2002; Cable et al. 2004). The elevated rate in the north may represent contributions to groundwater discharge from the Floridan Aquifer, which is more productive than the Surficial Aquifer. In theory, groundwater seepage is expected to decrease exponentially with distance from shore based on

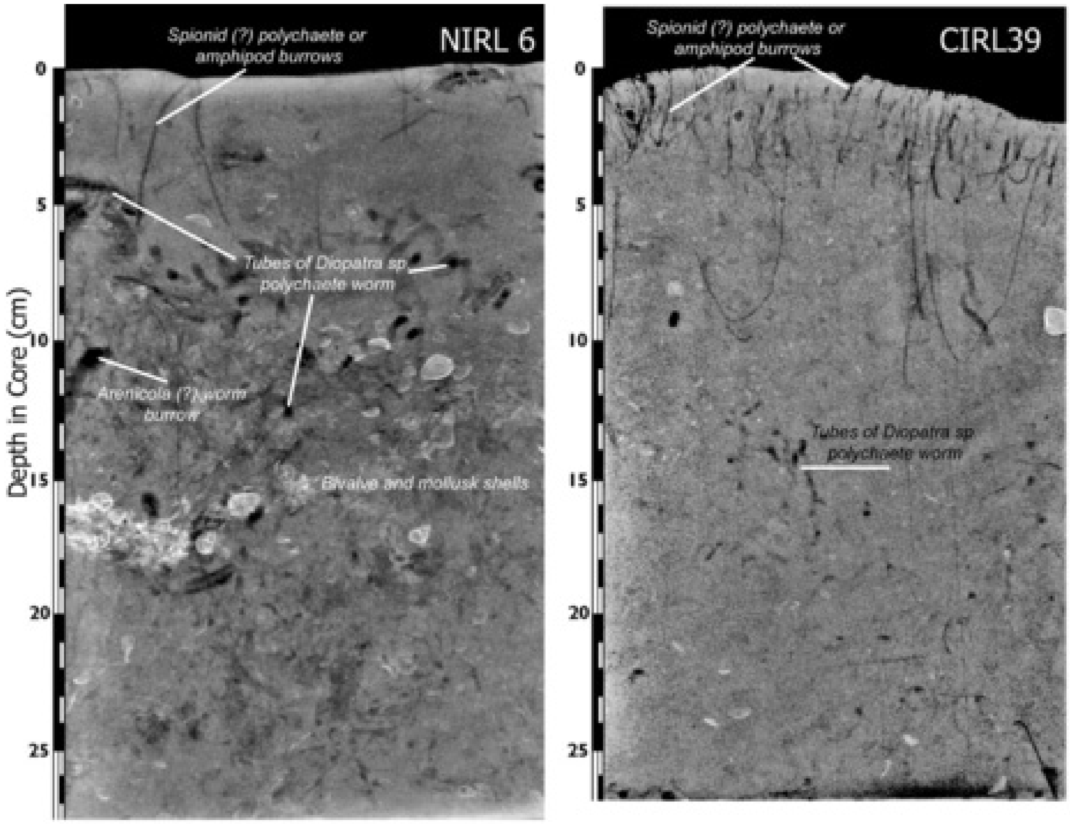

Fig. 4. X-ray radiograph negatives (denser = lighter) of slab cores collected within 2 m of the seepage meters in grass-free sediments at sites NIRL 6 (left) and CIRL 39 (right) from May 2004. Abundant bioturbation can be seen including thin (< 2 mm) near-surface burrows of possibly amphipods or *Spionid* (?) polychaetes. Tubes of the polychaete worm *Diopatra* sp. down to ~15 cm depth are also abundant. A shell hash is found at depths that may correspond to the feeding depth of *Arenicola*, which are known to create biogenic graded bedding (Bromley, 1990). Rapid deposition of sand coils on the surface by lugworm *Arenicola cristata* was observed at both sites.

topographic and potentiometric gradients of the terrestrial aquifer (McBride and Pfannkuch 1975). In practice, however, spatial heterogeneities in bottom sediments or the aquifer may influence measured seepage rates so that this classic exponential decrease is not always found (e.g., Bokuniewicz 1992; Taniguchi et al. 2003). Given that the northern stations were greater than 500 m from the nearest shoreline and BRL2 was almost 1 km from either shore, these sites are unlikely to be influenced by the Surficial Aquifer. Site CIRL39 was closest to shore of all stations (~ 300 m) but also was beyond the freshwater seepage face of the Surficial Aquifer, which extends about 25 m from shore in this area. It is impossible from these data to distinguish precisely from which aquifer the groundwater may originate.

The northern stations (NIRL6 and NIRL24) are located in seagrass beds with muddy, fine-grained sands, whereas the central stations (BRL2 and CIRL39) are located in sandy, shelly sediments. Previous studies have investigated the connection between seagrass and seepage. In a study of groundwater seepage rates in the Gulf of Mexico, Rutkowski et al. (1999) found that only 4 of 7 sites exhibited any significance between the amount of seepage measured and the presence of seagrass. They concluded that no relationship existed between seagrass presence and seepage measurements, either directly by providing greater conduit flow along roots or indirectly by enhancing seagrass growth due to nutrient import by groundwater. The elevated seepage rates in our northern IRL seagrass sites suggest an indirect causal link attributable to high productivity and biodiversity within seagrass-dominated sediments (Table 1). Site NIRL24 is in a protected cove with a lush seagrass bed, especially in the summer. In contrast NIRL6 usually has less productive seagrass growth and is more subject to late afternoon wave set-up from coastal breezes. These seagrass beds contain more organic material and appeared to contain more burrowing organisms than the central sites. Examination of near-surface sediments at the northern stations revealed a 30- to 60-cm layer of well-bioturbated muddy fine sand (Figure 4). Bioturbation (i.e., biological mixing of the sediment) may enhance pore water transport through sediments (recirculated seawater component), as in the case of the head-down deposit feeding lugworm, *Arenicola*, which injects surface water at depth to liquefy sediment for ingestion (Bromley 1990). Bioturbation also may promote ventilation of sediments by providing tubes and burrows for passive recircu-

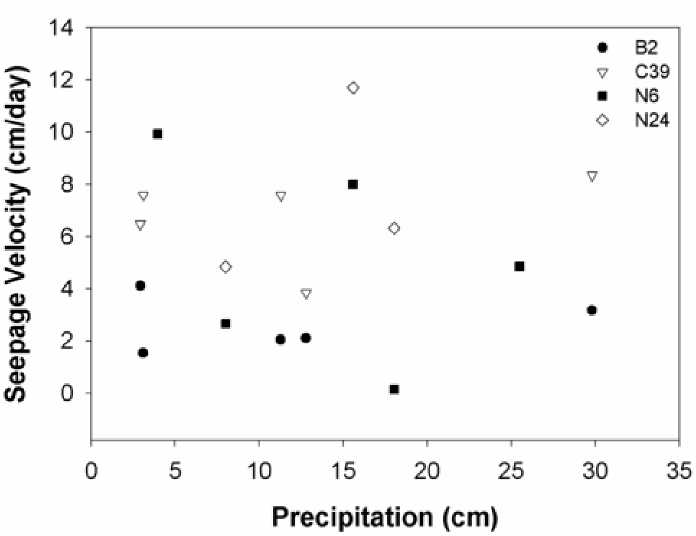

Fig. 5. Monthly precipitation was used as a proxy for terrestrial aquifer recharge and compared to seepage meter rates at each station. Precipitation appeared to have no effect on observed seepage rates at any of the field stations.

lation of seawater (Aller 1988). The burrowing organisms also flush water through their structures (a process termed bioirrigation) for respiration and feeding, and thus some of the spatial heterogeneity may be caused by these processes.

Temporal variations in seepage rates were compared with local precipitation as a proxy for potential aquifer recharge (Figure 5). In both the northern and central regions of the lagoon, there is little relationship between monthly total precipitation and measured seepage rates. Although seepage rates do vary through time, they stay within the small ranges of 3 to 12 cm day^{-1} in the north and 2 to 8 cm day^{-1} in the central region. Some of the highest rates occur in May 2003 at the end of the dry season, whereas some of the lowest rates occur in September 2003 at the end of the wet season. If the rates are controlled by links to terrestrial aquifers, our data suggest there is a lag between precipitation and groundwater discharging into the lagoon. Long-term and high-frequency studies over several years would be required to quantify the extent of the lag.

External physical forcing on seepage measurements—Researchers have used seepage meters in a variety of conditions and environments to quantify flux of water from sediments, but these devices recently have drawn criticism over concerns of Bernoulli-type flow induced around seepage meters. The Bernoulli flow was first suggested to be an influence in the Florida Keys by Shinn et al. (2002, 2003), who suggested that much of the water measured by seepage meters is not related to discharge from terrestrial aquifers. However, strong evidence gathered from the Keys has linked tidal motion and aquifer head fluctuations to seepage measurements (Chanton et al. 2003; Corbett and Cable 2003). An experiment performed using two automatic heat-pulse seepage meters, one inside a sand-filled plastic swimming pool (control) and an adjacent seep meter in Florida Bay sediments, showed consistently low baseline seepage at less than 1 up to 2.5 cm day^{-1} in the control (Chanton et al. 2003). In contrast the nearby seepage meter in sediments revealed rates between 2 and 15 cm day^{-1}, with clear diurnal variations in seepage coincident with tides. Chanton et al. (2003) raised the possibility that the seepage rates observed in the pool experiment "control" may be associated with the Bernoulli effect suggested by Shinn et al. (2002). Nonetheless, Shinn et al. (2002, 2003) raise an important point about seepage estimates; specifically that seepage rates are often assumed to be related to groundwater discharge from terrestrial aquifers in many locations around the world despite other evidence that suggests different sources for the discharging water. For example, Li et al. (1999) used a theoretical model to determine that the magnitude of submarine groundwater discharge (SGD) associated with waves and tides in the south Atlantic Bight was about 92% of the total estimated SGD contribution based on Moore's (1996) study.

Variables that may influence circulation of water into and out of sediments include hydraulic gradient, sediment permeability, burrow mound height, ripple length and amplitude, and the wavelength, height, and period of water waves. Shum (1992, 1993) demonstrated that water movement over a seabed can provide significant penetration of water into sediments if bedforms, such as ripples, are present. Recent work demonstrates that penetration of water into the sediments results from development of a pressure gradient into the sediment as water flows across the top of the bedforms (Huettel and Gust 1992; Huettel et al. 1996; Huettel and Webster 2001). Working in sandy ripple beds, Huettel et al. (1996) demonstrated that this differential pressure can drive vertical pore water velocities as high as 3 cm h^{-1} (i.e., 72 cm day^{-1}) in 2- to 3-cm high sand mounds when the bottom water current velocities approach 10 cm s^{-1}. These flow rates are 6 to 9 times greater than typical field-measured seepage results in the Indian River Lagoon. Recognizing that seepage meters act as a macro-topographical feature on the seabed, Shinn et al. (2002) argued that the venturi effect across the features would be greater than any natural advection signal, and subsequently, dubbed the effect "Bernoulli's revenge." In the simplest representation, bottom currents create a differential pressure between surrounding sediments and the seepage chamber top due to an increase in flow velocity above the chamber.

Our field program was designed to evaluate the effects of physical environmental conditions that may induce this pressure gradient, to combine these conditions with seepage meter flow rates to estimate the magnitude of the Bernoulli-type flow artifacts in seepage meters, and thus, to determine whether seepage meters are valid tools to measure groundwater discharge or pore water advection. In this program, we compare average seepage rates (mean of triplicate seep meter measurements for a given time of day) with instantaneous wind speeds, current velocities, and maximum wave heights

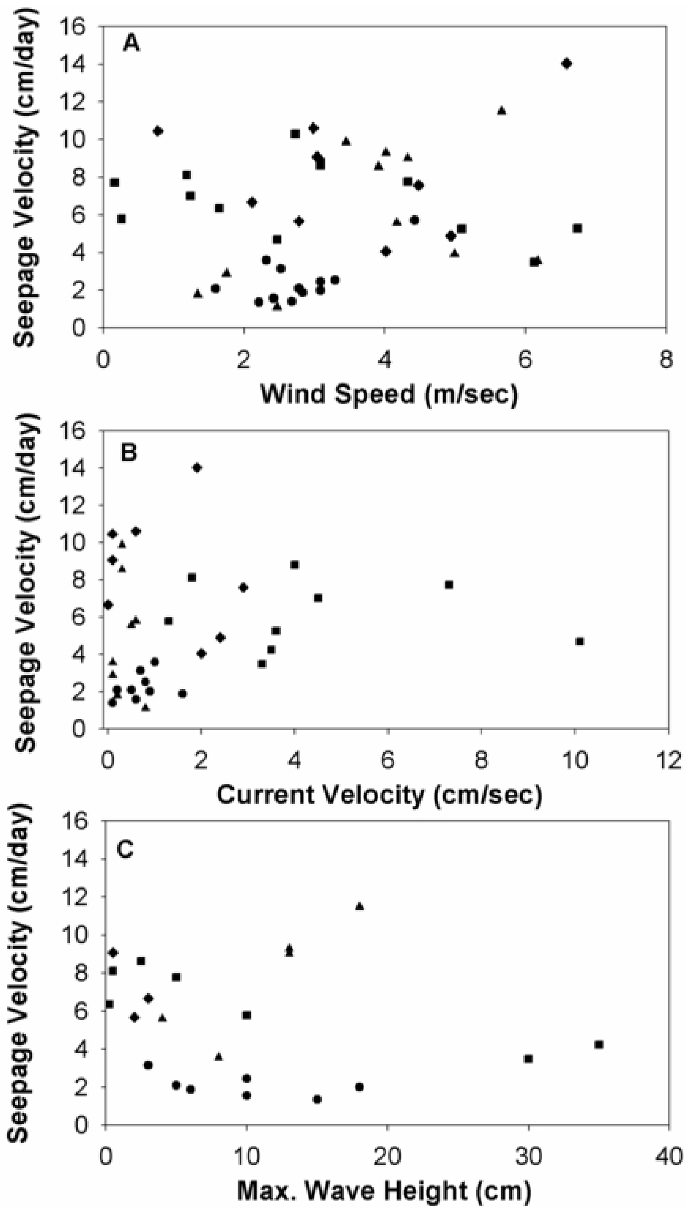

Fig. 6. Observed seepage velocities were compared to wind speed (A), current velocity (B), and wave height (C) at BRL2 (●), CIRL39 (■), NIRL6 (▲), and NIRL24 (◆).

at each station (Figure 6), each of which may affect the pressure gradients surrounding seepage meters. Wind and wave heights are indirect measures of the turbulence in the water column, and thus a measure of non-unidirectional flow across the meters. The current meters provide a direct measure of average unidirectional flow across the meters. Although Huettel et al. (1996) found correlations between current speed and pore water velocities, there are no correlations between wind speeds, current velocities, or wave heights to the measured seepage rates in the IRL data, even when individual stations are considered (Figure 6). The lack of correlation is likely caused by the protected nature of this lagoon and low current velocities across the seepage meters (see Figure 3), which are less than 5 cm s^{-1} in 95% of our measurements, and thus, more than 2 times slower than current velocities in Huettel et al. (1996) experiments. Although Huettel et al. (1996) demonstrate that bottom currents are important to pore water advection rates, the bottom currents must be of a greater magnitude than typically occur in the IRL to be a significant contribution to flow from seepage meters.

The following calculations estimate the magnitude of bottom currents required to create the Bernoulli effect. The differential pressure caused by flow across bedforms can be quantified by a lift force that is described by:

$$F_L = C_L \left(\frac{\rho u^2}{2} \right) A \qquad (1)$$

where F_L is the lift force (N), C_L is the lift coefficient (dimensionless), ρ is the fluid density (kg m^{-3}) based on typical salinities and temperatures in IRL bottom waters, u is the boundary layer current velocity (m s^{-1}), and A is the area of the protrusion exposed to flow, in this case the seepage meter (Dingman 1984; Huettel et al. 1996). Dividing the lift force by the area yields the pressure drop (P) across the topographical feature. This pressure change is applied in a calculation of Darcy velocity or specific discharge (q) through sediment of known permeability (k), after Batchelor (1967):

$$q = k\,1/\mu \left(\frac{P}{L} \right) \qquad (2)$$

where k is the mean of sediment permeabilities at each IRL station (m^2), μ is the dynamic fluid viscosity (kg m^{-1} s^{-1}) based on typical salinities and temperatures in IRL bottom waters, P is the pressure drop from Eq. 1, and L is the path length, where L is equal to the average distance across the circular seepage meter. Path length across the device can vary from a miniscule distance to the maximum distance at 0.57 m, which is the device diameter. Table 2 provides the input values of these variables for the Indian River lagoon.

Table 2. Lift force and pore water velocity calculation input parameters for typical shallow lagoon pore waters.

Input parameter	Symbol	Value	Units
Salinity	S	22	
Temperature	T	26	°C
Fluid density	ρ	1015	kg/m^3
Measured bottom current velocity	u	0.01 to 0.10	m s^{-1}
Area	A	0.0358	m^2
Sediment permeability	k	6.82E-12	m^2
Path length	L	0.403	m
Dynamic viscosity	μ	8.48E-04	kg m^{-1} s^{-1}
Effective sediment porosity	n_e	0.40	—

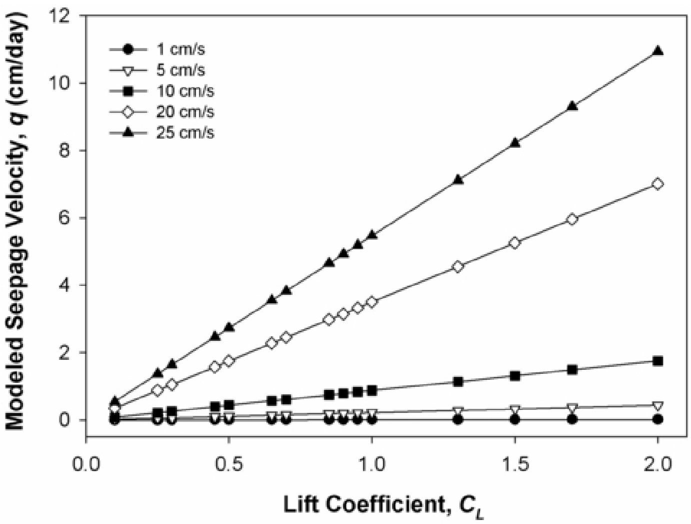

Fig. 7. Sensitivity analysis of the relationship between bottom currents, lift coefficient, and resultant calculated seepage velocity was calculated to evaluate the magnitude of the Bernouilli effect.

According to this calculation, seepage velocities respond to area, lift coefficient, path length, and current velocity. The path length and area are fixed because all seepage meters in this study have identical geometry, thus minimizing the variables affecting the lift force. Surface area exposed to flow is based on the typical height of the device above the sediments (~ 4 cm) such that the area becomes 0.0358 m^2. Selecting a lift coefficient appropriate for seepage meters is challenging. Huettel et al. (1996) estimated a lift coefficient of 0.30 to 0.47 for their rounded 30-degree slope sand mounds of 1- to 3-cm height based on literature values. The tops of seepage meters are generally 3 to 5 cm above the sediments, have a larger radial area, and longer path length over which the pressure gradient will occur than sand mounds. Consequently, we expect higher values of C_L than Huettel et al. (1996) to be appropriate. We performed a sensitivity analysis between lift coefficient (from 0.1 to 2) and the most variable parameter, bottom current velocity (based on u = 1, 5, 10, 20, 25 cm s^{-1}), to evaluate effects on the seepage velocity (Figure 7). Even though current velocities of 20 to 25 cm s^{-1} did not occur during our field program, they were included in the sensitivity analysis to demonstrate the current velocity required to achieve our highest measured seepage rates if the Bernoulli-induced pressure differential was the only cause.

Results of the sensitivity analysis indicated that the seepage velocity is more sensitive to bottom current velocity than the lift coefficient for velocities typical of the Indian River Lagoon (< 5 cm s^{-1}). At current velocities greater than those of the Indian River Lagoon field study, however, the lift coefficient also becomes important (Figure 7). Reynolds number (R) is a means of setting the scale for water column motion as currents move across the seabed; thus, as R increases, inertial forces dominate viscous forces and the flow regimen becomes more turbulent. We estimated R for the water column at each seepage meter site using 2 perspectives, the whole water column (~1 m) and the bottom waters only (≤30 cm above sediments) (Table 3). The whole water column was always classified as fully turbulent, with Reynolds numbers greater than 3000 at all velocities and depths. When only the bottom waters were considered, the gradient in current velocities created a more relaxed flow regimen. Laminar conditions exist at ≤30 cm above sediments for about 1 cm s^{-1}, transitional conditions occur as flow becomes turbulent around 5 cm s^{-1} current velocities, and fully turbulent conditions are present near the bottom at > 10 cm s^{-1}.

At higher bottom current velocities than those found in the IRL, it is obvious that the Bernoulli effect would dominate the seepage rate, indicating that seepage meters should be

Table 3. Reynolds numbers are given at the 4 seepage locations calculated for a total water column depth and within the bottom waters 30 cm above the sediment-water interface using a range of current velocities (u = 1, 5, 10, 20, 25 cm s^{-1}).

Reynolds number (R)		BRL2	CIRL39	NIRL24	NIRL6
Water column depth (m)		1.5	0.9	0.7	0.5
u (m s^{-1})					
0.01	Fully turbulent	17,225	10,335	8038	5742
0.05		86,126	51,675	40,192	28,709
0.10		172,251	103,351	80,384	57,417
0.20		344,502	206,701	160,768	114,834
0.25		430,628	258,377	200,960	143,543
Bottom water depth 0.30 m					
0.01	Laminar	345	345	345	345
0.05		1723	1723	1723	1723
0.10	Fully turbulent	3445	3445	3445	3445
0.20		6890	6890	6890	6890
0.25		8613	8613	8613	8613

Fluid density and dynamic viscosity are taken from Table 2.

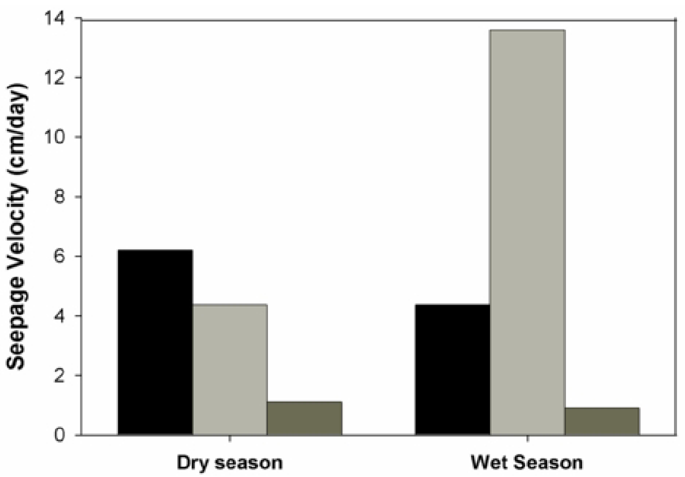

Fig. 8. Measured seepage velocities are given for seepage meters at BRL1 (black), CIRL39 (light gray), and a pool experiment (dark gray) during the 2001 field study.

restricted to quiescent water bodies. We found that Bernoulli-induced flow could explain all of our measured seepage meter flow rates if bottom current velocities were greater than about 20 cm s^{-1}. However, the highest measured current velocities in the IRL study were 10 cm s^{-1} or less. At these flow rates, the seepage velocities calculated from Eq. 2 are less than or equal to seepage rates measured during control experiment measurements performed in the lagoon, where seepage meters were installed within plastic children's swimming pools. Seepage rates of these control experiments average about 1 to 1.5 cm day^{-1} (Figure 8) (Martin et al. 2002). The similarity in values between calculated Bernoulli seepage and the control experiments suggest that the Bernoulli effect will contribute a small fraction to the total seepage rate. The majority of SGD measured using seepage meters in the IRL results from discharge across the sediment-water interface due to factors other than simply the differential pressure across the device. Seepage rates measured using seepage meters in the IRL appear to have about a 5% error associated with water flow around the meters from the Bernouilli effect (Figure 7; Table 1). This error implies that resolving seepage flows less than 1 to 2 cm day^{-1} may be difficult even in relatively calm conditions. Given that the physical conditions of the water column apparently did not explain the volume of water measured with seepage meters, we performed a literature search of other plausible mechanisms that could create the flow rates we measured. Subsequently some field measurements were made to evaluate the likelihood of biological forcing affecting seepage measurements.

Other factors influencing seepage measurements—Another potential driver for mixing of surface water through coastal sediments is bioirrigation, a process where burrowing organisms actively pump fluid into their burrows and sediment. In a previous study in the Indian River Lagoon, Martin et al. (2004) used Cl^- pore water profiles to examine flow rates and sources of fluids to the water column. They demonstrated that Cl^- in the upper 70 cm of marine sediments in the Indian River Lagoon more closely reflects lagoon surface water concentrations. Concentrations of Cl^- in the lagoon water are highly variable due to precipitation and evaporation, and the pore waters less than 70 cm deep exhibit a rapid (less than 48 h) response to surface water Cl^- concentrations. In contrast, advection-diffusion-reaction modeling of pore water Cl^- concentration gradients deeper than 70 cm revealed upward flows < 0.012 cm day^{-1} (Martin et al. 2004), which is similar to groundwater flow models in the area (Pandit and El-Khazen 1990). Martin et al. (2004) speculated that the higher flow rates in the shallow sediments (< 70 cm deep) may be attributed to bioirrigation.

A variety of burrowing organisms are endemic to the Indian River Lagoon; using visual observations of the burrow and tube morphologies, we were able to identify 3 to 4 dominant types of these infaunal tracemakers at CIRL39 (Figure 4). The organisms include 2 species of worms and possibly 2 species of shrimp, each of which had previously been studied to determine their respective bioirrigation rates (see Table 4; Dales et al. 1970; Forster and Graf 1995; Riisgard et al. 1996;

Table 4. Pumping rates for bioirrigators based on literature values for irrigation rates and observed burrow densities in the Indian River Lagoon.

Bioirrigating organism		Irrigation rates,	Number of burrows,	Volume exchanged,	Linear velocity,
Common name	Species	mL h^{-1}	m^{-2}	$m^3\ m^{-2}\ day^{-1}$	cm day^{-1}
Ghost shrimp[1]	*Callianassa sp.*	30	3	0.002	0.2
Mud shrimp[2]	*Upogebia affinis* (?)	300	3	0.022	2.2
Lugworm[3]	*Arenicola marina*	96	7	0.016	1.6
Plumed worm[4]	*Diopatra cuprea*	60	9	0.013	1.3
			Total	0.1	5

[1]Forster and Graf (1995).
[2]Webb and Eyre (2004).
[3]Riisgard et al. (1996); Timmermann et al. (2002).
[4]Dales et al. (1970).

Timmermann et al. 2002; Webb and Eyre 2004). Burrow/tube densities were determined by counting the features on the sediment surface in a 1-m^2 frame along shore-perpendicular transects at water depths equivalent to the seepage meters. By using these counts and published bioirrigation rates, we have calculated the volume of water exchanged through the burrows and converted the volume to a linear velocity. Summing the rates of the individual species across the area influenced by the burrows yields an average value of ~5 cm day^{-1} over the observation area. This value falls within the range of those measured using seepage meters of ~2 to 12 cm day^{-1} (Table 1). Considering that physical variables (wind, waves, and currents) do not appear to have a dominating effect on discharge measured by seepage meters, and that the seepage meters are all located on the seaward side of the freshwater seepage face, the correspondence in rates suggests that bioirrigating organisms may have a potentially large effect on the measured seepage meter rates in IRL.

It would be expected that if bioirrigation drives the observed fluxes measured by the seepage meters beyond the seepage face, these devices should also measure the flux of water into as well as out of the sediments. It is rare, however, that manual lee-type seepage meters record a negative discharge in IRL, as would be indicated if the volume of water used to prime the bags decreased during deployment. A possible explanation for why seepage meters typically only measure flow from the sediment to the water column at IRL may be variation in flow direction through the burrows caused by changes in the chemistry under the seepage meter. Seepage meters seal the sediment from the overlying water column, and as a result, oxygen is depleted and H_2S concentrations increase in water trapped under the meters. Dissolved oxygen in water collected from seepage meter bags in the IRL has been measured to be as low as 0.1 mg L^{-1} using a hand-held probe. Water column dissolved oxygen can be between 1 and 8 mg L^{-1}, depending on the time of year and location within the lagoon. These reducing conditions are likely to be toxic to some burrowing organisms, and as a result, we speculate that organisms may alter the flow paths through their structures to directly pump surface seawater toward the toxic water beneath the seepage meters and away from their positions within the sediments. It has been observed with the lugworm, *Arenicola marina*, that irrigation rates in the sediments increased by more than 17,000% when conditions in the sediments switched from normoxic to moderately hypoxic (Wohlgemuth et al. 2000). In this study they also found that under more severe hypoxic conditions, these irrigation rates were dramatically decreased. These findings would suggest that it is possible for seepage meter measurements to demonstrate high variability independent of physical conditions. The subsurface size and abundances of the types of burrows and galleries seen in the IRL can be quite high and can cover an area larger than that of a single seep meter (Shinn 1968; Suchanek 1983; Bromley 1990; Dineen et al. 2004). Random placement of seepage meters on the seafloor could easily cover only a portion of one or more burrows. As a result, organisms in the sediments may increase ventilation through the sediments and into the seepage meters.

Comments and recommendations

Studies using multiple techniques to measure SGD, such as tracer studies, seepage meters, and groundwater flow models, show that the magnitude of SGD strongly depends on the measurement techniques (e.g., Burnett et al. 2002; Cable et al. 2004). Our results suggest that seepage meters are a reliable technique for measuring pore water advection from sediments if the environment is calm. When current velocities approach 20 cm s^{-1}, modeled seepage velocities from sediments matched our measured seepage rates and indicated that the Bernoulli effect could explain seepage rates if the flow regimen was conducive. In our study, current velocities did not exceed 10 cm s^{-1}, so that the Bernoulli-induced flow was similar to control experiment measurements of seepage. Nonetheless, the average meteoric groundwater discharge rate in the Indian River Lagoon is ~0.05 cm day^{-1} based on numerical flow models, or nearly 2 orders of magnitude lower than the discharge rates measured from seepage meters. This difference in measured seepage rate for the different approaches supports the conclusion posited by other studies that seepage meter measurements include different water sources in addition to meteoric water discharging from terrestrial aquifers (e.g., Shinn et al. 2002; Cable et al. 2004; Martin et al. 2004).

Although the mechanisms for delivering seepage to the coastal environment will vary depending on geology, climate, consumptive groundwater usage, local biology, and surface water hydrodynamics, it is possible to evaluate the magnitude of some of these effects. Even though seepage meters do not directly allow us to identify sources of water in seepage, other techniques used in conjunction with the seepage meter, such as geochemical tracers or geophysical methods, make evaluation of seepage sources possible. No matter what fluid advection source you may expect to measure, bottom current velocities should be a consideration in attributing mechanisms that influence flow. We found Bernoulli-induced flow is a real, but maybe minor, component of measured advection using seepage meters. Calculations of Bernoulli contributions appear to be similar in magnitude to seepage "pool" blanks in the Indian River Lagoon, and these calculations are considerably less labor intensive than the pool experiments in evaluating this Bernoulli effect.

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