An alternative to traditional seepage meters: Dye displacement

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[1] A new seepage meter design that increases sensitivity to the small hydraulic gradients that drive submarine groundwater discharge was developed as an inexpensive alternative to traditional seepage meters. The new design replaces seepage meter bags with open-ended tubing through which the displacement of injected dye is a highly reproducible measure of discharge. Laboratory measurements, detailed mathematical modeling of groundwater flow around seepage meters, and parallel field tests of bag and dye displacement seepage meters demonstrated that the new design can improve the precision and temporal resolution of submarine groundwater discharge measurement. In parallel field tests, groundwater discharge to 15 cm diameter, bag-equipped seepage meters was half of the discharge to adjacent 15 cm diameter dye displacement seepage meters. Model results confirm that similar discrepancies, caused by groundwater diversion around bag-equipped seepage meters, may occur during the deployment of 57 cm diameter seepage meters in common field conditions. A second field deployment of 15 cm diameter dye displacement seepage meters showed saline inflow into sandy sediments at high tide and a high rate of discharge at low tide, similar to observations made with far more expensive, open flow path automated seepage meters in other studies.

1. Introduction

[2] Submarine groundwater discharge (SGD) is fluid of terrestrial, marine, or mixed origins that flows out of sediment pore spaces into overlying seawater [*Burnett et al.,* 2003]. In coastal waters this flow is driven by many factors, including the hydraulic gradient between terrestrial aquifers and bottom water, tidal pumping, density-driven displacement of pore waters, and sediment compaction. It is a source of biologically and geochemically important compounds to seawater as well as a driver of biologically and geochemically important processes in sediments [*Riedl et al.*, 1972; *Bokuniewicz,* 1980; *Simmons,* 1992; *Moore,* 1999].

[3] There are several approaches to determining rates of SGD. These include methods that rely on terrestrial water budgets and hydraulic gradients (both reviewed by *Burnett et al.* [2001]), geochemical tracers [e.g., *Moore,* 1996], vertical profiles of tracers (such as temperature) in sediments [*Taniguchi et al.,* 2003], eddy correlation [*Crusius et al.,* 2008], and seepage meters [*Lee,* 1977]. A seepage meter typically consists of a 55 gallon drum end that is inserted into the sediment. As groundwater flows into the device, it is collected in an attached bag and later quantified. The seepage meter is a valuable and well-tested approach that has been extensively used for many years, but there are methodological problems with manually operated seepage meters

and the bags they use. Empty 3.8 L polyethylene bags mechanically relax in water and may draw in as much as 300 mL of surrounding water when submerged [*Shaw and Prepas*, 1989]. In addition, the walls of polyethylene bags will exert a slight resistance to push or pull, requiring pressure for inflow and outflow. In highly permeable sediments this pressure cannot be neglected relative to the pressure that is capable of diverting a fraction of the groundwater flow around the seepage meter, biasing the measured seepage rate [*Murdoch and Kelly,* 2003]. Additionally, currents flowing across seepage meter bags can cause spurious SGD measurements, as flowing water outside of seepage meter bags may exert a suction or pressure on the walls of the bag [*Libelo and MacIntyre,* 1994]. The errors due to these problems may be small in low-current environments with SGD greater than 2 cm/d [*Cable et al.,* 2006].

[4] Automated seepage meters use mechanical, electronic, or osmotic devices to quantify SGD in place of seepage meter bags. Automated seepage meters typically give more reproducible measurements of low rates of SGD than manual seepage meters with bags. Heat pulse and continuous heat flow [*Taniguchi and Fukuo,* 1993; *Taniguchi and Iwakawa,* 2001], ultrasonic [*Paulsen et al.,* 2001], dye-partitioning [*Tryon et al.*, 2001], dye dilution [*Sholkovitz et al.*, 2003], and electromagnetic [*Rosenberry and Morin,* 2004] seepage meters have shown the capacity to measure not only low rates of SGD (<2 cm/d) but also, in some cases, the inflow of overlying water to submarine sediments. Despite their advantages, the cost of automated seepage meters typically restricts their use to the deployment of one, or a few, at a time. The common trait that gives automated seepage meters improved sensitivity over

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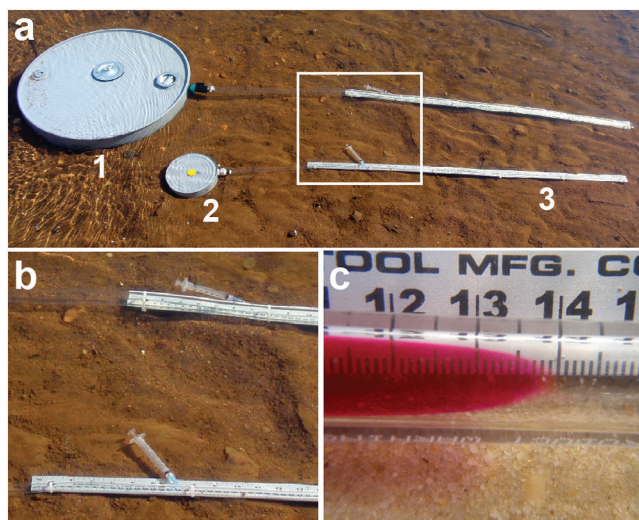
Figure 1. (a) Two sizes of dye displacement seepage meters prior to dye injection: a 57 cm diameter seepage meter (1) with an attached 1.5 m long PVC tube and a 15 cm diameter seepage meter (2) with an attached 1.25 m long PVC tube. An aluminum meter stick (3) was used to measure dye displacement. (b) An expanded view of syringes with needles inserted into tubing for dye injection. (c) The leading edge of dye after 10 min of displacement.

manual seepage meters with bags is that they are designed with open flow path detection systems with minimal physical restriction on flow into or out of the seepage meter.

[5] To obtain similar performance for manually operated seepage meters, we developed and tested a new and inexpensive open flow path seepage meter concept based on dye injected into a clear open-ended plastic tube (Figure 1). In laboratory measurements we determined the pressure required to generate flow through the tube and, at a SGD rate of 10 cm/d, found it to be an order of magnitude smaller than that required to introduce water to a polyethylene bag. A two-dimensional model in cylindrical coordinates was developed to describe the Darcy flow into and around seepage meters and predict the diversion of groundwater as a function of the pressure associated with the seepage meter measurement system. The new dye displacement design was field tested alongside bag-equipped seepage meters at a Chesapeake Bay beach. The dye displacement seepage meters allowed for quantification of SGD and inflow of overlying water into sediments at a higher temporal resolution and precision than traditional seepage meters.

2. Methods
2.1. Pressure Required by Seepage Meter Bags

[6] As a reference point for our dye displacement design we determined the pressure required to introduce water into three types of bags commonly used on traditional seepage meters. These bags are (1) 3.8 L twist-tie bags (Guaranteed Value^{TM} Gallon Storage Bags, available at Giant® Food Stores) made from 25 μm thick polyethylene, (2) 3.8 L press-seal bags (Ziploc® Double Zipper Storage Bags) made from 100 μm thick polyethylene; and (3) condoms (LifeStyles®) made from 65 μm thick latex. Gallon-sized

(3.8 L) polyethylene bags are commonly attached to 57 cm diameter seepage meters to capture SGD in nearshore waters [e.g., *Cable et al.*, 2006], while condoms are commonly attached to 10 cm or smaller diameter seepage meters to capture groundwater discharge in rivers [e.g., *Fryar et al.*, 2000]. The bags and condoms were submerged in a water tank, air bubbles were removed, and then they were attached to a 1 m long, 0.95 cm inner diameter (ID) PVC inlet tube. The open ends of the twist-tie bag and the condom were collapsed around the inlet tube and tied watertight, creating folds in the walls of the bag. The seal of the press-seal bag was closed, and the bag was attached to the inlet tube through a barbed fitting placed in an inside corner of the bag, minimizing folds in the walls of the bag. The opposite end of the water-filled inlet tube was mounted beside the tank so that the pressure within the submerged bag could be read as a water height in the tube outside the tank. With a second similarly mounted tube, the hydrostatic pressure of the tank could also be read. The bags were incrementally filled by adding water through the inlet tube to imitate gradual filling during a seepage meter deployment. The pressure required to introduce water to the seepage meter bag was the water height in the inlet tube minus the water height in the reference tube. To improve precision, 1.8 cm ID borosilicate glass tubes replaced PVC tubing at the point of measurement, at the test tank water level. The borosilicate glass minimized capillary effects and magnified an attached 0.5 mm graded ruler, allowing a resolution of less than 0.2 mm H$_2$O. For each type of collection bag, five identical trials, or filling sequences, were performed with a minimum of three different bags in order to test the reproducibility of the observed pressure differences.

2.2. Pressure Required by Dye Displacement

[7] The pressure required to force SGD into dye displacement seepage meters is given by the friction of laminar flow against the walls of the dye displacement tubing. This pressure was measured at different flow rates in the laboratory by generating steady, laminar flow through 2.2 m of a 0.95 cm ID flexible PVC tube. Measurements were made of the pressure loss as a difference in water height in attached tubes at the tube inflow and the tube outflow. The length of tubing used was greater than that used in field deployments of dye displacement seepage meters to more accurately quantify pressure differences. Laminar flows up to 130 cm^3/min were applied to generate pressure differences large enough to be consistently read. The observed pressure loss for laminar flow through PVC tubing was compared to the pressure loss predicted by *Poiseuille*'s [1846] equation for laminar discharge through smooth pipes,

$$\Delta P = \frac{8\mu QL}{\pi R^4}, \tag{1}$$

where ΔP is the pressure drop over the length of the tube, μ is the dynamic viscosity evaluated at the temperature of the flowing water (20°C), Q is the volume discharge, L is the length of the tube, and R is the inner radius of the tube.

[8] The laminar displacement of dye along the centerline of a tube connected to a seepage meter can be used as an effective measure of discharge. For laminar flows through pipes or tubes, friction with the wall creates a parabolic

velocity profile, with the maximum velocity along the centerline of the tube and zero velocity at the wall [*Kundu and Cohen,* 2004]. The velocity profile of laminar flow through a tube, integrated over the cross section, gives the volume discharge,

$$Q = \frac{\pi R^2 V_{\max}}{2},$$ (2)

where $V_{\max}$ is the centerline velocity. To determine the rate of SGD to the seepage meter, the volume discharge is divided by the area of the seepage meter. The precision of this approach was investigated in controlled laboratory trials. Continuous discharge at a range of $0.25-5$ cm^3/min was generated in a 2.2 m long 0.95 cm ID tube. These flow rates correspond to $2-40$ cm/d of SGD to a 15 cm diameter seepage meter. A 2.5% solution of Rhodamine WT dye (Bright Dyes® Liquid Red FWT 25, Kingscote Chemicals), with density reduced to 1.0 g/cm^3 with methanol to match the density of pure water, was injected in the upstream end of the tube. The displacement of the leading edge of dye along the centerline was measured at time intervals of $3-8$ min, depending on the discharge rate, giving three or four successive dye displacement measurements for every injection. Discharge from the tube was concurrently collected to determine the actual discharge rate. Centerline dye travel time and distance were used to quantify discharge through the tube according to equation (2). The maximum dye travel time through the tube was 32 min, and maximum total distance was 130 cm. Successive measurements were made to examine how the reproducibility of the dye displacement method was affected by travel time and distance.

2.3. Groundwater Diversion Model

[9] To determine if the pressure required to introduce water into a seepage meter bag or a dye displacement tube could divert groundwater, we developed a two-dimensional model of the groundwater flow into and around seepage meters. Cylindrical coordinates were used to take advantage of the symmetry around the central, vertical axis of the seepage meter (Figure 2). By combining Darcy's law and a mass balance for water we obtained the equation

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rK\frac{\partial h}{\partial r}\right) + \frac{\partial}{\partial z}\left(K\frac{\partial h}{\partial z}\right) = 0,$$ (3)

where r is radial distance, K is hydraulic conductivity, h is hydraulic head, and z is vertical distance. The equation was discretized following a control volume approach [*Patankar,* 1980] and solved using MATLAB® computational software.

[10] The horizontal extent of the calculation domain was to a distance of 5 times the seepage meter radius (Figure 2). Similarly, the vertical extent was to a depth of 5 times the penetration depth of the seepage meter, which was assumed to be equal to its radius. The boundary conditions imposed in the model (Figure 2) allowed no flow into or out of the model domain through the inner or outer vertical boundaries, and no flow was allowed across the seepage meter wall. Known, uniform, upward directed SGD was imposed through the lower boundary. A pressure was imposed at the upper boundary inside the seepage meter (P_{seep} in Figure 2) according to the results of laboratory testing of seepage
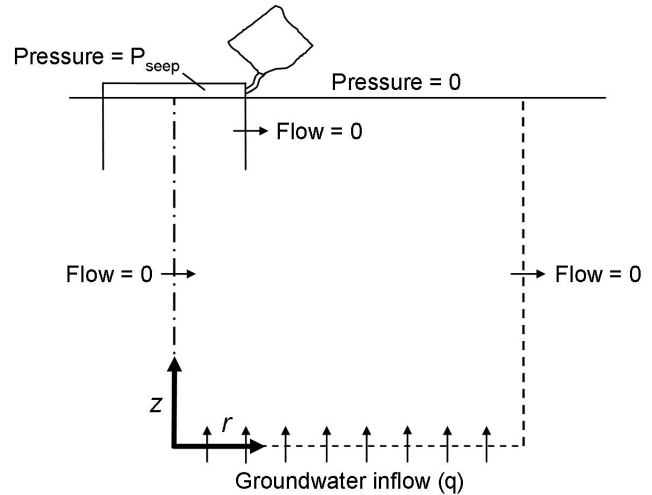

Figure 2. The domain and boundary conditions for the model used to solve the Darcy equation in cylindrical coordinates.

meter bags and dye displacement tubing. Outside the seepage meter the pressure at the upper boundary was set to zero. The hydraulic conductivity of sediments did not vary in the z or r directions. The model domain was separated into 40,000 (200 × 200) equally sized control volumes.

[11] The model, the appropriate location of the boundaries, and the control volume size were tested as follows. To confirm that mass was conserved as expressed in equation (3), it was confirmed that the integration of the imposed inflow along the bottom boundary exactly matched the integration of the calculated outflow along the top boundary. The latter included both the seepage meter and the adjacent free surface (Figure 2). Further, the boundary conditions were temporarily manipulated in two separate tests to give one-dimensional flows, first along the r axis and then along the z axis. For each of these unidirectional flows, analytical solutions exist and exactly matched the model results. Tests incorporating greater control volume density and model domain size yielded small changes in model results, indicating that the model was adequately dimensioned.

[12] For the model analysis, groundwater discharge through the base of the domain was varied between 0.1 and 100 cm/d, and the hydraulic conductivity of the domain was varied between 10^{-3} and 10^{-5} m/s. Beach sands typically have hydraulic conductivities between 10^{-3} and 10^{-4} m/s [e.g., *Urish and McKenna,* 2004]. For each measurement system the predicted diversion around large (57 cm diameter) seepage meters was compared with the predicted diversion around small (15 cm diameter) seepage meters to investigate the range of appropriate field conditions for deployment. The seepage meter error due to diversion was defined as the difference between the unrestricted groundwater flow into a seepage meter and the predicted groundwater flow, divided by the unrestricted groundwater flow.

[13] An additional model analysis was conducted to predict the cumulative diversion of groundwater around a seepage meter due to the increase in pressure within seepage meter bags as they fill. With a fixed SGD rate of 10 cm/d,

the filling rate of seepage meter bags during a deployment could be predicted on the basis of laboratory measurement of the pressure within bags at incremental fill volumes. Predictions of the filling rates were made in 200 mL increments for polyethylene bags and 20 mL increments for condoms from their prefill volumes up to their capacities. At each incremental fill volume the known volume of SGD was compared to the predicted volume within the bag to calculate the error of SGD measurement. Polyethylene bags were assumed to be prefilled with 1 L of water [*Shaw and Prepas*, 1989], and condoms were assumed to be prefilled with 20 mL of water. Predictions were made for polyethylene bags attached to large and small seepage meters and for condoms attached to small seepage meters. Sediment hydraulic conductivities of 10^{-3} and 10^{-4} m/s were tested.

2.4. Seepage Meter Design

[14] Large (57 cm diameter) and small (15 cm diameter) seepage meters were constructed from 208 L (55 gallon) steel drums and size 10 "coffee" (3.2 L) tinplate food service cans, respectively (Figure 1). The large seepage meters were cut to a height of 32 cm and the small seepage meters were cut to a height of 12 cm, allowing them to penetrate sediments to the depth of the seepage meter radius, as recommended by *Murdoch and Kelly* [2003]. Two ports were inserted in each seepage meter, a larger one at the center of the top for water expulsion during installation and a smaller one immediately below the rim to attach fittings for bags or dye displacement tubing. Press-seal bags (3.8 L) were used on both sizes of bag-equipped seepage meters. PVC tubing connected bags to seepage meters and was attached to the bags by insertion over a barbed fitting placed in the inside corner of the bag to minimize constriction of the bag.

[15] The seepage meters to be used for dye displacement were connected to clear, flexible PVC tubes (Figure 1). A 1.9 cm ID, 1.5 m long tube was attached to the large seepage meter and a 0.95 cm ID, 1.25 m long tube was attached to the small seepage meter. Meter sticks with millimeter markings were fastened to the dye displacement tubes to measure precise dye displacement distances (Figure 1). Rhodamine WT dye, in the xanthene family of dyes, was selected to indicate displacement because it is readily available, is highly visible in water, and has low toxicity [*Flury and Wai*, 2003]. The density of the dye is 1.03 ± 0.05 g/cm^3 at 25°C, close to the density of seawater. To more closely approximate the density of ambient water, 1 mL of 2.5% liquid Rhodamine WT dye was mixed with 4 mL of ambient water in a 5 mL syringe. The syringe needle was bent to approximately a 90° angle and inserted through the tube wall, allowing the syringe to be secured alongside the dye displacement tubing with the needle in place for multiple injections. Dye was typically injected at the 20 cm mark to allow measurement of dye displacement away from or toward the seepage meter, indicating groundwater discharge or inflow of overlying water, respectively.

2.5. Intercomparison of Seepage Meter Methods

[16] We conducted field trials of bag-equipped and dye displacement seepage meters of both sizes (57 and 15 cm diameter) positioned side by side at Sand Hill beach at the southern end of the Delmarva Peninsula on the Chesapeake Bay (37.2053°N, 76.0124°W), on 10 December 2008. The

beach was composed of clean, medium-grained sands. Pore water samples were collected from 10 cm below the sediment surface with a 2.4 mm diameter pore water probe [*Berg and McGlathery*, 2001], and salinity, defined as the conductivity ratio of a seawater sample to a standard KCl solution, was analyzed with a refractometer. The minimum pore water salinity was detected in a shore-parallel zone just offshore of the observed low-tide mark. A total of 16 seepage meters, 8 large and 8 small, were deployed in a shore-parallel line in that zone. In each size group, four seepage meters were equipped with 3.8 L press-seal bags and four were equipped with dye displacement tubing. Large seepage meters were deployed 50 cm apart, and small seepage meters were deployed 20 cm apart. The type of seepage meter alternated between bag equipped and dye displacement from seepage meter to seepage meter along the beach.

[17] Rates of SGD were determined after allowing 1 h of equilibration following seepage meter deployment. Approximately hourly SGD measurements were made from 1100 local time (LT) until 1600 LT, which included low tide at 1245 LT. Seepage meter bags, prefilled with 1 L of surface water, were connected for 30 min before they were replaced. Dye displacement readings were made in the interim and took less than 15 min to complete. At 1500 LT the bag-equipped seepage meters were switched to dye displacement measurement and vice versa. Water depth was logged every 10 s by an acoustic Doppler velocimeter (Vector, Nortek-AS, Norway).

2.6. Dye Displacement Measurement of Tidally Forced SGD

[18] To further examine the ability of dye displacement seepage meters to measure a tidal response in SGD, a second field trial was conducted using 12 small (15 cm diameter) dye displacement seepage meters at Sand Hill beach on 10 February 2009. Pore water samples were collected with a 2.4 mm diameter pore water probe [*Berg and McGlathery*, 2001], and salinities were determined with a refractometer. Seepage meters were deployed in a subtidal grid with three seepage meters in each of four alongshore transects. Seepage meter transect 1 was placed parallel to shore 1.5 m offshore of the observed low-tide mark, in a zone where the minimum pore water salinity was observed. Transects 2, 3, and 4 were placed 1.5, 3, and 4.5 m offshore of transect 1, respectively. Seepage meters within each transect were placed 2 m apart.

[19] Starting 1 h after seepage meters were deployed, 16 sets of dye displacement SGD measurements were made (total of 186) between 0930 and 1800 LT. This interval included high tide at 0930 LT and low tide at 1520 LT. Dye displacement measurements were initiated by injecting dye into every dye displacement tube in succession, then recording individual dye displacement distances. The maximum time interval between SGD measurements was 70 min, and the minimum was 10 min. To obtain an indication of marine and terrestrial contributions to SGD, pore water samples were taken from each of the 4 seepage meter transects at 6 time intervals for a total of 24 observations. Water depth was logged every 10 s by an acoustic Doppler velocimeter (Vector, Nortek-AS, Norway). The tidal range was 1.00 m.

3.   Results

3.1.   Pressure Required by Seepage Meter Bags

[20]   Filling sequences of seepage meter bags in laboratory tests showed that as a bag fills, the pressure within the bag incrementally increases (Figure 3), requiring greater pressure for additional water to be added. As a result, an increasing amount of groundwater can be diverted around the seepage meter, increasing the bias of SGD measurement. Empty polyethylene bags had a lower pressure than the hydrostatic pressure in the tank, consistent with the anomalous filling of empty seepage meter bags in stagnant water and the recommendation of *Shaw and Prepas* [1989] to partially fill them before use. However, at volumes of 200 mL in twist-tie bags and 400 mL in press-seal bags, the
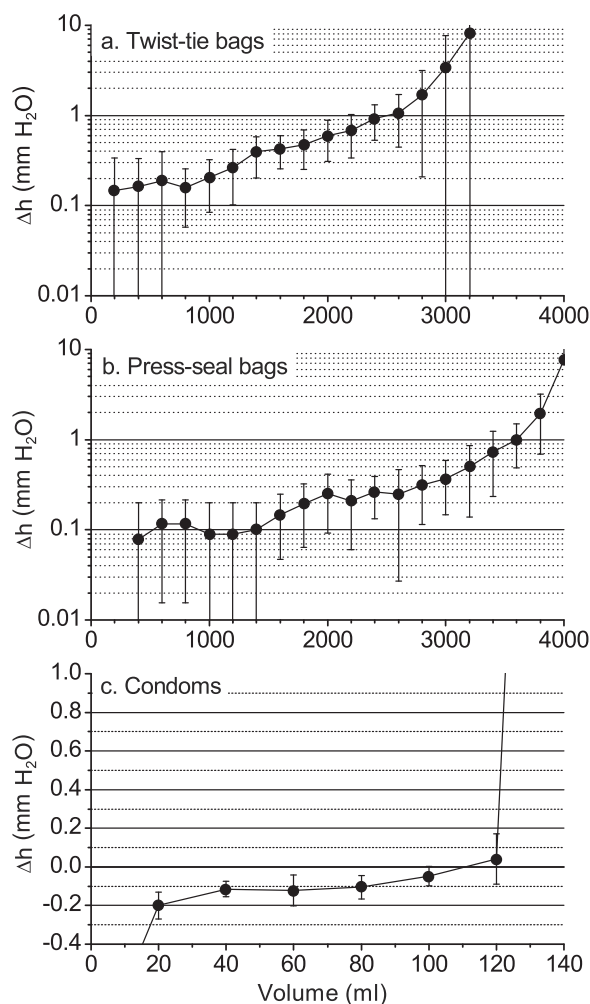
pressures within the bags exceeded the hydrostatic pressure within the tank (Figures 3a and 3b). At partial fill volumes between 1 and 2 L, there were 0.2–0.6 mm H_2O of pressure in the twist-tie bags and 0.1–0.3 mm H_2O of pressure in the press-seal bags. More pressure was observed in the thin-walled (25 μm) twist-tie bags than the thick-walled (100 μm) press-seal bags, in spite of wall thickness. *Murdoch and Kelly* [2003] also examined the pressure required to introduce water to seepage meter bags and found that the average pressure required to force flow into 25 μm nylon-polyethylene bags was 0.5 mm H_2O.

[21]   In contrast to polyethylene bags, the pressure within condoms at partial fill volumes was lower than that of the surrounding water in the test tank (Figure 3c). Specifically, relative to the test tank the pressure was −0.2 to −0.05 mm H_2O at partial fill volumes of 20–100 mL (Figure 3c). At a volume greater than 120 mL the inelastic threshold was reached, and the pressure within the condoms exceeded hydrostatic pressure within the test tank. These observations indicate that during a deployment on a seepage meter, condoms could draw in water until they reached capacity and thus could overestimate SGD. Our observations support *Schincariol and McNeil* [2002], who observed that under stagnant conditions in a test tank, condoms attached to seepage meters gained 43 mL of water over 9 h. They attributed this effect to the mechanical relaxation of the condom after it has been collapsed for attachment to the seepage meter.

3.2.   Pressure Required by Dye Displacement

[22]   The measured pressure needed to force laminar flow through dye displacement tubing was similar to the pressure predicted by equation (1), and the magnitude of it suggested that less pressure would be required to measure SGD with a dye displacement seepage meter than with a bag-equipped seepage meter. In laboratory observation, the pressure of the dye displacement method in mm H_2O (normalized to flow through 1.25 m of 0.95 cm ID PVC tube) was 0.0121 times the flow rate in cm^3/min ($n = 6$, $R^2 = 0.9444$). The equivalent prediction by equation (1) was 0.0107 times the flow rate in cm^3/min. The difference between them was possibly caused by a bend in the test tubing to make side-by-side measurements of the pressure difference between the inlet and outlet. As a result, equation (1) was used to predict the pressure needed to force flow through dye displacement tubing. On a large dye displacement seepage meter, with 1.5 m of 1.9 cm ID tubing, equation (1) predicted an operating pressure of 0.00142 mm H_2O times the groundwater discharge in cm/d. On a small seepage meter, with 1.25 m of 0.95 cm ID tubing, the predicted operating pressure was 0.00131 mm H_2O times the groundwater discharge in cm/d. At a SGD rate of 10 cm/d these operating pressures are close to one tenth the minimum operating pressures generated by partially filled polyethylene seepage meter bags (∼0.1 mm H_2O, Figure 3).

[23]   Laboratory testing of the dye displacement method indicated that the location of the leading edge of dye is a highly reproducible method for quantifying discharge (Figure 4). The comparison between discharge calculated from the dye displacement method and the actual discharge agreed, with a calculated rate of 0.9998 times the actual discharge rate ($R^2 = 0.998$). With a maximum time interval of up to 32 min between dye displacement readings and a
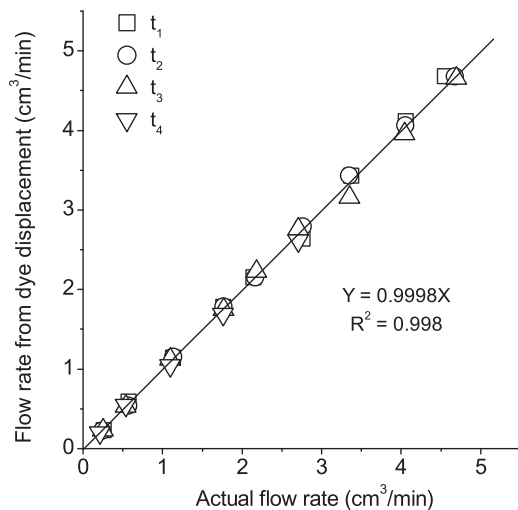

Figure 3.   The hydraulic pressure within seepage meter bags as a function of bag fill volume for three commonly used types of seepage meter bags: (a) polyethylene twist-tie bags, (b) polyethylene press-seal bags, and (c) latex condoms (note change in scale). Negative values indicate a lower pressure relative to the test tank. Each observation is the mean of five trials; error bars represent the standard deviation. At a groundwater discharge rate of 10 cm/d the fill rate for a bag attached to a 57 cm diameter seepage meter would be 1100 mL/h.

Figure 4. The volumetric flow rate calculated from displacement of the leading edge of dye as a function of the actual flow rate (0.95 cm inner diameter tube). Following dye injection, three to four successive observations of dye displacement were made ($t_1 - t_4$).

maximum distance of up to 130 cm, only small deviations from the actual discharge were observed. The average difference between the calculated discharge and the actual discharge was 2.6% ± 2.1% (standard deviation). This suggests that at these time and length scales the error due to dispersion of the dye is small.

3.3. Groundwater Diversion Model

[24] The mathematical model presented in Figure 2 allowed us to quantify the diversion of SGD around seepage meters as a function of the groundwater discharge rate, the seepage meter size, the sediment hydraulic conductivity, and the pressure required to force water into a seepage meter bag or through a dye displacement tube. In the first series of simulations, bag-equipped seepage meters were represented in the model by imposing a fixed pressure of 0.2 mm H_2O inside the top of the seepage meter, a representative pressure at a prefill volume of 1000 mL according to our laboratory tests of polyethylene bags shown in Figure 3a. Dye displacement seepage meters were represented in the model by setting the seepage meter pressure (P_{seep} in Figure 2) according to the relationships determined from equation (1), that is, 0.00142 mm H_2O times the SGD rate in cm/d for large seepage meters and 0.00131 mm H_2O times the SGD rate in cm/d for small seepage meters.

[25] The model predicted that the pressure required for groundwater to flow into a seepage meter bag can cause substantial diversion of groundwater around seepage meters under commonly encountered field conditions. Figures 5a and 5b give the model predictions as a function of groundwater discharge rates from 0.1 to 1000 cm/d and hydraulic conductivities from 10^{-3} to 10^{-5} m/s (typical of coarse, clean sands to silty sands, respectively [*Freeze and Cherry*, 1979]). The model predicted that bags attached to large seepage meters deployed in sands with a hydraulic conductivity of 10^{-4} m/s and a groundwater discharge rate of 1 cm/d would cause the diversion of 40% of groundwater around the seepage meter (Figure 5a). Similarly, the model pre-

dicted that bags attached to small seepage meters deployed in the same conditions would divert all groundwater around the seepage meter (Figure 5b). These model predictions are consistent with the unreliable performance of large seepage meters at discharge rates of 1 cm/d [*Cable et al.*, 2006].

[26] On the basis of observations of the lower pressure within partially filled condoms relative to the hydrostatic pressure of the test tank (Figure 3c) it is clear that condoms can cause an overestimation of SGD, as demonstrated by *Schincariol and McNeil* [2002]. The amount of this overestimation was evaluated with the model by imposing a pressure of −0.2 mm H_2O, suction, inside the top of the seepage meter (P_{seep} in Figure 2). The model predicted that because the magnitude of pressure was the same as that used for polyethylene bags (absolute value of 0.2 mm H_2O), the measurement error due to condoms would match those presented in Figures 5a and 5b but would be inverted, with error caused by SGD diversion into the seepage meter instead of diversion around it.

[27] The smaller pressure required to move water through the tubing in dye displacement seepage meters reduces seepage meter error significantly (Figures 5c and 5d). In addition, as the rate of SGD decreases, the friction of flow through dye displacement tubing decreases. As a result, the error of dye displacement measurement does not change with the rate of SGD. Figure 5c shows model predictions that frictional resistance to flow through a large dye displacement seepage meter deployed in sands with a hydraulic conductivity of 10^{-4} m/s will cause a groundwater diversion error of 0.3%. A small dye displacement seepage meter deployed in sands with the same hydraulic conductivity will cause a groundwater diversion error of 1% (Figure 5d).

[28] Furthermore, on the basis of our observations of the increase in pressure within seepage meter bags as they fill (Figure 3) we predict that total error due to groundwater being diverted around a seepage meter will increase with the volume collected in the attached bag. This was confirmed in the second series of model simulations in which these measured, increasing pressures were imposed. The errors shown in Figure 6 were calculated assuming a SGD rate of 10 cm/d and prefill volumes of 1000 mL in polyethylene bags and 20 mL in condoms. The model predicts that if the volume contained in a twist-tie bag when it is collected from a large seepage meter deployed in sands with a hydraulic conductivity of 10^{-4} m/s is 2.4 L, the measurement error is 9% (Figure 6a). If the bag were allowed to fill to a volume of 3.0 L, the predicted measurement error would increase to 19%. At volumes greater than 3.0 L we predict that the pressure within the bag would prevent further groundwater inflow. At a hydraulic conductivity of 10^{-3} m/s the model predicted that the hydraulic gradient driving groundwater flow at 10 cm/d would be incapable of adding groundwater to the bag at a volume of 2.0 L (Figure 6a). Because of the smaller pressures observed within press-seal bags (Figure 3b), those bags caused a smaller measurement error due to groundwater diversion as they filled (Figure 6b).

[29] In contrast to polyethylene bags, because of the low pressure within latex condoms relative to the test tank and the increase in pressure as they filled (Figure 3), the model predicted that the SGD measurement error will be smallest if condoms are collected containing a groundwater volume close to, but not exceeding, 120 mL (Figure 6c). Condoms
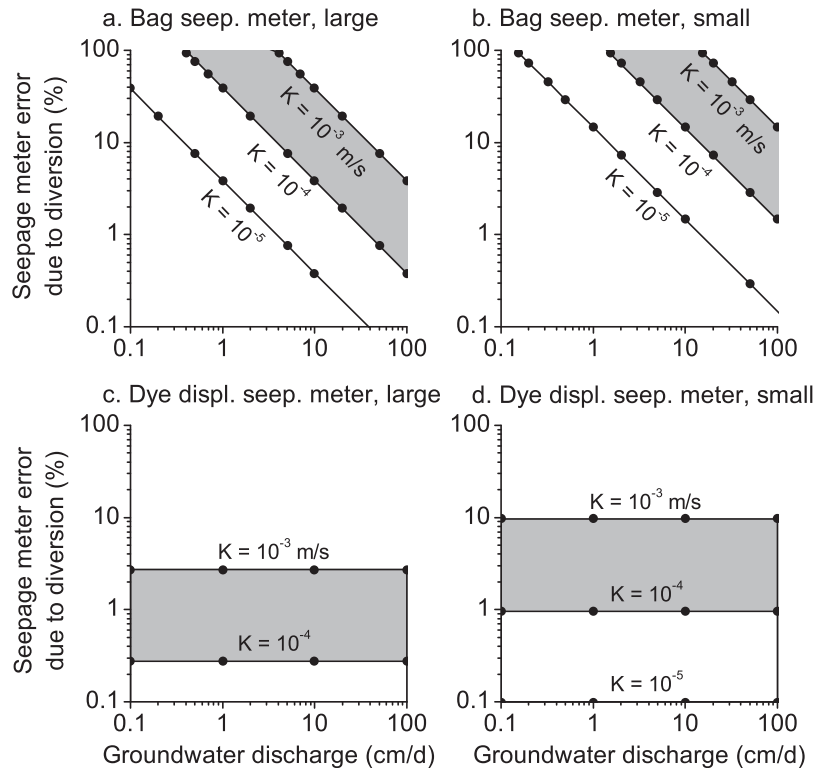
Figure 5. Model-predicted diversion of groundwater discharge around (a, b) bag-equipped seepage meters and (c, d) dye displacement seepage meters, plotted as a function of the groundwater discharge rate. Diversion around 57 cm diameter and 15 cm diameter seepage meters was predicted. The seepage meter error due to diversion was defined as the difference between the unrestricted and the predicted groundwater flow into a seepage meter, with the result divided by the unrestricted groundwater flow. At 100% error, no groundwater discharge would be detected. A hydraulic conductivity range typical of beach sands, 10^{-4} to 10^{-3} m/s, is shaded.

attached to small seepage meters in sands with hydraulic conductivities of 10^{-4} m/s and a SGD rate of 10 cm/d may have a measurement error of -12% at a fill volume of 40 mL (Figure 6c). The negative measurement error indicates that the predicted rate of groundwater flow into the condom exceeds the rate of SGD. At fill volumes greater than 130–140 mL, pressure within the condom prevented any further groundwater inflow.

3.4. Intercomparison of Seepage Meter Methods

[30] Field deployment of bag-equipped and dye displacement seepage meters side by side supported the model predictions that seepage meter bags can produce substantial SGD measurement error (Figure 7). Close to low tide, at 1205 LT, the large bag-equipped seepage meters (Figure 7a) recorded 48.1 ± 27.0 cm/d (mean and standard deviation, $n = 4$ seepage meters), while the large dye displacement seepage meters recorded a rate of 45.2 ± 11.0 cm/d ($n = 4$). In both sets of observations the tidal signal was evident, with a decline in SGD measured on the rising tide. Small, bag-equipped seepage meters did not reproduce the tidal signal clearly, recording 26.6 ± 37.8 cm/d ($n = 4$) at 1205 LT, and there was little evidence for an effect of tidal height on SGD (Figure 7b). Small dye displacement seepage meters performed similarly to the large seepage meters with an SGD rate of 52.6 ± 10.6 cm/d ($n = 4$) at 1205 LT and a decline in SGD on the rising tide. Integrated over the

5 h deployment, the small bag-equipped seepage meters measured 57% less SGD (Figure 7c), a significant difference (two-sample independent t test, $p = 0.001$). This apparent error is in line with model predictions. We did not determine the hydraulic conductivity at this site, but a typical range for beach sands is between 10^{-4} and 10^{-3} m/s [e.g., *Urish and McKenna*, 2004]. At an average SGD rate of 35 cm/d, in the middle of the hydraulic conductivity range of beach sands, the predicted measurement error caused by bags on small seepage meters at prefill volumes is 22% (Figure 5b). In the same conditions the predicted measurement error caused by bags on large seepage meters at prefill volumes is 5% (Figure 5a). Because the SGD rate observed was greater than that represented in Figure 6, the cumulative measurement error cannot be determined directly from it, but we would expect the error to be smaller than the errors presented there. The model predictions suggest that large bag-equipped seepage meters measured a similar rate of SGD as large dye displacement seepage meters because the hydraulic pressure of SGD overcame the pressure associated with the collection bags. This was less true of the small bag-equipped seepage meters.

3.5. Dye Displacement Measurement of Tidally Forced SGD

[31] The second field deployment at Sand Hill beach demonstrated the advantages in precision, sample rate, and
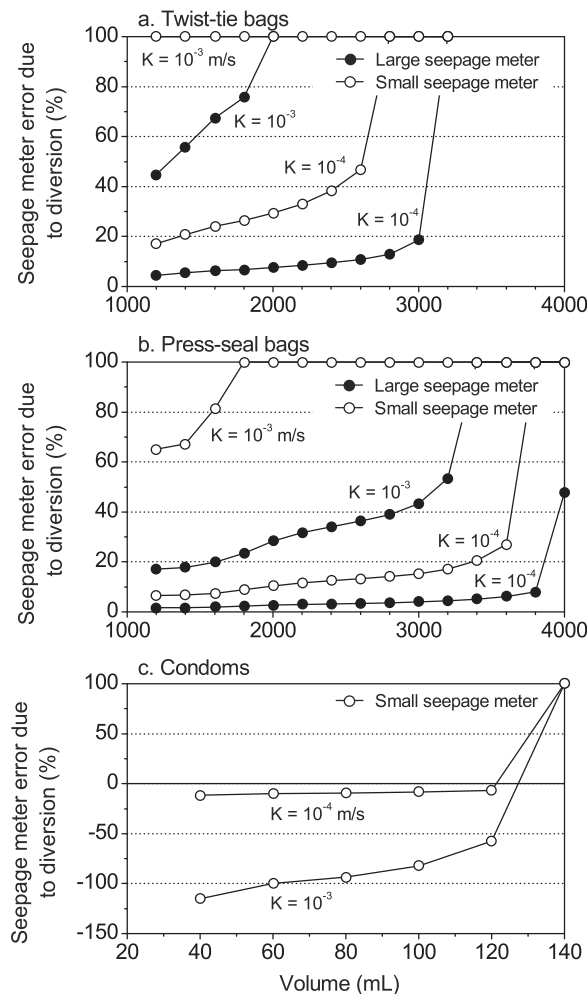
Figure 6. Model-predicted diversion of groundwater discharge as a function of bag fill volume at a groundwater discharge rate of 10 cm/d. Measurement error was predicted for (a) twist-tie bags, (b) press-seal bags, and (c) condoms attached to 57 cm diameter and 15 cm diameter seepage meters. Hydraulic conductivities were chosen to bracket the typical range of beach sands. Negative values indicate a greater measured rate of groundwater discharge than the actual rate.
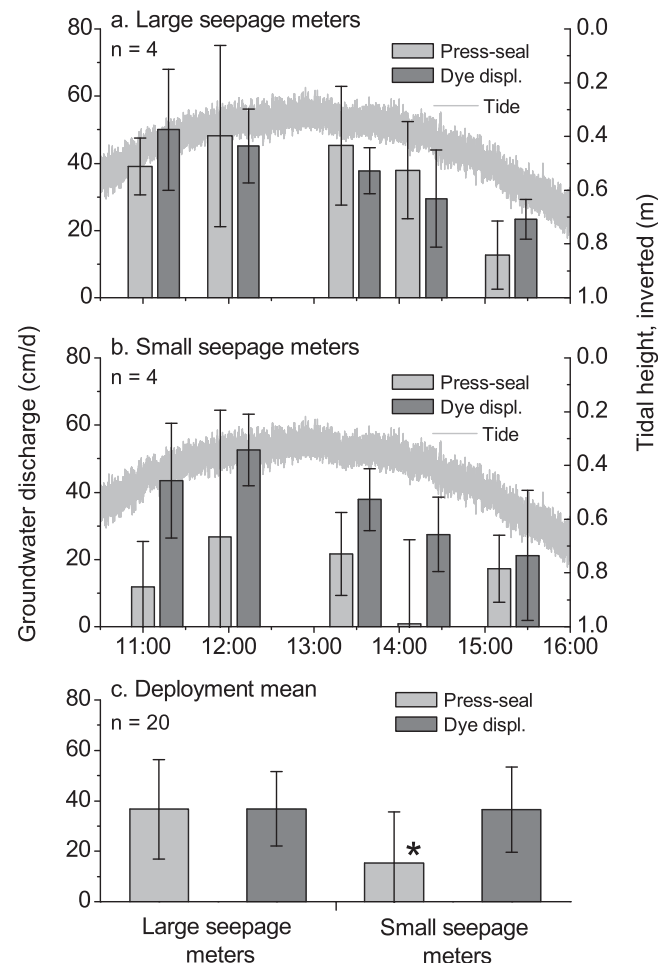
Figure 7. Intercomparison of groundwater discharge measured simultaneously with (a) 57 cm diameter and (b) 15 cm diameter seepage meters equipped with press-seal bags (light gray) or dye displacement tubing (dark gray). Bars are offset in time for clarity. Tidal height is inverted for comparison with groundwater discharge. (c) Means of each approach for the entire period. The asterisk denotes a significant difference in groundwater discharge for the small bag-equipped seepage meters ($p = 0.001$).

sensitivity of dye displacement seepage meters. Small dye displacement seepage meters were used to examine fine spatial-scale variation in SGD across a seepage face (Figure 8). Six measurements of SGD were conducted at high tide, constituting measurements from two seepage meters in each of transects 1 and 2 and additional measurements from one seepage meter in each of transects 3 and 4. These measurements showed a net inflow of overlying water into sediments (Figure 8, tide plot a) with a mean of -9.8 ± 5.4 cm/d (standard deviation). At 1200 LT, on the falling tide, nearly uniform discharge was observed in all four transects, with a maximum of 11.9 ± 0.9 cm/d in transect 1 and a minimum of 7.7 ± 3.1 cm/d in transect 3 (Figure 8, tide plot b). As the tide dropped, the rate of SGD increased to 56.1 ± 7.4 cm/d at transect 1 and increased slightly to 14.5 ± 1.4 cm/d at transect 4 (Figure 8, tide plot c). The maximum rate of discharge was observed in transect 1 at low tide with a SGD

rate of 78.8 ± 23.8 cm/d (Figure 8, tide plot d). On the rising tide the pore water salinity reached a minimum as the rate of SGD in transect 1 decreased to 20.5 ± 3.6 cm/d (Figure 8, tide plot e). A saline plume was identified in the upper intertidal zone, and with fresher pore water in the narrow subtidal zone covered by seepage meter transects 1 and 2, the overall pattern was consistent with the narrow, brackish SGD zone predicted by *Robinson et al.* [2007].

[32] The aggregate observations from transect 1, where the range of SGD rates was the greatest, are illustrated in Figure 9. Following high tide, at a tidal height of 0.9 m, the inflow of overlying water into sediments came to a halt. As low tide approached, the rate of groundwater discharge increased, generating a brief peak in discharge at 78.8 ± 23.8 cm/d (standard deviation) at low tide. The observation of inflow and the general pattern of the sharp peak in discharge at low tide were similar to observations made by automated seepage meters [*Paulsen et al.*, 2001; *Sholkovitz et al.*, 2003].
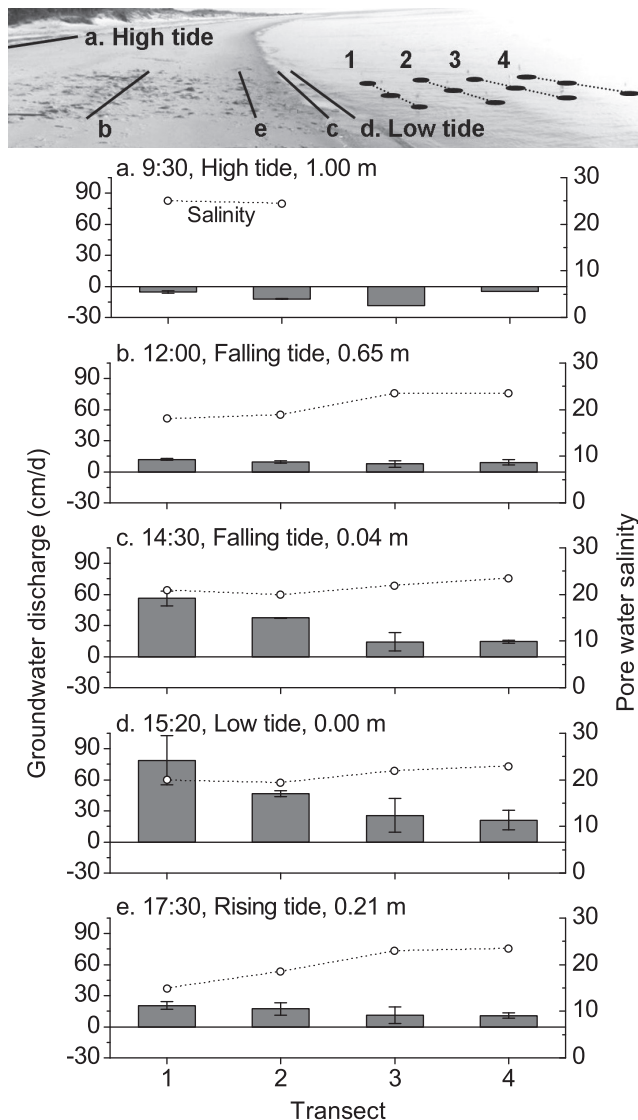
Figure 8. Tidal forcing of groundwater discharge measured with 15 cm diameter dye displacement seepage meters at Sand Hill beach, Virginia. The image at top indicates tidal positions and seepage meter transects 1 to 4. Tidal position plots show overlying water inflow to sediments at high tide (plot a) and the subsequent groundwater discharge on falling (b and c), low (d), and rising (e) tides. The salinity was 24 in overlying water.

Figure 9. Tidal forcing of groundwater discharge at transect 1 measured with 15 cm diameter dye displacement seepage meters ($n = 2$ before 1000 LT, $n = 3$ after 1000 LT). Tidal height is inverted for comparison with discharge. At low tide the pressure transducer was exposed to atmospheric pressure in wave troughs.

4. Discussion

[33] The laboratory test results for seepage meter bags suggests that bag thickness may not be the most important predictor of the pressures seepage meter bags impose on inflowing groundwater. Despite their thinner walls, a greater pressure was observed within twist-tie bags than within press-seal bags (Figure 3). This was possibly due to the method used for sealing the bag around seepage meter tubing. The opening of the twist-tie bags was collapsed around the tubing, reducing the maximum volume of the bag and creating multiple wrinkles and folds in the polyethylene. The press-seal bags, however, were attached throug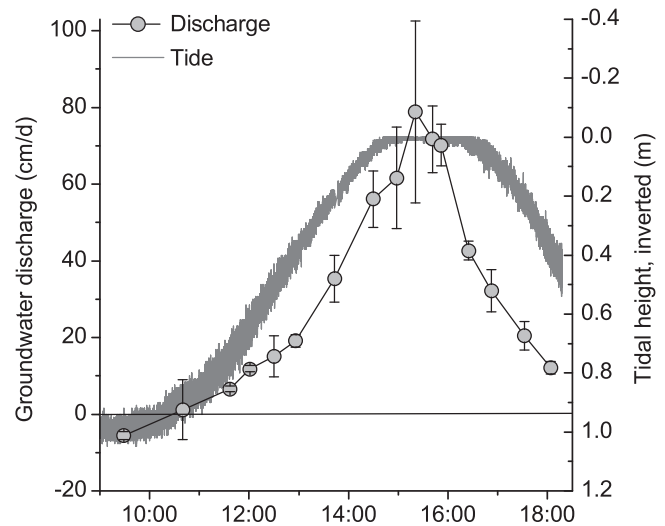h a barbed fitting to the seepage meter tube, minimizing constriction of the bag and the wrinkles that a constriction would create. The importance of wrinkles in polyethylene bags for generating resistance to inflow has been described previously [*Murdoch and Kelly,* 2003].

[34] The increase in SGD measurement error due to the increase in pressure within seepage meter bags as they fill has direct implications for seepage meter deployments. In ideal conditions (e.g., at hydraulic conductivities of 10^{-4} m/s or less and groundwater discharge rates of greater than 10 cm/d), polyethylene bags and latex condoms may generate a measurement error of less than 10% (Figure 6). However, as our results show, the error is highly dependent on hydraulic conductivity and groundwater flow rate. To reduce the error of SGD measurement with seepage meter bags, a thin-walled bag heat sealed along the open end, as employed by *Lee* [1977], may offer an improvement both in the increased capacity of a bag and in the reduced resistance to inflow that may be generated by folds in the walls. Additionally, if using polyethylene bags, a shorter time interval of SGD measurement to ensure that bag volumes do not approach capacity is likely to reduce the error of measurement (Figure 6).

[35] Because the pressure exerted by seepage meter bags on inflowing water is capable of causing significant measurement error in common field conditions, the dye displacement method of SGD can serve as a useful alternative. A comparison of the pressure required to introduce water into seepage meter bags (Figure 3) versus the pressure required to introduce laminar flow through dye displacement tubing, given by equation (1), demonstrates that at an SGD rate of 10 cm/d the pressure required for flow through dye displacement tubing is an order of magnitude smaller. Additionally, because the pressure required to make SGD measurements by dye displacement is a function of flow rate, the error of dye displacement measurement due to diversion will not change with SGD rate. This characteristic is shared among open path measurement systems, and

so we expect that the behavior of dye displacement would be similar to the behavior of far more expensive automated seepage meters.

[36] The groundwater diversion model confirms that the reduced pressure required by dye displacement improves the accuracy of SGD measurement in some common field conditions (Figure 5). If an acceptable amount of groundwater diversion due to measurement pressure in a seepage meter deployment is 10%, a large seepage meter equipped with a bag containing less than 2 L of groundwater would be restricted to measuring a minimum rate of 4 cm/d in sands with a hydraulic conductivity of 10^{-4} m/s (assuming a bag pressure of 0.2 mm H_2O; Figure 5a). However, a large dye displacement seepage meter would divert only 0.3% of groundwater at that site, regardless of the SGD rate (Figure 5c). Similarly, a small bag-equipped seepage meter would be restricted to measuring a minimum rate of 14 cm/d in sands with the same hydraulic conductivity (Figure 5b), while a small dye displacement seepage meter would divert less than 1% of SGD (Figure 5d). The diversion caused by the dye displacement measurement system could be further reduced with a small increase in the diameter of dye displacement tubing. A small increase will have a large effect on pressure because the friction of laminar flow within a tube predicted by equation (1) is inversely proportional to the tube radius raised to the fourth power.

[37] *Murdoch and Kelly* [2003] also developed a model of groundwater flow and diversion around seepage meters based on the pressure required to force groundwater into seepage meter bags. However, bag pressure in their model is represented as a linear function of the inflow rate, as a conductance, while we represented it as independent of flow rate, as a fixed pressure. Despite the discrepancies in formulation, the model predictions are similar. Our results support their assertion that seepage meter bags can cause the diversion of a substantial amount of SGD under common operating conditions.

[38] The results of the field deployments indicate that the dye displacement technique improves the sensitivity of seepage meters (Figures 8 and 9). In the second trial (Figure 9), dye displacement seepage meters detected patterns similar to those determined with far more expensive, open flow path automated seepage meters [e.g., *Paulsen et al.*, 2001; *Sholkovitz et al.*, 2003]. Specifically, dye displacement seepage meters measured inflow of overlying water into subtidal sediments at high tide and a sharp peak in SGD at low tide. These patterns are also predicted by numerical models of tidally forced SGD [*Robinson et al.*, 2007; *Maji and Smith*, 2009], yet reproducible observations of inflow into submarine sediments with bag-equipped seepage meters are less common [e.g., *Lee*, 1977]. We expect that an increase in the sensitivity of SGD measurement will lead to more common observations of this process.

[39] The dye displacement method allows a relatively high number of measurements per unit time. In this study, measurements of SGD through 12 dye displacement seepage meters were made at a rate of up to once every 10 min, for a total of close to 200 SGD measurements by two individuals in 8 h. The reduced time required for SGD measurement by dye displacement seepage meters allows more flexibility in sampling SGD at a greater spatial or temporal resolution than bag-equipped seepage meters. Addi-

tionally, the visual nature of the technique allows the use of submersible cameras for data recording, further reducing the time and effort required for SGD measurement.

[40] Dye displacement seepage meters offer advantages in measuring SGD, but there is work to be done to increase the range of applications in which they can be used. One area of work is in low-visibility water. We have performed dye displacement measurements of SGD with visibility as low as 40 cm, but visibilities in nearshore waters can be less than that. One approach to improve the usefulness of dye displacement in low-visibility waters is to use submersible point-and-shoot cameras, with submersible lights, which can be held within a few centimeters of tubing to capture images. Alternately, the ends of the tubing may be clamped, or closed, and the tubing carefully lifted to the surface for potential observation of dye displacement distances.

[41] Many other limitations of the dye displacement method match the limitations of traditional seepage meters. Substrate type, water depth, daylight, and currents affect the ease of use of all types of seepage meters. Rocky substrates are physically difficult environments in which to deploy seepage meters, and as water depth increases, the logistical demands of deployment also increase. Currents can have a substantial effect on the bags attached to seepage meters [*Libelo and MacIntyre*, 1994] and alter pressure gradients against the exposed surfaces of seepage meters. Dye displacement seepage meters should be used with care in environments with strong currents, at least until potential limitations have been investigated under such conditions. Shelters have been devised to minimize the effect of currents on seepage meter bags [*Libelo and McIntyre*, 1994], and the profile of seepage meters can be reduced to minimize the exposure of seepage meters to strong currents [*Rosenberry*, 2008]. We expect similar attention would lead to reproducible measurement of SGD by dye displacement seepage meters in high-current environments as well.

5. Summary

[42] Dye displacement seepage meters offer advantages over bag-equipped seepage meters in SGD precision, sample rate, and sensitivity for a similar construction cost. Their advantages are particularly noticeable at sites with high hydraulic conductivities (greater than 10^{-4} m/s) and low SGD rates (less than 10 cm/d). Furthermore, they are capable of measuring the inflow of overlying water into sediments, a trait that is typically reproduced only with far more expensive automated seepage meters.

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