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Seepage Meters and Bernoulli's Revenge

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ABSTRACT: Evaluation of seepage data from a network of 50 permanently deployed submarine seepage meters, specially constructed from fiberglass, indicates that the devices artificially advect (Bernoulli effect) shallow ground water. Reverse flow into the rock was not observed even when adjacent piezometers installed 2-m to 20-m below the rock-water interface indicated negative groundwater heads. Quantitative testing of five different designs, including conventional end-of-oil-drum designs, indicates that meters presenting positive relief on the sea floor are subject to the Bernoulli effect when placed in areas where there are waves and/or currents. Advection does not appear to be caused by flexing of the collection bags.

Introduction

Deployment of seepage meters in lakes, estuaries, and coral reef environments has increased significantly in recent years. Lee (1977, 1985) and Lee and Cherry (1978) pioneered seepage meter technology in freshwater lakes and estuaries while Simmons and Love (1984), Simmons (1986, 1992), Simmons and Netherton (1987), and Lewis (1987) applied the technology to marine and coral reef environments. The data obtained with seepage meters have been pivotal to the results of several recently published studies including those of Shaw and Prepas (1989), Shaw et al. (1990), Cable et al. (1997a,b), and Corbett et al. (1999), to name a few.

The most commonly used meters are constructed from the ends of standard 55-gallon steel oil drums. Drum ends are cut off 15 to 30 cm below the top and a threaded pipe nipple to which a flexible collection bag can be attached is screwed into the smaller of the two standard bungs. The thin metal skirt is forced into the sediment as far as possible to form a seal and reduce internal volume. As water seeps from the substrate into the void above the sediment, water is expelled through the bung into a flexible collecting bag. Collection bags are often pre-filled with a known volume of water, usually 1,000 ml (Shaw and Prepas 1989). Pre-filling reduces bag flexing and can be used as a measure of reverse flow into the sediment. After a predetermined time, the bags are removed and fluid volume is measured and/or chemical analyses are conducted. Seepage rates are calculated and generally presented as $ml^3\ m^{-2}\ min^{-1}$, $l\ m^{-2}\ h^{-1}$, or $l\ m^{-2}\ d^{-1}$. Taniguchi and Fukuo (1993) have developed an automatic seepage meter using a heat pulse and thermistors to measure flow through an outlet tube. A more elaborate advancement, Krupaseep (Krupa et al. 1998) consists of a relatively large polycarbonate dome, the bottom of which is forced into the sediment. This meter also measures flow using heat pulse technology.

The purpose of this paper is to report results from a series of tests conducted on three seepage meter designs. We also provide data from a large number of permanent meters previously placed in various environments in the Florida Keys. Our tests show that seepage rates from all existing designs should be viewed with caution.

Background

The experiments described here are an adjunct to a larger project aimed at determining lateral movement of ground water and vertical seepage into Florida Bay and the reef tract. The tests were conducted in the Florida Keys, Tampa Bay, and under controlled conditions in a wave-free test facility.

During the initial phase of the Florida Keys study, approximately 50 dome-shaped fiberglass seepage meters were permanently installed using hydraulic cement (Table 1). The meters were cemented to the porous Pleistocene limestone underlying Florida Bay. Numerous monitoring wells (piezometers), previously installed at depths ranging from 1 to 20 m below the rock-water interface, demonstrated pronounced tidally tuned groundwater-pressure fluctuations (Halley et al. 1994; Shinn et al. 1994, 1995, 1997, 1999; Reich et al. 2001).

Measurements of groundwater-pressure fluctuation were conducted with a simple diver-operated submarine manometer (Reich 1996). The manometer confirmed earlier digital recordings made with pressure transducers (Halley et al. 1994). Both methods revealed tidally tuned, semidiurnal reversing groundwater pressure heads ranging from as much as −30 to +30 cm relative to sea

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TABLE 1. Number and location of permanent fiberglass meters in the Florida Keys area. Meters are installed with hydraulic cement.

Seepage Meter	Location	GPS Coordinates
1–4, 9	Long Key Bayside, Keys Marine Lab	24°49.571′N 80°48.936′W
8	Long Key Oceanside	?
5–7, 10–13	Bayside Well Cluster-Key Largo	25°04.252′N 80°28.120′W
14, 15	Basin west of Pass Key	25°09.912′N 80°35.787′W
16, 29, 30	Nest Key Basin	25°08.653′N 80°29.616′W
17–22	Buttonwood Sound (Pleasant Point)	25°06.310′N 80°26.210′W
23–28	Sunset Cove, Buttonwood Sound	25°05.464′N 80°27.161′W
31, 32	Basin between Nest Key and Lake Key (31- Lake Key and 32- Nest Key)	25°08.646′N 80°31.683′W
33–35	Pickles Reef (North of Aquarius) #33 is cemented	24°59′28″N 80°24′22″W
36, 37	Sand Key Outlier Reef	?
38–43	Oceanside Well Cluster-Key Largo	25°03.990′N 80°27.941′W
44	23′7″ SE of Well M-2B (Mowrey Canal, Biscayne Bay)	25°28.475′N 80°20.106′W
45	Around Wells C-3 (Cutler, Biscayne Bay)	25°36.665′N 80°17.823′W
46	NE of Wells C-1.5 (Cutler, Biscayne Bay)	25°36.864′N 80°18.337′W
47–50	Just north of Port Largo Canal	?

surface. Fluctuations of this magnitude suggest significant groundwater flux at the submarine rock-water interface. Flux is retarded because the upper 1.5 m of limestone underlying Florida Bay is significantly less porous and permeable than the underlying rock (Shinn et al. 1994). Pressure heads below this relatively impermeable zone, as indicated by piezometers, cannot be used to calculate the actual volume of fluid passing through the rock-water interface. We therefore constructed special seepage meters that could be permanently attached directly to the limestone. End-of-drum meters that are forced into the sediment could not be used on rock. Approximately 75% of eastern Florida Bay bottom consist of bare limestone (Prager and Halley 1999). The carbonate mud comprising the remaining 25% of this area has extremely low permeability except where penetrated by open burrow tubes and seagrass holdfasts. Enos and Sawatsky (1981) measured permeability in seagrass-free Florida Bay muds as low as 0.1 millidarcy. Permeability of the underlying limestone is typically in the darcy range. Sixty long-lasting rigid fiberglass dome-shaped meters were constructed and ~50 were permanently installed using hydraulic cement (Table 1 and Fig. 1). Two-thirds of the meters deployed are located in Florida Bay and the remaining meters placed on the Atlantic Ocean side from nearshore hardbottoms out to the inner reef tract. Three were experimentally deployed offshore in a deep reef environment. Seven seepage meters were cemented to the bottom within an experimental circular well cluster located on the bay side of Key Largo, referred to as Bayside Well Cluster (BSWC). Six meters were deployed on the ocean side of Key Largo at a well cluster called Oceanside Well Cluster (OSWC; Fig. 2). These well clusters were designed to determine the direction and rate of groundwater flow (Reich et al. 2001).

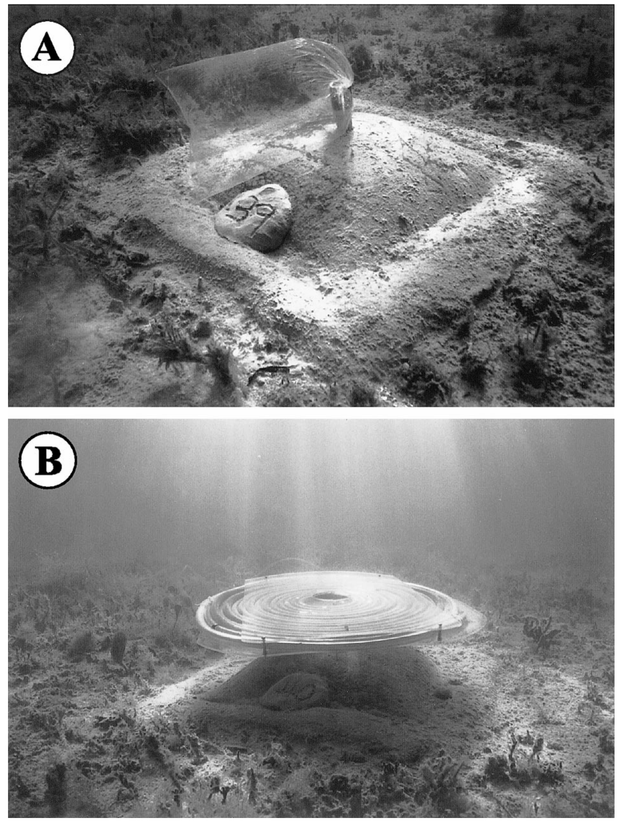

Fig. 1. (A) Permanently installed seepage meter (No. 39) with full collection bag attached to outlet port. Meters subsequently were grown over and encrusted, becoming virtually unrecognizable. (B) Seepage meter (No. 40) at Oceanside Well Cluster (OSWC) with collection system constructed from coiled tubing. Rhodamine dye was injected into meter before installation of tubing to outlet port. Dye flowed continuously. Clear water did not flow into meter even when all 18 piezometers located at this site indicated negative ground water pressure.

Initial seepage rates obtained from our network of meters indicated substantial local variations in flux (1 to 60 l m^{-2} d^{-1}) with a mean value of all meters at 15.1 l m^{-2} d^{-1} (Fig. 3). Repeated observations over a 6-mo period provided high rates of flux that supported the original purpose of the study. These measurements and observations never indicated reverse flow into the underlying rock

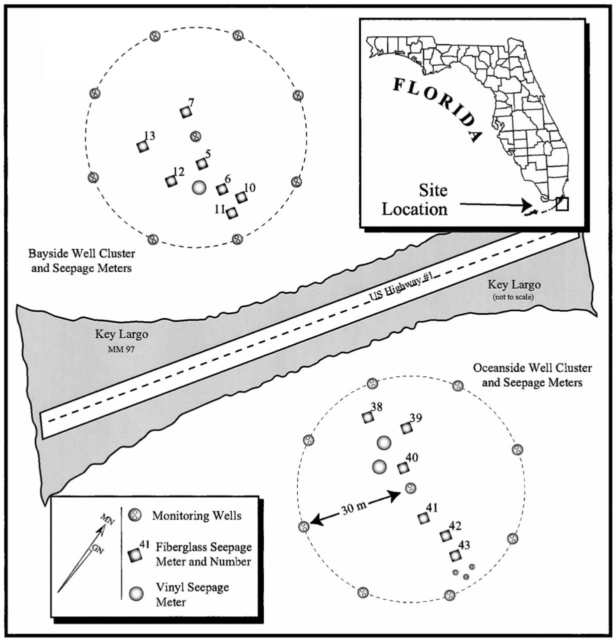

Fig. 2. Semi-schematic map of both bay-side and ocean-side well clusters (BSWC and OSWC) showing location of piezometers and seepage meters. Dyes and SF_6 tracer injected in the central well at each site showed that net groundwater flow is toward the Atlantic (Reich et al. 2001).

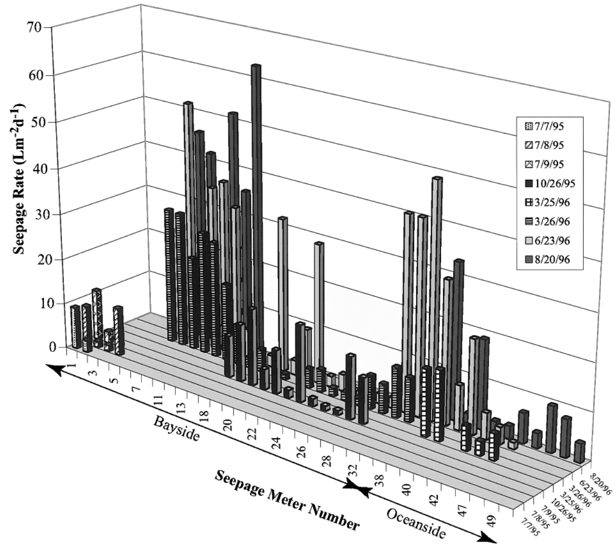

Fig. 3. Graph of seepage rates from all meters deployed on rock surface. Data is grouped for different times of collection. Seepage meter bags were collected after a 24-hour period and volume measured. Changes in rates most likely reflect differences in wind and wave height.

even when adjacent piezometers were showing negative pressure. Previous authors (Shaw and Prepas 1989) noted that flexing of collection bags might cause positive flow and suggested prefilling bags with a known volume of water. We did not employ prefilling but rather devised a system without bags to test if there was negative flow. Clear plastic tubing was coiled and sandwiched between Lucite plates and attached to the port of meter number 40 (Fig. 1b). Rhodamine dye was injected into the meter before attachment of the tubing to provide visual evidence of flow. The device was observed over a period of several hours during both rising and falling tides when adjacent piezometers indicated both positive and negative pressure. Dye-stained water was observed to completely fill the tubing and pour from the outlet after a few hours. Clear water did not enter the tubing, but outflow may have slowed, when adjacent piezometers were indicating negative groundwater pressure. This and other observations indicated the need to conduct simple tests and to experiment with alternative meter designs.

Methods

The precise nature of the mechanism that caused the bags to fill is still under consideration and it should be pointed out that the quantitative physics involved were beyond the purpose of this study. The primary goal of these experiments was to determine if seepage volume data obtained with seepage meters is reliable. We believe our simple tests indicate a relationship between seepage volume and wave height. Some pumping may result from bag flexing as suggested by Shaw and Prepas (1989) and is indicated by our wave-free experiments. The simple test with coiled tubing (Fig. 1b) where no bag was involved suggests that bag flexing is a minor problem. We did not attempt to partially fill the bags before conducting the experiments but our observations indicate that within a few hours many bags were partially filled and then continued to fill throughout the experimental period. We chose 24 h as the test period for convenience and as a way to average seepage over a period of time that incorporated at least 4 tidal changes. Six-hour intervals may have shown fluctuations in rate of flow while such a study may be worthwhile our original intention was to devise a system to obtain a long-term averaged rate of groundwater flux into the bay.

Experiments were conducted in sand filled containers with sealed bottoms at BSWC in Florida Bay and at OSWC on the ocean side of Key Largo (Fig. 2). Both sites consist of 9 piezometers arranged in circular clusters. Additional tests were later conducted in Tampa Bay and in a wave-free test facility that served as a control.

Key Largo Experiments

Tests were conducted at both BSWC and OSWC inside two, 30-cm-deep by 2-m-diameter plastic

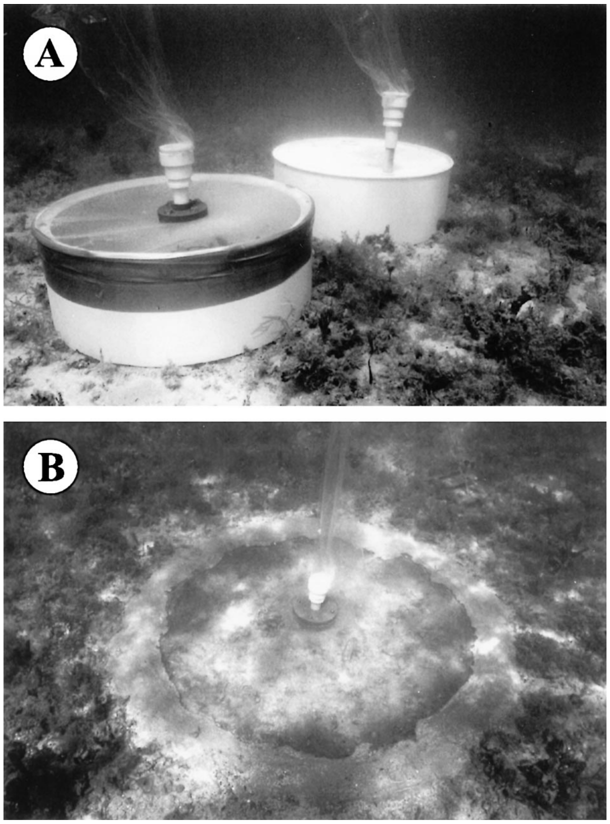

Fig. 4. (A) Two end-of-oil-drum meters resting on hard rock bottom at OSWC. Meter in foreground has flexible vinyl end with collection bag port installed in the center. Meter in rear (without vinyl end) is the design most commonly used in sediment areas. A third design, not shown, was constructed with the collection port attached to the side of the meter. (B) Clear vinyl meter at OSWC (1 m in diameter) cemented directly to bedrock with hydraulic cement. Note that the port and collection bag is mounted in the center.

swimming pools. The pools were placed on the bottom in 1.75 m of water and partially filled with commercial-grade, medium quartz sand. Three seepage meter designs were tested: a fiberglass dome like those previously installed in Florida Bay (Fig. 1a), a standard meter constructed from the end of a 55 gallon oil drum (Fig. 4a), and the end of an oil drum from which the end had been removed and replaced with a flexible vinyl cover (Fig. 4a). It was thought that a vinyl cover might flex with the passage of waves and prevent advection. All of the meters were fitted with a 2.5-cm I.D. PVC port 3 to 10 cm in length. A port assembly was mounted in the center of the vinyl cover on the oil drum meter. A 7.0-l clear-plastic basting bag was attached to the PVC ports as shown in Figs. 1 and 4. The bags were removed after 24 h and each 24-h test was conducted twice. The volume of fluid measured using a 2-l graduated cylinder was measured after each 24-h test. Conducting the test for 24 h was for convenience purposes. Any effect of negative groundwater pressure related to tidal fluctuation would not have been significant because tests were conducted within sealed containers. Any water entering or exiting the collection bags had to pass around the edges of the meters through the sand in which they were placed.

Test Facility and Little Bayou Experiments

Similar tests, using the same sand-filled plastic swimming pools were conducted at St. Petersburg, Florida. Tests were conducted simultaneously: on the bottom of a 2-m-deep wave-free freshwater test facility and in 2 m of water in a portion of Tampa Bay known as Little Bayou (27°43′N, 82°38′W). The two sites were approximately 500 m apart. Surface waves in Little Bayou were similar to those at BSWC. The tides in Little Bayou were diurnal but the range was similar to that at the OSWC site. There were no waves in the test facility. Pressure transducers were deployed in the test facility, Little Bayou, and a third was deployed in the air to record barometric pressure affecting both sites simultaneously.

Results

Key Largo Experiments

Water entered the bags on meters at both the OSWC and BSWC sites. The rate of flow was consistently higher at OSWC, a more exposed setting with higher waves and meter-range semi-diurnal tides (Fig. 5). The oil drum meter with flexible vinyl end produced the greatest flux at both sites. During two 24-h tests at the BSWC site where tides are minimal and the sea surface is generally calmer, the flexible meter collected between 15 and 18 l m^{-2} d^{-1}. The standard oil drum meter collected between 11 and 13 l m^{-2} d^{-1} and the fiberglass dome meter collected 7 and 9 l m^{-2} d^{-1}.

At the OSWC site the meter with the flexible end collected 37 and 43 l m^{-2} d^{-1} while the solid drum meter collected 22 and 26 l m^{-2} d^{-1}. The fiberglass dome meter collected 5 and 27 l m^{-2} d^{-1}. The fiberglass dome, identical to the 50 meters permanently installed throughout the Keys, advected the smallest volume of all the designs that were tested. The anomalous drop to only 6 l m^{-2} d^{-1} in the second test is thought to have been caused by twisting and partial obstruction of the collection bag at the point of attachment. The generally lower pumping rate of the fiberglass domes compared to those constructed from oil drums may be attributed to the 3-cm to 7-cm wide horizontal skirt that forms the base of the meter. We suspect the skirt created a more effective seal in the test sand than the other meters. Water would have to flow hori-

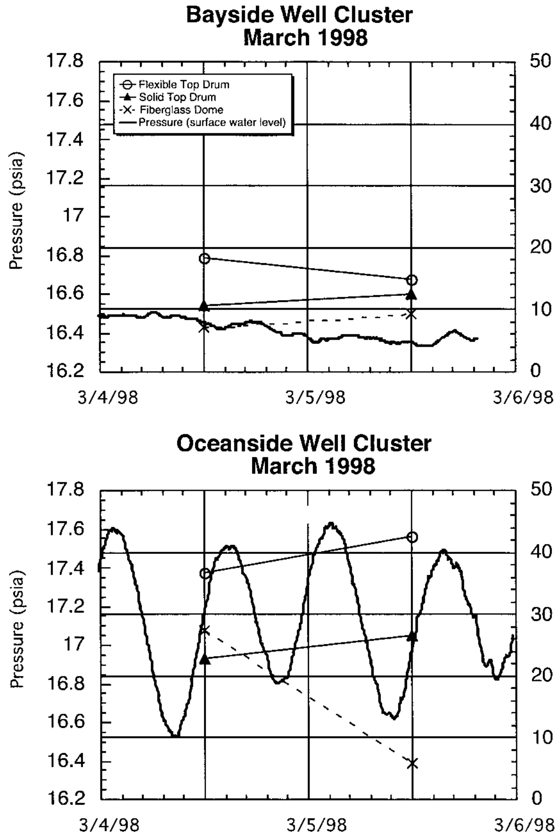

Fig. 5. Graphs of data from two 24-h seepage meter tests conducted in sand-filled plastic pools placed on the sea floor at BSWC and OSWC. Pressure curve from transducer at BSWC shows slight wind, wave, and tide changes and overall decrease in pressure, i.e., tide level. Note tide fluctuations shown by pressure curve at OSWC. At BSWC, the flexible top drum/meter the rate was reduced during second experiment while in the solid top drum and fiberglass dome meter the rate increased slightly. At OSWC, seepage rates in the flexible and solid top drums increased slightly while the fiberglass dome fell noticeably.

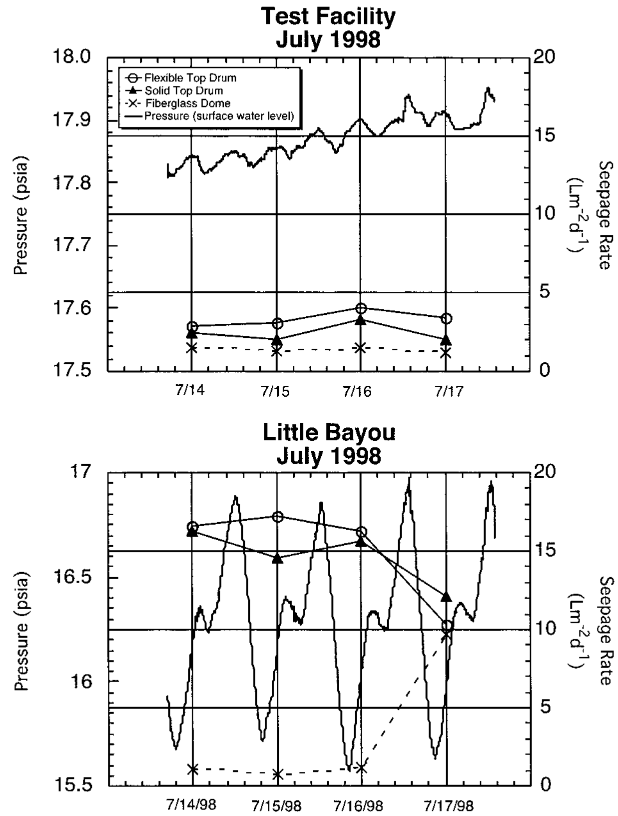

Fig. 6. Graphs of data from four tests of seepage meters in Little Bayou and the wave-free test facility. Rhythmic fluctuation in pressure in the test facility is due to barometric pressure change. Note higher rates in Little Bayou where there were waves and tidal fluctuations compared to tests in the wave-free and tide-free test facility.

zontally beneath the sand approximately 5 cm to enter the meter and reach the collection bag. The importance of these observations was an increase in flow rate within meters placed at OSWC where there are consistently larger waves and tidal fluctuation.

Test Facility and Little Bayou Experiments

Tests conducted in the test facility (no waves) when compared to those in Little Bayou (similar to OSWC described above) produced similar results. As mentioned earlier the tests were conducted using the same plastic child's play-pools that were used in the BSWC and OSWC site tests.

Four tests were conducted in the test facility and four tests were conducted in Little Bayou (Fig. 6). Note that the meter with the flexible top collected the largest volume of water. Even in the wave-free test facility the meter with the flexible end collected between 3 and 4 l m^{-2} d^{-1}. In Little Bayou, in the presence of waves and tides, the meter with the flexible end collected between 10 and 17 l m^{-2} d^{-1} during the same test period.

Other less rigorous observations support a relation between wave oscillation and advection. One fiberglass dome-shaped meter was permanently cemented to rock, and two were partially buried in a natural sand bottom at a deep forereef location several kilometers off the Florida Keys. Water depth was approximately 20 m. Waves and swells and a persistent current were present during the test period. Large custom-made polyethylene bags, 30 cm in diameter and 2 m in length, were deployed on all three meters. In all cases the bags were filled to maximum capacity (approximately 565 l) when they were collected after 24 h. The actual time required for them to fill was not determined.

Discussion

Flume experiments indicate that advection (i.e., the Bernoulli effect) is the most likely cause of the artificial pumping we observed and measured. Huettel and Gust (1992) and Huettel et al. (1996, 1998) showed that with flows of 10 cm s^{-1}, a rate insufficient to move sand grains, even the smallest topographic feature can induce upward advection of interstitial water. In experiments conducted by Huettel et al. (1996, 1998), Rhodamine dye in a horizontal layer below 2-cm to 3-cm high mounds of sand was advected upward into the mound. According to Huettel (personal communication), reversing orbital currents caused by waves can produce even greater advection than unidirectional flow. Libelo and MacIntyre (1994) had observed similar effects. These data and our observations and tests indicate that the positive profile of seepage meters, whether conical or constructed of oil drum ends, create an airfoil (Bernoulli) effect similar to the lift created by an airplane wing. The Bernoulli effect caused by orbital wave currents passing over the meters every few seconds probably account for most of the water in the collection bags. Bag design may have influenced the results of our study to some degree.

The flexible vinyl-top experiment was intended to allow flexing with the passage of each wave so as to translate external pressure to the inside of the meter (i.e., the sea floor within the meter would feel the same hydrostatic pressure changes as the sea floor outside). It is possible that the mounting of the port for the collection bag in the center of the vinyl top may have created additional pumping. In a related brief experiment, the port for the collection bag was attached to the side of the drum and a plastic cover, constructed of very thin more flexible plastic sheet was attached to the top such that it could flex and be independent of the outlet port. This design however did not appear to change the results. In two separate 24-h tests, the side-port meter pumped 3.2 l of water completely filling the collection bag used for this experiment. All of our tests suggest that protrusion of the meter above the bottom creates lift and that the collection bags are not the main problem.

Another test was conducted in which three 1-m diameter sheets of flexible vinyl were cemented directly to the bottom around the outer margin (Fig. 4b). These flexible meters (two were installed on the bottom at OSWC and one at BSWC) have a very low profile. These devices advected less water but were plagued by biogenic gas buildup. Gas raised the profile of the meter, and retarded flexing, which in turn led to enhanced advection. It also became apparent that even if there were significant seepage the meter would fill and create a dome, which in turn would create a wing-like profile that would enhance advection.

Two additional experiments were considered but not acted upon. The first consideration was to encase the entire meter in a cofferdam extending to the surface such that it would completely occlude orbital wave oscillation. It was considered impractical to deploy any devices that would be hazards to navigation in Florida Bay. If the work could be accomplished with a few meters, the approach may have merit. Because the karst limestone surface in Florida Bay is so variable, it was thought that installing several meters and recording many measurements were needed to get an accurate average measure of groundwater contribution to the overlying water column. The second approach would be to place a bucket over the collection bags. The approach would have the added effect of preventing curious fish from biting the bags, although we felt that buckets would add additional profile that might enhance Bernoulli advection.

Clearly natural advection of groundwater into the overlying water column is occurring because the sea floor contains a multitude of irregularities. Dye tracer experiments in the well clusters indicate that seepage is occurring (Reich et al. 2001).

It should be pointed out that standard end-of-oil-drum meters are useful and may be applied in areas free of currents and waves as well as in areas where there is a freshwater head created by nearby highlands. Water collected, even if advected by wave and current action, is nevertheless shallow ground water and useful for measuring nutrient levels and/or radiogenic tracers. Levels of radon may provide a first approximation calculation of seepage rates (Corbett et al. 1999). The actual rates of seepage remain to be determined. Determination of seepage rates is important but elusive. Seepage rate would be a valuable, if not a necessary, addition to any quantitative nutrient or hydrographic modeling effort in Florida Bay or elsewhere.

These relatively simple experiments indicate that volume data obtained from seepage meters installed in areas exposed to currents, waves, and ocean swells should be viewed with caution. Meters placed in wave-free lakes or marshes may perform as intended. To our knowledge, seepage meters have not been adequately tested and verified in these environments. Though we expect meters in wave-free areas to be relatively reliable, there is a possibility that oscillations in barometric pressure and/or other weather conditions could induce artificial flow.

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