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Spatial and temporal distributions of submarine groundwater discharge rates obtained from various types of seepage meters at a site in the Northeastern Gulf of Mexico

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Abstract. Direct measurements of submarine groundwater discharge (SGD) were taken by three different (continuous heat, heat pulse, and ultrasonic) types of automated seepage meters as well as standard Lee-type manually operated meters. SGD flux comparisons and the spatial and temporal variations in groundwater flow were analyzed. Seepage rates measured by the different meters agree relatively well with each other (more than 80% agreement). Comparisons of flux rates as a function of distance offshore using exponential approximations show that more than five measurement locations (200 m offshore) are needed for a precise integrated estimation of SGD offshore within an accuracy of ±10%. The dominant period of seepage variations is estimated to be about 12 hours, which closely matches the semidiurnal tides in this area. Our analysis also shows that short duration measurement periods may cause significant underestimates or overestimates of the daily averaged groundwater flow rates (±25%–±60% difference when the measurement duration is less than 12 hours). Thus, continuous measurements of SGD using automated seepage meters with high time resolution should enable us to evaluate temporal and spatial variations of dissolved material transports via groundwater pathways. Such inputs may affect biogeochemical phenomena in the coastal zone.

Introduction

Submarine groundwater discharge (SGD) is now recognized as a process which acts as a significant pathway for the transport of water and dissolved constituents from land to sea (Burnett 1999). Ecological effects in estuaries and the coastal zone depend on water quality which may be influenced by

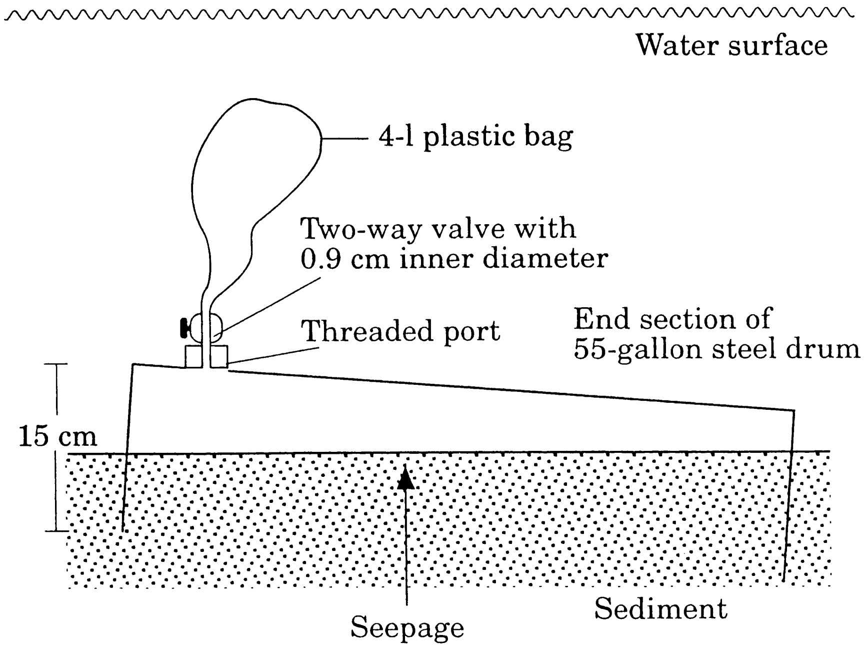

Figure 1. Lee-type manual seepage meter (modified from Lee 1977).

SGD (Johannes 1980; Simmons 1992; Moore 1999; Basu et al. 2001). Therefore, it is important to evaluate the fluxes and biogeochemical characteristics of the groundwater interfacing with ocean, because the location and volume of SGD may affect fauna and flora which live in these zones.

Dissolved material transport via SGD is based on the concentrations of the discharged water and the water flux rates. The former is relatively easy to evaluate, however the latter is very difficult to measure quantitatively. Methods that have been applied to evaluate SGD include tracers, piezometers, water balance calculations and modeling. However, the use of seepage meters is the only way to measure groundwater flux directly.

Measurements of groundwater seepage rates into surface water bodies are often made using manual "seepage meters." This device was first developed by Israelsen and Reeve (1944) to measure the water loss from irrigation canals. Lee (1977) designed a seepage meter consisting of one end of a 55-gallon (208 liters) steel drum that is fitted with a sample port and a plastic collection bag (Figure 1). The drum forms a chamber which is inserted open end down into the sediment. Water seeping through the sediment will displace water trapped in the chamber forcing it up through the port into the top plastic bag. The change in volume of water in the bag over a measured time interval provides the flux measurement.

Studies involving seepage meters have reached the following general conclusions (Taniguchi et al. 2002): (1) many seepage meters are needed because of the natural spatial and temporal variability of seepage flow rates (Shaw & Prepas 1990a, b); (2) the resistance of the flow tube (Fellows & Brezonik 1980) and bag (Shaw & Prepas 1989; Belanger & Montgomery 1992) should be minimized to the degree possible to prevent artifacts; (3) use of a cover for the collection bag may reduce the effect of surface water movement due to waves, currents or streamflow activity (Libelo & MacIntyre 1994); and (4) a seepage meter detection limit should be applied (Cable et al. 1997a). The problems using seepage meters are discussed in greater detail by Taniguchi, et al. (2003).

Despite these potential errors and detection limits as well as possible current-induced artifacts discussed by Shinn et al. (2002), a recent field evaluation of "Lee-type" seepage meters showed that consistent and reliable results can be obtained in coastal waters if one is aware of these potential problems (Cable et al. 1997a). This seems to be especially true in areas where flux rates are fairly high (>3 cm/day). Seepage meters are commonly employed in lake settings to determine groundwater – surface water interactions since the 1970s and are increasingly utilized in coastal marine environments for studies where simple, inexpensive methods are required.

The most serious disadvantage for evaluating SGD directly is that the traditional manual seepage meters are very labor intensive. In order to obtain the groundwater discharge rate automatically and continuously, various types of automated seepage meters have been developed. Installations of seepage meters remotely from the surface of various water bodies were attempted by Fukuo (1986), Cherkauer and McBride (1988), and Boyle (1994). Sayles and Dickinson (1990) constructed a seepage meter which consisted of a benthic chamber for the sampling and analysis of flow rates via thermal transport through sediments associated with hydrothermal vents. Flow meters based on ultrasonic measurements are also used to evaluate seepage flow (Paulsen et al. 2001). One example of such an automated approach for measurement of submarine groundwater discharge seepage is the heat-pulse device described by Taniguchi and Fukuo (1993) and a similar meter constructed by Krupa et al. (1998).

The purpose of this study was to evaluate seepage meter measurements by comparing discharge rates obtained from various types of seepage meters deployed in parallel. Improved measurements will assist the evaluation of dissolved material transport by SGD to the coastal zone. The second purpose of the study was to evaluate temporal and spatial changes in SGD rates for inter-scale issues.

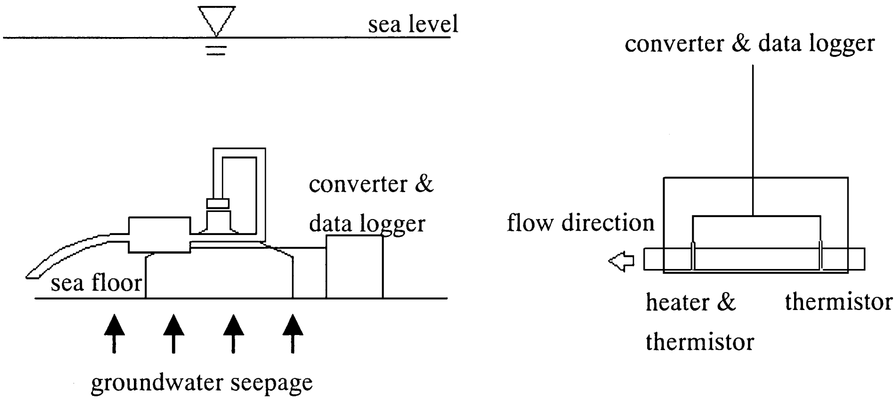

Figure 2. Continuous heat-type automated seepage meter (Taniguchi & Iwakawa 2001).

Description of automated seepage meters

Continuous heat-type automated seepage meter

A “continuous heat-type” automated seepage meter uses the effects of heat convection caused by water flow. The basis of the method is measurement of the temperature gradient between the downstream and upstream positions of the flow tube. The gradient is caused by continuous heat generated within the column (Figure 2). This method is the so-called “Granier method” (Granier 1985), and is used in many studys such as detecting water flux in trees (sap flow sensors). When there is no flow, the temperature difference in the column is maximum, and the temperature difference decreases with increasing the water flow velocity. After calibrating with known water flow velocities in the laboratory, the sensor is used to connect with a funnel (Figure 2). Measurements using this meter are based on the widely used technique of placing a chamber (area: 0.255 m^2) into the seabed to capture and concentrate submarine groundwater discharge. The sampling frequency and duration are programmed into a data logger. The meter is described in detail by Taniguchi and Iwakawa (2001).

Heat pulse-type automated seepage meter

The “heat pulse-type” automated seepage meter, which was developed by Taniguchi and Fukuo (1993) and improved by Krupa et al. (1998), is based on the travel time of a heat pulse using a string of thermistors in a column positioned above an inverted funnel covering a known area of sediment (Figure 3). The basis of the method is measurement of the travel time of a heat pulse generated within the column by a nichrome wire induction heater. Since

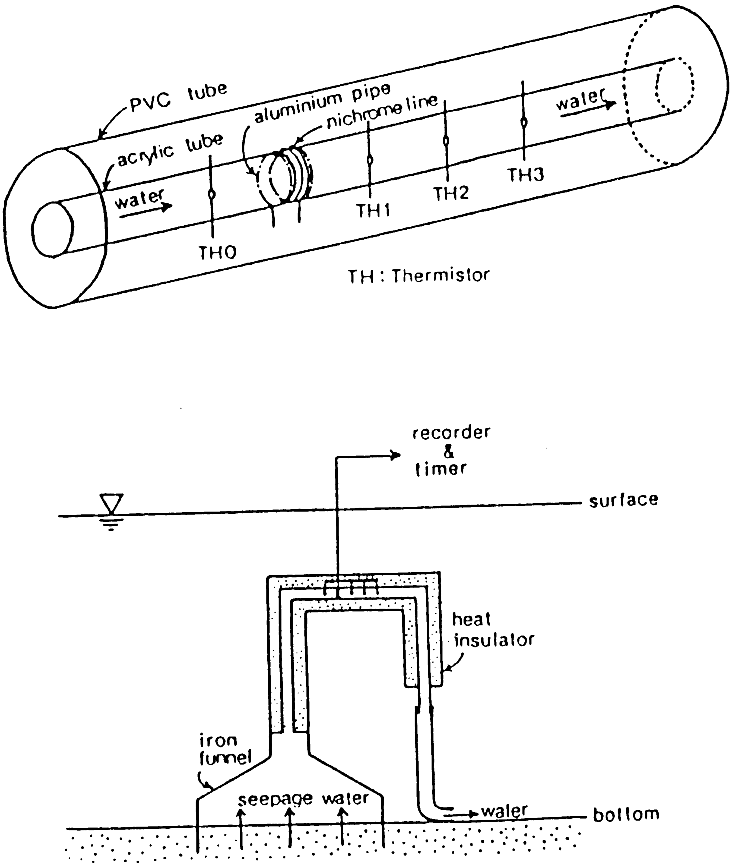

Figure 3. Heat pulse-type automated seepage meter (Taniguchi & Fukuo 1993, Figure is reprinted with the permission of publisher of Ground Water).

heat is a conservative property, the travel time is a function of the advective velocity of the water flowing through the column. Thus, once the system is calibrated in the laboratory, measurements of seepage flow at a field site can be made automatically on a near-continuous basis. The sampling frequency and duration are programmed into a data logger. The heat pulse-type seepage meter has successfully measured seepage up to several days at a rate of about one measurement every five minutes (Taniguchi & Fukuo 1996).

Ultrasonic-type automated seepage meter

An “ultrasonic-type” automated seepage meter uses the effect of the flow on the travel time of an ultrasonic signal as the basic for determining the flow rate (Paulsen et al. 2001). Figure 4 shows a cross section of the meter

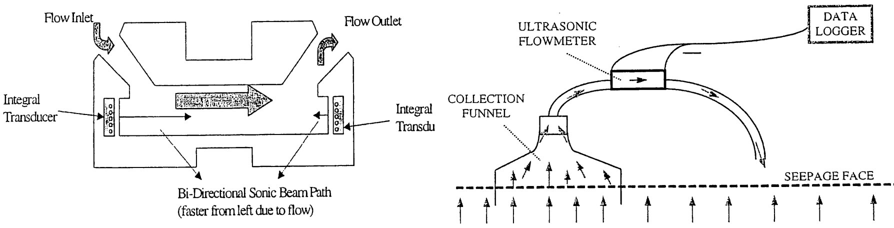

Figure 4. Ultrasonic type-seepage meter (modified from Paulsen et al. 2001).

indicating the flow of the sonic beam and positions of the non-intrusive transducers. A multi-pulse sonic signal is transmitted through the flow tube in both directions by transducers located at opposite ends. When there is no flow the signal will arrive at each transducer at exactly the same time. However, when there is flow in the tube upstream flow will cause the signal to arrive ahead of the signal traveling downstream. The difference in transit time between the two signals is directly proportional to the flow velocity. The constant of proportionality depends on: (1) the average of the upstream and downstream transient times; and (2) length of the tube. The sampling frequency and duration are programmed into a data logger and the system runs automatically thereafter. This meter can detect reversals in flow (recharge), and it includes a totalizer which acquires data on cumulative volume of water. Measurements using this meter are again based on placing a funnel (area: 0.5067 m^2) into the seabed to capture groundwater discharge.

Study area and experimental design

The study area is located in the north-eastern coastal Gulf of Mexico (Figure 5), an area well known for presence of seepage and submarine springs. This area lies within the Woodville Karst Plain, which extends from about 80 km inland to the coastal zone where the Florida State University Marine Laboratory (FSUML) is located at Turkey Point, Florida. The horizontal hydraulic conductivity of silty sand of the unconfined aquifer in the study area is estimated to range from 2×10^{-4} (3 m depth) to 6×10^{-3} (0.5 m depth) cm s^{-1} from slug tests (Rasmussen et al. 2003).

Twelve Lee-type manual seepage meters were installed along two transect lines which were set up normal to the shoreline (Figure 5). The measurement period for all seepage meters was from August 14 to 18, 2000. Five continuous heat-type automated seepage meters were set at stations Y1, Y2, Y3, Y4 and Y5. Unfortunately, the meters at Y1 and Y5 did not function because of problems with the connecting pipes and transducers. Therefore,

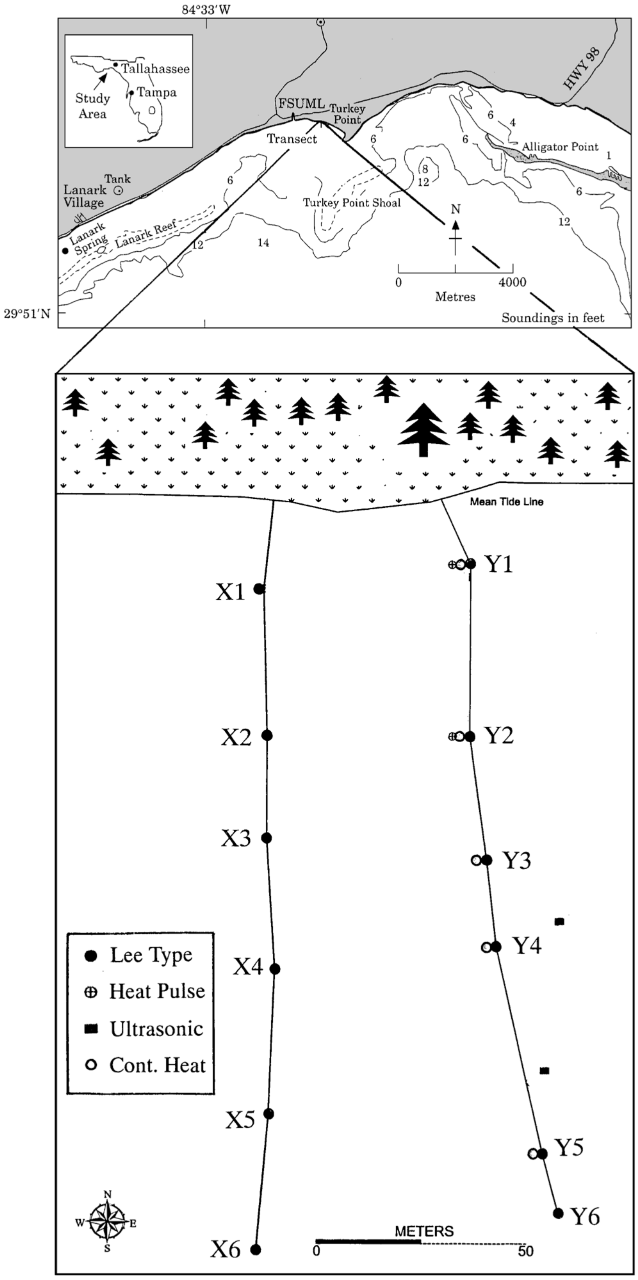

Figure 5. Study area and locations of seepage meters.

only SGD rates at Y2, Y3 and Y4 are analyzed for the continuous heat meters. Two heat pulse-type automated seepage meters were installed at Y1 and Y2. Unfortunately, the transducer in the meter at Y2 malfunctioned, so only data at Y1 was analyzed. Two ultrasonic-type automated seepage meters were deployed for various amounts of time at stations Y1, Y2, Y3, Y4A and Y4B.

Comparison of submarine groundwater discharge using various seepage meters

Figure 6 shows the daily averaged SGD rates observed using Lee-type manual seepage meters along transect lines X and Y. As can be seen, discharge rates have a general tendency of decreasing with distance away from the coast, which is consistent with theory (McBride & Pfannkuch 1975), and observation in lakes (Lee 1977; Fellows & Brezonik 1980; Shaw & Prepas 1990b) and marine systems (Bokuniewicz, 1980, Cable et al., 1997a). The seepage rates at X3 and Y4 do not fit the overall pattern, perhaps because of preferential flow caused by channeling. The observations are similar to those made previously at this site using manual seepage meters during August 1992 (22 cm/day at 100 m offshore and 3 cm/day at 200 offshore) and March 1993 (18 cm at 100 m offshore and 5 cm/day at 200 m offshore) by Cable et al. (1997a).

We assume that the discharge rates at each location represent the average value between the mid-observation-points (for example, SGD rates at X2 represent values from the mid-point between X1 and X2 to the mid-point between X2 and X3). The total integrated SGD rates (volume per unit width shoreline per unit time) along the two transect lines are then calculated and shown in Table 1 for each day. An estimate of the total discharge into the X-Y domain 100 m wide (along shore from X to Y transect line) by 200 m long (out to sea), is then made for each 24-hr period and also shown in Table 1.

Over the past few years, several studies have employed the use of natural uranium decay-series nuclides ^{226}Ra and ^{222}Rn to assess groundwater discharge into the ocean (Burnett et al. 1990, 1996, 2001; Moore 1996; Cable et al. 1996a, b). Ideally, in order to provide a detectable concentration, natural geochemical tracers should be greatly enriched in the discharging groundwater relative to coastal marine waters, conservative, and easy to measure. While radium and radon meet these criteria fairly well, other tracers exist which may be exploited for groundwater discharge studies. According to the SGD estimates using ^{222}Rn in the same domain, total groundwater fluxes were estimated to be 1.2, 1.2, 1.4, and 1.8 m^3 min^{-1} on August 14, 15, 16, and 17, respectively, by Lambert and Burnett (2003). Therefore, the estimations of

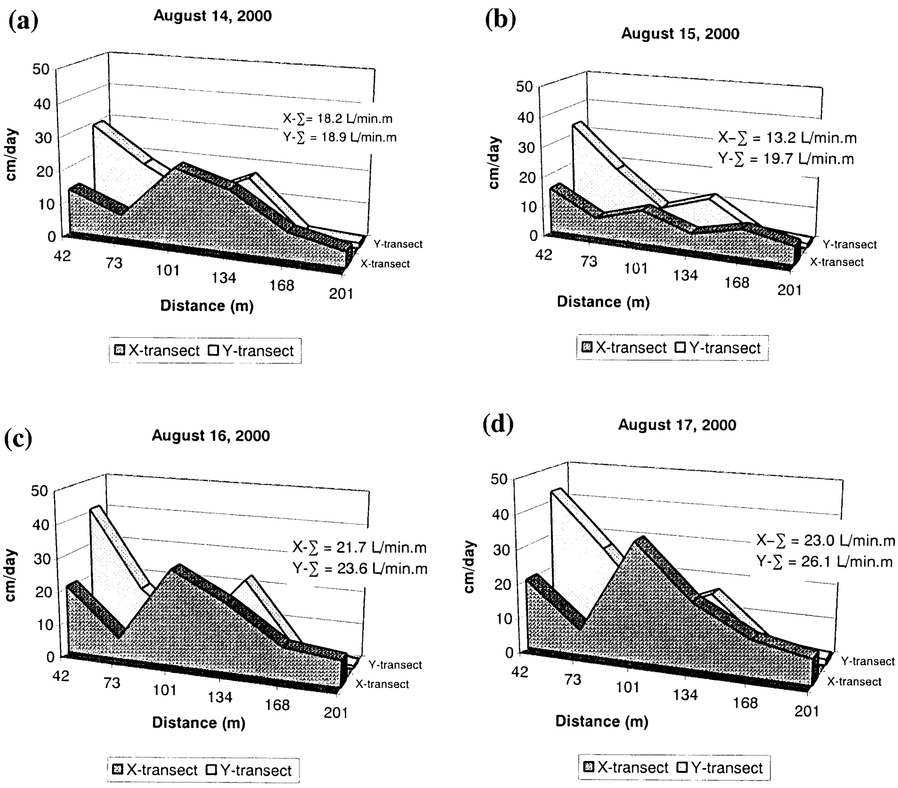

Figure 6. Distributions of groundwater discharge rates offshore observed by manual seepage meters.

Table 1. Daily averaged SGD rates

	Aug. 14, 2000	Aug. 15, 2000	Aug. 16, 2000	Aug. 17, 2000
X transect (10^{-3} L min^{-1} m^{-1})	18.2	13.2	21.7	23
Y transect (10^{-3} L min^{-1} m^{-1})	18.9	19.7	23.6	26.1
X-Y domain (m^3 min^{-1})	1.9	1.6	2.3	2.5

total discharge rates obtained by seepage meters agree well with those by ^{222}Rn.

SGD rates using Lee-type manual seepage meters and continuous heat-type automated seepage meters were compared at stations Y2 and Y4 from August 14 to 18, 2000. Measurements of discharge rates using manual seepage meters were performed during the day time about every 20–30 min at Y2 and 30–60 min at Y4, depending on the flux rates (i.e. how long it takes to collect sufficient water in the plastic collector bag). Continuous heat-type automated seepage meters were operated for four days, and the sampling rate was every 10 minutes. As can be seen from Figure 7, SGD rates obtained from the continuous heat-type automated seepage meters agree well with those obtained from the manual seepage meters with only a few exceptions at Y2. Obvious periodic changes in SGD rates were observed at both stations Y2 and Y4 from the continuous data. The dominant periods of those changes appear to be about 12 hours suggesting that tidal sea level changes result in seepage variations, perhaps due to the change in the groundwater potential between land and ocean.

Comparisons of the daily averaged SGD rates obtained by the manual seepage meters, continuous heat-type automated seepage meters, heat pulse – type automated seepage meter, and ultrasonic-type seepage meter, are shown in Figure 8. Although measurements of SGD by manual seepage meters had been done only during daylight hours and the duration time for SGD measurements by the ultrasonic seepage meter were mostly about half day (some were longer), the data were compared as daily means of the discharge rates at Y1, Y2, Y3 and Y4. SGD rates measured by continuous heat-type and ultrasonic-type automated seepage meters agree reasonably well with those measured by manual seepage meters. As the daily averages of the discharge rates have a semi-normal distribution, the regression analysis by least squares method has been applied. The regression line for the data shown in Figure 8 is:

$$SGD_{auto} = 0.805 SGD_{manual} + 3.570 \quad (R^2 = 0.460) \tag{1}$$

where, SGD_{auto} is the discharge rate obtained by the automated continuous heat and ultrasonic seepage meters, and SGD_{manual} is the discharge rate obtained by the Lee-type manual seepage meters. The discharge data collected by the heat pulse-type automated seepage meter showed about half of the discharge rates obtained by the manual seepage meters at station Y1. We observed strong wave-setups at this shallow station that may have caused a pumping effect on the collector bags.

Spatial change in submarine groundwater discharge

Theoretical and numerical analyses that have considered SGD in homogeneous aquifers show that discharge rates tend to decrease exponentially with distance from the coast (e.g. McBride & Pfannkuch 1975; Fukuo & Kaihotsu 1988), although different points of view have been expressed on this "exponential decrease" by Bokuniewicz (1992). Observed SGD rates also

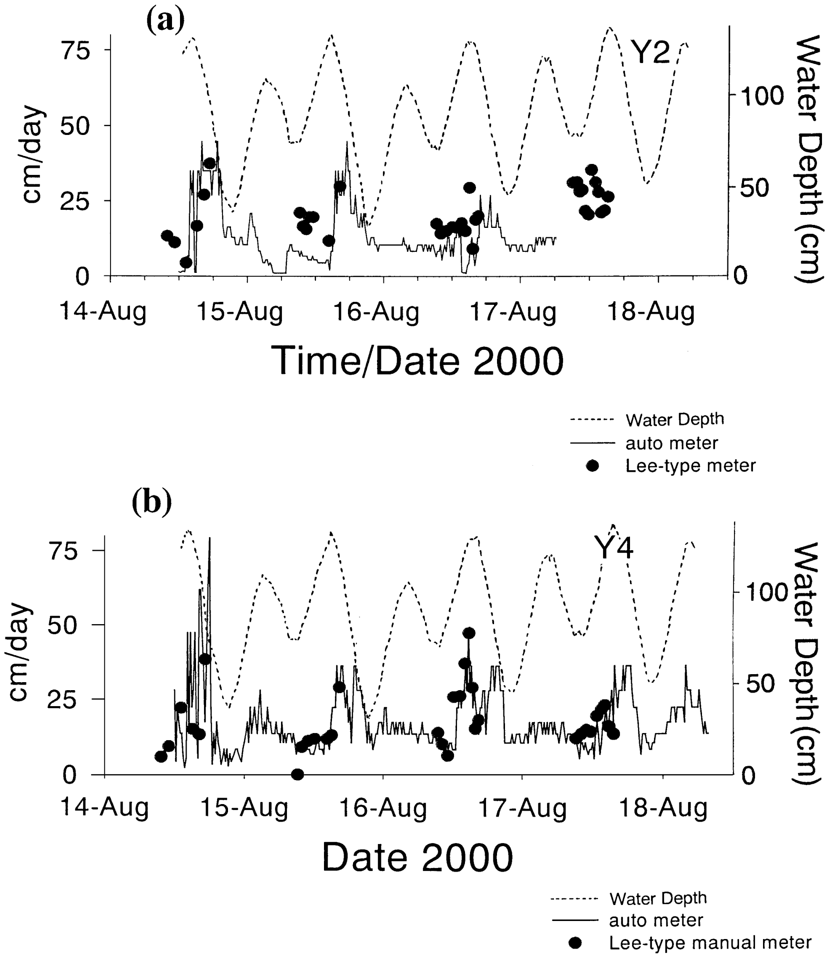

Figure 7. Comparisons of groundwater discharge rates between Lee-type manual seepage meters and continuous heat-type automated seepage meters at stations Y2 (a) and Y4 (b).

decrease exponentially with distance from the shoreline in some situations (e.g., Attanayake & Waller 1988). However, this is clearly not always the case (Connor & Belanger 1981; Woessner & Sullivan 1984; Cherkauer & Nader 1989; Cable et al. 1997b) because of aquifer heterogeneity. The sediment hydraulic conductivity may vary over several orders in some cases over short distances. Distributions of SGD observed via manual seepage meters are shown in Figure 9(a) along the X transect, and in Figure 9(b) along the Y transect. Typically, the integrated rate of SGD offshore is estimated using an exponential equation and observed data at a few locations along transect lines which are perpendicular to the coast. In order to evaluate the accuracy

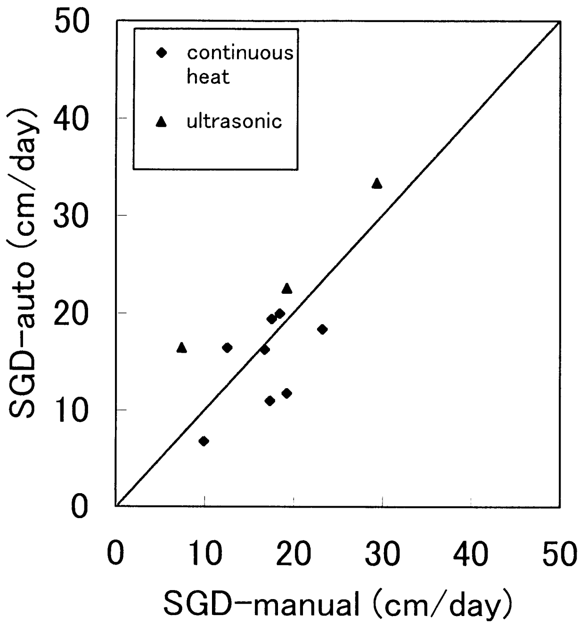

Figure 8. Comparisons of daily means of groundwater discharge rates between Lee-type manual seepage meters (SGD-manual) and automated seepage meters (SGD-auto).

of such estimations, we estimated SGD using different numbers of locations of discharge measurements.

The distribution of SGD offshore can be assumed by an exponential equation as follows;

$$SGD_i = A\exp X^{-B} \tag{2}$$

where, SGD [$T^{-1}L$, such as m/s] is the groundwater discharge rate, X is distance from the shoreline, A and B are constants, and i is the number (from 2 to 6 in this study) of locations which are used for estimation. The solid lines in Figure 9 show the estimated SGD_6 using the least squares method for each day during the experiment. Under the assumption that SGD_6 is the best estimation for groundwater discharge offshore, the accuracy of each estimation of discharge rates using fewer stations are then compared.

The ratios, R_i, of SGD between the best estimation assumed that is the case when i=6 and each estimation using different numbers of locations is described as:

$$R_i = \int_0^\infty SGD_i / \int_0^\infty SGD_6 \tag{3}$$

where i is 2 to 5.

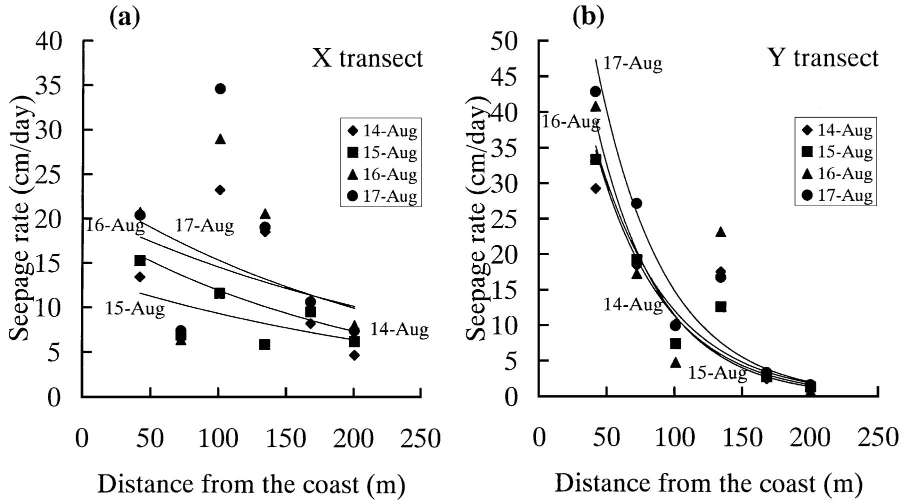

Figure 9. Integrations of submarine groundwater discharge offshore along (a) X transect line, and (b) Y transect line.

Figure 10 shows the R_i values along (a) X transect, and (b) Y transect. The B coefficient in equation (2) is estimated to be negative for SGD_3 and SGD_4 on August 14, 16, and 17, therefore R_i at the X transect is only shown for August 15 in Figure 10(a). Based on this exercise, we conclude that the error increases significantly with fewer than 5 stations. For instance, the maximum error of the estimations of the integrated groundwater discharge offshore is about $\pm 30\%$ for $i = 3$. More than five locations (out to 200m offshore) of SGD measurements are needed for integrated groundwater discharge estimates offshore with an accuracy of $\pm 10\%$ or better.

Temporal change in submarine groundwater discharge

Temporal changes of groundwater discharge will result in temporal changes in dissolved material transport into the ocean, which affect biogeochemical conditions in the coastal zone. In order to evaluate the dominant periods of SGD variation, Power Spectrum Density (PSD) analyses have been used for the continuous record at station Y4, the longest uninterrupted record that we obtained. Figure 11 shows the PSD result from 12:00 noon, August 14 to 4:00 am, August 17, 2002. To do this analysis, continuous data with a binary number (2^n) is needed, therefore 256 data points recorded every 15 minutes were analyzed, because this was the maximum binary number of continuous discharge measurements that could be applied during the observation period. As can be seen in Figure 11, a high peak of the power spectrum PSD is found

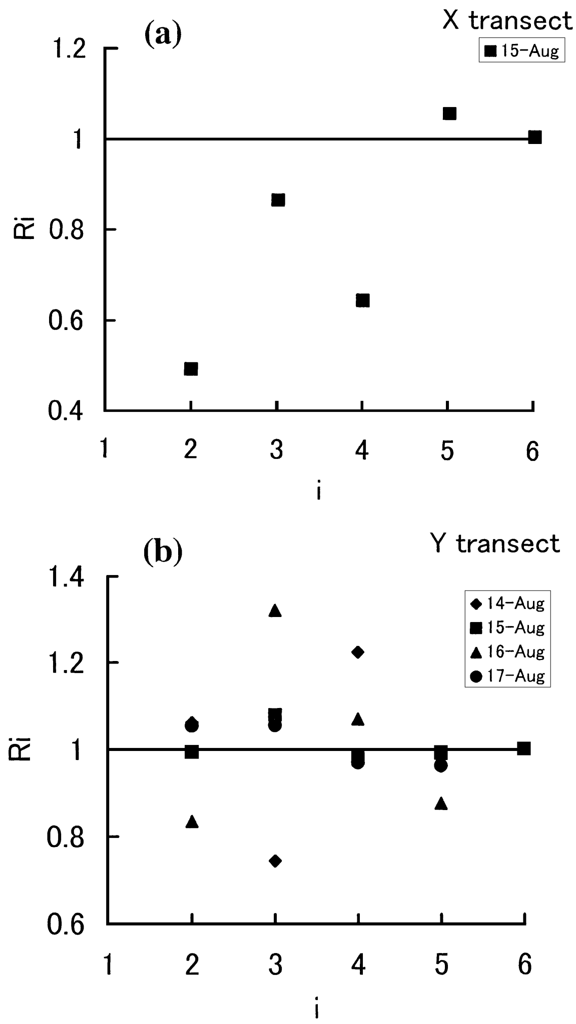

Figure 10. Ratios of estimations of integrated groundwater discharge rates offshore using different numbers of locations for estimating rates along (a) X transect line, and (b) Y transect line.

at a frequency of 0.0195 Hz. This frequency corresponds to a dominant period of 12.7 hours. This semi-diurnal variation of groundwater discharge was also found by Taniguchi (2002) at a field site in Osaka bay, Japan.

In order to evaluate how measurement duration periods affect groundwater discharge estimations, the ratio of estimated discharge rates using manual seepage meters (Qm) and estimated rates using continuous heat-type automated seepage meters (Qa), with various duration periods are compared at

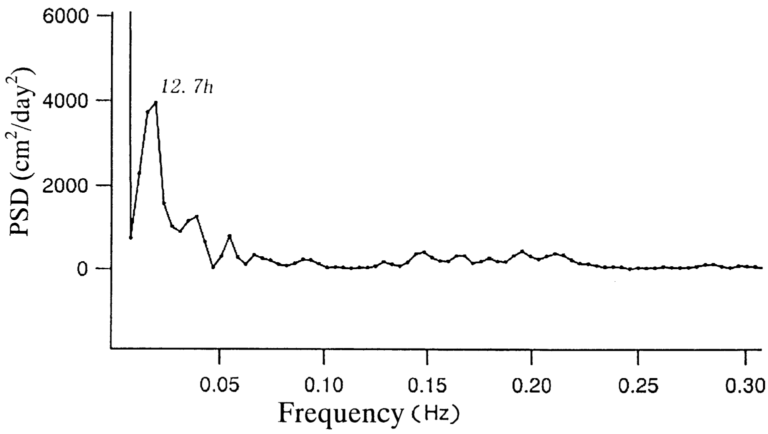

Figure 11. Power spectral density (PSD) analyses of groundwater discharge rate variations at station Y4.

Y2 and Y4 (Figure 12). It is clear from this figure that variations of Qm/Qa increases with decreasing duration time. These results show that a short duration period of groundwater discharge measurements in a coastal setting may cause significant underestimates or overestimates of the averaged groundwater discharge rates. For instance, SGD measurements averaged over three hours result in 30% to 230% of the averaged groundwater discharge rate over 60 hours at Y2. Even for 12 hour measurements of discharge rates, estimates result in 40% to 170% of the averaged discharge rate at Y4 for 72 hours because of the inter-diurnal variation of seepage. Furthermore, the variation of Qm/Qa with each duration period is larger at Y4 than that at Y2, because the diurnal change in discharge is also greater at Y4 than that at Y2.

Evaluations of temporal and spatial variations of SGD are needed for understanding the processes of dissolved material transport into the coastal zone. These groundwater inputs may often be the key for controlling the biogeochemical conditions in the coastal ocean. We find that seepage meters should be deployed over at least one tidal cycle and with enough stations to fully characterize the seepage offshore in order to evaluate precise rates of groundwater discharge.

Conclusions

Our main conclusions are summarized below:

(1) Groundwater discharge rates measured by different types of automated seepage meters agree relatively well with those measured by Lee-type manual seepage meters.

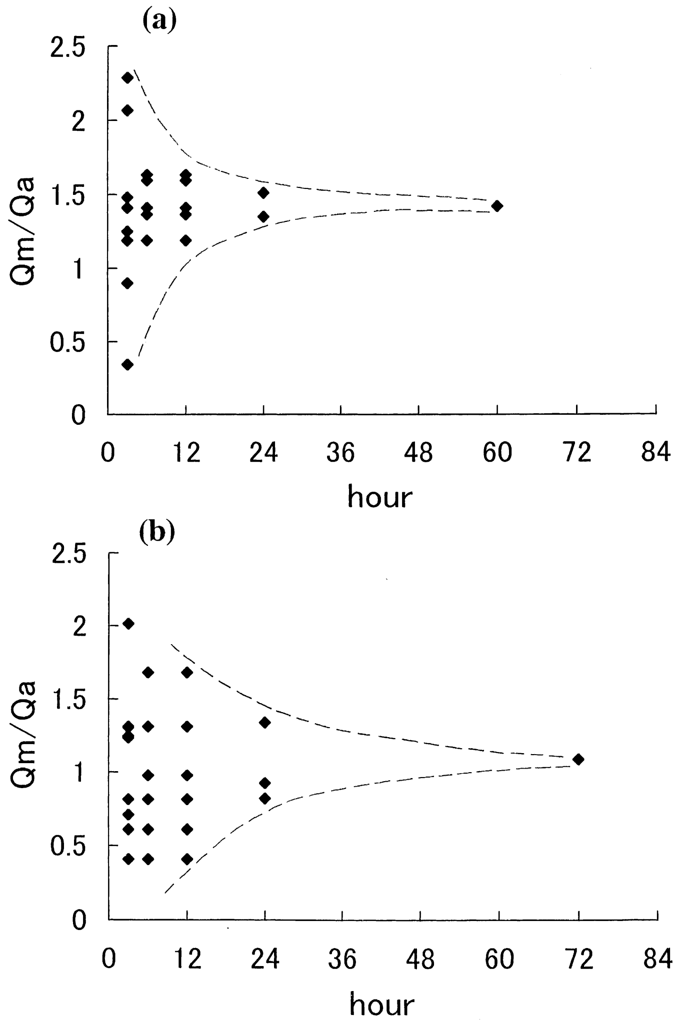

Figure 12. Effects of measurement duration periods on groundwater discharge rate estimations at (a) Y2, and (b) Y4. Dotted lines show the estimated trends of maximum differences.

(2) Comparisons of integrated SGD rates offshore (discharge per unit width of shoreline) using exponential approximations with different number of locations show that more than five locations of measurement (200 m offshore) are needed for an integrated estimation of discharge rates offshore with an accuracy of $\pm 10\%$.

(3) A dominant period of variations of groundwater discharge is estimated to be about 12 hours by power spectrum density analyses. This is attributed to tidally-induced sea level effects on the land-sea groundwater potential.

(4) Short duration periods of groundwater discharge measurements via seepage meters may cause underestimates or overestimates of discharge rates. Continuous automated measurements over several tidal cycles should produce the best results.

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