Direct measures of
Submarine Groundwater Discharge (SGD)
over a fractured rock aquifer
in Ubatuba Brazil

Henry Bokuniewicz
Marine Sciences Research Center
Stony Brook University
Stony Brook, NY 11794-5000
hbokuniewicz@notes.cc.sunysb.edu

Makoto Taniguchi and
Tomotoshi Ishitoibi
Research Institute of Humanity and Nature
335 Takashima –cho, Kamigyo-ku
Kyoto 602-0878 Japan
makoto@chikyu.ac.jp

Matthew Charette and
Matthew Allen
Department of Marine Chemistry and Geochemisty
Woods Hole Oceanographic Institution (MS #25)
Woods Hole, MA 02543
mcharette@whoi.edu, mallen@whoi.edu

Evgeny A. Kontar
Experimental Methods Laboratory
P.P. Shirshov Institute of Oceanology
36, Nakhimovskiy prospect, Moscow 117851
Russia
kontar@ocean.ru, ekontar@ocean.fu.fsu.edu

Abstract

Relatively few observations of the process of submarine groundwater discharge (SGD) have been made, but measurements along the South American coast and over fractured rock aquifers are especially rare. The rate and distribution of SGD was measured using three types of vented, benthic chambers on the floor of Flamengo Bay located at the southeast coast of Brazil. Discharge rates were found exceeding 271 cm day $^{-1}$. Large variations in SGD rates were seen over distances of a few meters. SGD was modulated by the tides with the highest values occurring at times of low tide, but the interaction was nonlinear and, the correlation was weak at tidal ranges less than 1m. We attribute the variation to the geomorphologic features of the fracture rock aquifer underlying a thin blanket of coastal sediments; clustering of fractures and the topography of the rock-sediment interface might be focusing or dispersing the discharge of groundwater.

Introduction

Although the occurrence of submarine, freshwater springs have been recognized in the folk wisdom of millennia, the scientific inquiry into submarine groundwater discharge is a recent development. Study sites have been overwhelmingly located in the northern hemisphere and usually either on unconsolidated or semi-consolidated coastal aquifers or in karst terrain (Taniguchi et al. 2002). Fractured rock aquifers present a special challenge because groundwater flows are confined to unseen fractures buried under a thin, but seemingly homogeneous, layer of coastal sediments. Few such sites have been investigated in detail, although some studies are available to indicate that submarine groundwater discharge (SGD) is significant in such situations. Examples are to be found on the Kamchatka Peninsula (Boldovski 1996) where submarine groundwater discharge is estimated to occur at a rate of about 4.2 liters per second per kilometer of shoreline; on a volcanic island in the Korean Sea (Kim, et al. 2003) where flow rates between 14 and 82 cm day^{-1} were measured; and on Hawaii (Garrison et al. 2003) where flow rates of 8.4 cm day^{-1} were found within about 1 km and 2.3 cm day^{-1} further offshore. We report in this article direct measurements of submarine groundwater discharge performed on the southeastern coast of Brazil. While flow rates were substantially higher, large spatial and temporal variability was recorded. Measurements were made with vented benthic chambers of three different designs. Though Israelson and Reeve (1944) first developed such a device to measure the water loss from irrigation canals, one of the devices we used was designed by Lee (1977). This device consisted of one end of a 55-gallon (208 liters) steel drum fitted with a sample port and a plastic collection bag. Although low cost, the most serious disadvantage for devices using collection bags is that they are labor intensive. To reduce the level of effort, various types of automated seepage meters have been developed which obtain the groundwater discharge rate automatically and continuously. These include flow meters based on ultrasonic measurements (Paulsen et al. 2001), heat-pulse devices described by Taniguchi and Fukuo (1993) Krupa et al. (1998), and the chambers by which the rate of SGD can be measured by the rate of dilution of injected dye (Sholkovitz et al. 2003). The other two devices used in the study were seepage devices with the bags replaced by automated flow meters, one based on a thermal pulse technology (Taniguchi and Fukuo 1993) and the other based on a dye-dilution technique (Sholkovitz et al. 2003).

Studies using vented, benthic chambers have reached the following general conclusions: (1) duplicate and replicate measurements are needed because of the natural spatial and temporal variability of seepage flow rates (Shaw and Prepas 1990a, b); (2) the resistance of the tube (Fellows and Brezonik 1980) and bag (Shaw and Prepas 1989; Belanger and Montgomery 1992) should be minimized to the degree possible to prevent artifacts; (3) use of a cover for the collection bag may reduce the effects of surface water movements due to wave activity (Libelo and MacIntryre 1994); and (4) caution should be applied when operating near the seepage meter detection limit (Cable et al. 1997). Such devices subsequently have been the subject of criticism due to potential artifacts introduced by the presence of the chambers themselves (e.g. Shinn et al. 2002); Corbett and Cable (2003), however, question whether there was sufficient evidence to support the conclusion that these devices are not a practical instrument to use in coastal environments. The devices have been widely used and experience suggests that they are reliable under calm conditions when the flow rate exceeds a few centimeters per day. Since the earliest use of vented benthic chambers, large variability in the results has been noted (McBride and Pfannkuch 1975; Zietlin 1980). In many locations, SGD has been shown to be modulated by the tide despite large, and largely unexplained variations.

Study Area

Flamengo Bay is in the Ubatuba region of the Sao Paulo State coast in southeastern Brazil (Figure 1). The embayment is a semi-enclosed marine environment formed between the projections of the crystalline rocks of the Complexo Costeiro unit, where the Serra Mar mountains reach the shore. This unit is composed by Pre-cambrian high-grade metamorphic rocks, granitic bodies with basaltic intrusions. Groundwater occurs in fractures through these metamorphic and igneous rocks. The rocky shoreline is blanketed offshore with a layer of fine sand (4 to 5 Phi; Mahiques et al. 1998). Some of the highest rainfalls in Brazil occur in this area (Reboucas, 2002). Despite the small drainage basins between the mountain range and the shore, freshwater discharge is sufficient to reduce the salinity of coastal waters (Ferreira et al. 1995).

A reconnaissance of submarine groundwater discharge using radon-222 as a natural tracer disclosed a substantial inflow of groundwater, which includes both fresh and saline pore water

(Oliveira et al. 2003). SGD in Flamengo Bay was calculated to average 4.3 cm day $^{-1}$. Direct measurements of submarine groundwater discharge were also made (Oliveira et al. 2003) using vented benthic chambers (Lee 1977). Measured fluxes were approximately 21 cm day $^{-1}$. The disparity between these estimates may be explained by the variability of SGD documented in this study. Areas of rapid seepage must be balanced by areas of low discharge in order to result in the integrated discharge measured by geochemical tracers. In this article, we will discuss the ranges of both temporal and spatial variations in SGD and how these variations are manifest in direct measurements. The measurements reported here were at the Lamberto beach in front of the base "Clarimundo de Jesus" of the Institutuo Oceanografico de Universidade de Sao Paulo, Ubatuba, Brazil.

Methods

One set of devices deployed in this study were provided by Dr. Oliveira (Devisao de Radiometria Ambiental, Centro de Metrologia das Radiacoes, Instituto de Pesquisas Energeticas e Nucleaares, Brazil). Individual chambers covered an area of 2550 cm^3 (being the top of a "standard" 55-gallon drum). After emplacement of the sea floor, plastic bags were connected to the chambers and allowed to fill for time intervals between several minutes to over 2 hours. The bags were pre-filled will 1000 ml of ambient sea water (e.g. Shaw and Prepas, 1989), except on occasions when it was desired to measure the salinity or other geochemical parameters of the SGD. In those cases, after the chambers had been left in place long enough to flush the headspace, empty collection bags were used, and the salinity of the discharged water was measured with a refractometer. The measured flow rates were not obviously affected. Although it has been recommended also to leave the devices in place for twenty-four hours in order to achieve equilibrium before collecting samples, measurements at this site were begun immediately because of the short duration of the field effort. Once installed, however, all devices were left undisturbed in place, for as much as 90 hours.

Six devices were deployed along a transect perpendicular from shore (Figure 2). The shoreward device (SD1) was exposed at low tide. The other five devices (SD2, SD3, SD4, SD5 and SD6 were placed at distances of 5, 10, 18, 32 and 44 m from the low-tide shoreline. The respective water depths (LW) were 0 m, 0.33 m, 0.71 m, 1.07 m, 1.46 m and 1.65 m. The tops of the devices were between 0.05 and 0.15 m above the sea floor. Two more devices were placed approximately at the low tide shoreline east and west of the transect; one was placed 19 meters alongshore to the east (SD1E) and one 14 meters alongshore to the west (SD1W).

A serious disadvantage of the devices described above is that they are not continuously recording. To better resolve temporal patterns two types of continuously recording devices were also deployed at this site. One of these was based on the travel time of a heat pulse down a narrow tube. The device uses a string of thermistors in a column positioned above an inverted funnel covering a known area of sediment (Taniguchi and Fukuo 1993). Measurement of the travel time of a heat pulse generated within the column by a nichrome wire induction heater 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 Taniguchi device has successfully measured seepage up to several days at a rate of about one measurement every five minutes (Taniguchi and Fukuo 1996).

Three devices were deployed. T1A was set near the low-tide shoreline slightly to the east of SG1. T3A was set near SG4 at a distance of about 18 meters from the shoreline and T4A was placed near SG5, 32m from shore (Figure 2).

The second type of automated device used was the dye-dilution seepage device. Colored dye is injected into a mixing chamber attached to the device. Subsequent measurement of the dye absorbance in the mixing chambers over time provide a measure of the dilution rate. The rate at which the dye is diluted by the inflowing seepage water is then used to calculate the flow-rate. In order to avoid the cost and complexity of a dedicated spectrophotometer, a nitrate analyzer is used to inject the dye and make the absorbance measurements (Sholkovitz et al. 2003). Dye was injected every hour into a mixing chamber of 0.5 liter volume and the absorbance was recorded every five minutes. One such dye-dilution device was set near SD1W close to the low-tide shoreline (Figure 2).

Results

The measured seepage rates are shown in Figures 3, 4, 5 and 6. The highest rates of SGD were found at the low tide shoreline (SD1, SD1E and SD1W, Figure 3) but they were not uniform. The device to the east (SD1E) recorded flow rates as high as 268 cm day^{-1} and collection bags with a capacity of about 6 liters had to be replaced every 10 minutes whereas at other locations flow rates were often sufficiently low that collections every hour or two were adequate. Of the three chambers using collection bags and placed at the low tide shoreline (i.e. SD1E, SD1, and SD1W), the average seepage rate was 61.5 cm day- ranging from 1 to 267 cm day $^{-1}$. The continuously recording heat-pulse device at the shoreline recorded seepage rates as high over 350 cm/day with an average rate of 271 cm/day. WHOI1 recorded an average rate of only 15 cm day $^{-1}$ but peaked values reached 110 cm day $^{-1}$.

The temporal variability was large; measured seepage rates were found to change by as much as 160 cm/day over a five-minute interval. Along the cross-shore transect, relatively high rates were recorded at SD1 and SD2 and again at SD5 and SD6 (Figure 4). The average rate at SD5 was calculated to be 8.2 cm day $^{-1}$ peaking at 43.4 cm day $^{-1}$ while TA4, located nearby, recorded an average discharge of about 193 cm day^{-1} ranging from a high as 378 cm day^{-1} to values of 90 cm day^{-1}. Low discharge was found at site SD4/T3A along the transect. SD4 recorded a discharge at an average rate of 5.5 cm day $^{-1}$ and T3A, situated nearby, recorded an average rate of discharge of 4.3 cm day $^{-1}$. (The dye-dilution device was not deployed further offshore).

At other locations SGD has been found to be inversely related to the tide (e.g. Lee 1977); discharge rates are lowest near the time of high tide. The devices operating with collection bags showed a temporally variable discharge but little relationship to the tide. This may be because the collection periods were limited by daylight and available manpower, a disadvantage overcome by the automated devices. SGD records at devices T3A and T4A did show semi-diurnal variations correlated to the tidal elevation, higher discharges tending to occur at periods of low tide. At T4A, the tidal modulation was weak at best during the early part of the sampling period when the tidal range was under one meter about 0.7 m; Figure 5. A few tidal cycles later, however, the tidal range increased, exceeding one meter (about 1.2) and the modulation of the SGD was more convincing.

A strong punctuated, tidal modulation was seen at the dye-injection device, WHOI1 (Figure 6). The discharge rate spiked sharply and strongly in a few hour period around the lowest tides reaching values of 110 cm/day against an average rate of 15 cm day^{-1}. The salinity inside this seepage chamber ranged from about 26 to 31 ppt. Given an ambient bay water salinity of about 31 ppt, the lower salinities suggest that a portion of the SGD at included freshwater. The pattern of gradual freshening of the water inside the seepage housing is likely explained by the replacement of bay water (which is trapped inside the housing upon installation of the meter) with fresh/brackish groundwater. The rate at which this bay water is replaced is a function of the seepage rate and the headspace volume inside the seepage chamber. If we assume a headspace volume of 5 L, a flow rate of 16 cm day^{-1} would be required to explain the gradual freshening inside the seepage chamber from 18 November to 20 November which is in excellent agreement with the average flow rate of our dye-dilution method.

Salinity was measured in other devices with a refractometer after they had been in place overnight. The lowest salinity recorded on the collected fluid was 20 ppt at SD1E (the device recording the most rapid discharge rate). The flow rate here was sufficient to exchange the pore water to a depth of up to five meters along a flow line every day. The relatively high salinity indicates that mixing and recirculation of sediment pore water must be effective over flow paths at least several meters long. Even though the measured flow rates were adequate to flush the head space of other devices (such as SD1, SD5, and SD6), the measured salinities in the collected discharge remained indistinguishable from that of the ambient, open water. Salt water must be mixed and recirculated with any freshwater SGD.

The discharge seemed to increase over the course of the three-day experiment; however, the temporal changes were somewhat puzzling. At the beach on 17 November 2003, about 1 cm of rain fell during the first twelve hours and about 1.5 cm fell over the rest of the day. Light rain then continued for a half-day more but the weather was subsequently dry. The very high relief near the shore (up to 1,000 m) tends to trap moisture along the coast. It is possible that localized heavy rains had occurred also in the coastal range influencing the SGD. SD5 exceeded 5 cm day^{-1} and then 10 cm day^{-1} early in the experiment then increased to about 45 cm day^{-1}. Near the end of the experiment the discharge at SD5 and at SD6 seemed to be decreasing while that at SD3 and SD4 briefly increased. If the local rainfall were the cause of increased SGD, a time lag of about 40 hours would be required between the recharge and the SGD response at the sea floor.

Discussion

In principle, the SGD should decrease rapidly over a homogeneous aquifer with distance from the shore over the first 100 meters or so. This has been described as “exponential” although the mathematical function is not strictly true either in theory or as described by measured SGD. However, in many locations, this has proven to be useful description. At Ubatuba there was a marked departure from this generalization, however. Along the transect, the highest rates were measured at the two locations closest to shore (T1A, SD1, SD1E, SD1W, WHOI1 and SD2) but the next two devices (SD3 and SD4 and T2A) recorded little or no flow and relatively high flow was found at distance of 30 or 40 meters from the low-tide shoreline. The most rapid flows, however, were off the transect; the longshore variation in flow rate being many times greater than the cross-shore trends. The fact that rates in excess of 200 cm/day were found with only twelve, more-or-less random, placements of the devices suggests that areas of high seepage are common. Although spatial variations in SGD could be due to spatial heterogeneity in the permeability of the unconsolidated sediments, this would not explain temporal changes.

The irregular distribution and high rates of SGD seen at Ubatuba may be characteristic of fractured rock aquifers (Bokuniewicz, et al. 2004a). The bay floor sediments were sandy and not noticeably different from place to place in the study area. However, bedrock is exposed at the shoreline and an irregular rock surface was encountered at shallow depths offshore. Other investigators could drive probes to a depth of a few meters in some places but less than half a meter at other adjacent locations. The water feeding the SGD is supplied to the bottom of the thin blanket of unconsolidated sediment through fracture system and concentrated (or dispersed) along the irregular surface of the buried rock. Presumably, this is fresh groundwater working its way seaward through the fractured rock. The relatively high salinity in the pore water of the sediment blanket, despite high discharge rates, must be due to some efficient mixing process in the surficial sediments themselves, perhaps a combination of gravitational, free convection and wave pumping (Bokuniewicz et al. 2004b).

We envision a fractured rock aquifer in which zones of high (and low) discharge are controlled, in part, by the clustering of fracture patterns and, in part, by the topography of the buried rock surface, which might focus or disperse groundwater flow through the unconsolidated cover depending on the thickness of cover and degree of lateral constriction. In a connected, but complex, fracture system, we can image how the zone of high SGD may shift from place to place over a period of days as the hydraulic heads in one part of the network of fractures are decreased by draining or increased by local recharge, perhaps out of sight in the coastal range. Rapid, but local, variation would propagate with unpredictable results through the interconnected system. This might be analogous to a complex, electrical grid where a change in voltage or resistance in one branch affects all other branches, in varying degrees.

Tidal modulations of SGD have been ascribed to oceanic forcing which drives, at least in part, the recirculation of seawater in the submerged aquifer. The strength of the modulation has been observed to increase with increasing tidal range. As shown by our results, the tidal modulation of SGD is non-linear. It is not the case that SGD decreases in proportion to the instantaneous tidal elevation; the discharge rates can be unaffected at small tidal ranges and punctuated by rapid increases at the lowest low tides. In addition, the signature of SGD tidal variations can be seen in these data to depend on the type of seepage device used; the use of collection bags which average over tens of minutes can mask a highly punctuated response captured by continuously recording devices. The hydraulic connections causing such a response deserve attention.

Conclusions

In designing a sampling strategy to measure SGD over fractured rock aquifer, a conceptual model of this system must allow for (a) the lack of an inverse relation between SGD with distance from shore as seen at other sites (b) large heterogeneity with very high and very low SGD being found within meters of each other and (c) a non-linear tidal modulation that may be sensitive to changes in tidal range from cycle to cycle (d) a temporal variability that might allow areas of high discharge to shift laterally over short periods (days). Rates are likely to be controlled by the presence, or absence, of buried fracture systems and focused, or dispersed, by the topography of the buried rock surface. In such a situation, characterization of SGD by direct measurements will necessarily rely on a statistical approach. Integrated SGD might best be described statistically from many, randomly situated, spot measurements either recording continuously to capture any tidal modulation or sampled at random stages of the tide. Measurements must be made at a statistically adequate number of locations (based on the range of variation encountered). Temporal variations also require observations to be made over time. Non-linear, tidal cycle variations are to be anticipated but spring-neap variations may also be significant. Benthic chambers can provide important information on the characteristics and physical hydrography of SGD; however, for regional, or even local, water budgets in such situations, a better approach may be the use of geochemical tracers in the open water that integrate over the range of SGD variation from place to place.

Acknowledgements

We gratefully acknowledge the support of the Scientific Committee on Oceanic Research (SCOR) for their support of Working Groups 112 (“Magnitude of Submarine Groundwater Discharge and its Influence on Coastal Oceanographic Processes”). The Land-Ocean Interaction in the Coastal Zone (LOICZ) project of IGBP provided additional support. We also wish to thank UNESCO's Intergovernmental Oceanographic Commission (IOC) and the International Hydrologic Program (IHP) for sponsoring the intercalibration intercomparison experiments. Additional support was provided by the International Atomic Energy Agency (IAEA) through their coordinated Research Project on Nuclear Isotopic Techniques for the characterization of Submarine Groundwater Discharge (SGD) in Coastal Zones. M.C. and M.A. were also supported by grants from the National Science Foundation (OCE-0095384) and the NOAA-CICEET program (NA17OZ2507-03-723).We were fortunate to have the help of Dr. Oliveira and the faculty and staff of the Instituto Oceanografico de Universidade de Sao Paulo. This research could not have been done without them.

REFERENCES

Belanger, T.V. and M.E. Montgomery, 1992. Seepage meter errors, Limnol. Oceanogr. 37, 1787-1795.

Bokuniewicz, H.J.; E. Kontar, M. Rodrigues; and D.A.Klein, 2004a. Submarine Groundwater Discharge (SGD) patterns through a fractured rock aquifer: a case study in the Ubatuba coastal area, Brazil Revista de la Asociacion Argentina de Sedimentologia 11: 9-16.

Bokuniewicz, H.J; M. Pollock; J. Blum; and R. Wilson, 2004b. Submarine groundwater discharge and salt penetration across the sea floor. Ground Water. Special Issue on Oceans and Estuaries, in press- volume and pages?

Boldovski, N.V. 1996. Ground-water flow in the coastal zone of the East-Sikhote-Alin volcanic belt in "Proceedings of an international symposium. LOICZ Reports and Studies. No. 8. LOICZ, Texel, the Netherlands. 179 pp.

Cable, J.E., W.C. Burnett, J.P. Chanton, D.R. Corbett, and P.H. Cable, 1997. Field evaluation of seepage meters in the coastal marine environment. Estuar. Coast. Shelf Sci., 45, 367-375.

Corbett, R. and J.Cable 2003. Seepage meters and advective transport in coastal environments: Comment on "Seepage meters and Bernoulli's revenge" Estuaries 26: 1383-1389.

Fellows, C.R. and P.L. Brezonik, 1980. Seepage flow into Florida lakes, Water Resour. Bull., 16, 635-641.

Ferreira, M.M.C; G.G. Faria; and E.T. Paes, 1999. Oceanographic characterization of northern Sao Paulo Coast: a chemometric study. Chemometrics and intelligent laboratory systems 47: 289-297.

Garrison, G.H.; C.R. Glenn and G.M. McMurty. 2003. Measurement of submarine groundwater discharge in Kahana Bay, O'ahu, Hawaii. Limnology and Oceanography 48: 920-928.

Israelsen, O. W. and R. C. Reeve, 1944. Canal lining experiments in the delta area, Utah, Utah Agr. Exp. Sta. Tech. Bull., No.313, 52pp, 1944.

Kim, G; K-K Lee; K-S Park; D-W Hwang and H-S Yang. 2003. Large submarine groundwater discharge (SGD) from a volcanic island. Geophysical Research Letters. 30, 2098.

Krupa, S.L., T.V. Belanger, H.H. Heck, J.T. Brok and B.J. Jones, 1998. Krupaseep – the next generation seepage meter, J. Coastal Res., 25, 210-213.

Lee, D.R. 1977. A device for measuring seepage flux in lakes and estuaries. Limnology and Oceanography 22: 140-147.

Libelo, E.L. and W.G. MacIntyre. 1994. Effects of surface-water movement on seepage-meter measurements of flow through the sediment-water interface. Hydrogeology Journal 2: 49-54.

Mahigues, M.M.; M. G. Tessler and V.V. Furtado, 1998. Characterization of energy gradient in enclosed bays of The Ubatuba Region, South-eastern Brazil, Estuarine, Coastal and Shelf Science. 47: 431-466.

McBride, M.S. and H. O. Pfannkuch. 1975. The distribution of seepage within lakebeds. Journal of Research. U.S. Geological Survey 3: 505-512.

Oliveira, J.; W. C. Burnett; B. P. Mazzilli, E. S. Braga; L.A. Farias; J. Christoff and V. V. Furtado, 2003. Reconnaissance of submarine groundwater discharge at the Ubatuba coast, Brazil, using ^{222} Rn as a natural tracer. J. Environmental Radioactivity 69: 37-52.

Paulsen, R.J., C.F. Smith, D. O'Rourke, and T. Wong, 2001. Development and evaluation of an ultrasonic ground water seepage meter. Ground Water, 39, 904-911.

Reboucas, A. 2002. Aguas Subterraneas, Aguas Doces no Brasil, 2nd Edition. A. Reboucas, B. Brago and J.G. Tundisi, editors. Escrituras, Sao Paulo. Brazil.

Shaw, R.D. and Prepas, E.E., 1989. Anomalous, short-term influx of water into seepage meters. Limnology and Oceanography, 34 (7): 1343-1351.

Shaw, R.D. and Prepas, E.E. 1990a. Groundwater-lake interactions: I. Accuracy of seepage meter estimations of lake seepage. J. Hydrol., 119, 105-120.

Shaw, R.D. and Prepas, E.E. 1990b. Groundwater-lake interactions: II. Nearshore seepage patterns and the contribution of ground water to lakes in central Alberta. J. Hydrol., 119, 121-136

Shinn, E.A.; C.D. Reich and T.D. Hickey 2002. Seepage meters and Bernoulli's revenge. Estuaries 25: 126-132.

Sholkovitz, E.R., C. Herbold, and M.A. Charette, 2003. An automated dye-dilution based seepage meter for the time-series measurement of submarine groundwater discharge. Limnol. Oceanogr. Methods, 1, 17-29.

Taniguchi, M.; W.C. Burnett, J.E. Cable and J.V. Turner. 2002. Investigation of submarine groundwater discharge. Hydrological Processes 16: 2115-2129.

Taniguchi, M., and Y. Fukuo, 1993. Continuous measurements of ground-water seepage using an automatic seepage meter. Ground Water, 31, 675-679.

Taniguchi, M. and Y. Fukuo, 1996. An effect of seiche on groundwater seepage rate into Lake Biwa, Japan. Water Resour. Res., 32, 333-338.

Zietlin, M.J. 1980. Variability and predictability of submarine ground-water flow into a coastal lagoon, Great South Bay, New York. Stony Brook University's Marine Sciences Research Center. M.S. thesis: 96 pp.

Figure Captions

Figure 1. Study site on the Brazilian coast. The Instituto Oceanografico de Universidade de Sao Paulo maintains a base in the northwest of Flamengo Bay, as indicated, at which the measurements were taken.

Figure 2. Approximate arrangement of seepage devices (SD). Actual spacing is given in the text.

Figure 3. SGD measured at the low-tide shoreline. Time is in hours starting at midnight on 17 November 2003. Note the difference in the scale of the vertical axes.

Figure 4. SGD measured along a transect offshore. Time is in hours starting at midnight on 17 November 2003. Note the differences in scale of the vertical axes.

Figure 5. SGD at TA3. Location of the deployment shown in Figure 2.

Figure 6. Submarine groundwater discharge as recorded by the dye-dilution seepage meter. The location of the deployment is shown in Figure 2.

HB/ed

Ubatuba.doc

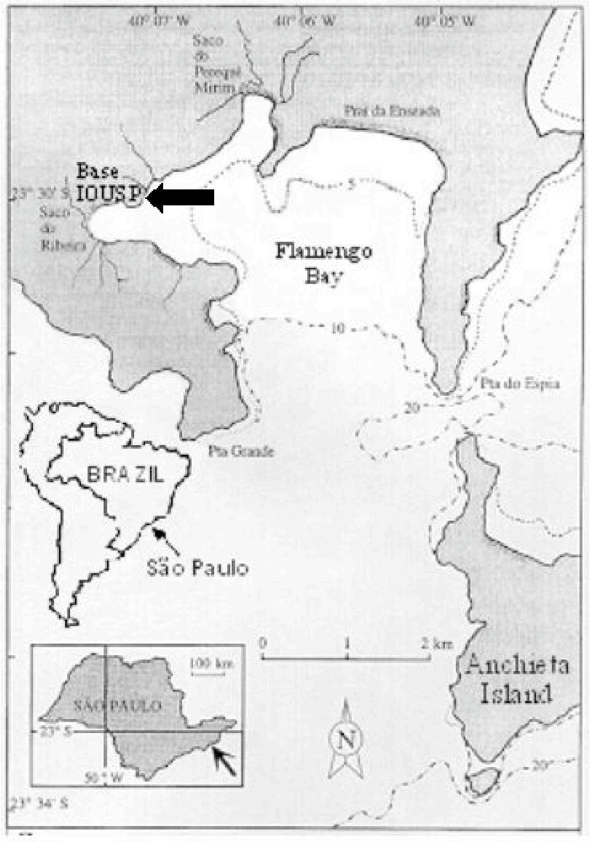

40° 07' W
40° 06' W
40° 05' W
Saco do Perequê Mirim
Prai da Enseada
Base IOUSP
23° 30' S
Saco do Ribeira
5
Flamengo Bay
10
Pta do Espia
20
Pta Grande
BRAZIL
São Paulo
0
1
2 km
100 km
SÃO PAULO
23° S
50° W
Anchieta Island
N
20
23° 34' S

figure 1

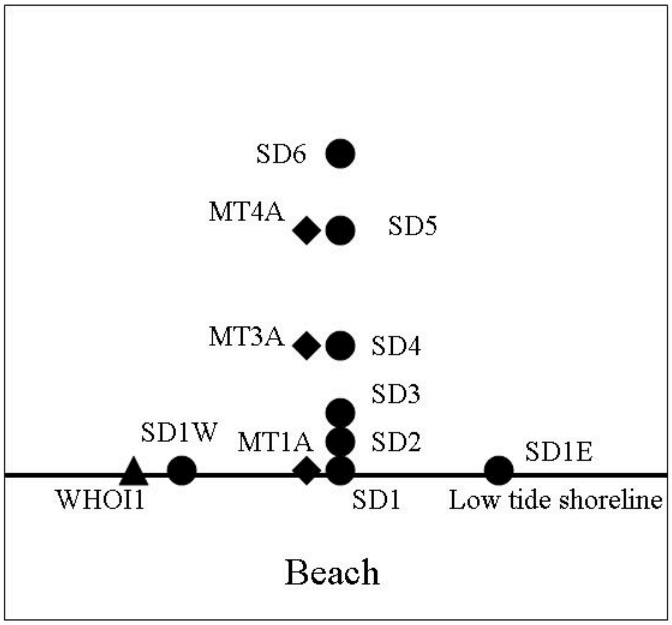
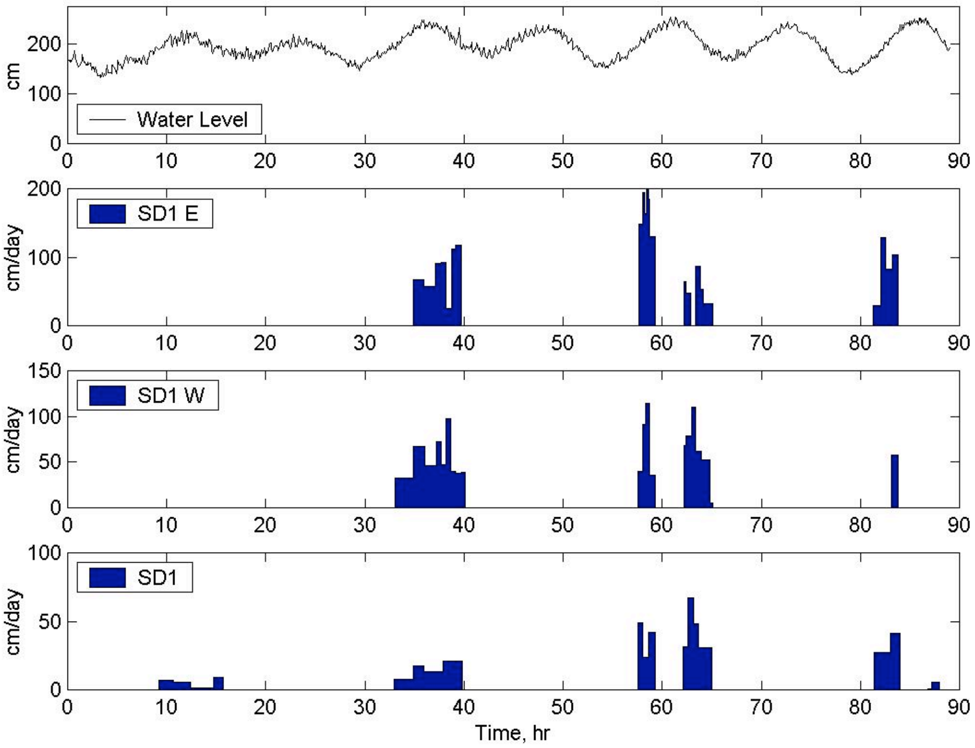
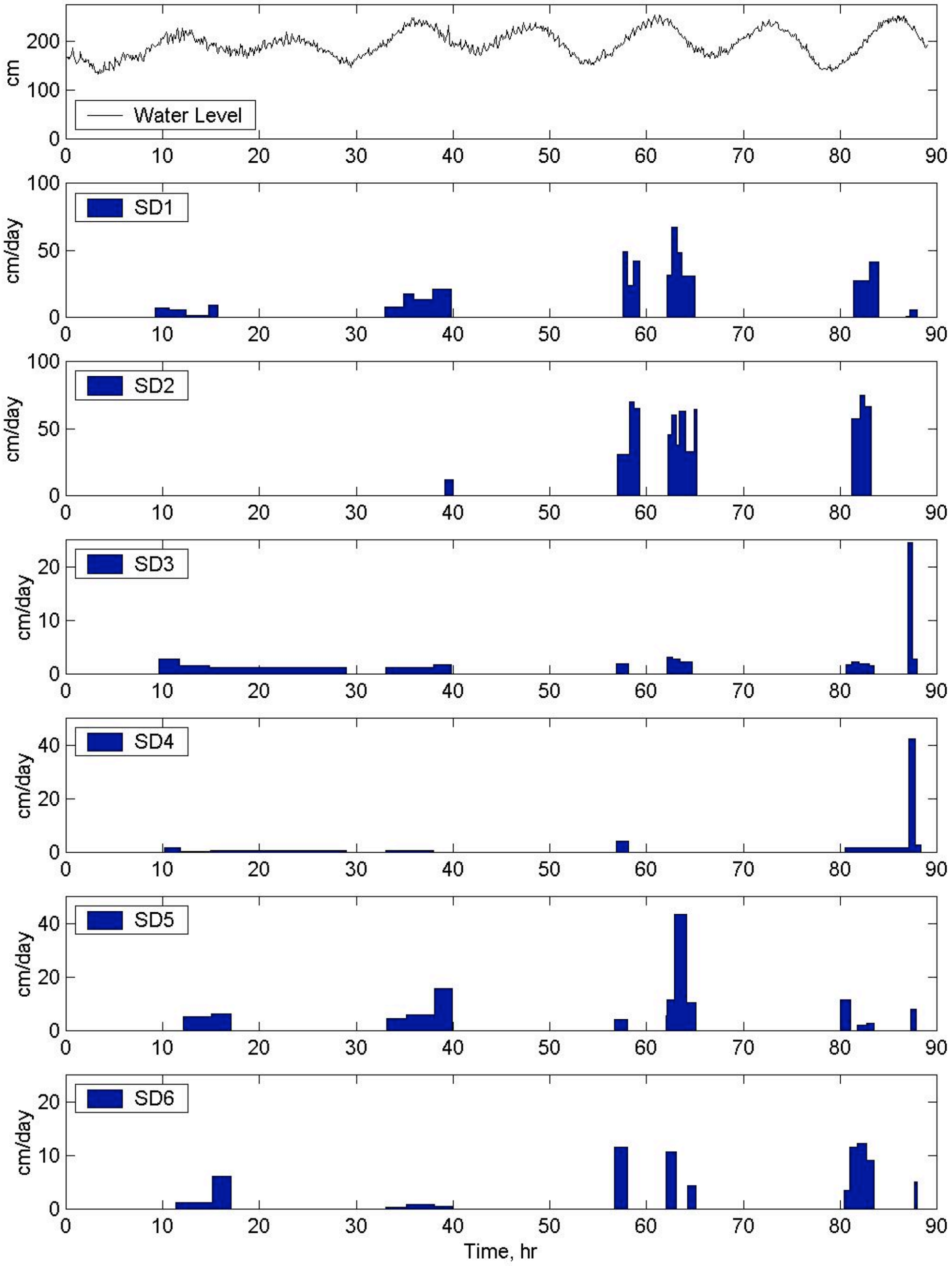

SD6
MT4A
SD5
MT3A
SD4
SD3
SD1W
MT1A
SD2
SD1E
WHOI1
SD1
Low tide shoreline
Beach

figure 2



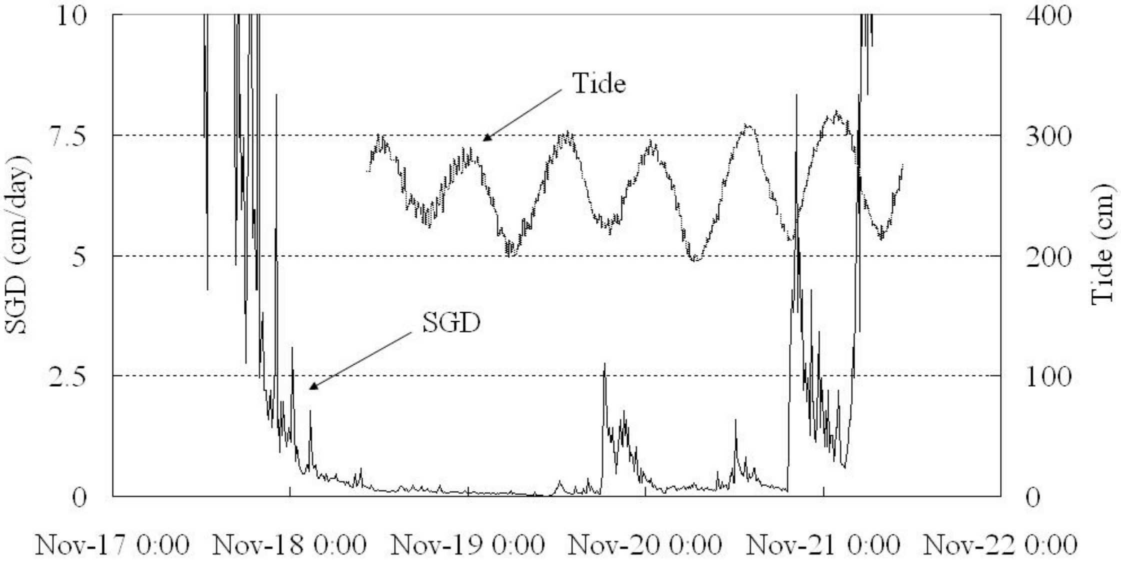
Water Level
cm
200
100
0
SD1 E
cm/day
200
100
0
SD1 W
cm/day
150
100
50
0
SD1
cm/day
100
50
0
0
10
20
30
40
50
60
70
80
90
Time, hr

figure 3.



cm
200
100
0
Water Level
0
10
20
30
40
50
60
70
80
90
cm/day
100
50
0
SD1
SD2
SD3
20
10
SD4
40
20
SD5
SD6
Time, hr

figure 4



Tide
SGD
SGD (cm/day)
Tide (cm)
10
7.5
5
2.5
0
400
300
200
100
0
Nov-17 0:00
Nov-18 0:00
Nov-19 0:00
Nov-20 0:00
Nov-21 0:00
Nov-22 0:00

figure 5

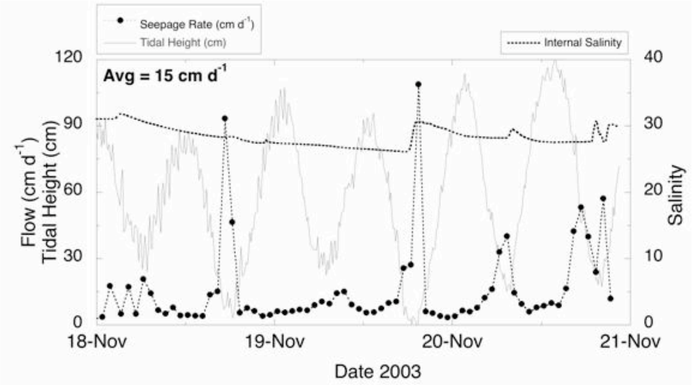

Seepage Rate (cm d^{-1})
Tidal Height (cm)
Internal Salinity
Avg = 15 cm d^{-1}
Flow (cm d^{-1})
Tidal Height (cm)
120
90
60
30
0
Salinity
40
30
20
10
0
18-Nov
19-Nov
20-Nov
21-Nov
Date 2003

figure 6.