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Source: Journal of Coastal Research, 24(sp1) : 15-24

Published By: Coastal Education and Research Foundation

URL: https://doi.org/10.2112/06-0636.1

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Journal of Coastal Research | 24 | 1A | 15–24 | West Palm Beach, Florida | January 2008

Groundwater Discharge as an Important Land-Sea Pathway into Manila Bay, Philippines

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ABSTRACT

TANIGUCHI, M.; BURNETT, W.C.; DULAIOVA, H.; SIRINGAN, F.; FORONDA, J.; WATTAYAKORN, G.; RUNGSUPA, S.; KONTAR, E.A., and ISHITOBI, T., 2008. Groundwater discharge as an important land-sea pathway into Manila Bay, Philippines. *Journal of Coastal Research,* 24(1A), 15–24. West Palm Beach (Florida), ISSN 0749-0208.

A multidisciplinary approach was taken to assess the potential importance of groundwater seepage to nutrient inputs into Manila Bay, Philippines. Three lines of seepage meters were installed in transects along the coast at Mariveles, Bataan Province, during the period 8–10 January 2005. The overall average seepage flux was 5.1 ± 5.4 cm d^{-1} ($n = 73$) with a range of 0–26 cm d^{-1} and a calculated integrated shoreline flux of 12.4 m^3 m^{-1} d^{-1}. Additional methodologies employed included automatic seepage meters, resistivity measurements, sampling for nutrient analyses in both seepage meters and ambient seawater, and use of natural radon as a groundwater tracer. Seepage meter and tracer results provided consistent results of estimates of submarine groundwater discharge into Manila Bay. Many lines of evidence suggest that seepage fluxes are not steady state but are modulated by the tides. Resistivity profiles show that the saline-freshwater interface moves on a tidal timescale, consistent with the observed drop in salinity of the seepage waters as low tide approaches. Our results show that dissolved inorganic nitrogen (DIN) fluxes via submarine groundwater discharge are comparable in magnitude to DIN fluxes from each of the two major rivers that drain into Manila Bay.

ADDITIONAL INDEX WORDS: *Submarine groundwater discharge, Manila Bay, land-sea pathway, seepage, nutrient flux.*

INTRODUCTION

We hypothesize that many water quality and associated problems influencing coastal environments around the world today are related to past and ongoing contamination of terrestrial groundwaters because those groundwaters are now seeping out along many shorelines. For example, chronic input of fertilizers and sewage on land over several decades has resulted in higher groundwater nitrogen, which, because of slow yet persistent discharge along the coast, eventually may result in coastal marine eutrophication. Such inputs may thus contribute to the increased occurrences of coastal hypoxia, nuisance algal blooms, and associated ecosystem consequences.

The direct discharge of fresh and saline groundwater into the coastal zone, called submarine groundwater discharge (SGD), has been recognized as a significant, but poorly quantified, pathway between land and sea (Burnett *et al.,* 2003a; Moore, 1996; Taniguchi *et al.,* 2002; Valiela *et al.,* 1978). As such, SGD acts as a source of nutrients and other dissolved species, including contaminants, to coastal waters and ecosystems. While the overall flow of fresh submarine groundwater into the ocean is likely no more than about 6% of the river flow on a global basis, it has been estimated that the total dissolved salt contributed by SGD may be as much as 50% of that contributed by rivers (Zektser, 2000).

Specific examples of the ecological impact of groundwater flow into coastal zones have been given by Valiela and D'Elia (1990) and Valiela *et al.* (1978, 1992, 2002), who showed that groundwater inputs of nitrogen are critical to the overall nutrient economy of salt marshes. Corbett *et al.* (1999, 2000) estimated that groundwater nutrient inputs are approximately equal to nutrient inputs via surface freshwater runoff in eastern Florida Bay. Bokuniewicz (1980) and Bokuniewicz and Pavlik (1990) showed that subsurface discharge accounts for greater than 20% of the freshwater input into the Great South Bay, New York. Follow-up studies by Capone and Bautista (1985) and Capone and Slater

DOI:10.2112/06-0636.1 received 20 January 2006; accepted in revision 17 October 2006.

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(1990) showed that groundwater is a significant source (~50%) of nitrate to the bay. LAPOINTE *et al.* (1990) found significant groundwater inputs of nitrogen and dissolved organic phosphorus to canals and surface waters in the Florida Keys and suggested that this may be a key factor for the initiation of the phytoplankton blooms observed in that area. Nitrogen-rich groundwater is also suspected of nourishing *Cladophora* algal mats in Harrington Sound, Bermuda (LAPOINTE and O'CONNELL, 1989). In the cases cited here, shallow groundwaters were enriched in nitrogen because of contamination from septic systems. In pristine coral reef environments, groundwater inputs have been shown to contribute significantly to reef nitrogen budgets in Discovery Bay, Jamaica (D'ELIA *et al.,* 1981), and Ishigaki Island, Japan (UMEZAWA *et al.,* 2002). Groundwater has also been shown to be a significant component of terrestrial nutrient and freshwater loading to Tomales Bay, California (OBERDORFER *et al.,* 1990). JOHANNES (1980, p. 371), while investigating coastal waters off Western Australia, stated that "it is . . . clear that submarine groundwater discharge is widespread and, in some areas, of greater ecological significance than surface runoff."

While investigations of groundwater discharge into the coastal zone have increased dramatically over the last several years, few studies have been performed in Southeast Asia (TANIGUCHI *et al.,* 2002). This may be a significant oversight because the region is characterized by many features that are typically present in areas of high SGD. For example, many parts of Southeast Asia contain regions of high rainfall, karst terrains, and high relief. As part of a project supported by the Asia-Pacific Network (APN), an international team of scientists performed a preliminary assessment of the nutrient flux into Manila Bay via SGD. Our objective was to derive an initial estimate of nutrient loadings via groundwater discharges and to compare these to calculated river fluxes.

Manila Bay is one of the areas heavily affected by harmful algal blooms in the Philippines. *Pyrodinium bahamense* var. *compressum* (PBC) blooms have been occurring almost annually in Manila Bay since 1988 but have ceased since 1999. The blooms have been previously attributed to eutrophication. However, the occurrence of PBC blooms in Malampaya Sound (Palawan), which is a relatively pristine environment, has weakened this hypothesis. Furthermore, the blooms in Manila Bay have typically been initiated along the western coast of the bay off the southeast coast of Bataan (BAJARIAS and RELOX, 1996), where the water, relative to the head of the bay, is relatively uncontaminated. Thus, some mechanism other than surface loading of nutrients may be triggering these outbreaks. The steep gradients and abundance of artesian wells along the southeast coast of Bataan suggest that there could be high levels of SGD, and this inspired the site selection for this study.

CHARACTERISTICS OF MANILA BAY, BATAAN PENINSULA

Manila Bay is a semienclosed bay located on the southwestern part of Luzon Island at 14°15′–14°50′ N, 120°30′–121°00′ E (Figure 1). It has a surface area of 1800 km^2 with

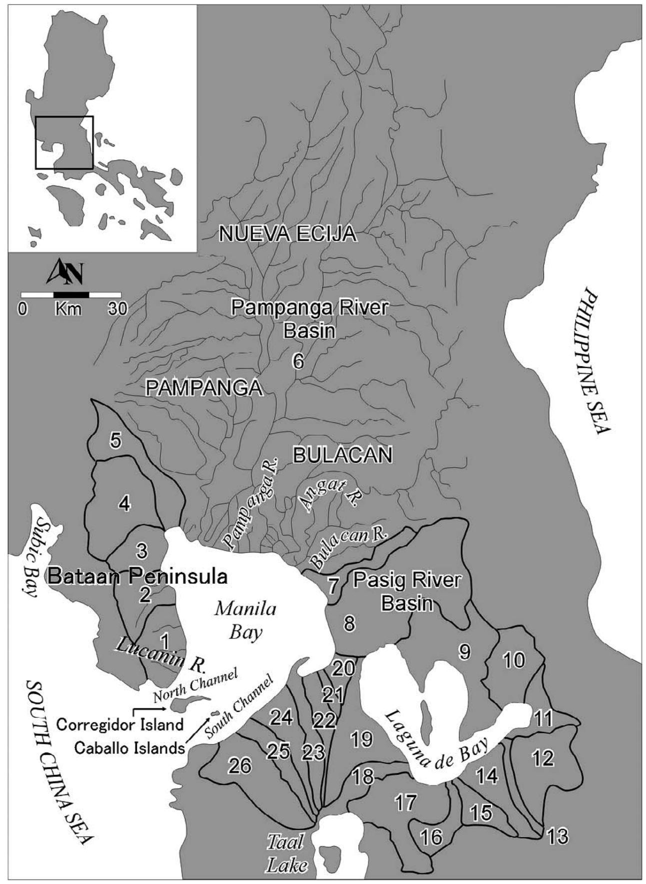

Figure 1. Index map of Manila Bay showing the different drainage basins in the area. The APN field work was performed along the southeast coast of the Bataan Peninsula (basin #1).

a coastline of approximately 190 km. It has an average depth of 25 m and is approximately 52 km long, with widths varying from 19 km at its mouth to 56 km inside the bay. The mouth is divided into a South Channel and a North Channel by Corregidor Island and the Caballo Islands, which reduce the net width of the entrance to only about 10 km. Slightly less than 4 km wide, the North Channel has a maximum depth of 71 m, whereas the South Channel, somewhat less than 6 km wide, is no more than 47 m deep. The deepest parts of both channels are adjacent to the intervening islands. Tides along the coast of Manila Bay are diurnal and within the microtidal range. The estimated mean tidal range for Port Lamao, Bataan, is 1.09 m (NAMRIA, 1996).

The study area selected for this project lies along the southeastern coast of the Bataan Peninsula. It is part of a small, elongate drainage basin that contains the east-southeast–flowing Lucanin River and has an area of roughly 1120 ha. The topography of the basin is rolling, mostly 5 degree slopes, but some as much as 14 degrees, with a relatively narrow, flat coastal area. The highest elevation in the basin is ~330 m.

Bataan has two pronounced seasons—a dry season (No-

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vember to April), which is when we made our measurements, and a wet season (May to October). The average annual rainfall in Limay, about 11 km north of the study area, is 3000 mm y^{-1}. In Balanga, about 25 km north of the study area, the mean monthly temperature varies from 25.5°C to 29.0°C, with an average annual temperature of 27.1°C. The coolest months are from December to February, while the warmest months are April and May.

The aquifers in the eastern part of Bataan Peninsula are associated with Pliocene to Quaternary sand- to gravel-sized volcaniclastic sediments derived from the nearby inactive volcanoes. Confining layers, mainly composed of fine (clay- to silt-sized) ash, form discontinuous layers at different levels in the lower slopes. The area directly north of the study area is underlain by a thick (about 18 m) fine ash layer that extends laterally for at least 1.5 km. Low electrical resistivity zones at and near the surface also suggest the presence of this layer. However, this clay layer does not extend south to the study site. The well nearest to the study site, DRU-10, indicates the presence of two confining layers, each about 3 m thick, between depths of 21 and 34 m below ground level. It is believed that these closely spaced confining layers extend to the study area because the free-flowing wells in Lucanin are about 50 m deep. The base of the unconfined aquifer is projected to extend at least several meters below the surface in the survey area.

Transmissivity values derived from constant-discharge pumping tests of the partially confined aquifers range commonly from 270 to 730 $m^2\ d^{-1}$. The hydraulic conductivity values are rather low, usually within the range of 2.2 to 5.1 m d^{-1}. The low hydraulic conductivities can be explained by the very poor sorting of the sediments due to the presence of subordinate amounts of clay. Based on well logs, the materials of the unconfined aquifers in the study area are inferred to be the same as the confined aquifers north of the study area.

EXPERIMENTAL METHODS

General Strategy Concerning Experimental Assessment of SGD

Principal geochemical tracers used in the past for assessment of SGD include radon and radium isotopes, which provide information on the extent of total SGD. Radon should provide total flow because both freshwater and saline water will pick up radon during transit through a coastal aquifer. Radium should be more representative of the saline flow (recirculated seawater and/or saline terrestrial waters) because radium adsorbs into particles in freshwater and is released into saline water through ion exchange processes. So in principle, one could evaluate SGD using both radioisotopes with the expectation that the radon would provide a higher (fresh + saline) result, while the radium isotopes would record just the saline flow. The difference would thus be the freshwater input. Unfortunately, in systems where seawater recirculation dominates, the two values would be very close, and the resulting uncertainty in the freshwater estimate would be very large. Since the main assessment tool in this study was to be seepage flux chambers (see below) that measure total flow, we decided to use radon tracing as an independent measure of this flow.

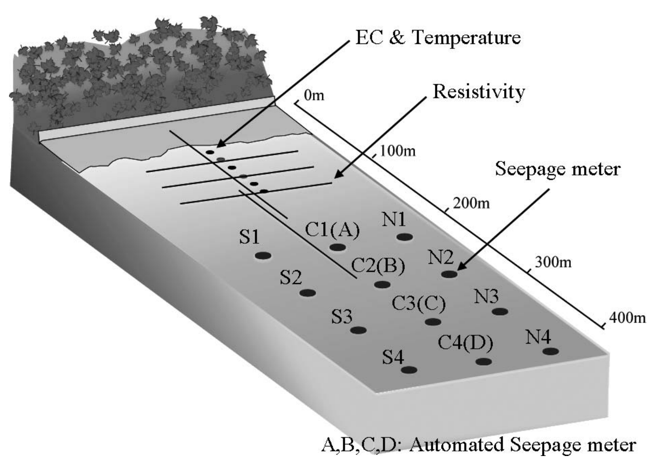

Figure 2. Schematic diagram showing locations of seepage meters (circles) and resistivity measurements (line segments).

One can use direct measurement via seepage meters and use continuous conductivity measurements inside the chambers to evaluate the extent of the freshwater *vs.* saline water flow. The difficulty with this approach is that a seepage flux chamber only sees a very small area of the seabed, and groundwater discharges tend to be very patchy. Thus, we felt that the best overall experimental approach was to use a combination of approaches (flux chambers and radon tracing in this case) in order to provide the most unambiguous data set. That is the procedure undertaken in this investigation.

Manual Seepage Meters

The assessment of SGD in Manila Bay using manual seepage meters (MSMs) was conducted during 3 days from 8 to 10 January 2005. The MSMs were of the classic design, consisting of a top or bottom section of a 55 gallon drum inserted into the seabed, open end down, with a hole on the top for water displacement into plastic bag collectors (LEE, 1977). There were 12 MSM in use, which were placed in the seabed along three transects (lines) perpendicular to the shoreline (Figure 2). Seepage meters N1 (N = north), C1 (C = central), and S1 (S = south), which belonged to the first row, were placed at a distance of 200 m from the coast at high tide (much less at low tide). The second row of seepage meters, N2, C2, and S2, which were at an average depth of ~2 m, were placed 270 m from the coastline. The third row of MSMs (N3, C3, and S3) was placed at an average depth of 2.5–3.0 m at a distance of 340 m from the coastline. The fourth row of MSMs (N4, C4, and S4) was placed at an average depth of 4 m at the distance of 410 m from the shore.

Seepage meter readings were averaged over each day of measurement, and the pooled results were then integrated by distance offshore as explained in CABLE *et al.* (1997). This procedure produced a seepage flux per unit width of shoreline, assuming that we captured the entire width of the seepage face with our transects. If the seepage face were wider,

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which appears likely in this case, then the integrated values would be underestimated.

Automated Seepage Meters

Automated seepage meters have been developed over the past decade using a variety of approaches, including heat pulse methods (Krupa *et al.,* 1998; Taniguchi and Fukuo, 1993, 1996), ultrasonic measurements (Paulsen *et al.,* 2001), electromagnetic methods (Rosenberry and Morin, 2004), and continuous-heat-flow measurements (Taniguchi and Iwakawa, 2001; Taniguchi *et al.,* 2003). Four continuous-heat automated seepage meters (A, B, C, and D) were located at 200, 250, 300, and 350 m distance offshore from the coast just beside the central transect line in the study area (Figure 2). These types of automated seepage meters are based on the effect of heat convection due to water flow, whereby they measure the temperature gradient of the water flowing between the downstream and upstream positions in a flow tube with a diameter of 1.3 cm. The principle of this style of automated seepage meter has been described in detail by Taniguchi and Iwakawa (2001) and Taniguchi *et al.* (2003).

The average depths of the seawater at the seepage meter locations were 0.9, 1.2, 1.5, and 1.8 m at locations A, B, C, and D, respectively. The area of the chamber of these seepage meters was 0.255 m^2. Measurements of SGD using these devices were performed every 5 min from 8 to 11 January 2005. The tidal (sea) levels were also recorded every 10 min at station D using a pressure transducer. Conductivities and temperatures of water within the chambers were measured continuously by conductivity-temperature (CT) sensors (Alec Electronics Co. Ltd., Kobe, Japan), which were installed inside each of the chambers of the four seepage meters.

Resistivity

Resistivity under the seabed and land surface over a transect line perpendicular to the coast was measured by a Sting R1 IP/Swift AGI instrument. The number of probes used was 14, and the length of the transect line was 130 m (the interval length between each probe was 10 m). The Wenner method and RES2DINV version 3.50 Geotomo Software were used for resistivity measurement analyses.

Radon Measurements

An advantage of geochemical tracers such as natural radon is that the coastal water column integrates the tracers coming into the system via various groundwater pathways. Smaller-scale variations, which are not of regional interest, are smoothed out. Thus, the tracer approach is a reasonable way to deal with the large spatial heterogeneity problems that are invariably associated with groundwater discharges. Several studies have now shown that radon is an excellent tracer of groundwater discharge (Abraham *et al.,* 2003; Burnett and Dulaiova, 2003; Burnett *et al.,* 1996; Cable *et al.,* 1996; Corbett *et al.,* 1999, 2000; Garrison *et al.,* 2003; Hussain *et al.,* 1999; Kim and Hwang, 2002). Radon works as a tracer because it is greatly enriched in groundwater relative to ocean water, behaves conservatively in seawater, and is relatively easy to measure.

An automated radon system (Burnett *et al.,* 2001) was used to analyze ^{222}Rn from a constant stream of near-surface water (driven by a submersible pump) passing through an air-water exchanger that distributed radon from this running flow of water to a closed air loop. The air stream was fed to a commercial radon-in-air monitor (Durridge RAD-7) that determined the activity of ^{222}Rn by collection and measurement of the α-emitting daughter, ^{218}Po. Since the distribution of radon at equilibrium between the air and water phases is governed by a well-known temperature dependence, the radon activity in the water is easily calculated.

We first used radon and conductivity in a qualitative manner at the study site by performing a survey of the area with a multidetector radon analysis system (Dulaiova *et al.,* 2005). We ran the radon system together with a temperature-conductivity probe while under way at slow speed ($\sim$5–6 km h^{-1}) from a small fishing boat (the *Sweet Caroline*).

Individual radon measurements from grab samples collected from seepage meters and a groundwater well on land were performed using an attachment to the RAD-7 analyzer called a "RAD-H_2O." This device allows one to sparge a 250 mL sample with air, which is then directed through a drying tube and measured for radon by the RAD-7.

The main principle of using continuous radon measurements to decipher rates of groundwater seepage is to monitor the inventory of ^{222}Rn over time, making allowances for losses due to atmospheric evasion and mixing with lower-activity waters offshore. Any changes observed in these inventories can be converted to benthic fluxes required to maintain the observed quantity of radon. Although changing radon inventories in coastal waters could be a response to a number of other processes (sediment resuspension, longshore currents, *etc.*), we feel that the advective transport of groundwater (Rn-rich pore water) through permeable sediment is usually the dominant process. Thus, if the radon activity in the advecting fluids can be measured or estimated, we can convert the ^{222}Rn fluxes obtained by the mass balance approach to water fluxes by dividing the radon fluxes by the radon activity of the groundwater. The principles and equations for gas exchange, mixing corrections, and discharge estimates have been described in detail in Burnett *et al.* (2003b) and Burnett and Dulaiova (2003).

Nutrient Analyses

Water samples collected from seepage meters and ambient coastal seawater samples were immediately filtered and analyzed for dissolved phosphate, ammonium, and nitrate (nitrate + nitrite) in the laboratory on-site following recommended procedures (Strickland and Parsons, 1972). Aliquots of all water samples were kept frozen and taken back to the Chemical Oceanography Laboratories at Chulalongkorn University, Thailand, for the analysis of total dissolved N and P and silicate. Dissolved organic N and P (DON, DOP) were obtained by difference between the total and inorganic nutrient concentrations. Dissolved inorganic nitrogen (DIN) was taken as the sum of nitrate (including nitrite) and ammonium.

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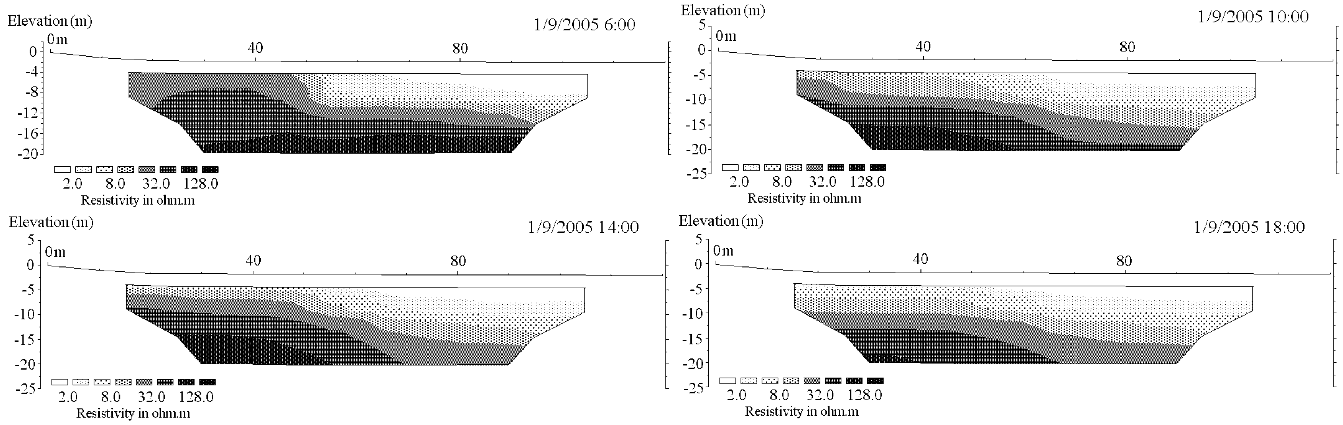

Figure 3. Temporal changes in resistivity from low tide (top left; 0600, 9 January 2005) to high tide (bottom right; 1800, 9 January 2005). Dark colors are freshwater and light colors are saline water.

RESULTS AND DISCUSSION

Freshwater-Seawater Interface Observations

The cross-sectional results of resistivity measurements along the transect lines, which were parallel to the coast at the lowest tide and at the mid-tide on 8 January 2005, show that fresher pore waters under the seabed occur during the low tide at the N line. Temporal changes in resistivity from low tide to high tide on 9 January 2005 show that the freshwater-saltwater interface moves toward land during the rising tide and moves offshore during the falling tide (Figure 3). Thus, the relative amounts of freshwater *vs.* saltwater that seep through the sediment at any one location are likely to vary in response to this moving interface. This was confirmed by salinity measurements inside the seepage flux chambers (see below).

Seepage Meter Results

Submarine groundwater discharge along the nearshore portion of the N line had the highest seepage rates, ranging from 7.1 to 10.9 cm d^{-1} (Figure 4), while the S line showed a higher rate in the station farthest away from shore. Temporal changes in seepage rate, water level, and electric conductivity inside one of the automated seepage chambers are shown in Figure 5. Diurnal variations of SGD were found that matched the tidal period in this area. The SGD rates increased with decreasing tidal level, as has been observed in several other areas (Kim and Hwang, 2002; Taniguchi, 2002). Although the magnitude was small, the conductivity of the SGD was also observed to decrease with the tide and with increasing SGD flow, confirming that the discharging groundwater was fresher than the ambient coastal water. These results are also consistent with the resistivity profiles, which indicated seaward movement of the freshwater–saline water interface as low tide approached. Because of the high variability in time and space of the seepage rates encountered in this study, we suggest that in order to more precisely evaluate SGD in Manila Bay, longer-term monitoring and several additional sites are necessary. However, the measurements taken here are sufficient to make a first attempt to quantify these inputs.

Radon Measurements

A radon and conductivity survey was conducted parallel to shore from the *Sweet Caroline* along about 25 km of coastline north and south of our base and then about 7 km directly offshore. The alongshore survey was run as close to the coastline as possible, but this was often hampered by shallow waters. In general, we were more than ~0.5 km offshore. The results showed generally low radon activities (<1.0 dpm L^{-1}) and inventories; an area about 10 km north of the base showed the highest radon (~2 dpm L^{-1}). The offshore transit showed a rapid drop-off in radon to levels below 0.5 dpm L^{-1}. The low activities are thought to be an effect of the influence of South China Sea water (low in radon), which enters Manila Bay and travels along the western shore where we were working during winter months. A summer (wet season) survey when the current direction is reversed would likely prove more fruitful for a radon survey approach.

Samples of groundwater for radon analysis were collected from two seepage meters and one groundwater production well onshore. The well was artesian and was developed into the main confined aquifer, about 40 m below the surface in this area. The salinities of the waters in the two seepage meters indicated a mixture of freshwater with seawater. The sample with the lower salinity also showed the highest radon, and a plot of radon *vs.* salinity shows that the seepage meter measurements extrapolate back to a radon activity at zero salinity that is essentially the same as in the groundwater well (Figure 6). This may indicate that there is freshwater leakage from the underlying confined aquifer in spite of the presence of the confining layers mentioned earlier. It is also possible, of course, that the surficial aquifer may just happen to have the same ^{222}Rn activity as the confined aquifer.

During the last few days of the fieldwork (9–11 January), we anchored the boat about 500 m from shore off the seepage

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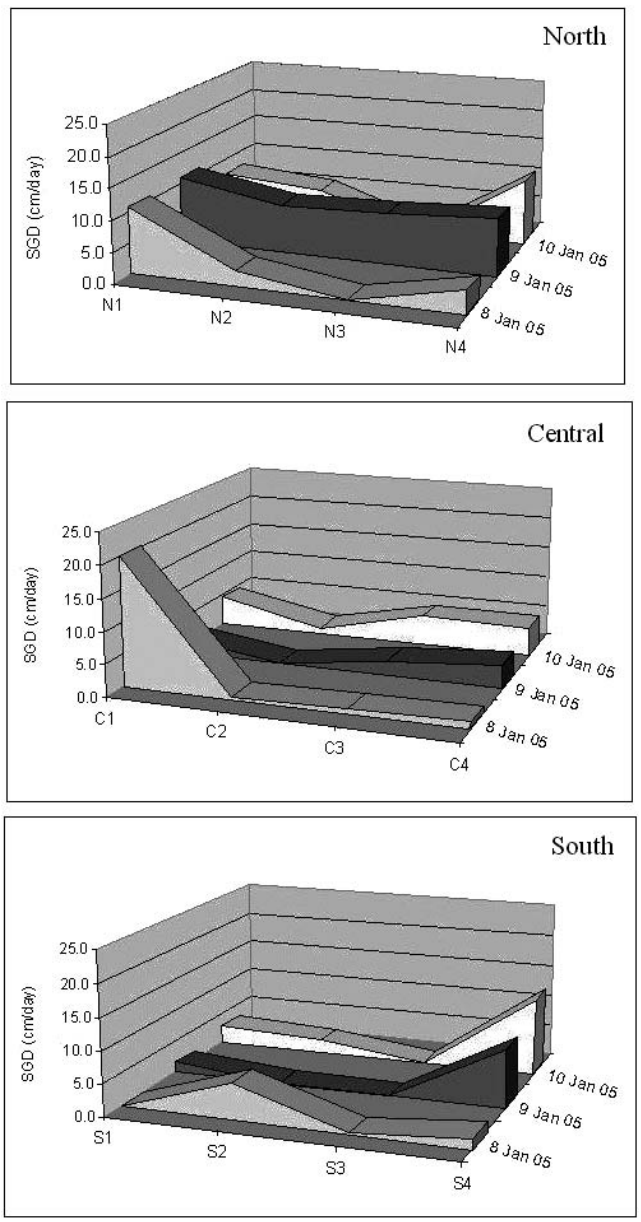

Figure 4. Seepage rate summaries for north (top), central, and southern (bottom) transect lines established off the Bataan Peninsula, 8–10 January 2005.

meter area in about 2.5 m water depth. The multidetector radon system was set for an integration time of 20 min, and it ran continuously for ~36 h to develop a time-series record at one location. The results (Figure 7) showed an increasing trend the first day, with a peak in radon activity just at the low-tide point. There was then another systematic increase and a second peak at an even higher activity that occurred during the falling tide early on 11 January. Applying the radon mass balance model with the appropriate corrections for atmospheric and mixing losses and an estimated radon groundwater activity of 240 dpm L^{-1} (Figure 6), we calculate a range in the total fluid advection from 0 to 17 cm d^{-1}, and a mean and standard deviation of 3.9 ± 4.9 cm d^{-1}. Our results are thus similar to the manual seepage meter results (range = 0–26 cm d^{-1}; mean = 5.1 ± 5.4 cm d^{-1}; n = 73). Note that the standard deviations reported here are not estimates of uncertainty, but they reflect the actual variation of advection in this non–steady-state system. Based on uncertainties associated with various components of the mass balance (inventories, atmospheric evasion, mixing losses), we estimate a total uncertainty in the radon-based SGD estimates of ~40%–50%. The radon results thus support those from the seepage meter measurements that suggest the SGD in this area of Manila Bay is not a constant flow but displays tidal-cycle variations.

When salinity measurements recorded from a conductivity meter installed on the outside of a nearby seepage meter (to measure ambient seawater) and from the boat are plotted together with the radon data (Figure 7), it is clear that there was distinct freshening of the water at precisely the same time as the maximum in radon early on 10 January 2005 and very close to the maximum early the next day. These measurements suggest that a freshwater component, most likely from groundwater seepage, is the source for the excess radon observed at this site.

Estimated SGD Nutrient Fluxes

The ranges and mean concentrations of the nutrients measured both in seepage water and ambient seawater are shown in Table 1. The seawater values we measured are close to average Manila Bay values reported previously for DIN (4.2 μM) and PO_4 (0.79 μM) by JACINTO *et al.* (1999). In general, nutrient concentrations measured from seepage waters were significantly higher than those from nearshore seawater samples. Nitrate was an exception; it was slightly higher in seawater than in the seepage meter waters. We only managed to recover three samples from freshwater wells for nutrient analyses. DIN concentrations in two of the wells were very high, with both wells at 68 μM; the DIN/PO_4 ratios of 100 and 170 were higher than N/P measured in any of the coastal seepage meter waters. While the data are obviously limited, it appears that the fresh groundwater in the area potentially represents a substantial contribution to the N loading of Manila Bay.

It is possible that higher nutrient concentrations in the seepage meters could be an artifact caused by the altered environment created inside the seepage meters. For example, if the benthic chamber resulted in a reducing environment, redox sensitive species could be affected. Phosphate adsorbed on iron/manganese oxides, for example, could be released if the environment became sufficiently reducing to dissolve these metal oxides. While the nitrogen speciation could also be influenced by changing redox conditions, the total amount of dissolved inorganic nitrogen (DIN) should remain the same.

Based on the average seepage fluxes measured in this study, we estimated an average integrated seepage of 8.6 L m^{-1} min^{-1} or 12.4 m^3 m^{-1} d^{-1}, which is the estimated total seepage flow per unit width of shoreline. Integrations of seep-

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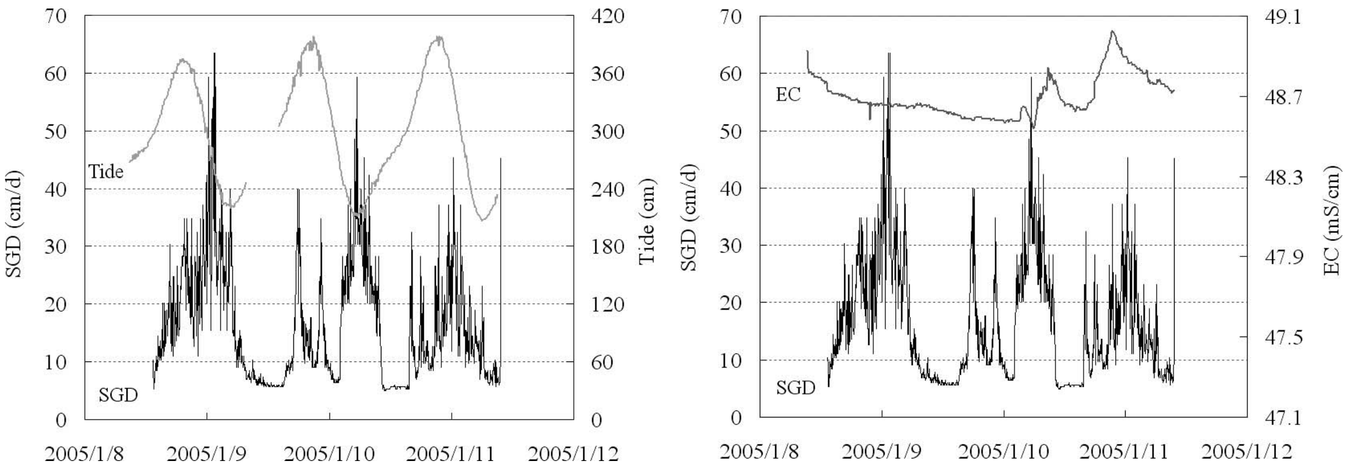

Figure 5. Temporal changes of SGD, water level, and electric conductivity of SGD at location C based on measurements from an automatic seepage meter.

age measurements in this manner assume that the entire width of the seepage face has been sampled by the meters. Since there was still some seepage detected in our meters farthest from shore, our estimate is likely a minimum value. This integrated SGD water flux is a total flow (fresh + recirculated seawater) and is useful for comparing biogeochemical inputs by groundwater flow to inputs via river flow. By multiplying the average nutrient concentrations in the seepage water (Table 1) by the average integrated flow rate and making appropriate unit conversions, we can calculate the nutrient flux per unit width of shoreline (Table 2). The flux of DIN is normally dominated by NH_4 and is less than the flux of DON, while the DIP flux is about the same as that of DOP. DON is the major form of nitrogen exported from the rivers to the bay, and it is derived from various urban and agricultural sources.

In order to make a comparison to river fluxes, we first estimated the total riverine nutrient fluxes of dissolved inorganic nitrogen (DIN = NH_4 + NO_3) and inorganic phosphate

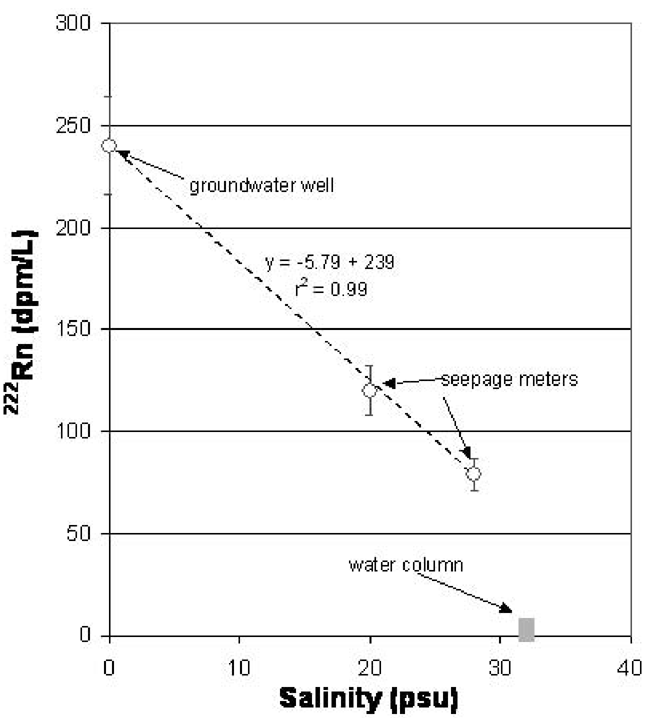

Figure 6. Radon-222 *versus* salinity in two seepage meters and one groundwater well (open circles). The solid square represents the range in measurements made in the overlying water column.

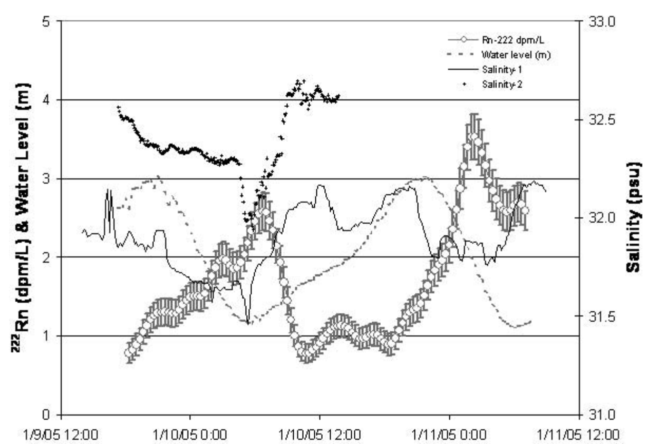

Figure 7. Time-series results showing radon activities (open circles), water-level variations (dashed line), and two records of salinity variations over an ~36 h period during 9–11 January 2005 at a station ~500 m offshore. Salinity record-1 was measured on the outside of the most seaward automated seepage meter (~350 m offshore), and record-2 was measured via a CT suspended into the water column (~0.5 m above the bottom) from the same boat used for the radon analyses. Uncertainties in the radon activities are 1σ and are based solely on counting statistics.

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Table 1. *Ranges and means of nutrient concentrations in seepage waters and nearshore seawater.*

Water Type	Nutrient					
	NH_4 (μM)	NO_3 (μM)	DON (μM)	PO_4 (μM)	DOP (μM)	SiO_2 (μM)
Seepage water						
Range	15.3–133	0.4–1.6	10.4–291	0.3–3.8	0.0–34.6	65.1–112
Mean ± s.d.	59.3 ± 36.7	0.6 ± 0.3	105 ± 75.4	1.8 ± 1.0	2.6 ± 8.6	84.7 ± 15.6
Seawater						
Range	1.1–6.1	0.6–1.6	0.5–23.4	0.3–0.9	0.1–4.4	18.1–49.5
Mean ± s.d.	2.6 ± 1.5	1.0 ± 0.4	11.1 ± 8.9	0.5 ± 0.2	1.5 ± 1.7	29.7 ± 9.9

Number of samples: seepage waters: $n = 16$; seawater: $n = 9$.

based on literature values. Manila Bay is reported to receive 24×10^9 m^3 y^{-1} of total freshwater runoff from approximately 17,000 km^2 of watershed composed of 26 catchment areas (EMB-DENR/UNEP, 1991; EMB, 1992). The two major areas contributing freshwater to the bay are the basins of the Pampanga and Pasig Rivers, which contribute about 49% and 21% of the total runoff, respectively. Other, smaller river systems contribute 26%, and the balance of 4% comes from the net precipitation over the bay (EMB, 1992). The 9000 km^2 catchment area of the Pampanga River Basin is the largest contributor, and it includes the Angat River and other river systems in the provinces of Pampanga, Bulacan, and Nueva Ecija. The Pasig River Basin has a watershed area of 3900 km^2 and includes the Marikina and Laguna de Bay catchment areas. The average river discharge from the Pampanga River Basin into Manila Bay is 391 m^3 s^{-1}, and the Pasig River has an average flow of 170 m^3 s^{-1}.

Based on the literature values for river discharge cited above and average nutrient concentrations for nutrients in rivers flowing into Manila Bay from the study by EMB-DENR/UNEP (1991), we calculate riverine DIN and PO_4 fluxes and made a comparison to our estimated fluxes via SGD. The groundwater fluxes were calculated by multiplying our average integrated seepage flux by the mean nutrient concentrations measured in the seepage waters (Table 2). We used an estimated length of shoreline of Manila Bay of 190 km. This calculation assumes, of course, that the measurements made at the study site off Bataan are characteristic of all of Manila Bay. While we have no way of evaluating this assumption at this time, we feel that this rough calculation is still useful for illustrating the potential importance of subsurface discharges into this embayment. The calculated fluxes of DIN by SGD are 42% and 96% of the fluxes from the Pampanga and Pasig Rivers, respectively. Estimated SGD inputs of PO_4 are lower, at 7% and 17% of the two rivers. This implies that SGD is comparable as a source of inorganic nitrogen to each of the two main river systems that discharge into Manila Bay. While admittedly crude at this time, these initial results provide motivation to examine groundwater discharge in more detail as a possible important source of biogeochemically active constituents.

Table 2. *Estimates of river and groundwater fluxes for DIN and PO_4. Comparison is based on the ratio of the river-to-SGD derived fluxes. Nutrient fluxes via seepage were calculated by multiplying the average integrated seepage flux by the mean nutrient concentrations measured in the seepage chambers.*

Pampanga River Basin						
	River Conc. mM	River Flux moles day^{-1}	Seepage Conc. mM	Seepage Flux moles m^{-1} day^{-1}	Seepage Flux moles day^{-1}	% River
DIN	10	3.38E+05	59.9	7.43E−01	1.41E+05	42
PO4	1.7	5.74E+04	1.8	2.23E−02	4.24E+03	7
River Discharge = 391 m^3s^{-1}						
Integrated seepage flux = 1.24E+04 L m^{-1} day^{-1}						
Manila Bay shoreline = 1.90E+02 km						
Pasig River						
DIN	10	1.47E+05	59.9	7.43E−01	1.41E+05	96
PO4	1.7	2.50E+04	1.8	2.23E−02	4.24E+03	17
River Discharge = 170 m^3s^{-1}						

CONCLUSIONS

Based on a variety of geophysical, hydrological, and oceanographic techniques performed in a coastal area of the Bataan Peninsula, our main findings are as follows:

(1) Seepage meter and radon tracing approaches provide consistent groundwater discharge estimates into Manila Bay.
(2) The waters seeping into Manila Bay along the southeastern shoreline of Bataan are a mixture of freshwater and saline water. The total discharge is highest at low tide, and the salinity of this flow is significantly fresher than the surrounding coastal waters.
(3) The source of the freshwater component may be from the confined aquifer in spite of the presence of confining layers in this area. Unfortunately, no wells were available to sample the unconfined aquifer, so we do not know if there is a difference in the radon activity. If there is flow from the confined aquifer, it could be an effect of ruptures in the confining units that provide pathways for the artesian waters.
(4) The SGD displays high variability in time and space in the area studied. Thus, more precise evaluations should involve longer-term monitoring and more sites than were possible during this initial study.
(5) Resistivity profiles show that the saline water–freshwater interface moves on a tidal timescale. The interface moves seaward as the tide drops, corresponding to the freshening observed in the seepage meters and offshore.
(6) Inorganic nitrogen fluxes via SGD appear to be compa-

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rable in magnitude to DIN fluxes from each of the two major rivers that drain into Manila Bay. While these estimates are rough, it implies that nitrogen fluxes into Manila Bay may be seriously underestimated if underground inputs are ignored.

ACKNOWLEDGMENTS

The authors thank the faculty, students, and staff at the National Institute of Geological Sciences and Department of Marine Sciences, University of the Philippines, for their cooperation and logistical assistance during the field program. We acknowledge the financial support from the Asia-Pacific Network that made this expedition possible. Additional funding was provided by the Research Institute for Humanity and Nature (Japan) and the U.S. National Science Foundation (grant OCE03-50514 to WCB).

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