Paulino, S., Gordon-Smith, D.-A., Buddo, D., Bokuniewicz, H., Rapaglia, J. and Zaggia, L. 2019. Occurrence of submarine groundwater discharge (FSGD) in six embayments along the north coast of Jamaica. *Caribbean Journal of Earth Science*, **51**, 7-14. © Geological Society of Jamaica. Available online 17th December 2019.

Occurrence of submarine groundwater discharge (FSGD) in six embayments along the north coast of Jamaica

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ABSTRACT. Fresh submarine groundwater discharge (FSGD) at the shoreline has been implicated as an important factor in the maintenance of coastal water quality and the sustenance of ecological goods and services. FSGD can be disproportionately large on oceanic, small island developing state (SIDS), like Jamaica, but developing countries may not be able to fund ideally developed FSGD sampling regimes. In order to provide a strategic road map for regulating and maintaining the quality of coastal ocean environments, the distribution of FSGD in Jamaica was explored using direct measurements with vented, benthic chambers, high-resolution aerial thermal infrared imagery (TIR), and naturally occurring radiometric tracers. FSGD was found to occur along the entire northern embayed coast of Jamaica both as submerged springs and as diffuse seepage at the shoreline.

Keywords: Submarine groundwater discharge, thermal imagery, submerged springs.

1. INTRODUCTION

Fresh submarine groundwater discharge (FSGD) is widely recognized as a principal pathway in the transport not only of freshwater, but also of dissolved nutrients and contaminants, to the ocean. FSGD provides a vector, largely unseen, for the pollution of coastal waters. It is especially important in the coastal zones of small-island developing states (SIDS). Not only are freshwater reserves limited but also maintaining good coastal ocean water quality is critical to fisheries and ecotourism although potentially compromised by rural agriculture and waste disposal. For tropical islands with high relief, such as Jamaica, orographic precipitation fuels large FSGD (**Naughton, 1982**). In addition, because of a large ratio of shoreline length to land area, SGD focuses the impact of land-use at the coast, so that changes to groundwater quality on land might have a more concentrated effect on any discharge to the coastal ocean (**Moosdorf et al., 2015**). Small islands also can lack well-formed surface drainage, so that flow paths to the ocean are short, reducing the time available for attenuation, adsorption and alteration of nutrients within the aquifer. As an added, practical constraint, many SIDS may not be able to support FSGD sampling regimes requiring long periods of study, dedicated staff and specialized equipment. As a result, beginning to document the location and strength of FSGD along the Jamaican coast may help provide a strategic road map to regulating and maintaining the quality of coastal ocean environments. Of particular concern is the interaction between coral nurseries and the location of submerged springs (e.g., **D'Elia et al., 1981**; **Lapointe, 1997**). In this article, we discuss a variety of evidence for the occurrence of substantial FSGD in six embayments along the north coast of Jamaica. Although the evidence is fragmented and incomplete in many ways, we believe that, in aggregate, these observations provide a basic characterization of FSGD in this setting and the efficacy of methods.

2. STUDY AREA

Jamaica (**Figure 1**), a small island developing state (SIDS), is the third largest island in the Caribbean with an area of 10,990 km^2, 1,022 km of coastline and population of approximately 2.7 million (**Statistical Institute of Jamaica, 2011**). The central north coast of Jamaica is marked by karstic terrain while the eastern focus includes mainly volcanic aquicludes. Limestones are found in northeastern Jamaica (**Miller et al., 2003**; **Mitchell, 2013**; **James-Williamson et al., 2014**). Average annual rainfall on the island is 1,981 mm/year

Figure 1. Study sites were located in **(1)** Discovery Bay, **(2)** Ocho Rios Marine Park, and **(3)** Boscobel, and **(4)** Turtle Crawle, **(5)** Cold Harbour and **(6)** San San Bay. **(A)** Sangster International Airport, Montego Bay. See **Table 1** for geographical coordinates of the study sites.

Table 1. Distribution of measurements among the seven study sites.

Location	Latitude and longitude	TIR	^{222}Rn	Seepage meters
Discovery Bay	18.469; -77.415	*	*	*
Ocho Rios	18.414; -77.101	*		
Boscobel	18.407; -76.980	*	*	*
Turtle Crawle	18.176; -76.422	*	*	*
Cold Harbour	18.174; -76.404	*	*	*
San San Bay	18.177; -76.394			*
San San Beach	18.175; -76.396			*

(**Miller et al., 2001**), concentrated on the eastern mountains and northern coast. This section of the coast fringes the Dry Harbour Mountains, the Blue Mountains and the John Crow Mountains from Discovery Bay (site 1, **Figure 1**) to the eastern coast. The tidal range is less than 0.5 m (**Greenaway and Gordon-Smith, 2006**), and the groundwater hydraulic gradients generally slope toward the north and south coastlines due to steep, mountainous interiors (**Water Resources Authority, 2019**). The northern coast is cut into a narrow coastal plain that provides both natural and man-made white sand beaches and fringing reefs that enclose shallow lagoons, bays, and protected rocky coves followed inland by uplifted karstic limestone that form cliffs. The shallow protected lagoons enclosed by fringing reefs and reef flats contain seagrass beds, corals and mangrove forests. In highly populated areas, the groundwater has often been found to be contaminated with excess nitrates due to agricultural practices and improper sewage disposal (**Miller et al., 2001**). To properly manage its important ecosystem services, Jamaica has established a series of marine parks, conservation areas and marine and fish sanctuaries.

This study was conducted along the northeastern shoreline of Jamaica at six locations, (1) Discovery Bay Marine Laboratory and Field Station, (2) Ocho Rios Marine Park (Mallards Bay), (3) Boscobel, (4) Turtle Crawle, (5) Cold Harbour and (6) San San Bay (**Figure 1**; **Table 1**). All are sites of existing or proposed marine conservation areas.

Discovery Bay covers an area of about 1.4 km^2 with a maximum depth of 56 m in a central depression. The fringing-reef system extends two-thirds of the way across the mouth of the bay. There are no permanent surface flows into Discovery Bay, but the bay is known to receive freshwater via diffuse seepage through bottom sediments as well as from submarine springs (**Gordon-Smith and Greenaway, 2019**). Of the six sites investigated here, Discovery Bay is the only one that has been studied previously with regard to FSGD although another "major spring" had been identified offshore east of Ocho Rios (**Sweeting, 1973**; approximately 18.4177 N; 77.1214 W). Submerged springs are known to have reduced salinity and increased nitrogen concentrations relative to the overlying bay water (**D'Elia et al., 1981**; **Greenaway and Gordon-Smith, 2006**). Submerged-spring discharges and diffuse seepage have been estimated by **Gordon-Smith and Greenaway** (**2019**) to provide 9,000 to 19,000 m^3 of water per day and 30,000 to 90,000 m^3 of water per day, respectively, to the bay.

The Discovery Bay Marine Laboratory and Field Station (DBML) is a facility of the University of the West Indies. DBML is located on the northwestern shore of the Discovery Bay Marine Reserve. For this study, observations were made in the anchorage of DBML which covers an area of about 4500 m^2. The second site, the Ocho Rios Marine Park Protected Area is a shallow, protected lagoon along 13.5 km of coastline. Seagrass beds, mainly *Thalassia testudinum*, are found inside the fringing reef interspersed with mudflats. At the third site, the Boscobel Marine Sanctuary covers an area of 0.5 km^2 along a strand 1.2 km in extent behind a reef 0.25 km offshore. Turtle Crawle Bay, Cold Harbour, and San San Bay are all located in the East Portland Special Fishery Conservation Area. Turtle Crawle Bay has a maximum depth of 5 m and contains coral nurseries and mangrove forests. Cold Harbour reaches water depths of 17.7 m; it contains seagrass beds and is well known for its cooler water temperatures. San San Bay is a small embayment less than 3 m deep with seagrass beds that is protected by shallow reefs and an uninhabited island.

3. Methods

Investigations employed a combination of aerial, high-resolution thermal infrared imagery (TIR), naturally occurring radiometric tracers, and vented benthic chambers. Because of various equipment failures or adverse weather conditions, not all measurements were able to be made at all locations (**Table 1**). However, the aggregate of available data was used in a reconnaissance of FSGD manifestation in the region. Direct measurements of FSGD were made with vented benthic chambers. These Lee-type seepage meters (**Lee, 1977**) were deployed in the DBML anchorage, Boscobel, and San San Bay in East Portland. Temperature and salinity were measured with a YSI 556 Multiprobe.

FSGD also has been detected successfully using high-resolution thermal infrared imagery (TIR), due to the thermal contrast of the cooler discharging groundwater and the warmer surrounding coastal waters (e.g., **Johnson et al., 2008**; **Tamborski et al., 2015**). Thermal differences in warm tropical coastal waters and cooler groundwater discharge were mapped with a FLIR Systems T400 TIR camera from a helicopter at an altitude of 1000 feet and 3000 feet on September 8, 2016 and on January 9, 2017. The camera was calibrated before each flight, for atmospheric reflectivity, humidity, and emissivity. The pixel-to-pixel thermal accuracy at 1000 feet was 1 K, with an absolute accuracy of about 2 K, wavelength range of 7.5–13 μm, and a lens field of view = 25° × 18.8°.

Radiometric tracers are routinely used successfully to detect FSGD. ^{222}Rn, in particular, is elevated in groundwater and often used in quantifying FSGD (e.g., **Burnett and Dulaiova, 2003**). Continuous surveys of ^{222}Rn activity were done using a radon-in-air monitor (RAD-7, Durridge Co.) from small, slow moving boats in September 2016. ^{222}Rn activity was recorded every five minutes along the track corresponding to a survey segment of about 100 m. The RAD-7 was also placed on a kayak and Rn could be detected in areas too shallow for a motorized boat to enter. Measured ^{222}Rn values from the surveys were reduced from the measured radon concentrations in air ($\boldsymbol{C_{air}}$) to radon concentrations in water ($\boldsymbol{C_w}$) according to the air-water partitioning formulas (**Schubert et al., 2012**):

$$C_w/C_{air} = K_{w/air} = b * T/273.15 \qquad [1]$$

where

$$\ln(\beta) = a_1 + a_2(100/T) + a_3*\ln(T/100) + S\{b_1 + b_2(T/100) + b_3(T/100)^2\} \qquad [2]$$

The "$\boldsymbol{a}$" and "$\boldsymbol{b}$" parameters are determined by salinity and temperature ranges. In this case, a_1 = 76.14, a_2 = 120.36, a_3 = 31.26, b_1 = 0.2631, b_2 = 0.1673 and b_3 = 0.027 (**Schubert et al., 2012**). The loss of ^{222}Rn due to atmospheric evasion is dependent on wind speed. It was calculated as:

$$^{222}Rn_{atm} = k * (C_w - \alpha C_{atm}) \qquad [3]$$

where $\boldsymbol{k}$ is the gas transfer coefficient (-0.5 or -0.667 for wind speeds above or below 3.6 m/s, respectively), $\boldsymbol{\alpha}$ is Oswald's solubility coefficient (0.21) and $\boldsymbol{C_w}$ and $\boldsymbol{C_{atm}}$ are the concentrations of ^{222}Rn in water and in the air respectively. Wind speeds were taken from hourly wind-speed records at the international airport at Montego Bay which is located on the north shore of Jamaica as are the study sites (**Figure 1**).

End-member radium samples were collected at the DBML site in Turtle Crawle Bay, and in Cold Harbour during January 2017 using 20 L cubitainers, which were filtered through manganese-impregnated fibers. The activity of ^{222}Rn's radium parent (^{226}Ra) in Discovery Bay was determined using the delayed coincidence counter (RaDeCC) system (**Moore and Arnold, 1996**). The amount of ^{222}Rn not supported by ^{226}Ra decay was calculated:

$$^{222}Rn_{excess} = {}^{222}Rn_{total} - {}^{226}Ra \qquad [4]$$

$^{222}Rn_{excess}$ values are reported in this paper as evidence of FSGD. It was not our intention and it was beyond the scope of this exploratory research to fully translate the values for $^{222}Rn_{excess}$ into rates of FSGD.

4. RESULTS

Aerial thermal infrared imagery was collected over Discovery Bay, Ocho Rios, Boscobel, Turtle Crawle Bay and Cold Harbour. Plumes of cooler water at the shoreline were not associated with stream discharge but rather interpreted as indicative of FSGD, both from diffuse sources and from submerged springs. The TIR imagery at DBML showed surface temperature anomalies of 2 °C in both September 2016 (**Figures 2A**) and in January 2017 (**Figure 2B**). Conditions in January were such that several distinct shoreline sources of cooler water could be seen along the western shore. Distinct, submerged springs were detected by divers between the pier and the western shore that could not be seen in the TIR imagery as surficial thermal anomalies. These features had also been identified in previous studies (**Gordon-Smith and Greenaway, 2019**; **D'Elia et al., 1981**; **Bonem, 1988**). The failure to detect these submerged springs was likely due to the depth of water but could have been artifacts of the thermal resolution of the camera or an off-nadir orientation of the camera.

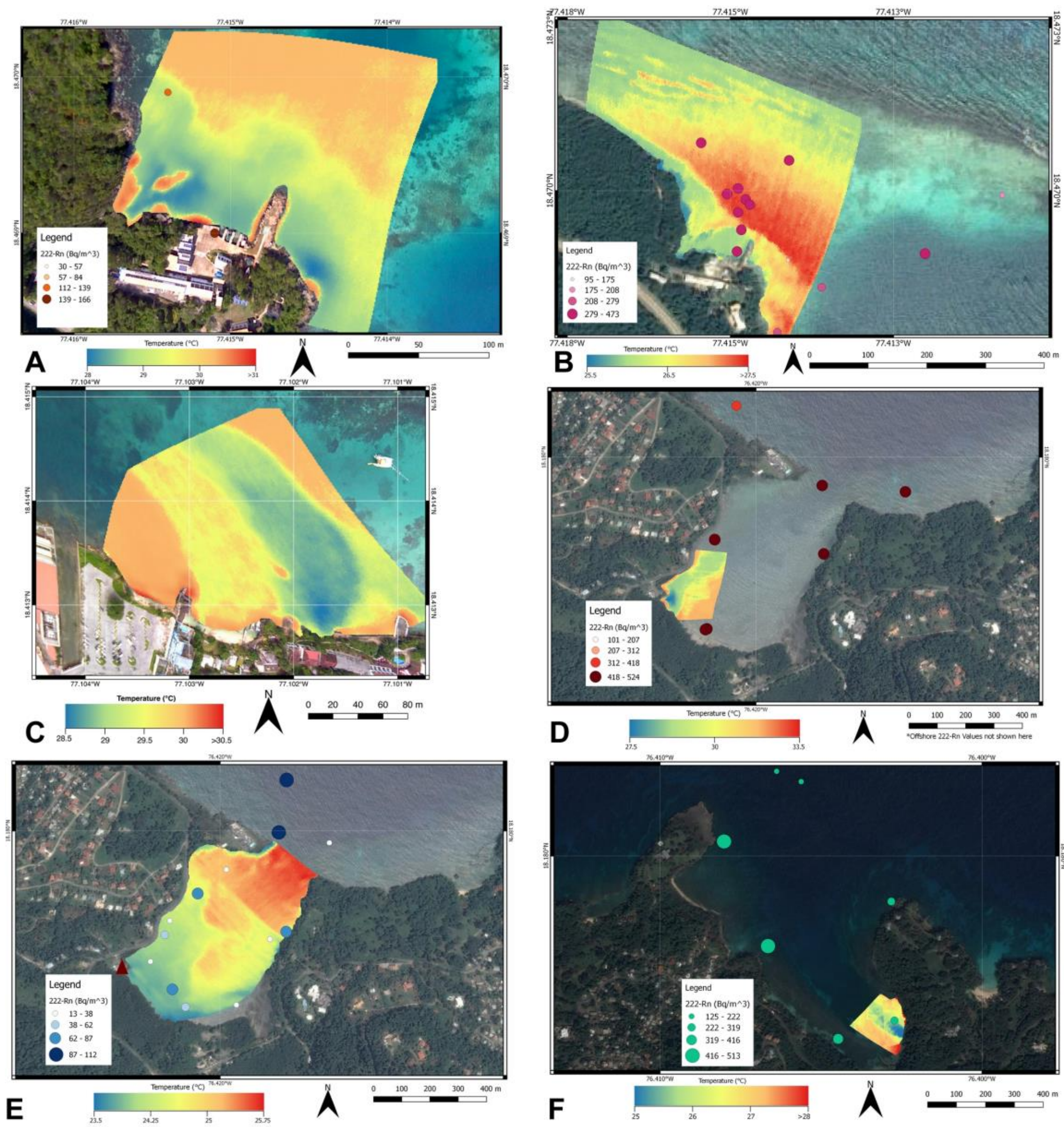
TIR imagery of Ocho Rios Marine Park showed a distinct plume of cool water, indicative of a concentrated, non-fluvial source of FSGD at the developed shoreline 300 m east of the mouth of a river between the Turtle River and the White River (18.4127; -77.1017; **Figure 2C**). The plume was about 1.5 °C cooler than ambient sea surface temperatures and was interpreted to be a point-source of FSGD at the developed shoreline of Mallard's Bay. TIR imagery of Turtle Crawle Bay in September (**Figure 2D**) indicated the presence of diffuse seepage at the bay's southwest corner near the Alligator Head Marine Laboratory (18.1755; -76.4227); the TIR imagery in January covered the entire bay (**Figure 2E**) and showed widespread SGD along the southern shore. In these areas the surface water was as much as 3 °C cooler than ambient bay temperatures. TIR imagery at Cold Harbour in both September (**Figure 2F**) and January (**Figure 2G**) indicated the presence of a concentrated plume of cool FSGD at the eastern shore. The surface water evinced thermal anomalies of over 2 °C. Elevated ^{222}Rn activities in the plumes could be enriched greater than ten-fold above ambient open-water activities. Elevated ^{222}Rn activities tended to correspond with plumes of cooler water at the shoreline but plume values were only about one-tenth of endmember concentrations.

^{222}Rn surveys were conducted in the DBML anchorage in both September and January (**Figure 2A-B**). The maximum excess ^{222}Rn was found to be 1309 Bq/m^3 with 38% of the measurements being over 1000 Bq/m^3. In January, a weak ($R^2 = 0.2$) inversely linear correlation was found with salinity suggesting a freshwater endmember of 1902 Bq/m^3 similar to a measured inland endmember ^{222}Rn value in the vicinity of DBML (Figure 3) of 2517 Bq/m^3. ^{226}Ra concentration in the Bay was found to be 5 Bq/m^3.

^{222}Rn activities were not elevated in the Boscobel Marine Sanctuary; the peak value being 41 Bq/m^3 within the reef. Salinity and temperature recorded during the survey ranged from 32.6 to 33.5 and from 29 to 30.37 °C, respectively. There was no evidence of FSGD based on the radon surveys; however, as we will discuss later, direct measurements using vented benthic chambers did indicate SGD at a beach site there.

In Turtle Crawle Bay, ^{222}Rn surveys done in September showed elevated, excess ^{222}Rn values. The September survey documented a maximum of 524 Bq/m^3, and a minimum of 101 Bq/m^3. The elevated values were located within the bay and along the shoreline, while the lower values were obtained in waters further offshore. Three areas of elevated excess ^{222}Rn activities in the Turtle Crawle Bay ranged from 66 to 81 to 84 Bq/m^3. During the January survey in Turtle Crawle Bay, the maximum and minimum activities of ^{222}Rn were 112 Bq/m^3 and 13 Bq/m^3, respectively. These values were between five and ten times lower than the previous survey in September. Measurements taken before noon were higher than the measurements in the late afternoon; the difference in wind speed (greater in the afternoon) leads to a higher atmospheric evasion of ^{222}Rn in the water column. The data were not well distributed, but a fairly strong ($R^2 = 0.46$) inverse linear correlation with salinity suggested a seawater endmember below 100 Bq/m^3 and a freshwater endmember of 14,167 Bq/m^3. Endmember activity was measured as 6368 Bq/m^3 at a nearshore spring on the southern coast (18.1724; -76.4263) nearly 60 times the maximum value from the open-water survey. ^{226}Ra was determined to be 2 Bq/m^3.

At Cold Harbour, offshore ^{222}Rn values were an order of magnitude lower than those within the bay. Unlike the surveys done in Turtle Crawle Bay, Cold Harbour ^{222}Rn values were similar in both September and January. ^{222}Rn surveys in September had a maximum of 513 Bq/m^3 and a minimum of 125 Bq/m^3, while values in February were between 557 Bq/m^3 and 4 Bq/m^3. The highest activities, up to 557 Bq/m^3, were seen along the



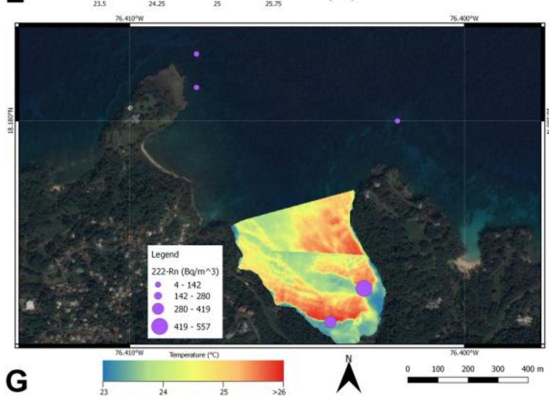


Figure 2. **2A,** (left) Discovery Bay Marine Lab Anchorage TIR in September. **2B,** (right) January TIR and Radon Survey Discovery Bay Marine Lab. **2C,** (center) TIR of Mallards Bay at Ocho Rios. **2D,** (left) Turtle Crawle Bay TIR/RN Survey September 2016. **2E,** (right) Turtle Crawle Bay TIR/Rn Survey January. **2F**, (left) Cold Harbour September TIR and Rn Survey. **2G**, (right) Cold Harbour January TIR and February Rn Survey.

shoreline, close to a submerged spring. A weak inverse correlation ($R^2 = 0.3$) with salinity was observed, with values in the seawater endmember below 160 Bq/m^3 and suggesting a freshwater endmember of 5499 Bq/m^3. A similar freshwater ^{222}Rn endmember value was determined inland to be 4684 Bq/m^3 at the mouth of a spring on the eastern shore (18.1742; -76.4022). ^{226}Ra was determined to be 12 Bq/m^3.

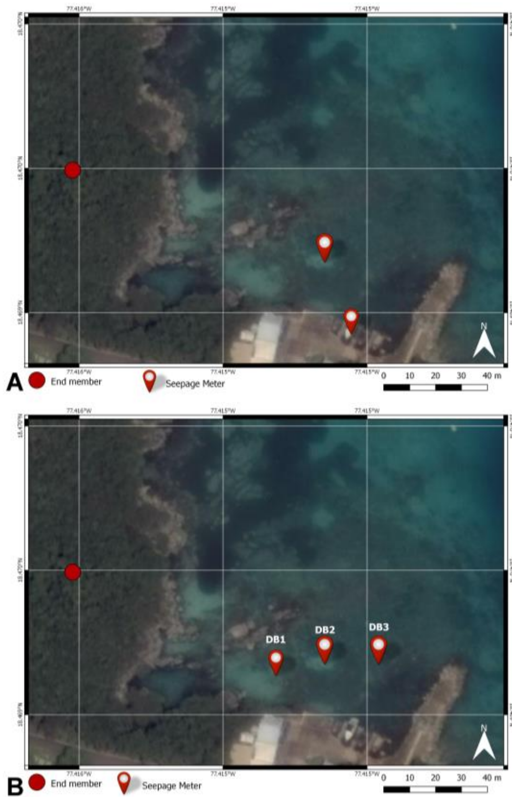


Figure 3. 3A. End-member and Seepage Meter Location in Discovery Bay, September 2016. **3B.** End-member and Seepage Meter Location, January 2017.

Table 2. Average seepage-meter SGD

Site	Average Salinity	Average SGD cm/day
Discovery Bay 1, 2016	30.3	17.3
Discovery Bay 2, 2016	31.2	15.8
Discovery Bay 1, 2017	33.6	20.4
Discovery Bay 2, 2017	34.8	41.8
Discovery Bay 3, 2017	31.3	41.3
Boscobel 1, 2017	35.2	21.3
Boscobel 2, 2017	35.0	8.0
Alligator Head 1,2017	36.3	16.6
Alligator Head 2,2017	36.4	15.8
San San Beach 1, 2017	34.8	8.7
San San Beach 2, 2017	35.0	8.7

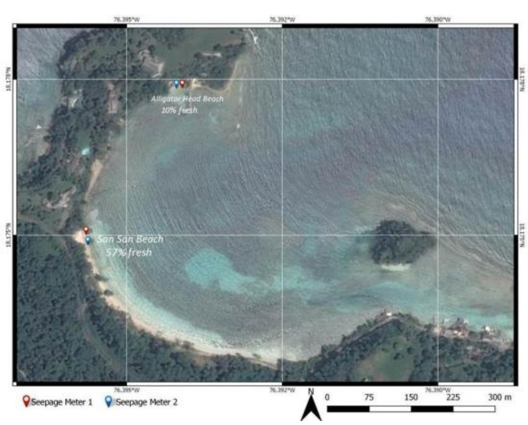


Figure 4. Seepage Meter Location in San San Bay.

In the DBML anchorage, seepage meters were deployed on September 8, 2016 and January 7, 2017 in the vicinity of submerged springs (**Figure 3**). FSGD rates as high as 115 cm/day and as little as 5 cm/day were recorded. These rates were similar to the seepage rates obtained during a previous study in the early 2000's (**Gordon-Smith and Greenaway, 2019**). Seepage meters in Boscobel within 15 m of the shoreline recorded FSGD rates up to 26 cm/day. The devices were not in place long enough to flush the headspace, but the salinity in the samples tended to increase over the course of the day, indicating a fresh-water dilution of recirculated seawater.

Only seepage-meter data were collected in San San Bay at two locations, San San Beach and Alligator Head Beach (**Figure 4**; **Table 2**); no TIR imagery or radon measurements were made. Seepage meters recorded SGD at beaches around the docking pier at the Alligator Head Beach at less than 22 cm/day, while the meters at San San Beach recorded at rates less than 16 cm/day. The devices were in place only for a few hours, so, at these seepage rates, they were not completely flushed; it might have taken one or two days to flush the headspace. Nevertheless, the salinity of samples decreased sequentially by about one unit during the time of deployment suggesting that the SGD contained a fraction of freshwater. From the measured rate of SGD in San San Bay and the rate at which salinity decreased, we estimated the freshwater fraction of SGD to be about 50% at San San Beach but only 10% at Alligator Head Beach.

All data referred to in this section are tabulated in **Paulino** (**2017**).

5. Discussion

Elevated ^{222}Rn concentrations themselves were good indicators of groundwater input in each embayment. Correlations between salinity and measured ^{222}Rn concentrations were consistent in showing high freshwater endmembers and low seawater endmembers. Although the range of salinities was not large, and correlations were weak, extrapolated freshwater endmembers agreed fairly well with measured endmembers.

Embayment studies should begin by identifying submerged springs. Over sixty such submerged springs have already been identified in Discovery Bay at depths up to 21 m using SCUBA or snorkeling (**Gordon-Smith and Greenaway, 2019**). Even though Discovery Bay, like the other sites, was a fairly protected embayment, some of the known springs were not detected by TIR imagery or geochemical data (e.g., radon or salinity) collected at the water surface. Apparently, any traces were diluted by mixing in the water column. Little has been done to document springs at the other locations in Jamaica. At these other sites, the TIR imagery provides a starting point, but whether detectable thermal or geochemical characteristics of an SGD plume reach the surface depends on the water depth, the degree of dispersion due to mixing in the water column and possible stratification as well as the strength of the source. In other Jamaican embayments, diver surveys like those that have been done in Discovery Bay or, perhaps, near-bottom temperature and salinity profiles would be needed.

In each embayment, bathymetric maps are needed in order to quantify the ^{222}Rn inventory and maps of sediment type would be a first step toward evaluating diffusive flux of radiotracers. Large uncertainties were associated with the calculation of ^{222}Rn loss via atmospheric evasion. We had no way of assessing how well wind speeds measured at the airport at Montego Bay were representative of conditions at our study sites, and, because ^{222}Rn loss via atmospheric evasion is proportional to the wind speed raised to the 1.6 power (**MacIntyre et al., 1995**), results are more sensitive to this factor at higher wind speeds. Wind speeds during the sampling times ranged over a factor of 2.5 from about 3.6 to 9 km/h, corresponding to about a five-fold increase in the calculated evasion and a two-fold increase in the final inventory excluding mixing losses, that is, the calculated losses due to evasion ranged from few percent to up to 98% of the steady-state flux.

At the bottom of Discovery Bay, submerged springs have been associated with crevices and depressions from the collapse of the rocky sea floor (**Bonem, 1988**; **Gordon-Smith and Greenaway, 2019**). In other Jamaican embayments, detailed bathymetric surveys could be an aid to locating submerged springs. Bathymetric surveys, too, would be needed to determine the cross-sectional area of the embayment's outlet. Combined with gradients of ^{222}Rn out of the mouths of the individual embayments, these cross-sectional areas are required to calculate the flux out of the embayment due to mixing. To complete a ^{222}Rn budget, the flux due to mixing would be added to the flux from the sediment due to the diffusion, although a diffusive flux might be expected to be small, less than 5%, based on other studies elsewhere (e.g., **Tamborski et al., 2015**). With a budget of ^{222}Rn, end-member concentrations could be applied to quantify FSGD. Combining these results with concentrations from nutrient samples will allow an assessment of nutrient inputs into the open water via FSGD.

6. Conclusions

Identifying the strength and location of FSGD along the Jamaican coast is needed to provide a strategic road map to regulating and maintaining the quality of its coastal ocean environments. Elevated concentrations of ^{222}Rn in plumes along with cool-water anomalies and direct measurements are evidence of substantial seepage of groundwater as FSGD into embayments along Jamaica's northeast coast. Both concentrated and diffuse FSGD at the shoreline are recognized in both TIR imagery and ^{222}Rn surveys. These data might serve in the design of future research in these locations. Because both diffuse seepage and the discharge from submerged springs are significant, identifying and quantifying spring locations is an important step in assessing the budget of SGD in order to put measurements of diffuse seepage in perspective. Based on the data collected during this study, multiple methods of detecting FSGD are recommended due to the distribution of these two sources. Because the FSGD is likely linked to rainfall, we call for sampling with seepage meters, TIR imaging, and ^{222}Rn surveys at least twice throughout the year, prior to and following the rainy season in October. On a similar note, wind-speed variations affect the rate of ^{222}Rn evasion into the atmosphere. To reduce uncertainty in the estimate of atmospheric evasion of radon gas, wind speed should be measured at each site at the time of sampling. Because of the sensitivity of evasion to wind speed, it is recommended that the ^{222}Rn surveys occur before wind speeds pick up in the afternoon. Following these methods, other locations both around Jamaica and at other islands in the Caribbean, in the Caribbean, FSGD should be expected to be found to be fairly ubiquitous and with similar characteristics.

Acknowledgements. *We were fortunate to have the help of Captain Martin Beek (Sandals Resorts International) and the attention of Heidi Clarke, Jonathan Hernould, Daniel Sale, Hugh Ramsay (Sandals Foundation). Operations out of the Discovery Bay Marine Laboratory and Field Station were facilitated by Professor Mona Webber (Director Centre for Marine Sciences, UWI), Mona Campus, Deana-Lee Douglas (Scientific Officer) and Pamela Housen (Administrative Officer). Denise Henry coordinated the effort at the Alligator Head Marine Laboratory and all field work benefited from the assistance of Kadane Coates, Abigail Richards, Rosano Green, Shanna Thomas, and Dalelan Anderson (UWI). A collaborative research project supported by UWI's Mona Office of Research and Innovation-New Initiative Grant Scheme, Stony Brook University's Groundwater Institute and the Joint UWI-SUNY Institute for Leadership and Sustainable Development.*

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Editorial Responsiblity: S. James-Williamson. Type setting: S. F. Mitchell

Accepted 14th November 2019