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Submarine Groundwater Discharge (SGD) from a Volcanic Island: A case study in Mauritius Island

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Abstract

The flow of groundwater from oceanic islands out across the sea floor not only has impacts on coastal water quality but also has the potential to influence oceanographic processes such as the characteristic of mesoscale, ocean eddies. Relatively few observations of submarine groundwater discharge (SGD) have been made; measurements at islands in the Indian Ocean and measurements over fractured rock aquifers of volcanic islands are especially rare. The rate and distribution of SGD was measured using vented, benthic chambers on the floor of a shallow lagoon on the west coast of Mauritius. Discharge rates were found exceeding 490 cm d^{-1} near a known spring, but large variations in SGD rates were seen over distances of a few meters. (This is the volume flow of water in cubic centimeters divided by the area covered by the sampling device in square centimeters normalized to a time period of one day). SGD rates were more typically on the order of 10 cm $d^{-1.}$ We attribute occurrence of high SGD to the existence of unobserved, buried conduits for preferential groundwater seepage, such as lava tubes or fracture clusters, in the fractured rock aquifer underlying a thin blanket of coral sand. By extrapolation from our small study area, SGD from Mauritius could supply as much as 76 million cubic meters of water per day to the coastal ocean, and would carry with it the geochemical signature of the subterranean estuary.

Keywords: Submarine groundwater discharge, Seepage meters, submarine spring, volcanic island, mesoscale eddies, coastal water quality

INTRODUCTION

Submarine groundwater discharge (SGD) has implications for the world ocean. The total groundwater discharge to the oceans has been estimated to be about 2400 km^3 y^{-1} [1] or some 6 to 7% of the world's river discharge. Regionally, however, the SGD contribution may be as high as 30%. More than one-third of the total, global SGD, or 915 km^3 y^{-1}, was estimated to be supplied from major islands [1]. Some of the largest islands, such as, New Guinea, Java, Sumatra, Madagascar, and the West Indies, are located in humid tropical regions with high rainfall accentuated by their high relief. In addition, large islands are often characterized by volcanic rock aquifers of high transmissivity, and an immature landscape with poorly developed, surface water drainage systems.

For example, Mauritius has a relief exceeding 600 m, receives up to four meters of rain annually, while it is drained by rivers with an average length of only 9.38 km [2]. While rainfall events, of course, are episodic, seepage from the aquifers they recharge is more uniform. As a result, SGD, although it had not been measured previously, should provide a fairly continuous source of freshwater to the coastal ocean all along an island's perimeter. In addition, much, if not most, SGD is seawater recirculated through the subterranean estuary [e.g. 3, 4] imparting a characteristic, island-chemical signature to SGD. Such a discharge would impact water quality of the coastal ocean. Water quality in an island's coastal zone might be contaminated *via* SGD from land by nutrients, heavy metals, organic compounds, mainly from untreated sewage and from agricultural activities [e.g. 5]. Commonly, excess nutrients trigger nuisance algae blooms originating in the lagoons [e.g. 6]. This is an important practical concern for an island economy based on both tourism and fishing. In Mauritius, for example, both sugar-cane agriculture and tourism place substantial demands on water resources as well as to add the associated contaminants to the discharge [2]. A better understanding of SGD is needed for the protection of the coral reef lagoon ecosystems.

Island SGD might also supply both a buoyancy flux and chemical signal into oceanic, mesoscale eddies generated in the lee of islands [e.g. 7] which propagate for hundreds of kilometers. In general, modeling has shown that oceanic eddies can entrain a tracer around its periphery and carry it away from the source water [8]. This mechanism could carry the signal of island SGD into the ocean influencing mesoscale biological processes [9,10].

Although the occurrence of submarine, freshwater springs have been recognized for millennia, the scientific inquiry into submarine groundwater discharge is a recent development. It is now a distinct field, however; a "critical mass" of investigators is engaged in the topic using a set of common methods to pursue joint research questions. Nevertheless, study sites have been overwhelmingly in the northern hemisphere and, usually, either on unconsolidated or semi-consolidated coastal aquifers or in karst terrain [11]. Volcanic, fractured rock aquifers present a special challenge because groundwater flows are confined to unseen fractures buried under a thin, and seemingly homogeneous, layer of nearshore sediments. Few such sites have been investigated in detail, although some studies are available to indicate that SGD is significant in such situations. On the Kamchatka Peninsula [12] where submarine groundwater discharge for a unit length of shoreline was estimated to occur at a rate of about 0.36 m^3 $m^{-1}d^{-1}$, that is, 0.36 cubic meters of water per meter length of shoreline per day*. On a volcanic island in the Korean Sea [13] area specific SGD rates were measured to be between 14 and 82 cm d^{-1} and, on Hawaii [14], SGD rates of 8.4 cm d^{-1} were found within 1 km of the shore and 2.3 cm d^{-1} further offshore. In this article, we are reporting direct measurements of submarine groundwater discharge performed on the western coast of Mauritius. These were the first measurements made in Mauritius.

STUDY AREA

The island nation of Mauritius covers 1865 km^2 (Figure 1). This volcanic island reaches elevations of up to 600 m. The coastal zone is largely comprised of lagoons created by the formation of either barrier reefs or fringing reefs. Lagoons are estimated to cover an area of 243 km^2. Lagoon water has been found to be colder than the adjacent, open ocean water on remote imagery with SGD proposed as one possible cause [15]. SGD could be an important source of nitrogen to the coastal reef lagoons and may have contributed to the eutrophication frequently observed in the lagoons of Mauritius. Groundwater nitrate levels have been an order of magnitude higher than coastal nitrate levels, and groundwater seepage has been implicated in the nutrient enrichment and contributed to the eutrophication frequently observed in the lagoons of Mauritius. Groundwater nitrate levels have been an order of magnitude higher than coastal nitrate levels, and groundwater seepage has been implicated in the nutrient enrichment and consequent degradation of the coral reef ecosystem in the nearby island of La Reunion [16 as cited in 15]. The coast has experienced algae blooms, occasionally red tides, confirming the impact of contaminants in the lagoons and their deleterious influence on the health of the coral reefs in the lagoons. Fluxes of SGD, however, have not been documented, although in some places at the west and east coasts, groundwater discharges are clearly visible.

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*A note on units: Various units have been used in the literature for quantifying SGD but units of cm d^{-1} are commonly used. This is a specific volume flux of water across a unit area of the sediment water interface, that is, cubic centimeters of water per square centimeter of sea floor per day. 1cm d^{-1} = 10 L d^{-1} m^{-2} = 0.1157 μm sec^{-1}. SGD measurements may be expressed also as a volume flux of water per unit length of shoreline, often in units of cm^3 $m^{-1}d^{-1}$ or m^3 $m^{-1}d^{-1}$, or as total volume rate of discharge (m^3/sec, Sv, m^3/day or m^3/year) into a specified region. We use cm d^{-1} for the area-specific rate of discharge and $m^3m^{-1}d^{-1}$ for discharge rates per unit length of shoreline.

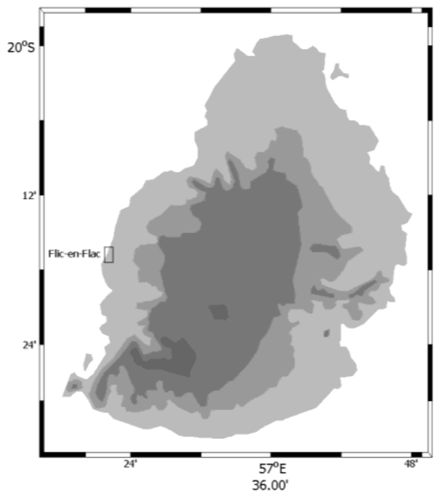

Figure 1. Study area on the west coast of Mauritius. The topography of the island is indicated (150m, 300m & 600m contours shown).Flic-en-Flac lagoon is located on the southwest coast near the town of Flic-en-Flac. (Figure provided by T. Stieglitz, James Cook University, Townsville, Australia)

The hydrology of Mauritius' freshwater supply has recently been summarized by Toth [2] and, more recently by Oberdorfer [17]. Mauritius uses groundwater for 56% of their potable water [18 as cited in 17] in addition to agricultural demands, primarily for the sugar-cane industry. In general, the Mauritian aquifers consist of permeable basaltic lava rocks between two aquitards [2]. In our study area, groundwater resides in the Curitibe Aquifer which extends from a high plateau in the center of the island 15 km to the western shoreline covering an area of 95 km^2. It consists of highly permeable, Recent (1.5 Ma to 25 Ka) lava flows with a saturated thickness of 10 to 20 m [19 as cited in 17].

Mauritius receives more rainfall per unit area than most other countries [20]. Average rainfall on Mauritius is 0.31 m $month^{-1}$ during the rainy season (December to April) reaching a minimum of 0.075 m $month^{-1}$ during the dry season. Precipitation reaches 4.0 m y^{-1} near the groundwater divide on the central plateau and decreases with decreasing elevation to about 0.80 m y^{-1} near Flic-en-Flac [19 as cited in 17]. Rainfall in excess of evapotranspiration is about 0.07 m y^{-1} along the coast (Medine meteorological station), 0.84 m y^{-1} halfway inland (Vacoas meteorological station), and 2.16 m y^{-1} on the central plateau at the Union Park meteorological station [21 as cited in 17]. The excess rainfall would go to groundwater recharge because the highly permeable rocks of the aquifer preclude surface runoff. About 20 million m^3 y^{-1} of the recharged water is pumped from the aquifer. Some of this water represents non-consumptive use, but at least 75 million m^3 of freshwater must be discharged at the shoreline annually. The shoreline of the Curitibe Aquifer is about 8 km long. As a result, the discharge rate was estimated to be 26 m^3 m^{-1} d^{-1} [17].

The importance of integrated coastal zone management in Mauritius was examined by investigators from the International Institute for Applied Systems Analysis using a "population-environment-development" (PDE) model [20]. Water resources, in particular, groundwater reserves, were the critical environmental parameter in assessing scenarios of future paths of sustainable development [2]. Because of the high population density in Mauritius, water resources *per capita* is relatively low [22], but vital to the sustainability of both sugar agriculture and tourism. The latter also relies on maintaining good water quality in the lagoons [2].

In conjunction with the direct measurements of SGD reported here, geochemical tracers were also used to estimate SGD at the study site [23]. Excess radon measured in the water column was assumed to have been provided by the SGD of radon-rich groundwater, and SGD rates between 13 and 140 cm d^{-1} were calculated and used to estimate SGD between 5.2 and 56 m^3 m^{-1} d^{-1} on the basis of a unit length of shoreline [23].

METHODS

The rate and distribution of SGD was measured using vented, benthic chambers [24] on the floor of two, shallow lagoons on the west coast of Mauritius Island (Flic-en-Flac). Flic-en-Flac Lagoon is approximately 400 m across and 5.5 km in length along the western coast of the Mauritius (Figure 1). The embayment is partially enclosed by a fringing coral reef and blanketed offshore with a layer of fine, coral sand. In addition much of the shallow seafloor is covered with patchy, branching, plate-like, massive, and encrusting coral. The tidal range is about 0.2 m and the inshore waters have a salinity of about 33. A well-known submarine spring is found in the area. Freshwater discharge from this submarine spring, and possibly others, is sufficient to reduce the salinity of coastal waters from oceanic salinities of about 36.

Vented, benthic chambers used in this study were embedded in the sediment to directly measure the SGD. These devices have been used over fractured rock aquifers previously and successfully [25, 26]. Individual chambers covered an area of 2550 cm^3, being the top of a "standard" 55-gallon drum 58 cm in diameter. These are cut to a height of 20 cm and typically pushed into the sediment to a depth of 15 cm depending on the nature of the sediment. After emplacement of the sea floor, plastic bags were connected to the chambers which were then allowed to fill for time intervals between several minutes to over two hours. The bags were pre-filled will 500 ml of ambient sea water [e.g. 27], except on occasions when it was desired to measure the salinity 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 could be measured with a refractometer with a resolution of about 1 psu. The measured flow rates were not obviously affected by not prefilling the collection bags. 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. The devices were left undisturbed in place, however, for as much as 90 hours. These devices have been the subject of criticism due to potential artifacts introduced by the presence of the chambers themselves [e.g. 28].

However, they have been widely used and experience suggests that they are reliable under calm conditions when the flow rate exceeds a few centimeters per day [29]. Uncertainties, however, are difficult to assess; the measurements of volumes and times are subject of combined errors of less than 3%, but SGD may contain uncertainties of perhaps 20% due to naturally occurring variations in both time and space.

RESULTS

Nine chambers were placed at a total of 28 locations (Figure 2). Devices were deployed in three shore normal transects. A central, shore-normal transect was adjacent to a submerged spring; a second transect was one kilometer north of the spring, and the third was about 0.5 km south of the spring. In addition, devices were set along a 1.5-km, shore parallel transect. The measured seepage rates were variable over the entire study area, ranging from negative seepage (i.e. flow of lagoon water into the sediment) to SGD of over 490 cm d^{-1} near a known, submerged spring. The average SGD for all measurements was 74 cm d^{-1}.

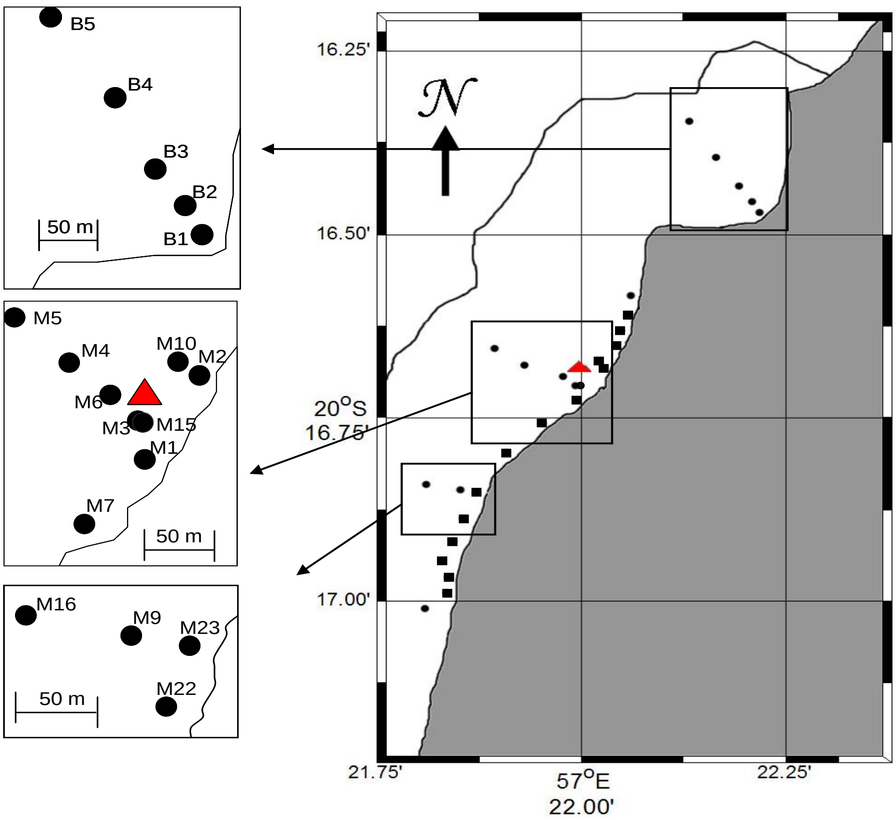

Figure 2. Location of seepage devices. These consisted of three shore-normal transects shown in the insets, and one alongshore transect designated by the square ornaments and shown in Figure 6. Not all locations were occupied at the same time. Triangle denotes location of a submarine spring referred to in the text.

The central shore-normal transect (Figure 3) consisted of five devices adjacent to the submarine spring. The shoreward device (M1) was placed in a water depth of 0.5 m. The other four devices (M3, M6, M4, and M5) were placed at distances of 20, 50, 80, and 150 m from the low-tide shoreline. The respective water depths at low tide were 1.6 m, 1.9 m, 1.4 m, and 1.6 m. The tops of the devices were between 0.04 m and 0.1 m above the sea floor. Measurements were taken at this transect over a period of 72 hours. SGD showed an expected pattern in the vicinity of the spring. Devices placed near the spring recorded high rates of hundreds of cm d^{-1} while devices placed away from the spring were consistently lower, in some cases less than 10 cm d^{-1} (Figure 3, N.B. the change of vertical scale).

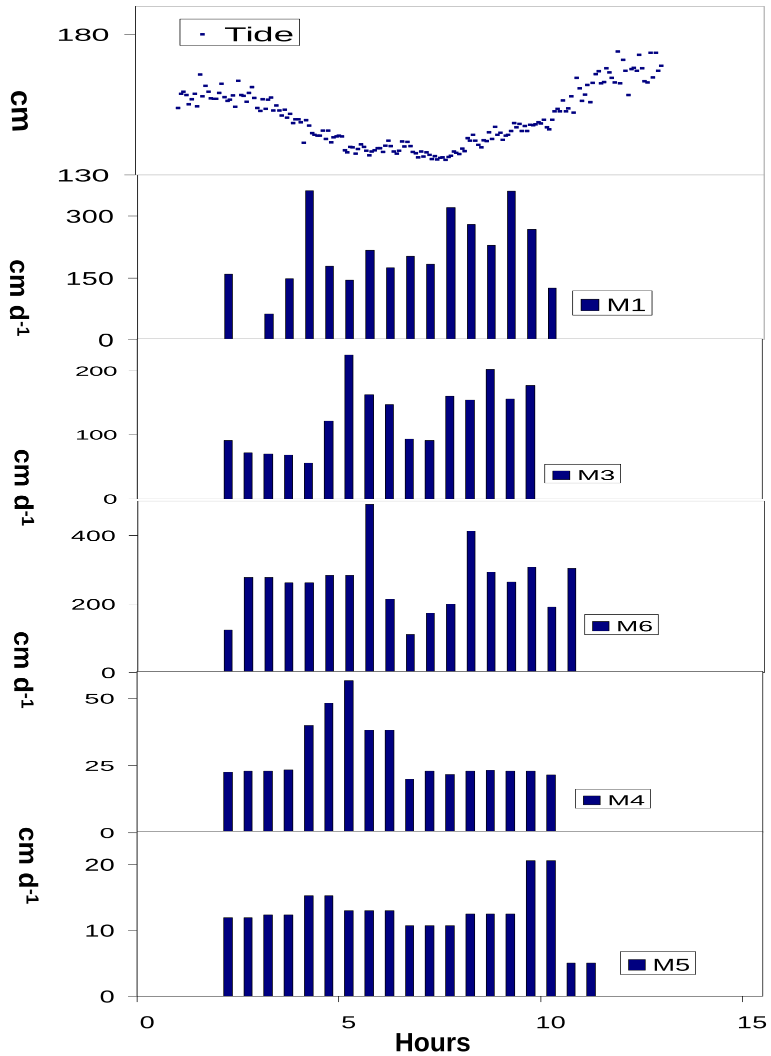

Figure 3. Central shore-normal transect in the vicinity of the spring.

The northern, shore-normal transect consisted of five devices (Figure 4) was located about one kilometer north of the spring in a cove which received discharge of an ephemeral surface stream. The shoreward device (B1) was placed at a depth of 30 cm. The other four devices (B2, B3, B4, and B5) were placed at distances of 20, 50, 120, and 250 m from the low-tide shoreline. The respective water depths were 1.0 m, 1.2 m, 1.7 m, and 2.1 m. Measurements were taken at this transect over a period of 24 hours. Along the northern transect SGD never exceeded 24 cm d^{-1}. SGD at particular locations were seen to abruptly increase (or decrease) in time, and to persist at the new levels, for no obvious reason. We had observed the same behavior at a fractured rock site on the Brazilian coast [26] and attributed it to the complexity of hydraulic connections in the aquifer. On the basis of a unit length of the shoreline, SGD would be 35 m^3 m^{-1} d^{-1} over the 250-m transect length, a value similar to the 26 m^3 m^{-1} d^{-1} calculated from the water budget [17].

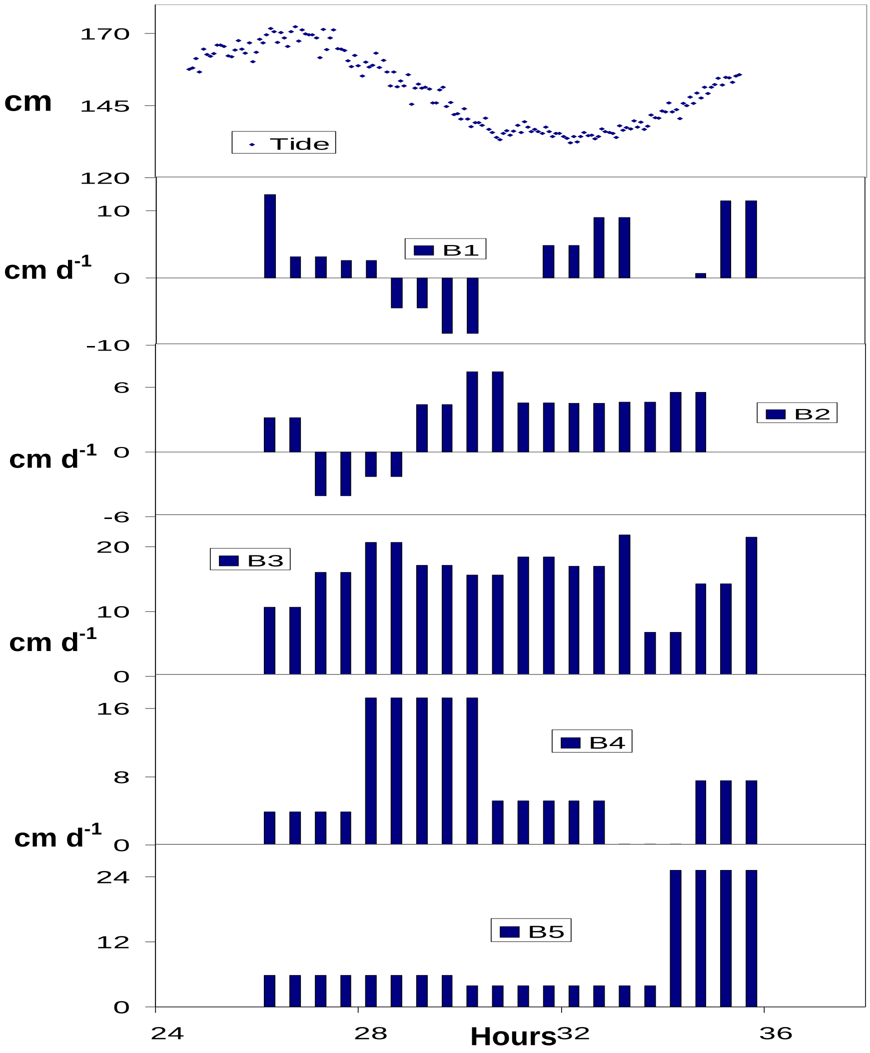

Figure 4. Northern shore-normal transect.

The southern shore normal transect (Figure 5) was located about 0.5 km south of the spring. This transect consisted of three devices located within 30 m of the low tide shoreline. Beyond 30 m, the sea floor was hard coral, devoid of sand and benthic chambers could not be placed there. The devices M23, M9, and M16 were located 7, 15, and 30 m from the shore at depths of 0.8, 1.0, and 1.5 m respectively. Measurements were taken along this transect for a period of 10 hours. Radon measurements made in the vicinity of M9 yielded estimates of SGD rates between 13 and 23 cm d^{-1} [23], in good agreement with the rates directly measured at M9 which ranged from 2.5 to 22 cm d^{-1} and averaged 8.3 cm d^{-1}.

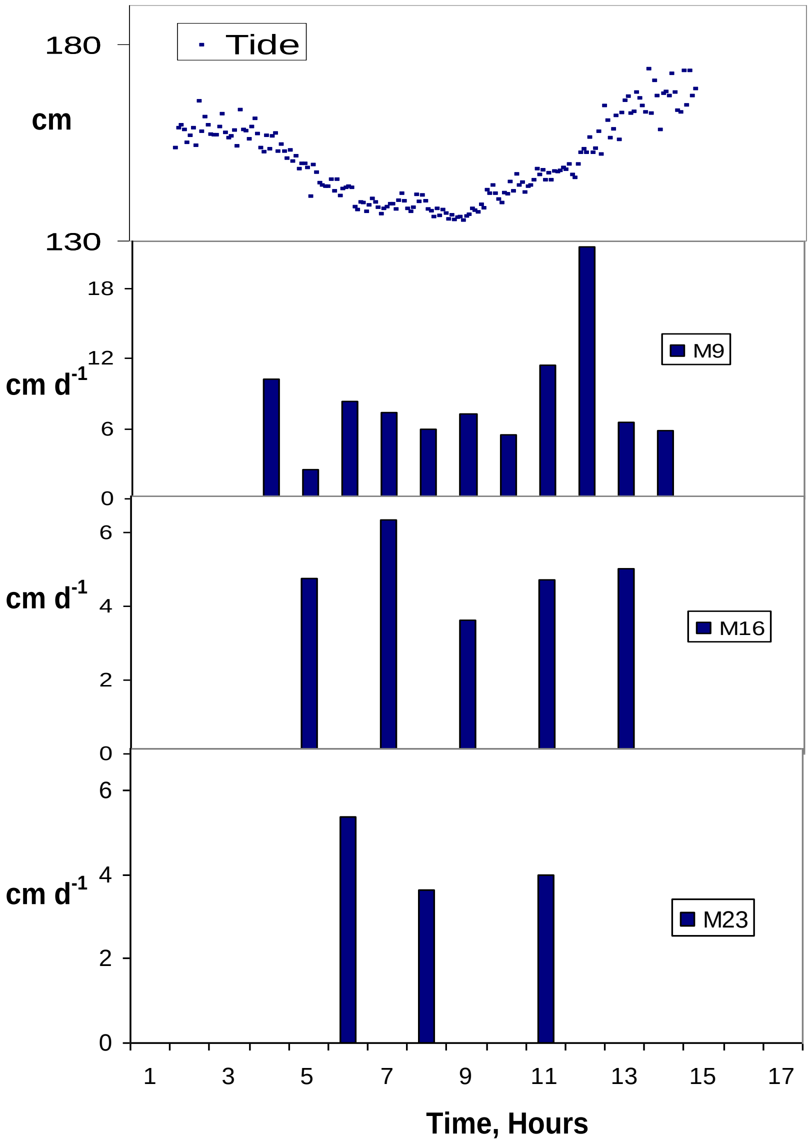

Figure 5. Southern shore-normal transect.

There was no persistent pattern of mean SGD rates with distance from the shoreline along any of the three offshore transects (Figures 3, 4 and 5). Measurements for each transect were taken simultaneously, however, measurements from each transect were taken on separate days. However, a pattern alongshore was found (Figure 6).

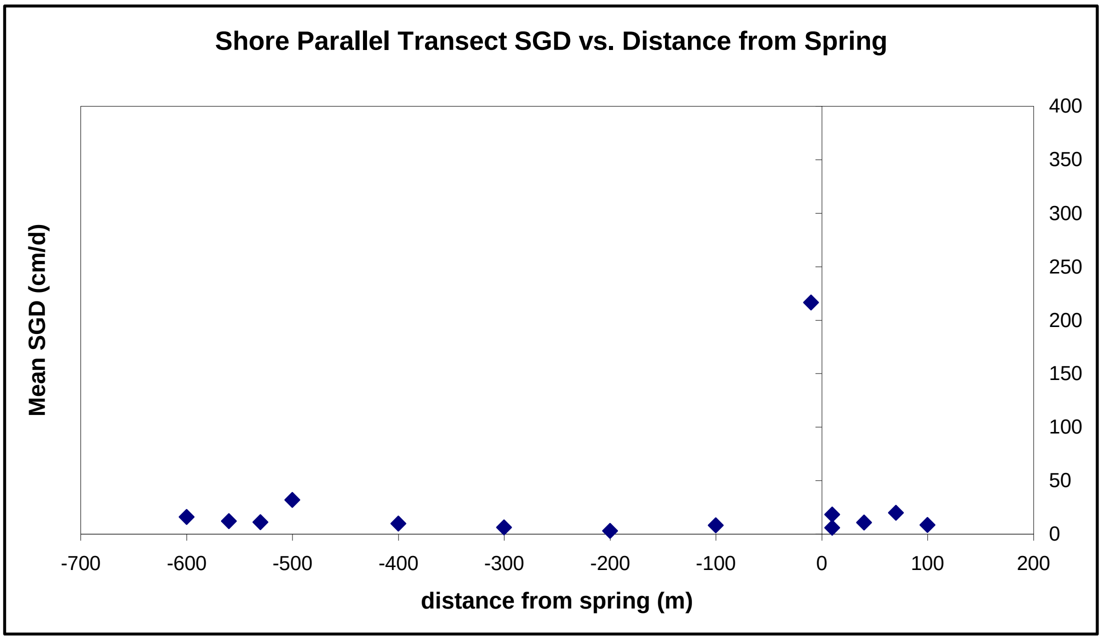

Figure 6. Mean SGD flow rates versus distance from spring taken from devices located immediately offshore in a shore parallel transect. There is a peak in discharge immediately south and shoreward of the spring, although these flow rates were not the highest measured in the area.

The shore parallel transect consisted of measurements within 15 m of the low tide line. This transect consisted of 18 locations at which devices were in place for a periods between ten hours and five days. Not all measurements along this transect were made simultaneously; however, at least six devices along this transect were measuring SGD throughout the sampling period. All of the devices in the alongshore transect were deployed in a homogenous, and presumably permeable, carbonate sand. SGD was 216 cm d^{-1} south and shoreward of the spring. At the same distance north of the spring, SGD was found to occur at a value of between 5 and 15 cm d^{-1}, more typical of the rest of Flic-en-Flac Lagoon. Another area of significantly higher SGD was located about 0.5 km south of the spring. Here (M22) average flow rates were as high as 32 cm d^{-1}. High SGD corresponded to elevated radon concentrations in the open lagoon water at this site recorded two days before deployment of the benthic chambers [23].

Little evidence of tidal modulation was found anywhere in the study area**.** At other locations, a modulation of SGD with tidal elevation is often, but not always, found with higher seepage rates occurring at low tide [e.g. 30]. In this study, a strong tidal modulation of SGD was not found (Figure 7). SGD measured at M6, which had some of the highest seepage rates, did seem to show an inverse correlation with tidal elevation, but the relationship is weak. Apparently, the hydraulic gradients driving SGD here were able to adjust to the changing tide by some unknown manner; perhaps fixed pore space in the aquifer can modulate variations in the hydraulic head to compensate for the tide.

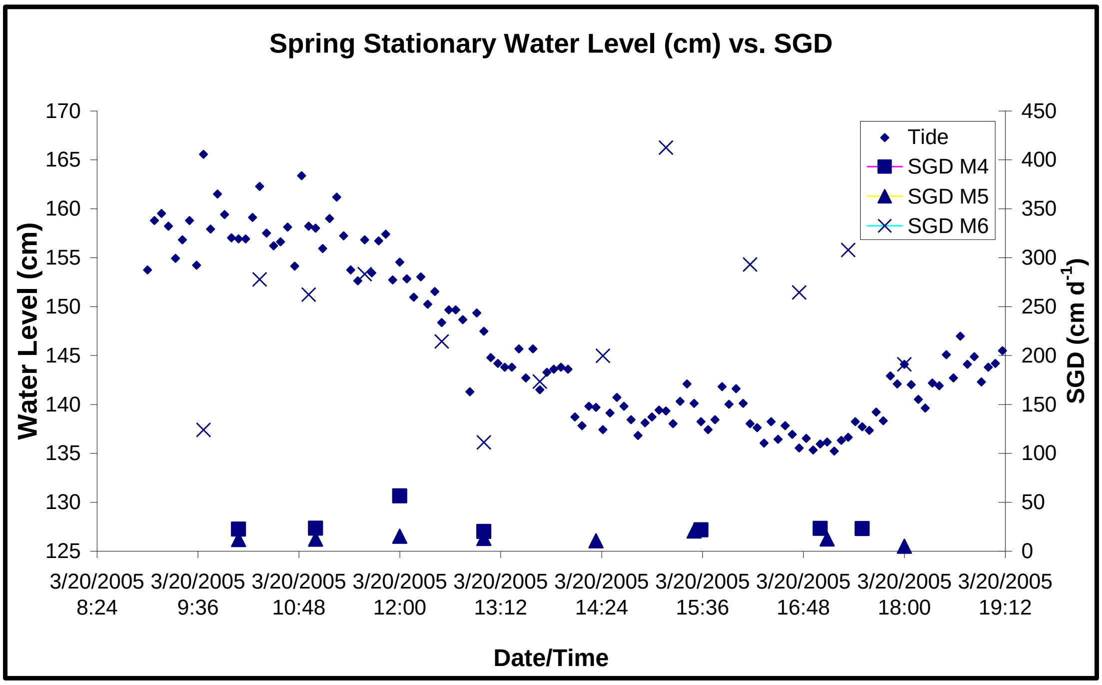

Figure 7. Tidal elevation vs. SGD at three devices along the central, shore-normal transect in the vicinity of the spring.

Evidence was found, however, for the recirculation of seawater through the coastal aquifer. At most locations, the measured salinities in the collected discharge were indistinguishable from that of the ambient, open water. In these areas, salt water must be mixed and recirculated with any freshwater SGD. Water collected from the benthic chambers showed fresh water dilution only in the vicinity of the spring. Here water with salinity as low as 5 accumulated in the benthic chambers with an inverse correlation was seen between salinity and SGD rates (Figure 8). Below a flow rate of 40 cm d^{-1} the seepage device water had virtually the same salinity as ambient sea water. At intermediate salinities between 10 and 20 corresponded with fairly high flow rates between 100 and 170 cm d^{-1}. The salinity decreased to 5 where SGD rates were between 210 cm d^{-1} to 360 cm d^{-1}; a salinity of 5 was measured directly at the spring.

The salinity of water collected in the chambers remained at 5 even during maximum flow at 490 cm d^{-1}. Salinity in the open water above the spring was also 5.

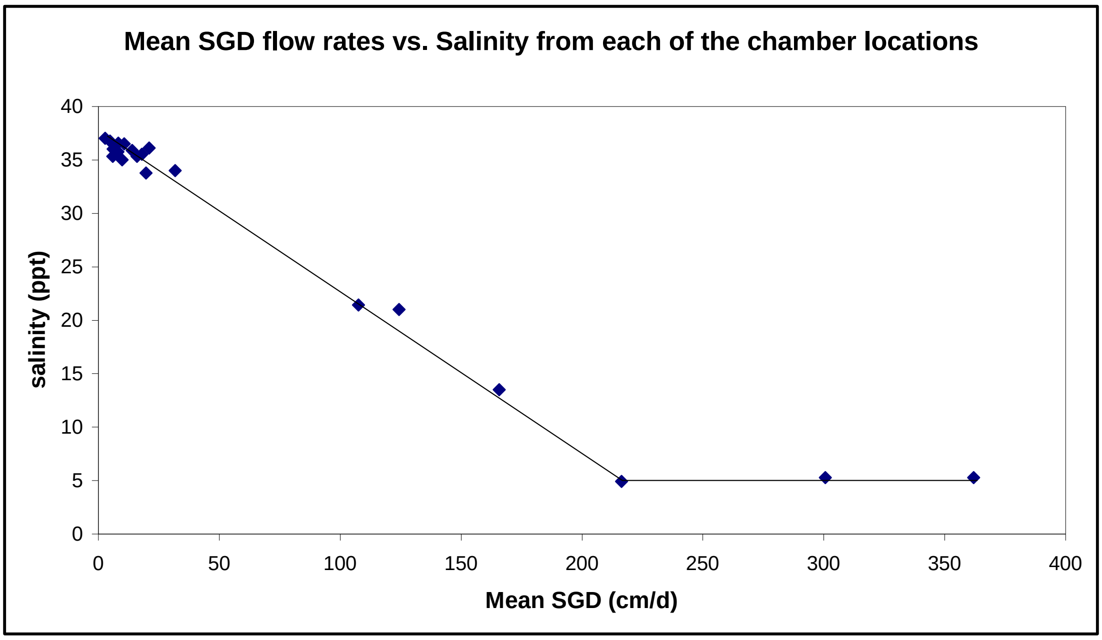

Figure 8. Mean SGD versus the mean salinity measurements of the water which was discharged through the seepage device.

Apart from the spring, salinities of the SGD remained high despite the fact that the SGD rates are similar to those calculated from the water budget which would be the freshwater discharge. This suggests to us that the in mixing of salt water occurs at the sediment water interface at a scale smaller than the size of the device itself. Such a process might be gravitational convection [31] or bioturbation [32]. In such a case, the net flow of salt water across the interface would be zero while the net flux of salt would be downward into the sediment pore water. The net SGD out of the subterranean estuary would be equivalent to the volume discharge of freshwater, since the mixing produces no net volume flux of water, but the salinity as near the ambient salinity as needed depending on the strength of the mixing. In this study, salinities were measured with a refractometer, so differences less than a few psu would not be resolved. (This is similar to what is found at the mouths of open-water estuaries where the salinity is near oceanic salinity but the net flux is equal to the river input).

Some idea of the transit time of recirculated seawater might be obtained from the variations in salinity associated with the passage of a storm system. On March 24, 2005, a cyclone (Tropical Storm Hennie) brought increased precipitation and high winds that forced freshwater discharging from the Black River up into the lagoon. The storm reduced the surface salinity of the Flic-en-Flac lagoon from 35 on March 22 and 23, to 30. The salinity returned to 35 on March 25 as the storm subsided.

Discharge measurements were made in benthic chamber location M22 before during and after the cyclone. SGD was elevated to around 32 cm d^{-1} at a distance of 500 m south of the spring (Figure 6). Measurements showed no significant change in discharge rates from March 23-25; on 23 March the salinity of the water taken from chamber M22 was equal to the ambient water of the lagoon at 35. However on 24 March, as the of the lagoon water dropped to 30, the salinity of the water in the chamber remained at the ambient lagoon water from the previous day. Twenty-four hours later the salinity in the lagoon had returned to pre-cyclone values, but the salinity inside the chamber had dropped to 31 or very close to the values seen in the ambient water during the cyclone (Figure 9), suggesting a recirculation residence time of about 24 hours, at least through the surficial sediment. Apparently, fresher lagoon water provided by the storm had been recirculated over as distance of 20 to 64 cm through the sediments to appear in the chambers one to two days after the event.

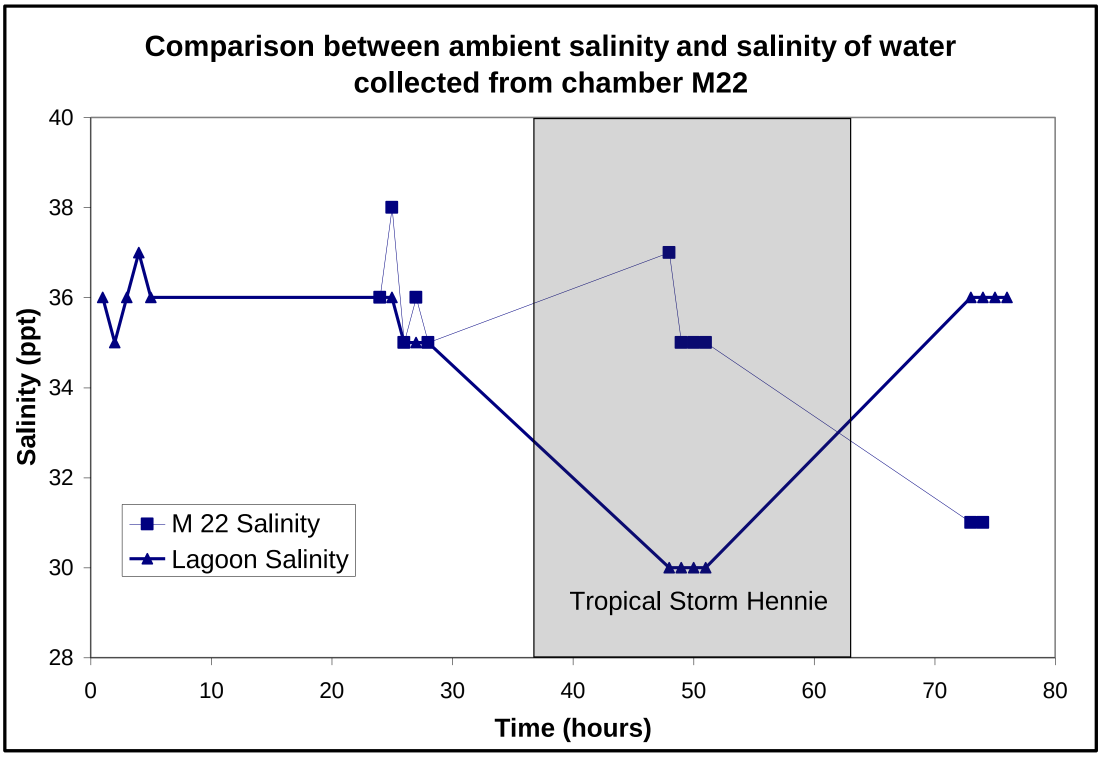

Figure 9. Salinity measurements were taken from the ambient lagoon water south of the spring using a refractometer on March 22-25.

DISCUSSION

The irregular distribution and high rates of SGD observed are probably a characteristic of fractured rock aquifers and the presence of a lava tube intersecting the sediment-sea interface. Near the shoreline, for the entire extent of the study area, the bay floor sediments were sandy and not noticeably different from place to place (except within the cove whose sediments were finer as suspended sediment is transported here from a creek). However, an irregular coral surface was encountered at shallow depths offshore. Beginning anywhere from 20 m to 100 m offshore the coral forms patchy clumps which become more continuous further from shore. Groundwater feeding the SGD is supplied to the bottom of the thin blanket of unconsolidated sediment along the irregular surface of the buried hard material. Preferred conduits of groundwater seepage may exist across this surface as lave tubes or clusters of fractures. We were told that the underwater spring in our study site represented fresh water entering the lagoon through a lava tube about two meters in diameter. The relatively high salinity in the pore water of the sediment blanket (except near the spring), despite significant discharge rates, must be due to an efficient process of mixing and dispersion in the surficial sediments themselves, perhaps a combination of gravitational, free convection, wave pumping [30] and bioturbation [32]. Where discharge rates were exceptionally high near the spring, we did find a freshening of both the pore water and in water collected from the seepage devices.

Flow rates above 50 cm d^{-1} were only found in the vicinity of the spring, where a good correlation between salinity and the magnitude of flow rates was found. Large variability in flow and salinity were found over distances of less than five meters. It seems that, near this spring, there are other, small, localized conduits of fresh water flowing up into the lagoon. The pore-water salinity, and, in turn the salinity of the seepage water, changes from fresh to salt over short distances. Because intermediate flows correspond with intermediate salinities, mixing of the freshwater with seawater in the upper few meters of the sediment can be overcome by sufficient SGD. Assuming a sediment porosity of 0.5, a SGD of 100 cm d^{-1} would mean flushing of a two-meter path through the sediment every day, and SGD is sufficiently strong to substantially reduce the salinity at the sediment water interface. In places where SGD reaches 200 cm d^{-1}, SGD has the same salinity as the groundwater measured inside the spring. It seems that saltwater can not penetrate into the sediment against a SGD rate of 200 cm $d^{-1}$and the saltwater/freshwater boundary is at the sediment/sea interface.

South and north of the spring, flow rates were, on average, much lower than those found near the spring. The majority of the water collected from these chambers had salinities similar to ambient lagoon. SGD in these locations appears to be comprised mainly of recirculated saltwater. The salinity signal response to the tropical storm suggests to us the recirculation is shallow, probably within the upper meter of sediment.

It may be interesting to speculate on the total amount of SGD that could be supplied to the coastal ocean around Mauritius, even though measurements showed substantial variability and were made for a short time in a small area only. The average flow rate along transect made parallel to the shoreline was 54.5 cm d^{-1}. If this average flow is assumed to persist across the entire 400-m width of the lagoon, it would correspond to a total discharge of 220 $m^3 m^{-1} d^{-1}$. Taking the island's shoreline to be 254 km long*, the total discharge would be 56 million $m^3 d^{-1}$. Alternatively, the average of all measurements, including those near the spring, was 74 cm d^{-1}, corresponding to a total discharge of 76 million $m^3 d^{-1}$. Both estimates probably overestimate the SGD far from the spring. If the average discharge of groundwater is taken instead to be 35 $m^3 m^{-1} d^{-1}$, which is the value determined at the northern transect far from the spring, the total discharge would be calculated as 8.9 million $m^3 d^{-1}$. Estimates made using radon as a geochemical tracer of SGD were as high as 56 $m^3 m^{-1} d^{-1}$ near the spring [17], which would correspond to total discharges by our extrapolation of about 14 million $m^3 d^{-1}$, falling to between 5.2 and 9.6 $m^3 m^{-1} d^{-1}$ away from the spring [17], which would correspond to a total, extrapolated discharge excluding the spring of between 1.3 million and 2.4 million $m^3 d^{-1}$. At this time, we have no reason to prefer one of these estimates over the others, but, whatever the value, SGD would be a mix of fresh water and seawater recirculated through the subterranean estuary. The terrestrial component would carry excess nutrients and may be a source of nutrients to the coral reef [e.g. 34]. Other geochemical signatures result from the mixing of fresh and seawater and seepage through chemically reactive sediments. The enrichment of radium, for example, is a well-known indicator of SGD.

CONCLUSIONS

Measurements show significant discharge of groundwater into the Flic-en-Flac Lagoon, Mauritius. This discharge exhibits large spatial and temporal heterogeneity likely caused by the presence of specialized conduits of groundwater flow created by the coralline and volcanic basement of the lagoon. Most of the samples collected show no significant difference between SGD salinity and ambient lagoon salinity due to saltwater recirculation and mixing. In the region of a submarine spring, however, SGD was measured to be as high as 490 cm d^{-1} and the salinity of SGD was reduced accordingly. Extrapolated from our small study area, SGD from Mauritius might supply at least 3 million $m^3 d^{-1}$ and as much as 76 million $m^3 d^{-1}$ ($8.8*10^{-4}$ Sv) to the coastal ocean; any SGD should carry with it the geochemical, terrestrial and anthropogenic signatures, as well as that of the chemical transformations produced by the intermixing of freshwater and seawater in the subterranean estuary. Around oceanic islands these distinctive signatures could be shed from coastal waters and exported to the deep ocean, perhaps, *via* mesoscale eddies.

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*The length of the coast of the Mauritius depends upon the resolution (s) with which it is measured [33]. The fractal dimension (D) of Mauritius was calculated to be 1.14. The shoreline length (l) is then calculated as $M (s)^{(1-D)}$, where M is an empirical parameter. For Mauritius M=223.14 for values of s and l in kilometers. For a resolution of 0.4 km, the width of the lagoon used in the extrapolations in the text, the coast of Mauritius is 254 km in length. (At a resolution of one meter, the coast of the Mauritius would be 587 km in length).

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