Limnol. Oceanogr., 51(4), 2006, 1876–1886

The importance of submarine groundwater discharge to the nearshore nutrient supply in the Gulf of Aqaba (Israel)

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Abstract

We used two short-lived radium isotopes (^{223}Ra, ^{224}Ra) and a mass balance approach applied to the radium activities to determine the nutrient contribution of saline submarine groundwater discharge to the coastal waters of the northern Gulf of Aqaba (Israel). Radium isotope activities were measured along transects during two seasons at a site that lacked any obvious surficial water input. An onshore well and an offshore end member were also sampled. For all samples, nutrients and salinity data were collected. Radium isotope activities generally decreased with distance offshore and exhibited significant tidal variability, which is consistent with a shore-derived tidally influenced source. Submarine groundwater contributes only 1–2% of the water along this coast, but this groundwater provides 8–46% of the nutrients. This saline groundwater is derived predominately from tidally pumped seawater percolating through the unconfined coastal aquifer and leaching radium and nutrients. This process represents a significant source of nutrients to the oligotrophic nearshore reef.

The importance of atmospheric and groundwater inputs as sources of new nutrients to coastal systems has been suggested by many studies in the last three decades (Valiela et al. 1978; Dollar and Atkinson 1992; Paerl 1997). Since groundwater is typically elevated in nutrients compared to coastal waters, even a small amount of groundwater discharge can significantly elevate the nearshore nutrient supply (Li et al. 1999). Coastal coral reef ecosystems, residing in seas of low nutrient concentrations, may be particularly dependent on and influenced by nutrient input from groundwater discharge (Hamner and Wolanski 1988; Hatcher 1997). However, non–point source groundwater discharge into the coast is difficult to identify or quantify (Burnett et al. 2002).

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Acknowledgments

We thank Willard Moore (University of South Carolina) for providing critical understanding of radium activities and study design and being instrumental in teaching us to measure radium. Megan Young, Karen McLaughlin, and Garav Misra (Stanford University), along with Tanya Rivlin, Inbal Ayalon, Moti Ohevia, and Ruti Motro (Interuniversity Institute, Steinitz Marine Biological Laboratory), assisted with field and laboratory work. Alexandria Boehm (Stanford University) and two anonymous reviewers kindly added suggestions that greatly improved the manuscript. This work was funded by the BIO-X Initiative at Stanford University, the Red Sea Marine Peace Park, and a National Aeronautics and Space Administration-New Investigator Program grant to A.P.

Moore and collaborators over the last 30 yr have pioneered the use of the naturally occurring radium isotope quartet as tracers for riverine and saline groundwater input to coastal systems (e.g., Elsinger and Moore 1980; Moore 1997; Krest and Harvey 2003). The divalent cation radium is bound to soil particles in freshwater but readily desorbs via ion exchange in the presence of higher ionic strength solutions (Elsinger and Moore 1980; Yang et al. 2002). This results in radium enriched saline groundwater, and, thus, radium can be used as a tracer of such water, particularly when mixed into seawater with low radium concentrations (Moore 2000). Indeed, the four isotopes, which vary in half-life (^{223}Ra, 11.4 d; ^{224}Ra, 3.7 d; ^{226}Ra, 1,600 yr; and ^{228}Ra, 5.7 yr), have been used to study mixing processes on a wide range of timescales and to quantify submarine groundwater fluxes to the coast (Moore 2003).

Radium isotopes have been used to calculate groundwater fluxes in relatively wet regions of the world, such as the Carolina coast, Florida, and New England (Moore 1996; Charette et al. 2001; Burnett et al. 2002). However, few published studies have applied the use of radium isotopes to explore the influence of groundwater in arid coastal regions (Boehm et al. 2004) or to explore groundwater influence on the nutrient supply to coral reefs (Paytan et al. 2006). It has been assumed that groundwater discharge and associated nutrient supply in dry areas are negligible because of the low precipitation and groundwater recharge rates.

In the present study, we use the two short-lived radium isotopes (^{223}Ra and ^{224}Ra) and a mass balance approach to determine the nutrient contribution of saline submarine

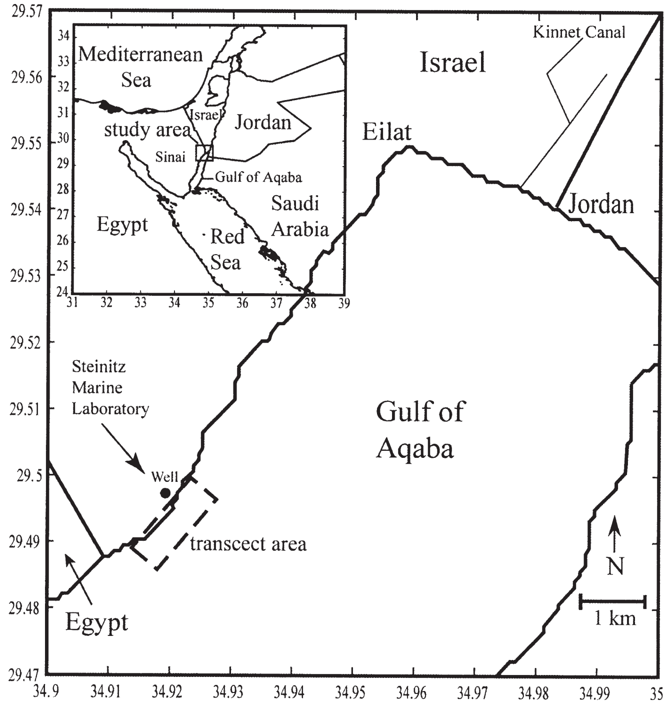

Fig. 1. Map of the study area and region. Transect sampling was conducted along the shore at the Steinitz Marine Laboratory. Transect area pictured is not to scale.

groundwater discharge (SGD) to the coastal waters of the northern Gulf of Aqaba. The SGD is not necessarily of terrestrial origin, but it is primarily seawater that infiltrates into the subsurface and is subsequently discharged to the coast with changed chemical characteristics (*see* definition in Burnett et al. 2002). In this paper, we are going to use the term SGD to mean saline groundwater that is fresher than coastal waters.

Materials and methods

Study site—The Gulf of Aqaba is the narrow northeastern extension of the Red Sea. It is 180 km long and a maximum of 26 km wide; it has an average depth of 800 m and a maximum depth of 1,800 m. Coral reefs are abundant along the coastal reaches of the gulf. This study was conducted about 8 km south of Eilat along the west coast immediately north of the Egyptian border (at the Steinitz Marine Laboratory, 29°30.1′N, 34°55.0′E, Fig. 1).

The local geology is characterized by granitic cobble beaches with carbonate coral debris, steep topography, and no surficial water input. Terrestrial inputs to the groundwater are limited to leachate from small-scale local drip-irrigated gardens or lawns and outflow from the laboratory seawater system. The nearshore benthic slope (within 25 m of the beach edge) is 7° but increases dramatically about 50 m offshore.

Meteorology and hydrography—The study site is characterized by northerly along-axis diurnal winds that peak in the afternoon (Karnieli pers. comm.). Ocean currents are mostly tidally driven (on the order of 10–20 cm s^{-1}).

Table 1. Water depths (m) for transect sampling locations. The west transect was not sampled (ns) in the fall.

Offshore distance (m)	Winter transects			Fall transects		
	West	Center	East	West	Center	East
0	0.1	0.1	0.1	ns	0.1	0.1
3	0.6	0.2	0.3	ns	0.5	0.5
10	1.3	0.8	1.1	ns	1.2	1.3
25	4.0	4.0	2.5	ns	4.2	2.8

Seasonal currents overlaid on the tidal flows exhibit a northward flow in the fall and switch to the south during the winter (Genin and Paldor 1998). The west coast currents are typically alongshore currents. Thermally driven flows contribute to weak cross-shore currents on the order of 1–21 cm s^{-1} (Monismith et al. in press).

The region is extremely arid, with average air temperatures ranging from 16°C in the winter to 34°C in the summer (Genin and Paldor 1998). Average rainfall, occurring mainly in the winter, is only 3 cm yr^{-1} (Morcos 1970), while the average net evaporation is 1 cm d^{-1} (Assaf and Kessler 1976). Sea surface temperatures range from about 20.6°C in the winter to 27°C in the summer, and salinity ranges from 40.3 to 40.8 (Paldor and Anati 1979; Reiss and Hottinger 1984).

Sampling periods and design—This study was conducted during two periods: 06–20 January 2002 (winter) and 28 September–07 October 2002 (fall). Water was collected and analyzed for salinity, radium activities, and nutrient (nitrate, nitrite, and soluble reactive phosphorus [SRP]) concentrations. In addition, an acoustic Doppler current profiler (ADCP, RD Instruments) was deployed to measure nearshore currents. Three water sampling transects running perpendicular to the shore were sampled in the winter period. For the fall period, only two transects were sampled. A transect consisted of four sampling points at 0, 3, 10, and 25 m from shore. Sampling was limited to within 25 m of the shoreline because preliminary sampling in 2001 showed radium and nutrient gradients were much smaller beyond 25 m, and concentrations were typically at or near background values by 25 m from shore (data not shown). Water was collected from 10 cm below the sea surface (water depths for these stations are listed in Table 1). Groundwater was collected from an onshore well about 15 m upland from the edge of the water located between the east and center transects. The well is <3 m deep and was the water source for the laboratory's seawater system but was no longer used for that purpose by the time of this sampling. Radium activities and nutrient values reported from the well are based on a single measurement at each tidal condition (high and low tide) during each season. Offshore samples were taken from at least 1 km offshore. A high-frequency study, with water samples collected every 3 h over an 18-h period, was conducted in the fall at two locations (3 and 25 m from the shoreline). Replicates were collected for some of the samples. Water samples from a depth profile were collected from a site ~350 m offshore (60 m water depth) with samples taken from

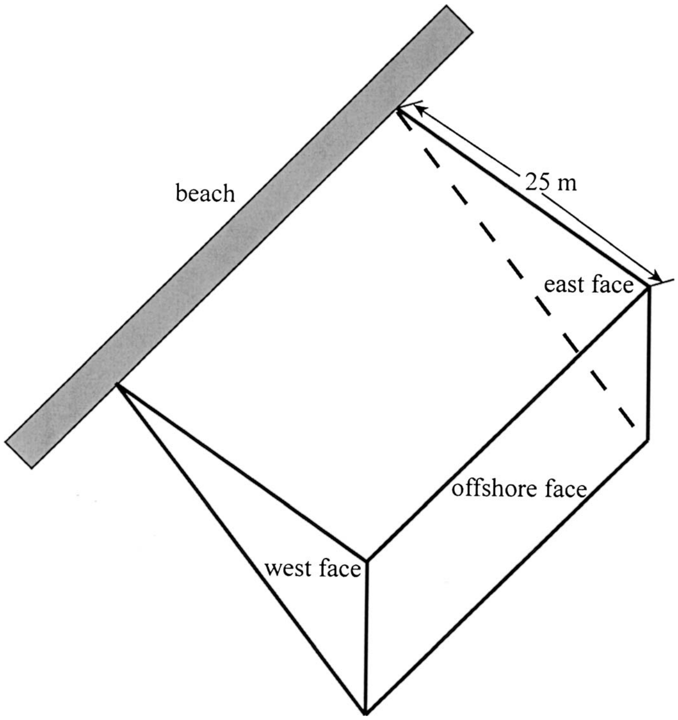

Fig. 2. Schematic of the control volume used for the box model. The alongshore distance varied with sampling period.

40, 30, 15, and 0 m deep to determine whether deep water was an important source of radium.

Salinity measurements—Field salinity measurements were collected with an OS-200 conductivity, temperature, and depth probe (CTD, Ocean Sensors) for onshore well salinities and a SBE-19 CTD (Seabird) for coastal measurements. When sampling with a CTD was impractical, water samples were collected and filtered through a 0.45-μm filter, and the density measured in the laboratory with a densitometer (Anton Paar DMA 4500). Densities were converted to salinities with the United Nations Educational, Scientific, and Cultural Organization (UNESCO) equation of state (International Equation of State [IES] 80) (Fofonoff 1985). Tide data are derived from WXTide32, version 2.8 (2002, freeware by Michael Hopper) applied to the Gulf of Aqaba and confirmed with a pressure transducer that was deployed during part of one sampling period (data not shown).

Radium isotopes—Between 20 and 100 liters of water were collected using a submersible pump (Rule 20A). Each sample took between 2 and 3 min to collect. The sample was gravity filtered through a column packed with manganese-coated acrylic fiber (Mn fiber, preparation described in Moore 1976) at flow rates not exceeding 1.5 L min^{-1}. Plugs of untreated acrylic fiber were placed at the head of each column to prevent sediment from contacting the Mn fibers (Veeh et al. 1995). Prior to analysis, samples were rinsed with Milli-Q water, and the short-lived radium isotope activities were measured as soon as possible using a delayed coincidence counter

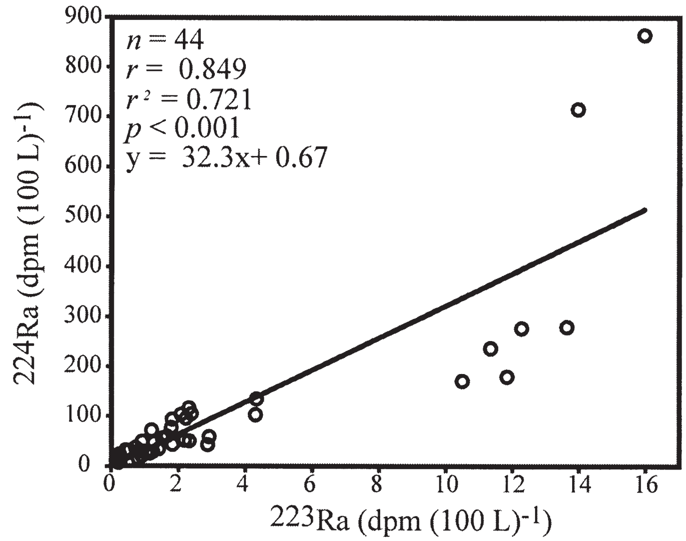

Fig. 3. Correlation and regression between ^{224}Ra and ^{223}Ra activities from the coastal transects.

(Moore and Arnold 1996). The measurement error using this technique is about 10% (Rama et al. 1987; Charette et al. 2001; Moore 2003). Preliminary sampling during September 2001 showed that the correction for ^{228}Th-supported ^{224}Ra activity was typically less than 5% (data not shown). This finding agrees with that of Rama et al. (1987), who assert that, because of the high particle reactivity of ^{228}Th, ^{228}Th-supported ^{224}Ra is insignificant in nearshore water. Therefore, corrections for ^{228}Th-supported ^{224}Ra were not performed on subsequent samples. Because results presented here are based on the activity differences between groundwater and coastal water, neglecting this small correction will not significantly influence the gradients observed in this study (e.g., our reported ^{224}Ra activities for all samples may be systematically $\sim$5% too high).

Nutrients—Samples for nutrient (nitrate, nitrite, and SRP) analysis were collected concurrently with radium samples and filtered through 0.45-μm filters. Nitrite, nitrate, and SRP were analyzed using colorimetric methods described by Hansen and Koroleff (1999) and modified for a flow injection autoanalyzer (FIA, Lachat Instruments Model QuickChem 8000). SRP was preconcentrated by a factor of about 20 using the magnesium coprecipitation method (Karl and Tien 1992), followed by measurement using the FIA. The FIA was fully automated, and peak areas were calibrated using standards prepared in low nutrient filtered seawater over a range of 0–10 μmol L^{-1}. The precision of these methods is 0.05 μmol L^{-1} for NO_2 and NO_3 and 0.01 μmol L^{-1} for SRP. Samples with high nitrate content were diluted with low nutrient concentration seawater to fit into the calibration range. The nitrogen numbers reported are a combination of NO_2 and NO_3 referred to as N+N.

Box model—Simple mass balance box model calculations (following Moore 1996) were performed for a box

Table 2. Radium activities (dpm [100 L]$^{-1}$) and nutrient concentrations (μmol L^{-1}) used for box model calculations (Eq. 1). The discharge volume and nutrient discharge are calculated values. The number reported for the terrestrial end member is the average of the high and low tide values as sampled in the well. The designation na means not applicable because these values were not used for calculations. Dimensions for winter—beach face, 570 m; box area, 14,250 m^2; box volume, 356,250 m^3; average depth, 1.3 m. Dimensions for fall—beach face, 150 m; box area, 3,750 m^2; box volume, 4,780 m^3; average depth, 1.3 m.

	Box average	Offshore end member	Terrestrial end member	Discharge volume (m^3)	Nutrient discharge (μmol L^{-1})
Winter 2002					
^{223}Ra	1.83	0.04	153	212	
^{224}Ra	40.1	6.78	2,070	292	
N+N	na	0.89	30.6		0.41
SRP	na	0.06	0.38		0.0051
Fall 2002					
^{223}Ra	1.44	0.18	61.1	100	
^{224}Ra	68.4	29	2 520	80	
N+N	na	0.76	33.5		0.64
SRP	na	0.02	0.48		0.0065

that was spatially defined by the transects (Fig. 2) to determine the contribution of terrestrially derived water to the nearshore radium activities. The radium activity in each box was determined by averaging the radium activities for all the sites within the defined box confined to 25 m offshore. The well and open ocean samples served as end members to allow for mixing calculations. The residence time of the water in the box is much shorter than the decay time for ^{224}Ra (the shortest lived isotope) based on cross-shore currents measured by the ADCP and the relatively constant ^{224}Ra : ^{223}Ra ratio in our samples (Fig. 3). Accordingly, both isotopes were treated as conservative tracers within the box. This allowed the determination of the fractions of terrestrially derived water and offshore water at a coastal site during the sampling period via the equation:

$$V_{GW}A_{GW} + (V_{Box} - V_{GW})A_{Offshore} = V_{Box}A_{Box} \quad (1)$$

where V is volume (m^3); A is radium activity in decays per minute (dpm [100 L]$^{-1}$); V_{Box} is the volume of the control box; and V_{GW} is the volume in the box that was contributed by groundwater, the only unknown in the equation. The activities A_{GW} and $A_{Offshore}$ are those of the well and offshore end members, respectively. The radium activity used for the well represented an average of activities measured at high and low tide.

The average contribution of the groundwater-derived nutrients to the nutrient levels in the box can be calculated using the average calculated contribution of groundwater to the box (averaging the ^{223}Ra- and ^{224}Ra-based mass balance calculations) and the average nutrient concentrations in the groundwater end member. The fractional contribution of the groundwater nutrients to the box can be determined by

$$C_{BoxGW} = f_{GW} \times C_{GW} \quad (2)$$

$$\%C_{BoxGW} = \frac{C_{BoxGW}}{(C_{BoxGW} + C_{Offshore})} \quad (3)$$

where C_{BoxGW} is the concentration of nutrients in the box contributed by SGD; f_{GW} is the fraction of SGD in the box; C_{GW} is the concentration of nutrient in the SGD; $C_{Offshore}$ is the concentration of nutrient offshore; and $\%C_{BoxGW}$ is the percentage of nutrient in the box delivered by SGD.

The method of Moore (1996) to calculate the amount of groundwater needed to balance the excess radium seen in a coastal control volume simplifies in Eilat because of the lack of surficial water input to the gulf at this location. Therefore, the calculation only requires radium activity in the box, in the submarine groundwater, and offshore:

$$\frac{(\bar{A}_{Box} - A_{Offshore})V_{Box}}{RT} = A_{Excess} \quad (4)$$

where an over bar represents an average for the radium activity in the box (dpm L^{-1}); RT is the cross-shore residence time (d); V is the volume of the box (liters), and A_{Excess} (dpm d^{-1}) is the radium flux to the box not supported by the offshore water that must therefore be supplied by SGD. A_{Excess} divided by the radium activity of the submarine groundwater end member (dpm L^{-1}) gives an estimate of the groundwater flow required to balance the excess radium activity (L d^{-1}). It must be emphasized that the SGD includes both fresher groundwater and recirculated seawater. With the calculated flow and nutrient concentrations of submarine groundwater (based on concentrations measured in the well), a nutrient flux can be determined. Extrapolating these fluxes in time can then be used to calculate estimated yearly inputs of each nutrient, assuming our sampling periods are representative of the entire year.

Extensive measurements made from 1999 to 2002 by Monismith et al. (in press) show that the primary means for cross-shore exchange is buoyancy driven flows that develop because shallow in-shore regions heat and cool more rapidly than deeper offshore regions. The steepest temperature gradients exist within 20 m of the shoreline. The

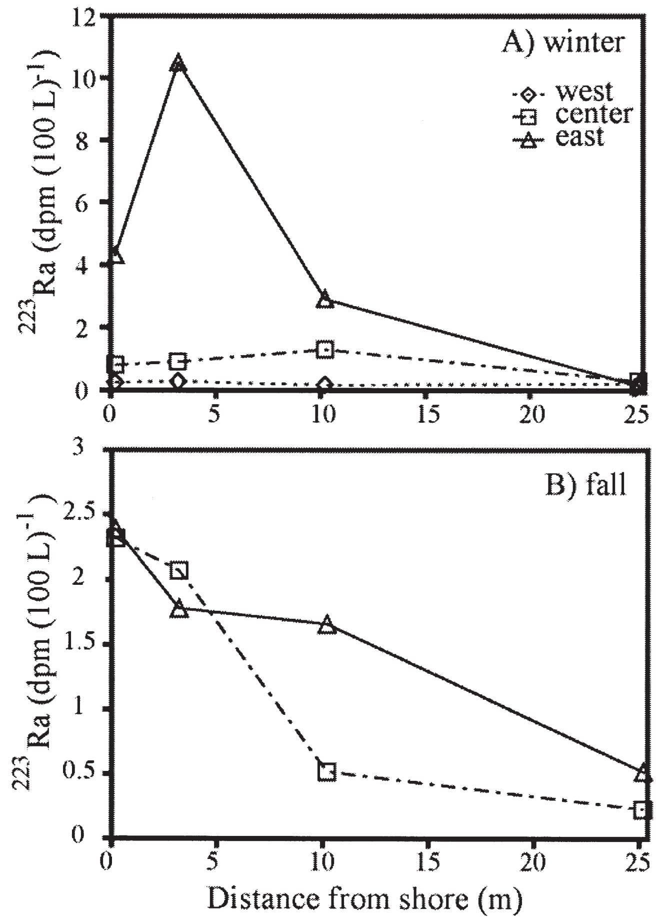

Fig. 4. Transect radium activities as a function of the distance from the beach. Panels correspond to different seasons.

cross-shore residence time (RT) was estimated as

$$RT = \frac{V}{0.6\left(\frac{\alpha g \tilde{H} D}{\rho c_p}\right)^{1/3} DL} \quad (5)$$

where V is the volume of the box; D is the depth on the offshore face of the box; L is the alongshore length of the box; $\tilde{H}$ is the surface heat flux (W m^{-2}); α is the thermal expansivity; ρ is the density of water; and c_p is the heat capacity at constant pressure. Typically for Eilat, Eq. 5 gives $RT \sim 3$ to 6 h. We note that the denominator of Eq. 5 follows the scaling presented by Sturman et al. (1999) but with an empirical constant derived from observations made in Eilat.

Results

Radium activities—Activities of ^{223}Ra and ^{224}Ra are well correlated ($r^2 > 0.72$, $n = 44$ for all sampling periods, Fig. 3), suggesting a common source and no significant decay. Accordingly, only ^{223}Ra activities are shown in subsequent figures, but box value averages for both isotopes are presented in Table 2. All radium transects showed generally decreasing activity with distance offshore (Fig. 4), which is consistent with a shore-based source. ^{223}Ra activities along transects in the winter of 2002 ranged from 0.08 to 10.5 dpm (100 L)$^{-1}$, and ^{224}Ra activities were 6.25 to 171 dpm (100 L)$^{-1}$. In the fall of 2002, the activities ranged from 0.23 to 2.32 dpm (100 L)$^{-1}$ and 24.1 to 117 dpm (100 L)$^{-1}$ for ^{223}Ra and ^{224}Ra, respectively. The offshore radium activities were considerably lower than the average activity for the coastal samples, with ^{223}Ra of 0.04 dpm (100 L)$^{-1}$ and ^{224}Ra of 6.78 dpm (100 L)$^{-1}$ in the winter and 0.18 dpm (100 L)$^{-1}$ and 29.0 dpm (100 L)$^{-1}$, respectively, in the fall.

Spatial variability in radium activities along the various transects at each site was observed (Fig. 4). For example, during the winter sampling, the east transect exhibited elevated activities relative to the other two transects. This phenomenon was not observed in the fall.

Radium activities from the well were about two orders of magnitude higher than coastal activities (Table 2; Fig. 4). The activities in the well during winter 2002 ranged between 112 and 193 dpm (100 L)$^{-1}$ and 1,740 and 2,390 dpm (100 L)$^{-1}$ for ^{223}Ra and ^{224}Ra, respectively, and in the fall, the activities were between 55.9 and 66.3 dpm (100 L)$^{-1}$ for ^{223}Ra and between 2,320 and 2,720 dpm (100 L)$^{-1}$ for ^{224}Ra. The lowest activities in coastal waters and in the well were typically during high tide, reflecting the dilution effect of increased tidally pumped seawater during high tide in the submarine zone as observed in other locations (Bollinger and Moore 1993; Moore 1997). Variability of radium activities and nutrient concentrations between seasons in the well was not specifically explored but most likely results from changes in groundwater recharge sources and the contact time of the interstitial water with the local soil.

The tidal cycle study showed changes in the radium and the nutrient signals over the timescale of the tide, with higher activities for both isotopes and higher nutrient concentrations at low tide (two- to sixfold higher radium) (Fig. 5). The ^{223}Ra activity ranged from 0.56 to 2.9 dpm (100 L)$^{-1}$ at 3 m and from 0.06 to 0.48 dpm (100 L)$^{-1}$ at 25 m. The ^{224}Ra activities ranged from 36.8 to 93.3 dpm (100 L)$^{-1}$ at 3 m and from 21.2 to 38.2 dpm (100 L)$^{-1}$ at 25 m. The replicate samples agreed well and showed standard deviations typically less than 15% (Fig. 5).

The depth profile did not indicate any radium enrichment at depth, suggesting that there is not a major sedimentary or deep-water source of radium (Shellenbarger 2003). The radium activities of samples from the depth profile (~350 m offshore) are indistinguishable from offshore surface values and are consistently lower than activities in nearshore water.

Nutrients—Nutrient (N+N and SRP) concentrations also generally decreased with distance from shore (Figs. 6 and 7, respectively) but did not always correlate well with radium (Fig. 8), most likely because of the nonconservative nature and rapid uptake of the nutrients. The concentrations in the well were substantially higher than in the coastal waters. N+N concentrations in the well ranged from 30.0 to 31.3 μmol L^{-1} at high and low tide, respectively, in the winter and 26.4 to 40.6 μmol L^{-1} in the fall. The SRP

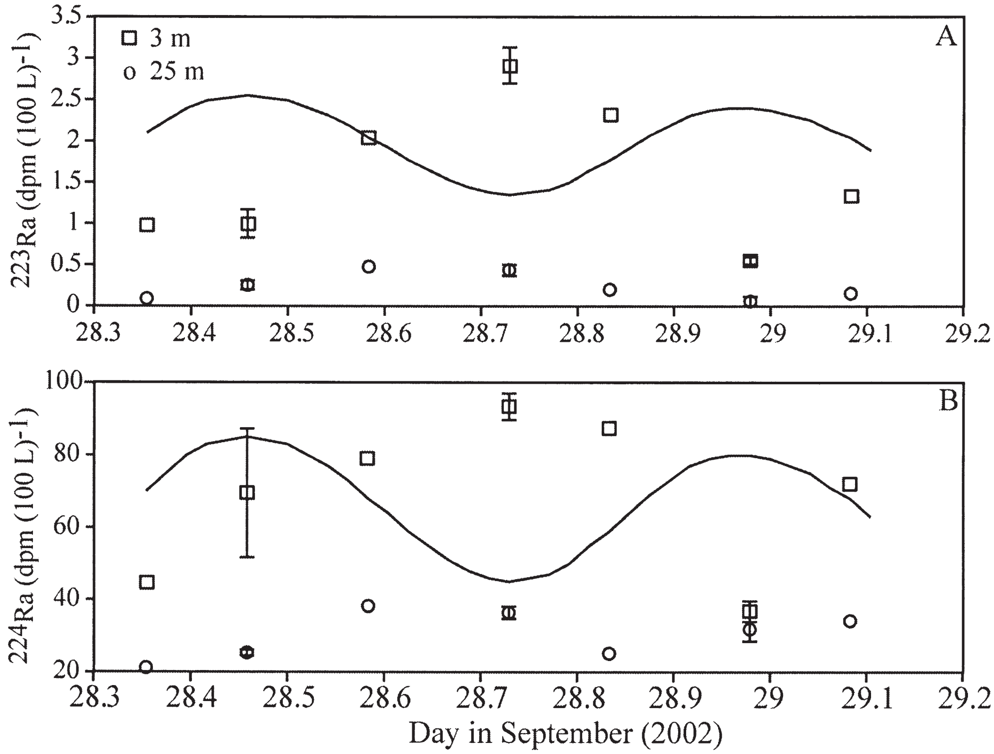

Fig. 5. Activities of (A) ^{223}Ra and (B) ^{224}Ra during the tidal study. The solid line refers only to the tidal stage and does not represent actual tidal heights. Error bars represent one standard error ($n = 2$ for September 28.45 and 28.975; $n = 3$ for September 28.725).

concentrations at the same time were 0.19, 0.57, 0.40, and 0.55 μmol L^{-1}. The offshore concentrations were about an order of magnitude lower and are listed in Table 2. The transect samples were on average more elevated than the offshore concentrations (maximum 2.43 μmol L^{-1} N+N and 0.1 μmol L^{-1} SRP).

Box model and groundwater flux calculations—Table 2 details the activities and volumes used for the box model calculations, as well as the results of the calculations. The contribution of SGD to nearshore waters calculated using radium mass balance was similar for both seasons. The winter sampling suggests that between 1.1% (^{223}Ra) and 1.6% (^{224}Ra) of the coastal water could be attributed to SGD. This agrees closely with the fall sampling that suggests between 1.7% (^{224}Ra) and 2.1% (^{223}Ra) of the coastal water is from SGD.

The nutrient contribution from terrestrially influenced water to the box, which extends to only 25 m offshore, was also substantial. During the winter, SGD-derived N+N accounted for 32% of the N+N in the box, while the SRP contribution was only 7.8%. This low contribution is due to an unusually low SRP measurement in the onshore well. In the fall, the SGD nutrient contributions were higher, 46% for N+N and 21% for SRP. It must be noted that these calculations ignore the nonconservative nature of the nutrients in the coastal zone and do not include ammonium as an additional source of nitrogen.

Using the excess radium inventory and an average cross-shore residence time of 3 h (estimated from heat flux calculations), we calculated the submarine saline groundwater discharge (similar to Moore 1996). For the winter sampling, the ^{223}Ra excess activity suggested a SGD of 19 L s^{-1}, while ^{224}Ra calculation gave 27 L s^{-1} across the shoreline edge of the box. During the fall, these values were lower. ^{223}Ra excess activity showed 10 L s^{-1} of groundwater flow versus 6.4 L s^{-1} for ^{224}Ra. The seasonal data for each isotope were pooled and averaged (and the box volumes were averaged), and an average annual groundwater flow of 16 L s^{-1} was obtained. The calculated average SGD flux is the same using either isotope, despite the higher uncertainty in the ^{224}Ra measurement. The fluxes calculated from the range of discharge rates based on the range in the radium data (6.4 L s^{-1} to 27 L s^{-1}) are 1,500 to 6,500 L m^{-1} d^{-1} along the average length of the beach face (360 m). If the discharge is assumed to be over the entire box area (average between the two sampling periods is 9,000 m^2), the flux results become 60 to 260 L m^{-2} d^{-1}. The average integrated flux across a 360-m beach face (based on an average discharge of 16 L s^{-1}) is 0.044 L m^{-1} s^{-1} (3,800 L m^{-1} d^{-1}) and becomes 0.0018 L m^{-2} s^{-1} (160 L m^{-2} d^{-1}) when calculated over the entire box area.

Discussion

It is well established that surficial water discharged to coastal regions provides the nearshore with nutrients and other materials. However, in the last decade, studies have shown submarine groundwater to be an important com-

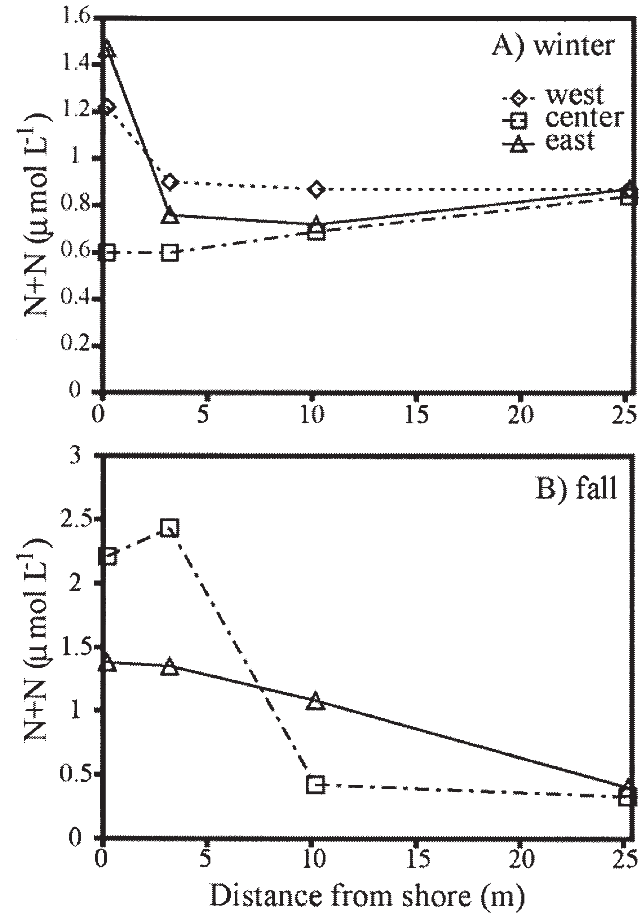

Fig. 6. Transect nitrogen (N+N) concentrations as a function of the distance from the beach. Panels correspond to different seasons.

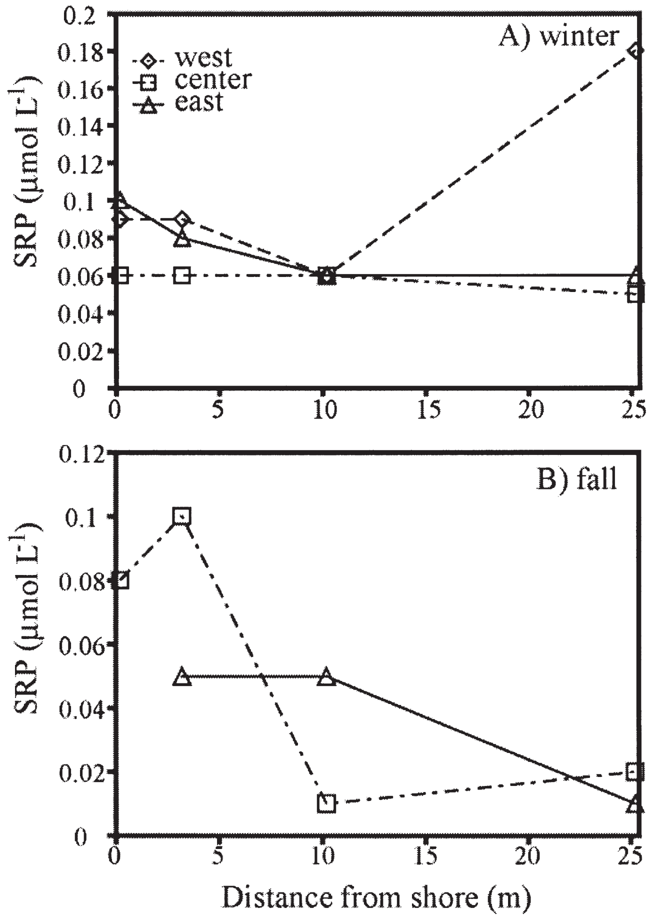

Fig. 7. Transect soluble reactive phosphorus (SRP) concentrations as a function of the distance from the beach for each season. Panels correspond to different seasons.

ponent to material fluxes in the nearshore region (Dollar and Atkinson 1992; Paerl 1997; Moore et al. 2002). This site has an unconfined surficial aquifer that drains to the gulf and contributes nutrients and potentially other substances (e.g., trace metals, pollutants) to the coast. A major component of the submarine groundwater in this arid region is tidal and wave pumped seawater moving through the aquifer (Li et al. 1999). In addition, local proximal sources of freshwater from landscape irrigation, leaks from pipes, and other anthropogenic sources may add some freshwater to this aquifer.

Radium activities—The radium activities measured in this study are comparable to values reported previously. The ^{223}Ra activities from the groundwater sampled in this study compare well with data from other parts of the world (i.e., between 0.84 and 193 dpm [100 L]$^{-1}$; Rama and Moore 1996; Charette et al. 2001). Also, the range of offshore ^{223}Ra end member activities (0.04–0.18 dpm [100 L]$^{-1}$) and coastal activities (0.13–16 dpm [100 L]$^{-1}$) compare well with other studies (Webster et al. 1994; Hancock et al. 2000; and Moore 2003).

Published ^{224}Ra activities are more plentiful. Reported groundwater and tidal creek activities range from 130 to 1,390 dpm (100 L)$^{-1}$ (Bollinger and Moore 1993; Rama and Moore 1996; Charette et al. 2001) along the East Coast of the United States. The activities from this study are of the same magnitude, but peak values are substantially higher, up to 2,720 dpm (100 L)$^{-1}$. The reported ^{224}Ra activities for coastal and estuarine areas typically range from 3 to 120 dpm (100 L)$^{-1}$ (Charette et al. 2001; Kelly and Moran 2002; Moore 2003). The coastal activities in our study range from 14 to 280 dpm (100 L)$^{-1}$.

The distribution of radium activities (decreasing offshore) and the high activities in groundwater suggest a SGD source. However, another potential source of short-lived radium isotopes may be regeneration in local sediments (Bollinger and Moore 1993). Sediments in this region are largely relict quartz sands and granitic gravel with coral fragments and are not expected to be large radium sources. Moreover, a local sediment source cannot explain the alongshore variability observed in radium activities at similar water depths (ranging from 6 to 865 dpm [100 L]$^{-1}$ for ^{224}Ra and a similarly large range for ^{223}Ra) and the associated nutrient concentrations. A sediment desorption experiment conducted following Bollinger and Moore (1993) and Hancock et al. (2000) also suggests that the marine sediments do not contribute a significant fraction of

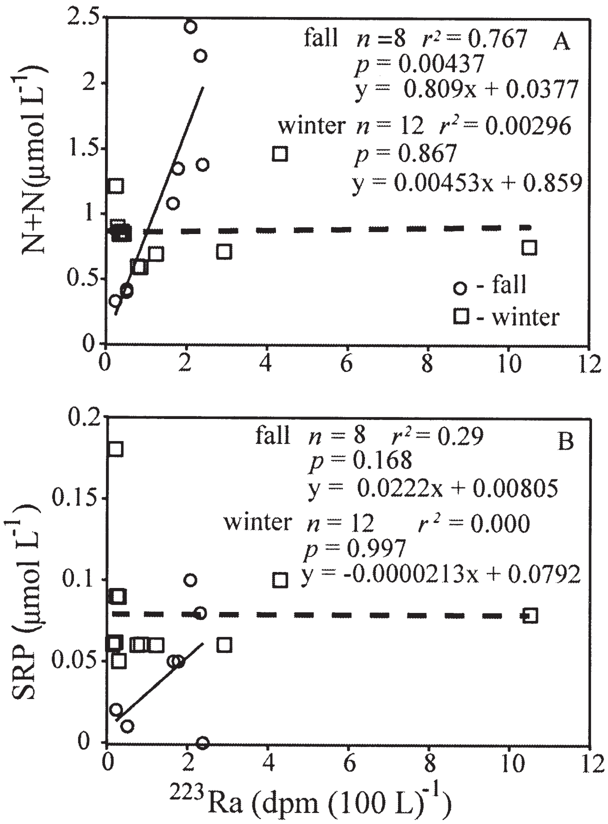

Fig. 8. Correlations and regressions between ^{223}Ra and N+N or SRP for the coastal transects. Panels refer to different nutrients.

radium activity seen in this coastal zone (Shellenbarger 2003).

Tidal study—A change in nearshore radium activity with the tidal stage is to be expected in regions with tidally pumped seawater (Bollinger and Moore 1993). Even in the absence of fresh groundwater, SGD can be explained by the physics of the interaction of the waves and tide with the beach (Nielsen 1990; Horn 2002). The sloping beach face acts like a highly nonlinear filter to the movement of water across it. Because of the nonlinearity, an over-height of the water in the beach relative to the coast is maintained. This over-height implies that tidal physics alone will always provide (in the tidally averaged sense) a hydraulic gradient driving water from the beach to the sea. The beach water over-height is increased further with the presence of waves (Li et al. 1999). Owing to the nonlinearity of the flow in and out of the beach, the water exiting the beach during low tide is substantially higher in radium activity than the water leaving the beach just past high tide. The activity of the radium isotopes with the shorter half-lives (^{223}Ra and ^{224}Ra) is particularly elevated, since their regeneration can be significant on the timescale of several tidal cycles.

The results of this study (Fig. 5) are consistent with the above explanation. Both ^{223}Ra and ^{224}Ra showed peak nearshore activities near low tide and lowest activities near high tide, with up to a sixfold difference in ^{223}Ra. In addition, it appears that the increase in radium activity with the falling tide occurs more slowly than the decrease in activity with the rising tide. This would be expected if the water enters the beach more quickly than it leaves. This supports the hypothesis of Elsinger and Moore (1983), Webster et al. (1994), and Burnett et al. (2002), who showed that the dissolved radium activities were generally highest at or near low tide and lowest at high tide. This is also consistent with the salinity, water height, and radium activity fluctuations in the coastal well in our study (Fig. 9).

Considerable spatial and temporal variability in radium activities within the sampling area is observed (Fig. 4). This variability could be at least partly explained by sampling of the various transects during different times of the tidal cycle. Additional causes for variability are proximity to an unknown source of discharge or the variability in the permeability of onshore sediments.

Groundwater fluxes—The average SGD flux calculated using radium isotopes in Eilat, 2.7 L m^{-2} min^{-1} (range 60–260 L m^{-2} d^{-1}), seems high for an arid region. However, upon observing the seepage face on the beach at low tide, visible water "trickles" are seen with a rate that seems to be consistent with a 2–3 L m^{-2} min^{-1} discharge. This by no means implies that the discharge is of freshwater, but rather that the tidally pumped seawater is a significant component of the submarine groundwater. Thus, the lack of precipitation in this area may not be an important limitation on the delivery of SGD (which includes tidally pumped seawater) and associated radium and nutrients to the reef.

Fluxes calculated here are comparable to or even higher than results obtained using radium isotopes at other sites. Groundwater input reported for the coast of Florida ranges from 10 L m^{-2} d^{-1} (Corbett et al. 1999) to 108 L m^{-2} d^{-1} (Moore 2003). Along the New England coast, Kelly and Moran (2002) report groundwater fluxes of 1.5 to 22 L m^{-2} d^{-1}. These results are surprising given that this region of Israel is very arid and had been experiencing a 4-yr drought. The disparity could result from the difference in sampling scale between this and other studies. Our study has explored the near shore, on a scale of tens of meters, rather than the several kilometer scale used in most previous studies. The effect due to scale is this: averaging values over a smaller area will produce larger results. If our box had been defined on the scale of several hundred meters, the average radium activities in the box would have been lower, which suggests lower SGD fluxes. However, the radium and nutrient gradients from the shore were steep, and values past the 25-m point were similar to offshore values or dropped very slowly. This implies that the spatial resolution was sufficient for this system. In addition, we were concerned with the contribution of SGD-derived nutrients to coral reefs, which in Eilat are typically constrained to within 50 m from shore because of the steep bathymetry.

Nutrient fluxes—Our calculations indicate that the combination of groundwater and tidally pumped seawater (combined to form SGD) contribute significant amounts of nutrients to the reef. The results of the box model calculations show that the average SGD of 16 L s^{-1} along

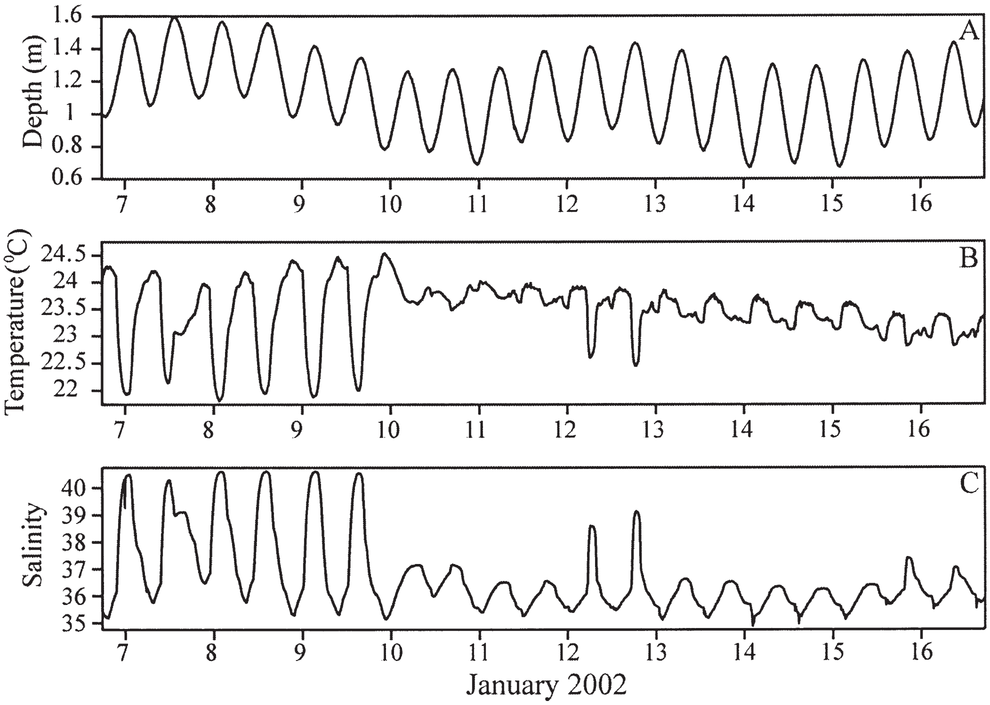

Fig. 9. The (A) depth, (B) temperature, and (C) salinity in the well for 10 d during the winter sampling. Depths were not referenced to a datum and were, therefore, relative. Large variations in salinity and temperature occur when the tide exceeds a certain elevation and seawater intrudes into the well.

the shoreline box results in about 3% of the water in the box at any given time being of submarine groundwater origin. However, this water is accounting for about 32–46% of the N+N and 7.8–21% of the SRP within 25 m of the beach (from Eq. 3). Multiplying the average nutrient concentrations from the well with the seasonally averaged discharge of 16 L s^{-1}, a yearly integrated input to the reef of 1.4×10^4 mol N and 190 mol P (200 kg N and 5.8 kg P) can be projected. Converting these concentrations to fluxes over the entire box area, ranges of 2.9–10 mmol N m^{-2} d^{-1} and 0.018–0.20 mmol P m^{-2} d^{-1} are obtained. The linear nutrient fluxes across the face of the beach (instead of the entire box area) are 25 times higher (the ratio of the average box area to the average length of the beach face) at 71–240 mmol N m^{-1} d^{-1} and 0.45–5.2 mmol P m^{-1} d^{-1}.

It is possible that the actual amount of dissolved inorganic nitrogen supplied by SGD to the coastal ocean is higher than our calculations suggest because we have not accounted for the potential contribution of ammonium. Ammonium was measured in the well at the field site in the fall of 2005, where it was found to be 0.053 and 0.070 μmol L^{-1} at high and low tide, respectively. Nitrate and nitrite analysis on the same samples showed nitrate concentrations two orders of magnitude higher and nitrite concentrations the same order of magnitude as the ammonium. Assuming that ammonium concentrations were similar in fall 2005 as during the original sampling periods, it suggests that ammonium likely contributes minimally to the total coastal nitrogen flux via SGD at this field site. However, the box model calculations should be viewed as a conservative estimate of nitrogen flux from the SGD to the oligotrophic coastal waters of the Gulf of Aqaba.

Published studies of similar nutrient flux calculations range widely. Krest et al. (2000) report fluxes of DIN-derived N (dissolved inorganic nitrogen which includes NH_4), for the North Inlet in South Carolina, between 0.27 and 0.93 mmol N m^{-2} d^{-1}, while SRP ranged from 0.048 to 0.081 mmol P m^{-2} d^{-1}. In New England, Kelly and Moran (2002) report fluxes of 61–180 mmol N m^{-2} d^{-1} and 4.5–13 mmol P m^{-2} d^{-1}. Therefore, the radium-derived nutrient fluxes on the west coast of the northern gulf are comparable to nutrient fluxes seen in other regions of the world. This is a significant contribution of nutrients to the reef given that the offshore nutrient levels are very low and cannot contribute much to the overall productivity of the reef. Although reefs are efficient recyclers of nutrients, SGD-contributed nutrient supply identified here may constitute a "new" nutrient source (i.e., allochthonous) to the nearshore region, evidenced by the depression of the salinity in the well compared with the coast. We cannot discount that the supply of fresher water to the beach aquifer is carrying significant nutrient concentrations. Thus, this nutrient source may support net productivity in the ecosystem.

It is interesting to note what this supply of nitrogen to the nearshore reef implies to the local primary productivity rate. The C : N ratio in the Gulf of Aqaba follows the Redfield ratio between 6 and 7 (Genin unpubl. data), while the ratio for typical coral reefs is 10–30 (Atkinson and Smith 1981). For calculation purposes, a C : N of 6.6 for the Gulf of Aqaba and 20 for typical coral reefs will be assumed. Given the calculated nitrogen fluxes along the coast (2.9–10 mmol N m^{-2} d^{-1}), a presumed new primary productivity rate, supported by SGD associated nutrients, can be calculated. This nitrogen input implies between 22 and 77 mmol C m^{-2} d^{-1} of new production in the gulf and 68–230 mmol C m^{-2} d^{-1} of new production on a typical coral reef (assuming this is the only source of allochthonous nitrogen). The average primary productivity rate for the photic zone in the gulf is 42 mmol C m^{-2} d^{-1} (Genin unpubl. data), whereas it has been reported as 330–500 mmol C m^{-2} d^{-1} for typical coral reefs (Kinsey 1985). This suggests that the SGD-derived N+N can account for 50–200% of the primary productivity in the gulf or 20–60% of the productivity in a typical reef (assuming 100% use and no nutrient export from the reef). It should be stressed that ammonium was not measured as part of this study and could provide an additional source of nitrogen to the gulf. These results reiterate the potential importance of such small exchanges of tidally pumped water to the coastal nutrient budgets in these oligotrophic waters.

The presence of SGD and its potential impact on coastal nutrient budgets is not unique to the Gulf of Aqaba. Coral reefs in many regions of the world occur near shore (e.g., fringing reefs) and could be affected by SGD and associated nutrients. Of course, many reef systems are equatorial and tropical. The influence of proximity to the equator would lessen the effect of tidal pumping because of reduced tidal ranges, but these areas often are exposed to more intense wave activity than Eilat. This can serve to promote a net seaward flux of submarine groundwater. In addition, reefs often occur in regions that have much higher precipitation than Israel; precipitation greatly increases groundwater discharge by increasing aquifer recharge. In that sense, the results from the arid Gulf of Aqaba could serve as a lower end of the estimates of the impact of SGD on coral reef nutrient budgets.

Several important conclusions can be derived from this work. Small-scale spatial sampling for radium and nutrients is effective and may be required for studying SGD in arid regions or in areas with rapid water mixing along the coast. In addition, tides have significant effect on the volume of SGD, and thus it is important to control for tidal stage when sampling radium isotopes, particularly in studies close to shore. Finally, nutrient contributions from even a small rate of tidal and wave pumped SGD can be significant to the nearshore nutrient supply.

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Received: 8 July 2005
Accepted: 13 January 2006
Amended: 6 March 2006