Temporal variability of submarine groundwater discharge: assessments via radon and seep meters, the southern Carmel Coast, Israel

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Abstract Seep meter data from Dor Bay, Israel, showed a steady decrease in submarine groundwater discharge (SGD) rates between March and July 2006 (averages of 34, 10.4 and 1.5 cm d^{-1} in March, May and July, respectively), while estimates based on radon time series showed remarkably uniform averages (8 cm d^{-1}). The May seep meter data show a rough positive correlation with sea level, unlike the negative correlation shown by the Rn-calculated rates. Smaller-size meters, deployed in July adjacent to the regular-size ones, showed significantly higher rates (10 cm d^{-1}), which negatively correlated with salinity. It is suggested that the decreased rates documented by the seep meters are the result of an increased shallow seawater recharge in the bay (due to decreasing hydraulic gradients). This is not captured by the radon, since recharging water is radon-poor. The positive correlation of discharge with sea level is due to increased seawater recycling in times of high sea stand.

Key words submarine groundwater discharge; radon; seep meter; seawater recycling; electrical resistivity

INTRODUCTION

Submarine groundwater discharge (SGD) is now well-established as a major process in coastal areas and as an important factor in coastal water mass balances (Moore, 1996). It has been shown that, in most cases, the discharging water is a mixture of saline and fresh groundwater, and it is usually assumed that the saline component is recycled seawater (e.g. Michael *et al.*, 2005). The mechanisms, locations and scales involved in this recycling are less clear. Most relevant publications highlight the role of tidal or seasonal forcing (e.g. Li *et al.*, 1999; Michael *et al.*, 2005; Prieto & Destouni, 2005), and to less extent that of wave-induced recycling (e.g. Li *et al.*, 1999; Robinson *et al.*, 2006), though its existence is commonly acknowledged (e.g. Taniguchi *et al.*, 2006a,b).

The various methodologies used to assess SGD do not always refer to the same component. While hydrological balances usually estimate the discharge of fresh groundwater, radium isotopes are usually used to study recycling of seawater (e.g. Moore, 1996). On the other hand, direct measurements by seep meters, as well as estimates based on ^{222}Rn time series (Burnett & Dulaiova, 2003) are measuring total SGD (fresh + recycled seawater, e.g. Mulligan & Charette, 2006).

In this paper we compare seep meter measurements and radon estimates taken in three campaigns during March–May 2006 in the Dor Bay, northern Israel. We relate the differences between measurements and patterns to discharge–recharge interplay in the bay.

GEOGRAPHICAL AND HYDROGEOLOGICAL BACKGROUND

Dor Bay is located about 30 km south of Haifa, Israel, west of Mount Carmel (inset in Fig. 1). The bay was formed by a submerged calcareous sandstone ridge (locally known as Kurkar), which closes the embayment on its northern and western sides (Fig. 1). Its average dimensions are 100 × 150 m, and its average depth is about 1 m.

The coastal aquifer in the Dor area is composed of two units: the Pleistocene Kurkar sandstone and the overlying Holocene quartz sands (Michelson, 1970; Sivan

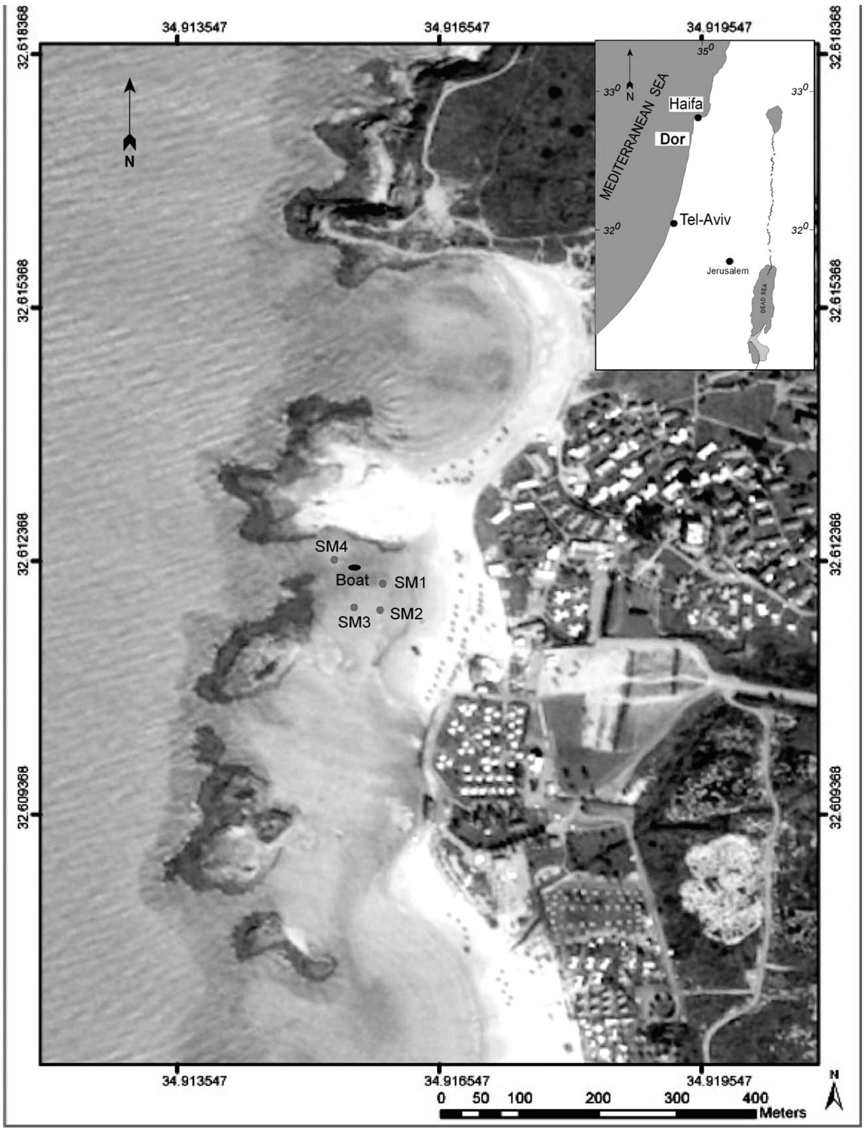

Fig. 1 An air photo of the Dor area, showing Dor Bay and other embayments and the locations of seep meters and the boat, where radon was measured.

et al., 2003). A variably thick clay unit is usually found as a confining layer between the two units (Sivan *et al.*, 2003). In the embayment, the Kurkar is exposed at the seafloor in about one third of the area (Fig. 1), while all the rest is covered by variably-thick loose sand. It is unknown, whether and to what extent the sand in the bay is underlain by clays.

METHODOLOGY

We report here on seep meter measurements taken in Dor Bay during three field campaigns in 2006. We used two different Lee-type seep meters. The first is a dome-shaped plastic meter (hereafter: plastic SM), with a diameter of 80 cm (bottom area of 5.027 cm^2) and 60 cm tall. The second type was smaller, made of metal (hereafter: small SM), 40–60 cm in diameter (1257–2827 cm^2, respectively) and 40 cm tall. All meters follow basic principles of manual seep meters, including a sharp bottom edge that penetrates the sediment to about 10 cm and a threaded pipe nipple at the top to which a 4-L flexible collection bag is attached. The collection bag was pre-filled with 0.5 L water to reduce artifacts due to bag expansion. Measurements started 24 hours after deployment, in order to allow meter equilibration.

Meters were deployed in four sandy sediment sites in Dor Bay (SM1–4, Fig. 1) at distances that varied between 15 and 60 m from the low-tide line. The measurements in March 2006 included just two plastic SMs in SM1 and SM2 and just for a few hours (5 and 2 h, respectively). In May, plastic SMs were deployed in all four sites, and in July two meters (one of each type) were deployed at SM1–3 (Fig. 1). Depths of the bay at deployment sites varied between approx. 1 m (low tide) at SM2, 1.5 m at SM1 and SM3 and approx. 1.7 m at SM4.

RESULTS

The SGD rates measured in Dor Bay are shown in Figs 2–4 and in Table 1. Advection rates measured by the plastic SMs were highest in March 2006, when the few measurements taken indicated averages of 18.1 ± 1.9 and 49.7 ± 4.8 cm d^{-1} in SM1 and SM2, respectively. In May, discharge was significantly lower, with typical advection rates of 0–20 cm d^{-1} and averages of 7.1–12.6 cm d^{-1}, and in July rates were the lowest (Fig. 4), with rates not exceeding 6.4 cm d^{-1}, frequently showing a zero discharge, and averages of 0.2–2.4 cm d^{-1} (Table 1).

Table 1 Average advection rates measured by seep meters and estimated by ^{222}Rn time series in Dor Bay during 2006 (Burnett *et al.*, 2007; Weinstein *et al.*, 2007).

	March	May	July
Large seep meters (cm d^{-1})	33.9 [b]	10.4 ± 5.0 [c]	1.5 ± 1.9
Small seep meters (cm d^{-1})			10.0 ± 7.7
^{222}Rn (calculated)[a] (cm d^{-1})	7.7 ± 6.0	8.4 ± 7.2	8.1 ± 7.2

[a] Calculated from radon time series assuming that radon activities in the groundwater end member is 235 dpm L^{-1} (the weighted average of radon discharging to the Bay, Weinstein *et al.*, 2007).

[b] March average was calculated from the results of two meters that worked for just a few (2–5) hours.

[c] May averages were calculated for the last two days (28–30 May), when discharge was more steady.

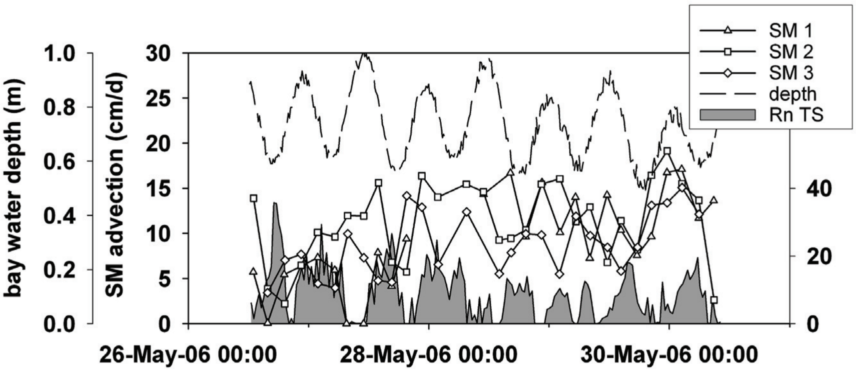

Fig. 2 Seep meter discharge rates measured in May 2006, compared with advection rates estimated by radon time series (Weinstein *et al*., 2007).

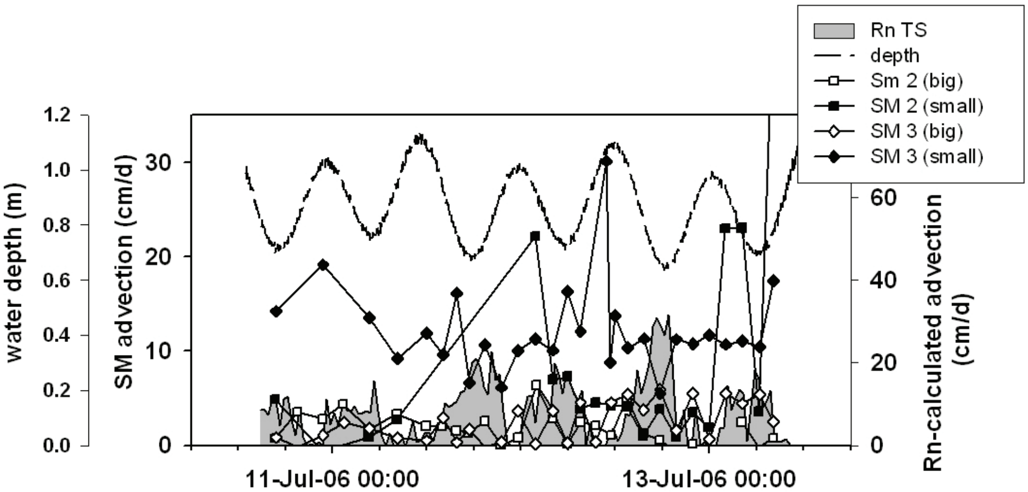

Fig. 3 Seep meter discharge rates (two types of meters, see text) measured in July 2006, compared with advection rates estimated by radon time series (Weinstein *et al.*, 2007).

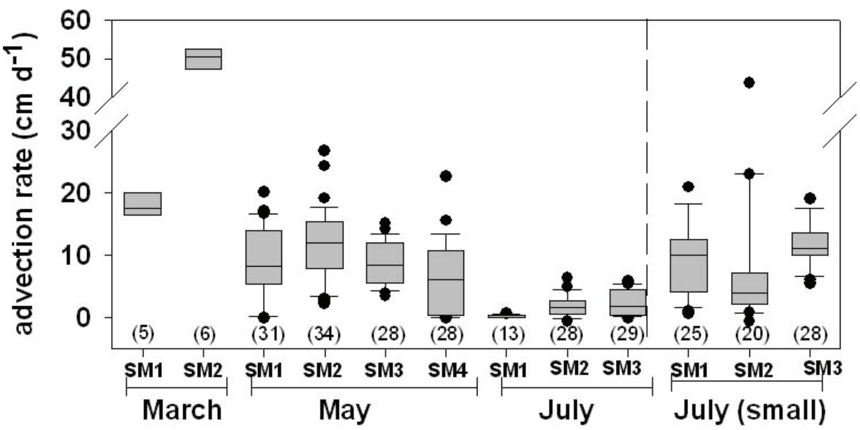

Fig. 4 Box plot of discharge rates measured by the seep meters. July (small) refers to the small SMs (see text). Each box defines the interquartile range; the line inside is the median; the bars are for the 90th and 10th percentiles and the dots for outliers. In parantheses are the numbers of measurements.

Table 2 Average advection rates and discharge measured in July by the two meter types (plas = plastic SM).

	SM1 plas	SM1 small	SM2 plas	SM2 small	SM3 plas	SM3 small
Advection (cm d^{-1})	0.2 ± 0.3	9.7 ± 6.8	1.8 ± 1.7	8.3 ± 11.1	2.4 ± 2.1	12.1 ± 4.7
Discharge (ml m^{-1})	0.8 ± 0.9	19.1 ± 13.3	6.4 ± 5.8	7.2 ± 9.7	8.5 ± 7.2	23.8 ± 9.3

In May, the close-to-shore meters (SM1 and SM2, 15–25 m from the low-tide line) showed the highest rates (averages of 12.6 and 12.1 cm d^{-1}, respectively, compared with 6.8 and 8.8 cm d^{-1} in SM3 and SM4, at 50 and 60 m from shore, respectively). In July, the trend changed and the highest rates were measured in the offshore SM3 site (2.4, compared with 0.2 and 1.8 cm d^{-1} in SM1 and SM2, respectively, Table 2 and Fig. 4).

Advection rates measured in July by the small SMs were significantly higher than those measured simultaneously by the plastic SMs (average rates of 8.3–12.1 cm d^{-1}, Table 2) but very similar to those measured in May by the plastic SMs in the same sites (all-meter average of 10.0 and 10.4 cm d^{-1}, respectively, Fig. 4). A key observation is that even the volumetric discharge was higher through the small SMs than through the plastic meters (by a factor of 2–3 in SM1 and SM3, Table 2), despite the significantly larger area covered by the latter. Advection rate variability was very high, especially in the close-to-shore sites (1–31 and 1–44 cm d^{-1} in SM1 and SM2, respectively, and 6–30 cm d^{-1} in SM3). As in the plastic SMs, the highest rates were measured in the furthest-from-shore meter, SM3 (Table 2).

Rates measured by the plastic SMs showed a tidal pattern during the last two days of the May campaign, which, at least in SM1 and SM2, seemed to correlate positively with Bay water level (Fig. 2). Tidal or any other periodic pattern was not observed in July (Fig. 3).

Salinity was measured in water discharging from the meters after being flushed by advecting water (not less than two days after deployment). Due to the low rates observed in the plastic SMs, salinities in July were measured just in the small SMs. Salinities in the seep meters ranged between 15 and 30. The lowest salinity was observed in SM2, and it increased slightly from March to July (15.2–18.9). However, in July, the lowest average salinity was observed in the furthest-from-shore SM3 (average of 23.4, compared with 24.8 in SM2), coincident with the highest-observed discharge rates during this period (Table 2 and Fig. 4). Water in the closest-to-shore SM1 was the most saline in July (average of 28.3). Unfortunately, due to the large size of the plastic SMs, we do not have a similar follow-up on salinities during the May campaign. Salinities do not show a tidal pattern, but in SM1 and SM3 they do show a general pattern of negative correlation with discharge rates (Fig. 5). In SM2, the correlation is less clear due to a group of samples with low salinities at low discharge rates (circled in Fig. 5).

DISCUSSION

Direct measurements of discharge by seep meters and estimates based on ^{222}Rn time series (Burnett & Dulaiova, 2003) are both documenting total SGD (fresh + recycled

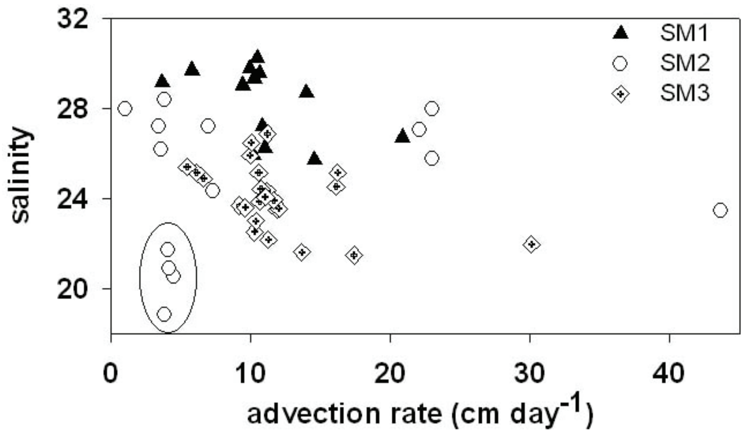

Fig. 5 Salinity *vs* discharge rates measured by the small SMs in July.

seawater, e.g. Mulligan & Charette, 2006). However, unlike the radon mass balance, which yields information on a relatively large area, the seep meters give very local information, and thus often show a patchy pattern with high variability from meter to meter. Nevertheless, often there is a close agreement between the average of meter results and radon mass balance calculations (e.g. Lambert & Burnett, 2003; Mulligan & Charette, 2006), and even if the two methodologies do not quantitatively agree, they tend to show similar patterns (e.g. negative correlation with sea level, Burnett & Dulaiova, 2006; Dulaiova *et al.*, 2006; Taniguchi *et al.*, 2006a). This is not the case in Dor Bay. While calculations based on radon time series found remarkably constant advection rates from the rainy into the dry season (averages of 7.7–8.4 cm d^{-1} in March to July 2006, Table 1 and Figs 2–3; Swarzenski *et al.*, 2006; Burnett *et al.*, 2007; Weinstein *et al.*, 2007), the seep meter data of the plastic SM defines a strong trend of decreasing rates from March to July 2006 (Fig. 4). In March, average rates measured by the meters (though a very small data set) were 2–6 times the average rates calculated from the radon time series, while in July the plastic SM average rates were just 20% of the rate calculated via radon. In May, the two methods were in a good agreement (10.4 and 8.4 cm d^{-1}, Table 1). This suggests that the seep meters and the Rn in Dor documented partly decoupled components of SGD. The positive correlation of seep meter discharge rates with bay water level in May and the absence of tidal patterns in July (in both types of meters), as opposed to the usually very clear negative correlation shown by Rn-calculated rates (e.g. Figs 2–3), also suggest that the two data sets did not document the same discharge process. We note that the accuracy of seep meter measurements has been questioned by several authors (e.g. Shinn *et al.*, 2002). However, erroneous measurements cannot explain the overall pattern of decreasing discharge from March to May. Thus, we prefer to seek a hydrological mechanism.

The radon measurements were taken in the Kurkar area of the northern part of the bay (Fig. 1), while all seep meters were deployed on sand-covered bay bottom. Thus, it could be argued that, while discharge was uniform in the Kurkar areas, it was decreasing in the sandy areas during the dry season (May–July). However, the observation of high discharge rates in all three small SMs placed adjacent to the plastic ones in July implies that discharge did occur in the sand-covered areas, and for some reason was not documented by the larger plastic SMs. Moreover, high radon activities were found in July in all three SMs (115–237 dpm/L, compared to 110–220 dpm/L in March and May; Weinstein *et al*., 2007). Since high radon water is supplied from the underlying Kurkar (Weinstein *et al*., 2007) and since decline of discharge would result in abrupt decrease in radon activity (by dilution and decay), these high activities clearly imply that sand bottom discharge rates in July were similar to those operating in previous months. We suggest that the observations from Dor Bay could be explained by the co-operation of discharge and recharge in the Bay, which is discussed below.

Weinstein *et al*. (2007) showed that radon activities and salinity of the water discharging in the seep meters sit on a mixing line between radon-rich Kurkar groundwater and radon-poor seawater. Weinstein *et al*. suggested that the radon is mainly supplied to the bay by discharge of fresh groundwater from the Kurkar, which, when it discharges through a sandy bay bottom, mixes to various proportions with recycled seawater. Based on this, as well as on hydrological measurements and on multi-electrode resistivity images of onshore and submarine sediments (Swarzenski *et al*., 2006), Weinstein *et al*. (2007) further suggested that the patterns of discharge and seawater recycling in Dor are strongly dependent on the local hydrogeology. While seawater recycling is a major process in the shallow superficial sands, it hardly occurs in the Kurkar due to its relatively high hydraulic heads.

Following the above, it is suggested that the disagreement between Rn-calculated rates and measurement by seep meters are related to the discharge–recharge interplay. We suggest that the abrupt decrease in rates measured by the plastic SMs in July was mainly caused by increased seawater recharge in the bay. While any recharge of seawater into the sediment in the deployment site results in a lower discharge rate measured by the meter, the effect on the Rn inventory (and thus on the calculated advection rate) is negligible, since the recharging bay water is relatively radon-poor. The relatively similar minimum salinities measured in all three campaigns (in SM2, 15–19) and the fact that most salinity measurements were lower than 25 imply that the proportions of recycled seawater in the discharging water did not change much. What could change was the location of seawater recharge, namely: while in May, recharge occurred further away from shore and discharge was the main process in the bay and in seep meters deployment sites, in July the recycling was more local and recharge was more frequent in the deployment sites. This could possibly happen due to a landward shift of the freshwater–saline groundwater interface and its intersection with bay floor (e.g. Michael *et al*., 2005), a result of inland decreasing hydraulic heads in the dry period and of the relatively high sea levels in July (the average level was 12.2 cm higher than in May; IOLR data from the offshore Hadera station).

We note that the seawater recycling we envisage is a shallow process, which at least during March was relevant just to the sand unit (Swarzenski *et al*., 2006), and which operates on a local, high spatial and temporal resolution. This kind of recycling is probably induced by wave setup, which could be enhanced by the very irregular bathymetry of the Dor Bay. This could also be the reason for the large difference in advection rates measured by the two types of meters in July (Table 2 and Fig. 4). The plastic SMs, with relatively large bottom area (approx. 5000 cm^2), possibly documented both recharge and discharge, while the small meters mainly focused on discharge spots.

The rough positive correlation with bay water level in May (Fig. 2), unlike the negative correlation shown by the Rn estimates, could also be the result of increased seawater recycling in the bay during high stands of the sea, which on one hand increased the saline discharge, but on the other hand further diluted the radon in the discharging freshwater. In July, a tidal pattern is not observed, probably because both recharge and discharge occur in the vicinity of the deployment sites. Thus, the possible signal of increased saline discharge during high tide is counterbalanced by an increase in recharge. Unfortunately, we do not have salinity time series from May to support this hypothesis.

The interpretation of low advection rates as actually higher recharge events also explains the negative correlation with salinity observed in the small SMs in July (mainly in SM1 and SM3, Fig. 5). The increased volume of seawater in the sediment due to higher recharge (= low advection rates) caused an increase in salinity, and *vice versa* during times of low recharge (= high advection). The lowest salinities (on average) and highest rates were measured in July in the offshore meter SM3, while the highest salinities were documented in SM1. A similar pattern of lower salinity of SGD in offshore sites was shown by Taniguchi *et al*. (2006b) for the Yatsushiro Sea, Japan. In the Dor Bay, this probably means that recharge was higher at the close-to-shore northeastern corner of the Bay than in its central part (see Fig. 1), which could be the result of stronger wave action close to shore. This is also reflected by the permanent occurrence of saline water (17–25) at the water table in the nearby onshore sands up to at least 10 m from high tide coastline (Weinstein *et al*., 2007).

The very high discharge rates measured in SM2 in March 2006 (50 cm d^{-1}) were measured two days after a strong winter storm. This storm introduced large volumes of seawater into the onshore sand (Burnett *et al*., 2007), which could be the source of the high discharge. However, salinity in discharging water was kept low (15) and radon activity was relatively high (110–190 dpm L^{-1}), just slightly lower than the activities measured in May (170–219 dpm L^{-1}, Weinstein *et al*., 2007), which cast doubt on the feasibility of this scenario. The discharge/recharge regime during winter storms should be studied further.

CONCLUSIONS

We suggest that the observed decrease in discharge rates measured by seep meters in Dor Bay could be caused by an increase in local, shallow seawater recharge in the bay. This process was not evident in radon time series due to the low radon in the recharging water and was apparently “ignored” by small seep meters, which showed high discharge rates. Increased recharge could also explain the positive correlation of SGD with sea level. This suggestion should be further studied by automated meters, preferably with small bottom area.

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