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# Radon-222 budget in Catalina Harbor, California: 2. Flow dynamics and residence time in a tidal beach

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*Abstract*

We measured the flux of water through a beach at the head of Catalina Harbor, California, by monitoring the water table in a transect of wells perpendicular to the shoreline. During a 24-h period, the volume of sediments filled and drained, the tidal wedge, was 7.4 $m^3$ (m shoreline)$^{-1}$, and the flux of water pumped across the beach face was 1.0 ± 0.3 $m^3$ $d^{-1}$ (m shoreline)$^{-1}$. $^{222}Rn$ concentrations measured in four wells were used to calculate the minimum age of water in the beach. Radon samples collected below the tidal wedge were not in equilibrium with the production rate, suggesting vertical mixing across the base of the tidal wedge. The age of water ranged from up to 8.0 d landward of the high water mark to less than 2.0 d in the littoral zone. This latter age agreed with an independent estimate of 1.7 ± 0.5 d on the basis of a mass balance for radon at the head of the harbor. However, a mass balance for water in the tidal wedge was significantly greater, 3.0 ± 0.5 d. The difference was most likely due to evasion of radon from wet, unsaturated sediments. Water draining out of the beach was a mixture of water that infiltrated the beach on the previous high tide and older water from either below or the back of the tidal wedge.

The hydraulic gradient between sea level and the beach water table will fluctuate throughout a tidal cycle. During high water, sea level may be higher than the beach water table, driving surf-zone water into the beach. Conversely, during low water, sea level may be lower than the beach water table, and water in the beach aquifer will flow into the surf zone. This "tidal pumping" fills and drains a wedge of sediments during each tidal cycle, the tidal wedge. Tidal pumping will carry contaminants and nutrients, washed into the surf zone from rivers, marshes, storm drains, or offshore, through the beach. Organisms that live in this interstitial environment take advantage of tidal pumping to supply organic matter and oxygen (Jiao and Li 2004) and remove wastes, creating vertical and horizontal gradients of bioactive solutes (McLachlan 1989; McLachlan and Dorvlo 2005). Water draining out of the beach can be enriched in nutrients from the remineralization of organic matter that occurred within the beach (Hays and Ullman 2007).

To predict the location of solute concentration gradients requires understanding the dynamics of flow within the beach. Mathematical models to predict water table fluctuations and circulation in the beach have been developed and generally assume horizontal flow to satisfy the Boussinesq equation (Nielsen 1990; Raubenheimer et al. 1999; Li and Jiao 2003). This limits the volume of sediments affected by tidal pumping to those filled and drained during a tidal cycle. However, modeling studies have shown evidence for the downward flow of water out of the tidal wedge (Boufadel et al. 2006) and the upconing of water at the shoreline (Raubenheimer et al. 1999; Boufadel 2000). Upconing represents water draining out of the beach that was not immediately within the tidal wedge and necessitates more complicated flow paths by adding a vertical component. Although the hydraulic head may not be affected by small vertical flows, advective as well as diffusive exchange with water below the tidal wedge may significantly affect the distribution of solutes.

The residence time of water provides information on the bulk flow of water in the beach. Previous residence time estimates calculated on the basis of the wave-driven flux of water into the beach neglected tidal pumping (McLachlan 1982; McLachlan 1989; McLachlan et al. 1985). This is a fair assumption at beaches with a steep slope and small tidal range, where the flux of water driven through the beach by wave pumping is significantly greater than the flux generated by tidal pumping. At a tidal beach with little wave activity, this method predicts very long residence times of water in the beach (McLachlan 1989). However, the residence time of water in beaches with little wave activity may instead be controlled by the tidally induced changes in hydraulic gradient between the shoreline and the beach water table.

In this paper, new limits on the flow of water in a beach are identified on the basis of the naturally occurring radioactive noble gas, $^{222}Rn$ (radon). Radon has a mean life of 5.5 d and is produced by the decay of $^{226}Ra$, primarily found in the sediments. As a noble gas, radon behaves conservatively. As low-radon coastal water flows into the beach, radon begins to accumulate in pore waters because of production from $^{226}Ra$ decay. The longer water

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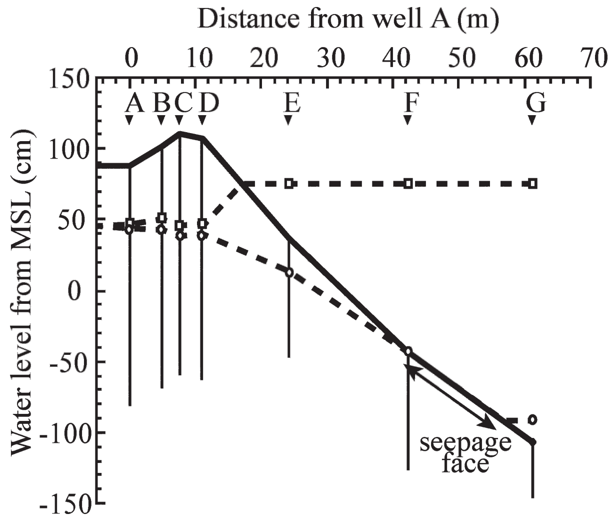


Fig. 1. Cross-section of Catalina Harbor beach (vertical exaggeration = 20 : 1). Bold line is the beach surface. Vertical lines are wells, demarcated by their letter across the top. Maximum and minimum water table heights in each well are shown. Interpolation between water table extremes is shown with a dotted line, which outlines the tidal wedge. The minor fluctuations between wells are due to the uncertainty of ±2 cm between the well height and the datum. The distance from well A to where the water table fluctuations are negligible is assumed to be 15 m.

remains in the beach, the more radon will accumulate in this water mass. The radon concentration and distribution in beach pore water may therefore provide information on the flow path and residence time of water in the beach.

We studied the beach at the head of Catalina Harbor, California, during a 24-h period, 19–20 July 2000. During an earlier study at Catalina Harbor, tidal pumping was determined to supply 38% of the total radon input (Colbert et al. 2008). The following study was conducted to determine if the tidal pumping radon flux determined via mass balances was a reasonable value. First, the volume of the tidal wedge and the flux of water through the beach were measured. Then, the distribution of radon in the interstitial waters of the tidal wedge was measured, and on the basis of the ingrowth of radon, an age was calculated for each sample. Finally, three different methods (models relying on physical parameters, age of water draining out of the tidal wedge, and the tidal pumping flux mass balance) to compute the residence time of water in the tidal wedge were compared.

*Study site*—Research was conducted at Catalina Harbor, Santa Catalina Island, California, about 35 km southwest of Los Angeles (see Colbert et al. 2008, fig. 1). In the harbor, there are moorings for about 100 boats and three fish pens where sea bass are raised to stock West Coast fisheries. At the head of the harbor, the bathymetry shoals to a broad, shallow (<2 m) region that is surrounded by a sandy beach and a gentle plain. At the head of Catalina Harbor is a low-energy, fine-grained sandy beach. Below the low-water mark, the sediments become more silty. During this study, waves at the beach reached a maximum height of about 5 cm in the mid-afternoon, when the strongest winds blew. This beach provides a unique environment for studying tidal pumping because the importance of wave action is expected to be negligible when compared to the tidal range of 167 cm. This study was conducted during typical summer conditions, with mild temperatures buffered by the cool seawater. Each winter, about 30 cm of rain falls, and the summer remains essentially dry. During these dry months, no river discharges into the harbor. Behind the beach and at a lower elevation than the berm was a dry playa, providing evidence of negligible surface and limited fresh groundwater flow.

## Methods

*Water table measurements*—Borehole wells were constructed of 2-m lengths of 2.5-cm outer diameter steel tubing, machined with 1-cm holes offset by 90° at a 1-cm interval that allowed for pressure equilibration and infiltration of ambient water. Wells were screened throughout the saturated zone. Nylon mesh screen wrapped around each well prevented sediments from entering. A pointed nose cone helped to drive the well into the sediments. Seven wells were installed perpendicular to the shoreline between the lower low-water line and 17 m behind the higher high-water line (Fig. 1). A hand-held sight level was used to relate each well to the datum, designated as the top of well D, with an uncertainty of 2 cm between wells. Any settling of the wells was assumed to be negligible.

Water table measurements began with the lower low water on 19 July 2000, and were collected hourly for 24 h. The distance between the top of the well and the water table was measured with a graduated steel rod with an open circuit at the end, which was closed when the wires touched the water, illuminating a light bulb. The uncertainty of the water table measurements is 0.25 cm.

*Radon analysis*—Well radon samples were collected using a syringe. First, 80 mL of water was flushed out of the well, then a 120-mL sample was collected from 10 cm below the water table. The sample was then transferred to a 100-mL glass ampoule, with minimal contact with air, for transport back to the laboratory. The radon concentration was measured using a rapid radon extraction system (Berelson et al. 1987). The stripping efficiency was estimated to be 95% on the basis of previous work with similar samples. Radon adsorption in the sediments is neglected because of the low organic content of these beach sands (e.g., Wong et al. 1992). Radon concentrations were calculated after accounting for decay that occurred between sample collection and analysis.

*Radon emanation analysis*—Surface sediments were collected at each well except well A. To measure the radon emanation rate ($E$; disintegrations per minute [dpm] $g^{-1}$), a slurry was made from a split of each sample, flushed with helium to remove initial radon, sealed, and incubated for at least 2 weeks (Hammond and Fuller 1979; Key et al. 1979). Then, radon was stripped out of the sample and analyzed (Mathieu et al. 1988). For each sample, emanation measurements were repeated until the SD was less than 5%. Any increase in emanation due to porosity increase in the slurry

Table 1. Well location and water table statistical data for each well. Lateral position is relative to well A. Beach surface and water table measurements are relative to the mean of the tidal measurements at well G. Water table measurements have a precision of ±0.25 cm. Absolute elevations have an uncertainty of ±2 cm, limited by the precision of determining the relative station elevation. Salinity measurements were normalized to seawater (well G).

| | Well A | Well B | Well C | Well D | Well E | Well F | Well G |
|---|---|---|---|---|---|---|---|
| Lateral position ($x$), m | 32.42 | 27.39 | 24.68 | 21.18 | 8.18 | −9.9 | −28.85 |
| Beach surface ($z$), cm | 88 | 101 | 110 | 107 | 36 | −44 | −107 |
| Water table range, cm | 3.5 | 6 | 8.5 | 14.5 | — | — | 167 |
| Water table ht. avg., cm | 45.2 | 46.4 | 43.2 | 45.7 | 30.3 | 5.4 | 0.0 |
| Normalized avg. salinity | 1.15 | 1.12 | 1.11 | 1.02 | 1.16 | 1.02 | 1.00 |

(Hammond and Fuller 1979) was assumed to be negligible for these sandy sediments. The radon production rate ($P$; dpm $mL^{-1}$) in the sediments per unit volume of pore water is related to the emanation rate: $P = (1 - \varphi)\rho E/\varphi$, where $\varphi$ is the sediment porosity and $\rho$ is the sediment density, assumed to be 2.6 $cm^3$ $g^{-1}$ for these arkose sands. The porosity of beach sand collected at each well was measured by drying a split of saturated sand and assessing the volume of water lost. The average porosity was 0.40 ± 0.05.

## Results

*Water table observations*—Well locations and water table details are presented in Table 1, and the hydrographs from representative wells are presented in Fig. 2. Well G was submerged throughout the experiment, which permitted the local tidal height to be measured. Tides were mixed, with the higher high water preceding the lower low water, and had a range of 167 cm. The actual tidal range was probably slightly greater because the tidal extremes occurred between samplings. The mean of the measurements at well G was assumed to be local mean sea level (MSL) and all heights were referenced to this datum. Water table fluctuations were observed in all the wells, and the amplitude decreased with distance inland. Changes in head were smooth in each well and consistent between wells, implying that the beach is homogeneous and isotropic (Emery and Foster 1948).

During the lower low water, sea level and the water table became decoupled, producing a seepage face. This is evident in the well F hydrograph where the tide continues to drop, but the water table remained fixed (Fig. 2B). The water table at the top of the seepage face was observed as the boundary between dull sand and glistening sand, the result of a thin film of water at the surface (Riedl 1971). During the lower low water, this boundary remained less than 2 m inland from well F. The formation of a seepage face is generally attributed to a drop in sea level that occurs faster than the interstitial water can drain (Turner 1993).

The water table height at well A was 45 cm above MSL, significantly higher than even the lower high-water maximum. The elevated inland water table was most likely not caused by fresh groundwater flow. Salinity measurements were made in all of the wells and generally increased with distance inland (Table 1). Evaporation of seawater most likely accounts for these elevated salinities, since the water table was close to the beach surface. The high-water table at well A was the result of the rapid filling of the beach during the flood tide and slower draining during the ebb tide due to increasing flow paths (Emery and Foster 1948; Isaacs and Bascom 1949; Lanyon et al. 1982). This also produces water table fluctuations that were asymmetric, increasing quickly and decreasing slowly, which can be seen in Fig. 2. During timescales on the order of a tidal cycle, the inland water table is essentially at a fixed elevation above MSL, but over longer periods (i.e., lunar

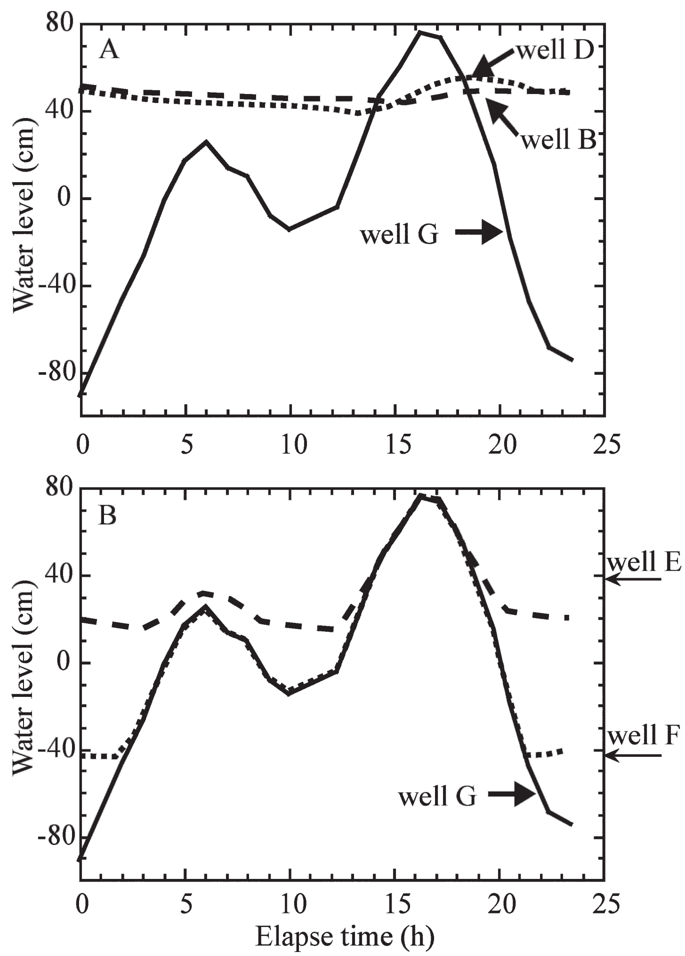


Fig. 2. Well hydrographs compared to the tide. All water heights are relative to mean sea level, as defined in the text. (A) Hydrographs for well B (dotted line), well D (dashed line), and the local tide (well G; solid line). (B) Hydrographs for well E (dashed line), well F (dotted line), and the local tide (well G; solid line). Land surface for well E and well F is marked along the $y$-axis.

Table 2. Radon emanation rate and calculated radon production rate at each site. Average porosity of 0.40 ± 0.05 was used to calculate the radon production rate. Radon emanation rate uncertainty is based on counting statistics; production rate uncertainty is calculated by the propogation of errors.

| Sta. ID | Emanation rate ($E$) (dpm g$^{-1}$) | Rn production rate ($P$) (dpm L$^{-1}$) |
|---|---|---|
| Well B | 0.056±0.002 | 210±30 |
| Well C | 0.046±0.004 | 170±30 |
| Well D | 0.049±0.001 | 190±30 |
| Well E | 0.059±0.003 | 220±40 |
| Well F | 0.060±0.003 | 220±40 |
| Well G | 0.108±0.003 | 420±60 |
| Average of wells B–F | | 200±30 |

cycles and longer), the inland water table may fluctuate (Raubenheimer et al. 1999).

*Radon distribution in the tidal wedge*—The radon emanation and production rates were similar among all of the wells, except for well G (Table 2). Higher emanation rates at well G were undoubtedly due to the increased fraction of silts with distance off shore. The sediment composition at the other wells is believed to be representative of conditions within the beach, so well G was not included in the average radon production rate used in the following discussion. Well-water radon samples, collected near the water table, were all less than the equilibrium concentration and generally increased with distance inland (Table 3).

## Discussion

*Tidal wedge volume*—The tidal wedge is the volume of sediments filled and drained during one tidal cycle and is defined by taking the absolute maximum and minimum water table elevations and linearly interpolating between the wells (Fig. 1). The tidal influence on the water table decreased exponentially from well D to well A. We define the landward end of the tidal wedge 15 m inland from well A, where the tidal fluctuations are predicted to be less than 0.5 cm. Integrating the area, the tidal wedge volume was 7.4 m$^3$ (m shoreline)$^{-1}$. Assuming a constant porosity of 0.40 ± 0.05 throughout the beach, the tidal wedge can hold 3.0 ± 0.4 m$^3$ (m shoreline)$^{-1}$ of water. Most of the tidal wedge volume (86%) was seaward of the beach berm.

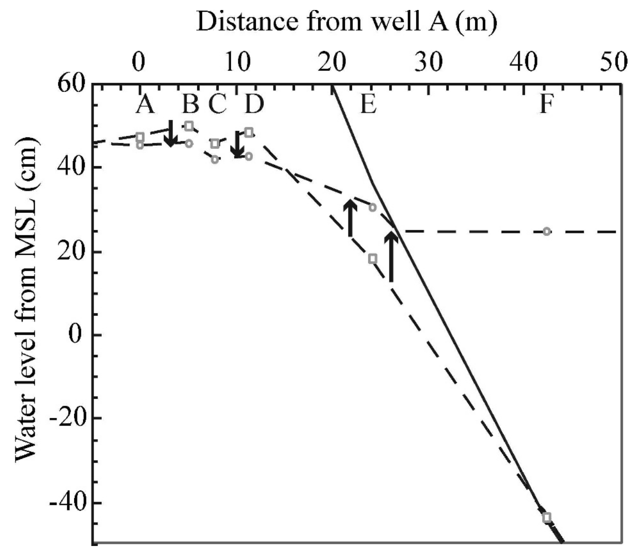


Fig. 3. Change in water table height between lower low water and lower high water. Arrows indicate direction of water table movement.

*Water fluxes*—In general, water infiltrates the beach during the flood tide, and drains out of the beach during the ebb tide. But because of the propagation of the tidal pulse through the tidal wedge, there was no specific time when the tidal wedge was completely full or empty. For example, during the flood to lower high water, the water table near the beach face rose, while the inland water table fell (Fig. 3). The water table rose in the seaward portion of the tidal wedge because seawater infiltrates the beach and water was redistributed from the back of the tidal wedge. Similarly, during the ebb tide, the water table dropped in the seaward portion of the tidal wedge, because of both water flowing out of the beach and water flowing inland.

The volume of water filled or drained during each flood and ebb tide was computed by taking the difference in the water table height at each tidal extreme and multiplying by the effective porosity, the volume of water that can freely drain from these sands, determined to be 0.15 ± 0.05 on the basis of our measurements from similar sands (Table 4). In general, the seaward and landward portions of the tidal wedge were out of phase, with one filling while the other was draining. By dividing the tidal wedge into these two sections, we can account for the redistribution of water in the tidal wedge. The net change in volume, computed by summing the seaward and landward changes in volume, reflects a flux of water across the beach face. The water flux was computed by dividing by the time between the tidal extremes.

Table 3. Pore-water radon measurements. Uncertainties are 1 SD on the basis of counting statistics. The time water is in contact with the sand, calculated using Eq. 2, is presented as an "age range" to account for the uncertainty in the interstitial water radon activity and the radon production rate. These "ages" are lower limits because escape to the atmosphere is assumed to be negligible. Start time is 19 July 2000 at 06:39 h (Pacific daylight time).

| Sta. ID | Elapsed time (h) | Radon conc. (dpm L$^{-1}$) | Age range (d) |
|---|---|---|---|
| Well B | 7.8 | 107±3 | 3.3–5.7 |
| Well B | 21.0 | 124±3 | 4.1–7.6 |
| Well B | 33.0 | 114±4 | 3.6–6.5 |
| Well D | 7.5 | 121±2 | 4.0–7.1 |
| Well D | 20.4 | 127±3 | 4.3–8.0 |
| Well D | 23.2 | 127±3 | 4.3–8.0 |
| Well D | 32.8 | 123±5 | 4.0–7.7 |
| Well E | 6.5 | 30±1 | 0.7–1.1 |
| Well F | 22.0 | 37±2 | 0.9–1.4 |
| Well F | 23.0 | 50±2 | 1.3–2.0 |

Table 4. Change in water volume (DV) within the tidal wedge and the calculated water flux, during flood and ebb tides. Volumes are given in $m^3$ (m shoreline)$^{-1}$, and fluxes in $m^3$ $h^{-1}$ (m shoreline)$^{-1}$. Increase in volume during the time period are positive values; negative values represent decreases in volume. The initial flood to lower high water was shortened by 2 h as water continued to drain out of the tidal wedge through the exposed seepage face. "Total DV" is the sum of the changes in the landward and seaward sections of the tidal wedge.

| Elapse time (h) | Time (h) | Landward section DV | Seaward section DV | Total DV | Net water flux |
|---|---|---|---|---|---|
| Flood tides | | | | | |
| 2:13 h–6:01 h | 3.8 | −0.103±0.034 | 0.32±0.11 | 0.22±0.11 | 0.06±0.03 |
| 9:59 h–16:17 h | 6.3 | −0.008±0.003 | 0.80±0.27 | 0.79±0.27 | 0.13±0.04 |
| Net | 10.1 | −0.111±0.034 | 1.1±0.3 | 1.0±0.3 | 0.10±0.03* |
| Ebb tides | | | | | |
| 6:01 h–9:59 h | 4.0 | 0.00±0.00 | −0.37±0.12 | −0.37±0.12 | −0.09±0.03 |
| 16:17 h–23:28 h | 7.2 | 0.058±0.019 | −0.73±0.24 | −0.67±0.24 | −0.09±0.03 |
| Net | 11.2 | 0.058±0.019 | −1.1±0.3 | −1.0±0.3 | −0.09±0.02* |

* Weighted average water flux.

After accounting for the redistribution of water in the tidal wedge, the net flux of water into the beach (0.10 ± 0.03 $m^3$ $h^{-1}$ [m shoreline]$^{-1}$) was nearly identical to the net flux out of the beach (0.09 ± 0.02 $m^3$ $h^{-1}$ [m shoreline]$^{-1}$). The small discrepancy was most likely due an underestimate of the net flux out of the beach because sampling did not capture the final ebb to lower low water. Agreement between these two water fluxes suggests that there was little long-term storage of water in the beach. In general, less time was spent filling the tidal wedge. The greatest flux of water into the beach occurred during the flood to the higher high water, when the landward hydraulic gradient was the greatest. During both ebb tides, the water fluxes out of the beach were identical. Applying Darcy's Law, this suggests that the average hydraulic gradient was the same when water was draining out of the beach.

*Tidal pumping versus tidal mixing*—Tidal mixing of harbor water was compared with the tidal pumping flux of water through the beach at the head of the harbor. Within 300 m of the head of the harbor, there is 826 m of shoreline and an average water depth of 1.3 m (box 11, Colbert et al. 2008). If the flux of water through the beach was constant along the shoreline, then it would take 80 d to filter the water at the head of the harbor. However, with a tidal range of 1.1 m, tidal exchange will replace the water at the head of the harbor about every 2 d. Thus, only a modest fraction of the harbor water is filtered through the beach before it is replaced.

*Water mass age*—During tidal pumping, water deficient in radon (relative to equilibrium with the sediments) enters the tidal wedge, and begins to acquire radon until equilibrium between the rate of production and decay is achieved. If this water is treated as a closed system, with no evasion to the atmosphere, ingrowth can be expressed as a differential equation:

$$\frac{dC}{dt} = P - \lambda C \quad (1)$$

where $C$ is the radon concentration measured in the tidal wedge water (atom $L^{-1}$), $t$ is time, $\lambda$ is the decay constant, and $P$ is assumed constant (200 dpm $L^{-1}$) from Table 2. To solve this equation, two boundary conditions were needed. First, the activity concentration of water flowing into the beach was defined. A radon survey at the head of Catalina Harbor found 1.8 dpm $L^{-1}$ (Colbert et al. 2008). Since this is <1% of the equilibrium pore water concentration, we can simplify $\lambda C(0) = 0$. Second, after a sufficient time (about a month), interstitial waters will be in equilibrium with the sediments, and the activity concentration of the water is equal to the production rate: $\lambda C(\infty) = P$. The solution of Eq. 1 was arranged to calculate time on the basis of the ratio between the observed radon concentration and the equilibrium radon concentration:

$$t = -\frac{1}{\lambda}\ln\left[1 - \frac{\lambda C(t)}{P}\right] \quad (2)$$

This is a parametric age that includes the effects of any diffusive gains or losses of radon, and provides a qualitative estimate of the water residence time. This estimate is a lower limit because the loss of radon to the atmosphere is not included (*see* below). Water flowing into the beach has an initial age of 1 h, which was not subtracted from the reported ages. At wells B and D, samples collected below the tidal wedge had only been in contact with the sediments for between 3.3 and 8.0 d (Table 3). Wells E and F were sampled as the tide dropped and the shoreline was relatively close to the wells. These samples had been in contact with the sediments for between 0.7 and 2.0 d.

Using the minimum ages from the radon data and a mass balance for water in the tidal wedge, the average residence time of water in different sections of the tidal wedge was estimated. Plotted on the cross-section of the tidal wedge is the age and location of each pore-water sample (Fig. 4). At wells B and D, the average radon age was 5.2 d and varied little, despite measuring in and below the tidal wedge and sampling at times of seaward and landward hydraulic gradients between these wells. If tidal pumping only exchanged water within the tidal wedge, then radon in water below the tidal wedge should be in equilibrium with the production rate. Instead, samples collected below the tidal wedge were not in equilibrium, suggesting that tidal pumping cycled water through a

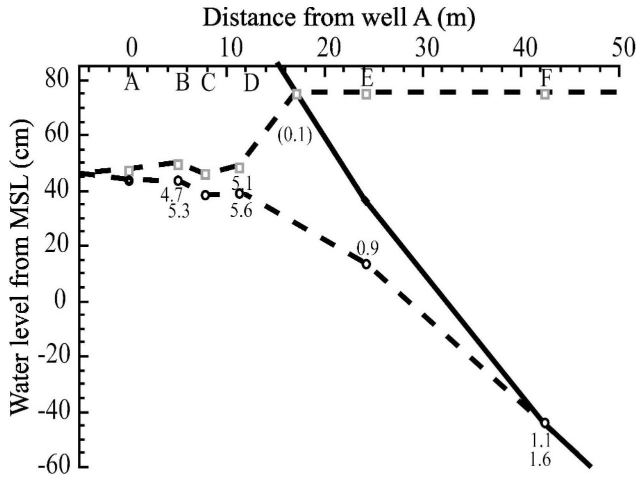


Fig. 4. Minimum ages of water (d) in the beach. Solid line is the beach face, and the dashed line is the outline of the tidal wedge. Letters at the top demarcate well locations. Location and average radon age in days of pore-water samples are shown with a number (Table 3). When multiple samples were collected at a well, the top and bottom samples are shown. The value in parentheses is the expected age on the basis of the physical transport of water.

greater volume of sediments than just the tidal wedge. Seaward of well D, the tidal wedge thickness increased up to the higher high-water mark. In the top part of the tidal wedge, we can estimate the residence time on the basis of the water table measurements. During the higher high tide, about 2 h was required to fill and drain this volume of sediment. Well E was sampled after the lower high water and had a mean age of 0.9 d. This water represents a mixture of water that infiltrated the beach on the previous higher high tide, about 0.67 d earlier, and older water from the back of the tidal wedge. Finally, the water sampled at well F was collected below the tidal wedge during the ebb to lower low water. This water represents a mixture of water that infiltrated the beach during the higher high tide, 0.25 d earlier, and older water from the back and below the tidal wedge. As different mixtures of water drain out of the tidal wedge, the radon concentration and mean age of the water will also change. For example, although only 1 h passed between the two samplings at well F, the age of the water increased by 12 h.

*Residence time estimates*—Samples collected at wells E and F represent water draining out of the tidal wedge and provide a constraint on the residence time of water within the beach, between 0.7 and 2.0 d. An independent estimate of the average radon concentration of water draining out of the beach ($C_{TP}$), and therefore its age, can be calculated. In an accompanying paper, the radon flux out of the tidal wedge, $J_{TP}$ (atoms d$^{-1}$ [m shoreline]$^{-1}$), was calculated on the basis of a radon mass balance for the head of Catalina Harbor: 5,200 ± 1,900 atoms s$^{-1}$ (m shoreline)$^{-1}$ (Colbert et al. 2008). Using the tidal pumping water flux, $Q_{TP}$, calculated above:

$$C_{TP} = \frac{J_{TP}}{Q_{TP}} \quad (3)$$

On the basis of this analysis, the average radon concentration draining out of the beach was 57 ± 20 dpm L$^{-1}$, which corresponds to an average age of 1.8 ± 0.4 d for water draining out of the tidal wedge. This estimate is similar to the radon concentration and the estimated residence time of water in the beach measured at wells E and F.

However, a third estimate on the basis of a mass balance of water in the tidal wedge predicts a greater residence time. If the exchange of water was isolated to the tidal wedge and has reached steady state, then this system can be simplified as a one-box model. The residence time of water in the tidal wedge will be the ratio of the tidal wedge water volume (3.0 ± 0.4 m$^3$ [m shoreline]$^{-1}$) to the flux of water through the tidal wedge (1.0 ± 0.1 m$^3$ day$^{-1}$ [m shoreline]$^{-1}$). This estimated residence time of water yields 3.0 ± 0.5 d. This calculation assumes that water only flushes into and out of the tidal wedge. However, the radon samples collected below the tidal wedge suggest that there is a flow of water out of the tidal wedge and into deeper sediments. Water that discharges through the seepage face must also pass through sediments below the tidal wedge. To maintain the same flux of water through a larger volume of sediments, the residence time of water must increase.

Radon serves as a chronometer for water circulating through permeable sands and indicates a residence time of about 1 d for the water in the tidal wedge. This is less than the 3 d suggested by the physical model of circulation in the tidal wedge. The radon budget may underestimate the residence time due to the evasion of radon. On the basis of a consideration of length scales for advective and diffusive transport, the ability of groundwater to degas into the overlying gas space should be negligible, even when considering the impact of dispersivity on diffusion as summarized by Fetter (1999). However, the oscillation of the water table leaves sand grains coated with significant water. When drained, only 63% of the water present actually leaves the sand, so for a total porosity of 40%, the tidal wedge volume is 60% sand, 25% water, and 15% air. It is likely that the air should equilibrate with the water, and then be lost when the tidal wedge is resaturated on the next high tide. The dimensionless Henry's Law constant (air concentration/water concentration) for radon is about 4 (Clever 1980), so about half of the radon dissolved in the water is lost to gas exchange on each tidal cycle. Consequently, the residence time for radon in the beach water should be about half that of the water.

In summary, along the shoreline at Catalina Harbor, water flowed into the beach during flood tide and drained out of the beach during the ebb tide. During the lower low water, a seepage face developed. This allowed water to continue to drain out of the beach during the beginning of the flood tide, until sea level moved above the seepage face. During a 24-h observation of the beach water table, 7.4 m$^3$ (m shoreline)$^{-1}$ of sediment were filled and drained, and the flux of water through the beach was 1.0 ± 0.3 m$^3$ day$^{-1}$ (m shoreline)$^{-1}$. At the head of Catalina Harbor, tides only pump 1.3% of the harbor water through the beach each day.

Water table and radon measurements were used to constrain the circulation in the beach. The flux of water into the beach was greatest during the flood to higher high water. Only during the higher high water was there a landward hydraulic gradient. Landward of the high-water mark, water in and below the tidal wedge had a minimum age between 3.3 and 8.0 d. Beach water not in equilibrium with the radon production rate suggests that tidal pumping circulates water through not just the tidal wedge, but also through saturated sediments below the tidal wedge.

The age of water draining out of the beach was not constant. The youngest water draining out of the beach was during the ebb from lower high water to higher low water. Sea level at lower high water was below the inland water table, so water that fills the tidal wedge during the flood to lower high water flows back seaward during the ebb tide, with little mixing with older water. During the ebb to the lower low tide, the water draining out of the beach was a mixture of older water and water that infiltrated the beach during the previous flood tide. During this ebb, the fraction of older water draining out of the beach increases with time.

Three estimates of the residence time of water were calculated. First, the age of water draining out of the tidal wedge ranged between 0.7 and 2.0 d, which should be equivalent to the residence time of water if the samples were representative. This age was consistent with an independent estimate of $1.8 \pm 0.4$ d on the basis of a mass balance for radon at the head of the harbor. These ages were less than the age predicted on the basis of the assumption that water flushes into and out of the beach on each tidal cycle. Radon likely underestimates the tidal wedge residence time because of gas exchange from water-covered sand grains when the tidal wedge is unsaturated.

During a previous study, a mass balance for radon in Catalina Harbor was developed, and two radon sources were identified: benthic inputs (molecular diffusion and bioirrigation) and in situ production (Colbert et al. 2008). However, an additional radon source was required to balance the budget. The radon flux from tidal pumping of seawater through beach sands was sufficient to balance the radon budget for harbor waters. Other mechanisms, such as fresh groundwater advection or physical pumping of water through seafloor sediments, were negligible.

This study demonstrates the potential for radon as a tracer of water circulation within beaches. With higher-resolution sampling, both spatial and temporal, further information on tidal circulation in the beach can be deduced. This information will be essential to developing budgets and understanding the beach pore-water distribution of other solutes, including surf-zone pollutants and bioactive solutes.

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