

The use of sulfur hexafluoride (SF₆) as a tracer of septic tank effluent in the Florida Keys

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Abstract

To determine the fate and movement of sewage derived contaminants and their possible interaction with surface waters in the Florida (USA) Keys, two types of experiments were conducted using SF₆ as an artificial tracer. The first type of experiment examined fluid flow from septic tanks placed in Miami Oolite on Big Pine Key, where there is a shallow freshwater lens overlying saline groundwaters. Here groundwater transport rates were constrained to be between 0.11 and 1.87 m/h, travelling in an easterly direction. The second type of experiment took place on Key Largo where there is no freshwater aquifer and the matrix of the aquifer is solely the more porous Key Largo limestone. Here we injected the tracer into a shallow well which was screened from 0.6 to 10 m. This allowed us to evaluate groundwater movement in the shallow upper portion of the aquifer, the area to which inputs by septic tanks occur. Groundwater transport rates in the Upper Keys were as great as 3.7 m/h and were controlled by the Atlantic tide. SF₆ laden groundwater plumes moved back and forth due to tidal pumping and reached nearby surface waters within 8 h. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Current methods of wastewater disposal in the Keys employ the use of 10 000 unregulated cess pits, 30 000 septic tanks, over 200 small package plants, and two municipal wastewater treatment plants in Key Colony Beach and Key West (USEPA, 1996). Effluent from the package plants and the Key Colony municipal wastewater plants is disposed of via shallow (10–30 m) injection wells. These disposal practices introduce extraordinary nutrient loads to the shallow groundwaters of the Keys. The USEPA (1996) calculates that approximately 897 kg of nitrogen and 217 kg of phosphate are placed into the

subsurface daily by these methods. Lapointe et al. (1990) have shown significant nutrient enrichment (up to 5000-fold) in groundwaters contiguous to septic tanks on Big Pine Key. In another study, Lapointe and Clark (1992) showed that phosphate and dissolved inorganic nitrogen levels were elevated in canals and some nearshore waters of the Keys. Canal waters may be particularly impacted as they were cut deep into the Key Largo limestone and are thus in direct contact with contiguous groundwaters.

The Keys separate the Atlantic Ocean which experiences semi-diurnal tides on the order of 1 m from Florida Bay. The eastern portions of Florida Bay do not experience tidal changes but can be affected by long-term wind forcing which either blows water in or out of the Bay. Diurnal differences

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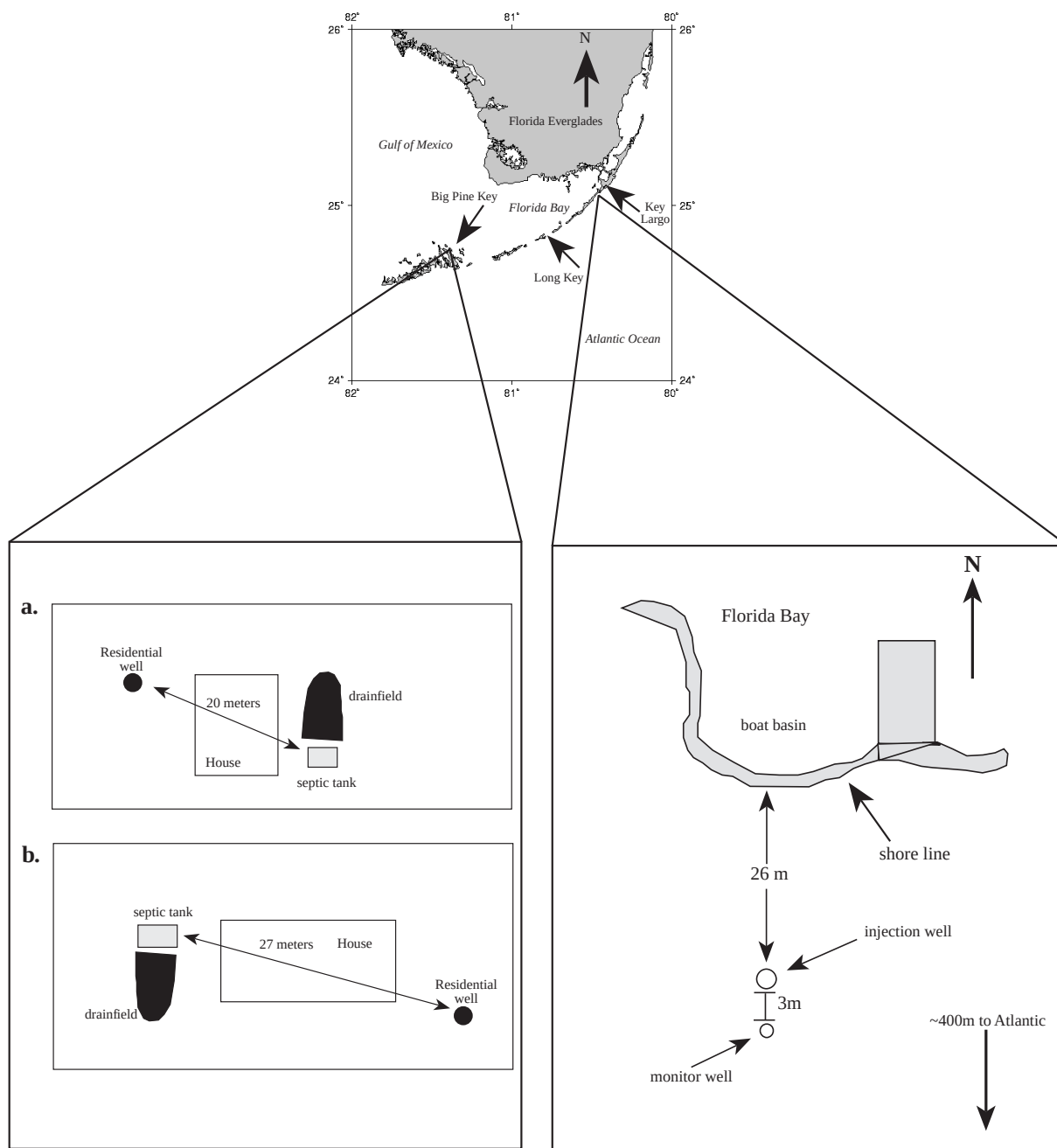


Fig. 1. Study sites on Big Pine Key (septic tanks) and Key Largo (Ranger Station). Maps of sites are not drawn to scale. North is toward the top of the page in each map.

in water levels between the two water bodies appears to be responsible for a tidally driven exchange of water into and out of the carbonate rock (Shinn et al., 1994). When the tide is high in the Atlantic, the Atlantic sea level typically stands above the Bay's forming a hydraulic gradient that is sloped toward the Bay, forcing water into the Keys, northward toward Florida Bay. With low Atlantic tide the situation reverses and water is driven southward from the Bay through limestone towards the Atlantic. Halley et al. (1995) showed that the average sea level in Florida Bay is higher than that of the Atlantic side of Keys more than 50% of the time, suggesting that net groundwater flow is toward the Atlantic.

On Key Largo, Paul et al. (1995a) introduced bacteriophages to the subsurface via a septic tank and a 2.5 cm diameter well. At 11 and 23 h, the phages were detected in adjacent canal waters and Atlantic surface waters, respectively. Calculated groundwater transport rates ranged from 0.57 to 24.2 m/h and seemed to be heavily influenced by the Atlantic tide. In another study, Paul et al. (1997) repeated the simulated injection experiment on Key Largo and obtained similar transport rates (2.5–35 m/h) which were found to correlate with the Atlantic tide. Paul et al. (1997) also conducted an experiment with a 27 m injection well on Long Key and found slower transport rates (0.12–2 m/h) with no evidence of tidal pumping. They attributed the slower flow and lack of tidal pumping at the Long Key site to differences in geology, rate and force of tidal pumping, and/or the lack of numerous boating canals cut into the limestone. Other studies in the Keys have detected the presence of fecal indicator bacteria in onshore and offshore wells as well as in canals (Shinn et al., 1994; Paul et al. (1995b)) suggesting that groundwater and surface waters in the Keys may be contaminated due to these waste disposal methods.

The objective of this study was to quantify horizontal flow rates of groundwaters and dissolved contaminants in the subsurface of the Florida Keys, and to determine their possible interaction with surface waters. Two types of experiments were conducted using sulfur hexafluoride (SF_6) as an artificial tracer. Sulfur hexafluoride is an inert, non-toxic, volatile gas that has been shown to act conservatively in a saturated media (Wilson and Mackay, 1993, 1996).

2. Area descriptions and methods

2.1. Septic tank experiments on Big Pine Key

In the first type of experiment, we examined flow from two septic tanks placed in Miami Oolite on Big Pine Key. On this island there is a shallow freshwater lens with a thickness of approximately 5–8 m (Hanson, 1980; Wightman, 1990; Vacher et al., 1992) overlying saline groundwater. The Miami Oolite is about 6 m thick and overlies the Key Largo limestone formation. In 1980, Hanson estimated that approximately 150 residences on this island obtain their tap water from individual wells that penetrate the thin underlying fresh water lens at a depth of about 2 m. There are not many records of wells installed since this time and it is believed that this number has grown over the years (Kruczynski, personal communication). These residences have their septic tanks in close proximity to these wells. Septic tanks in the Keys are typically placed less than a meter below the land surface since the tank leeching lines must be installed above the water table.

Water saturated with SF_6 was introduced into the septic tanks via toilets at two different residences on Big Pine Key. The residents then collected samples from their kitchen faucets for as long as two months to ascertain the potential of well contamination. The approximate locations of the septic tanks in relation to these residential wells are shown in Fig. 1(a) and (b). The first experiment started in December 1996 at the first site (Fig. 1(a), exp. A). In June 1997, we began two more experiments: one at the first site (exp. B) and the second at a nearby site (Fig. 1(b), exp. C). Background samples were collected from the kitchen faucet before each injection. In each case, approximately seventy liters of tap water were sparged with 99.8% pure SF_6 (Scott Specialty Gases) for 20 min and then poured down the toilet. Samples were collected from each well via a sink faucet within 20 min of injection and then once daily for a week or more. After this initial period, samples were collected at the convenience of the residents for approximately two months in the case of experiments A and C. Experiment B was only conducted for one week.

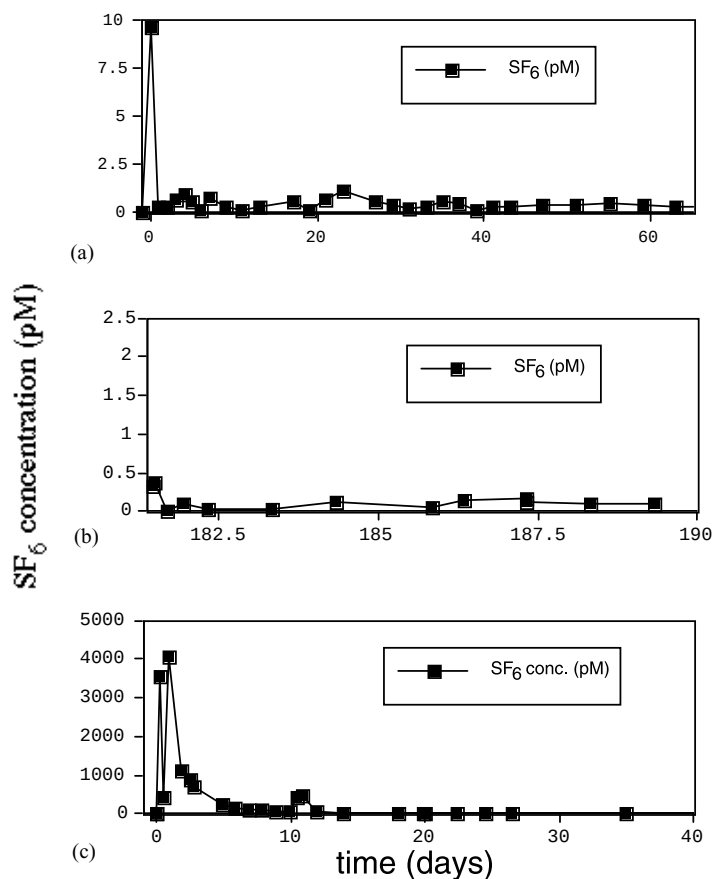


Fig. 2. SF₆ concentrations vs. time for (a) site A, December 96; (b) site A, June 97; and (c) site B, June 97. Note that the time scale for (b) is continued from (a), also note the difference in concentration scale for site B.

2.2. Shallow injection well experiments on Key Largo

The second type of experiment was conducted on Key Largo where there is no freshwater lens and the aquifer's matrix is the very porous Key Largo limestone. Here we injected the tracer into a well (diameter = 20 cm) which was screened from 0.61 to 10 m. This allowed us to evaluate groundwater movement in the shallow portion of the aquifer, the area to which inputs by septic tanks occur. Approximately 3 m to the south of the well used for injection is a monitoring well that is 5 cm in diameter with a depth of 6 m. It is screened from 1 m to the bottom. Twenty six meters to the north of the injection well lies Florida Bay (Fig. 1). The Atlantic Ocean is approximately 400 m to the south. Three experiments were conducted at this site. For the first two experi-

ments (July and August, 1996), SF₆ was bubbled directly into the injection well for 10 or 20 min during a low Atlantic tide. In the third experiment, 100 l of water was pumped from the injection well, sparged for 20 min with concentrated SF₆, then pumped back into the well at a rate of 10 l/min during high tide.

SF₆ samples at the Key Largo site were collected from the monitor well and the Bay periodically. Due to the large screened portion of the monitoring well, it was assumed to be in equilibrium with the ambient groundwater and therefore it was not purged before sampling. Tubing was inserted 2 m into the well and purged a minimum of three times the tubing volume prior to sampling. A second piece of tubing, looped at the end and weighted, was used to sample Florida Bay waters. Water was collected from just above the sediment/water interface approximately 3 m from shore.

The tubing was put into position before injection and was not moved during the course of each experiment. The water levels within the injection and monitor wells were determined from the top of the well which was then compared to the relative Atlantic tide. The tide modeling program, “Tides and Currents for Windows” (Version 2.0, Nautical Software), was used to plot the relative Atlantic tide. Observations from a nearby site on the Atlantic side of Key Largo have confirmed that this program is accurate for this location (Dillon, 1998). Water levels in Florida Bay were measured with a meter stick.

2.3. Analytical methods

Sulfur hexafluoride samples were analyzed with a Shimadzu model 8A gas chromatograph equipped with an electron capture detector. The gas chromatograph contained a stainless steel column (180 cm $\times$ 0.1 cm ID) packed with molecular sieve 5A (80/100 mesh). Column and detector temperatures were set at 90°C and 220°C, respectively. SF₆ was extracted from the samples with a head space extraction technique. A headspace of ultra-high purity nitrogen was added to a syringe or serum vial which was then shaken for 2 min to extract the SF₆ from solution into the headspace. This extraction method has been shown to strip at least 95% of the SF₆ from solution. Serum vial samples were stored on their side until analysis. Standards stored in this fashions have shown no loss of SF₆ for more than 500 days (Dillon, 1998). All samples were analyzed within two weeks of collection.

Duplicate samples were collected for approximately 20% of the samples collected. In addition duplicate injections were run on at least 20% of the samples. Standard deviations are reported for these samples in the figures and results.

Groundwater transport rates were estimated for each sampling location by dividing distance to the well or water body from the site of injection by the time of the peak concentration of the tracer at that sampling location.

3. Results and analysis

3.1. Septic tank experiments on Big Pine Key

The SF₆ concentrations of the 70 l injection

slugs used in the septic tank experiments on Big Pine Keys were $42.96 \pm 2.65 \mu\text{m}$, $199.93 \pm 2.12 \mu\text{m}$, and $210.46 \pm 4.67 \mu\text{m}$ for experiments A, B, and C; respectively. Results from the first two experiments are summarized in Fig. 2(a) and (b). There were no conclusive peaks in SF₆ concentration during these two experiments. The initial peak observed in experiment A is believed to be due to contamination during the sparging process as an unreasonably large groundwater flow rate of 80 m/h would be required for this peak to be valid. When the experiment was repeated (Fig. 2(b), exp. B) no peak was observed. The presence of trace amounts of SF₆ during both of these experiments indicates that some of the injected SF₆ slug does reach the well although it is diluted by more than eight orders of magnitude.

Experiment C showed much higher concentrations than either experiment A or B (Fig. 2(c)). Before injection, background levels at this second site were $0.48 \pm 0.09 \text{ pM}$ ($1 \text{ pM} = 10^{-12} \text{ M}$), presumably from the previous work done at the first site, which is only 2 or 3 blocks away. The first sample collected ($t = 0.18$ days) revealed a concentration of $3.5 \pm 0.07 \text{ nM}$. By 0.44 days, the concentration fell to $0.41 \pm 0.02 \text{ nM}$ then increased to $4.0 \pm 0.05 \text{ nM}$ at 0.85 days, a 5000-fold dilution of the injection concentration. After this second peak, values began to steadily decrease until day 10 when two elevated samples were observed with values of 0.41 ± 0.10 and $0.48 \pm 0.01 \text{ nM}$ (Fig. 2(c)). After this rise, values fell to $39 \pm 0.32 \text{ pM}$ and continued to fall, eventually becoming undetectable at 47 days. Values remained below detection for the remainder of the experiment which lasted for 68 days.

Transport rates were not calculated for either experiment at the first site due to the lack of a reliable peak in SF₆ concentration. The larger peak observed at 0.85 days during experiment C suggests a transport rate of 1.37 m/h (32.9 m/day). This is considerably higher than previously published flow rates of groundwater through Miami oolite and it is possible that this peak was due to contamination during the sparging process. The small peak observed at 10 days; however, corresponds to a flow rate of 0.11 m/h, very close to the flow rate of 0.15 m/h reported by Lapointe et al. (1990) on Big Pine Key.

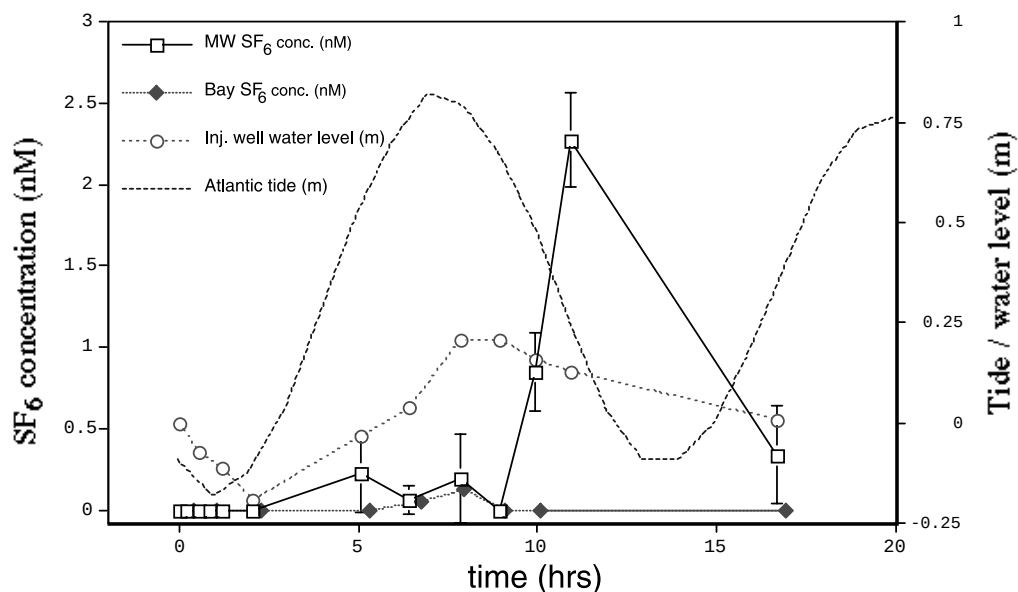


Fig. 3. SF_6 concentrations and tidal levels vs. time for July 1996 simulated septic tank experiment. MW represents the monitor well.

3.2. Shallow injection well experiments on Key Largo

The results from the July 1996 experiment on Key Largo are shown in Fig. 3. SF_6 samples from the monitor well and the Bay waters were collected for approximately 16 h after injection. The water levels plotted from the monitor well and the Atlantic tide level indicate a 1.43 h lag between their respective high values. There is also a 60% damping of the tidal amplitude as the pressure wave moves through the carbonate rock. The tidal levels in Florida Bay were not monitored during this experiment but the water level in the Bay appeared approximately constant. There are few direct inlets to the Atlantic on Key Largo. The tidal level in this region of the Bay is controlled primarily by local winds as diurnal tides are damped by the numerous mud banks which isolate the bay from the Gulf of Mexico. The highest Bay tides occur when the winds blow from the west, piling water up in the Northeast Bay. Lowest tides are typically associated with easterly winds which force water out of the Bay. There was little wind during this experiment and the water level in the Bay did not visually appear to change by more than a couple of centimeters during the entire experiment.

Sulfur hexafluoride was detected in Florida Bay, a distance of 26 m to the north of the injection well, 6.75 h after injection at a concentration of 53.3 ± 43.3 pM (Fig. 3). A peak concentration of 128.0 ± 28.5 pM corresponding with a high Atlantic tide was observed after 7.93 h, yielding a transport rate of 3.28 m/h. Recall that the tracer injection occurred on a rising Atlantic tide which should cause advection of groundwater to the north towards Florida Bay once the Atlantic's water level rises above the bay's. As the Atlantic tide began to fall, the SF_6 concentration quickly fell below detection, presumably degassing from the surface waters and/or advecting from the sampling area. SF_6 was detected in the monitor well (south of the injection well) 5 h after injection at a concentration of 0.22 ± 0.24 nM. Values fluctuated slightly for 3 h and then dropped below detection. At just under 10 h, the SF_6 concentrations began increasing again, reaching a peak concentration of 2.27 ± 0.29 nM an hour later during a falling Atlantic tide which should drive groundwater in a southerly direction, towards the Atlantic. Based on this peak in concentration of the tracer, a transport rate of 0.27 m/h was calculated from the monitor well data. This is most likely an underestimate if the SF_6 plume moved first north toward the Bay with the rising

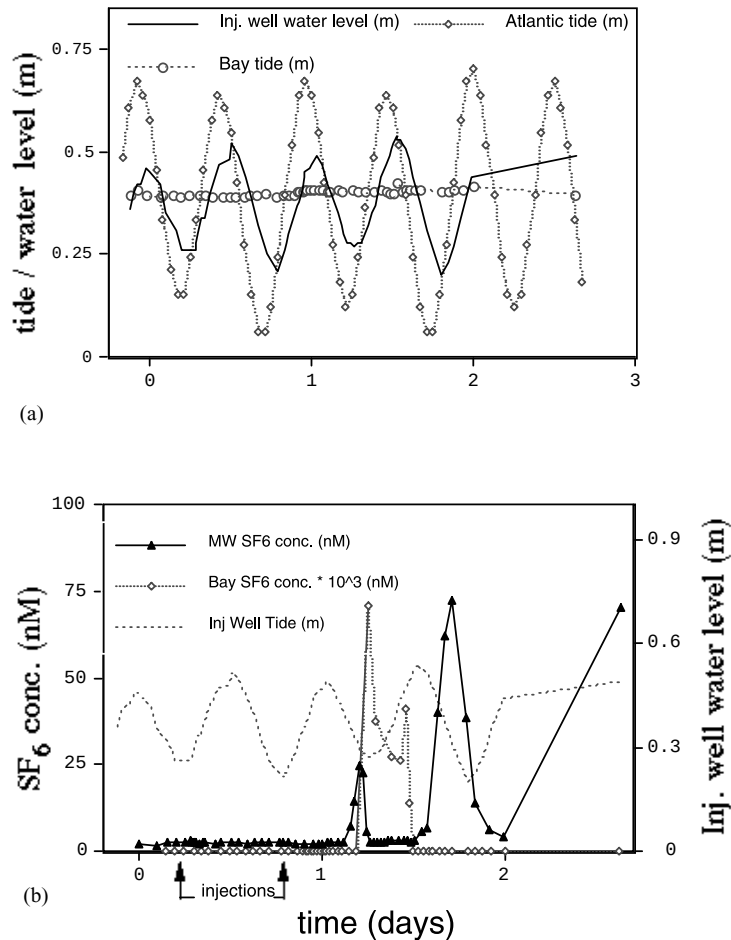


Fig. 4. (a) Tides and water levels for August 1996 simulated septic tanks experiment. (b) SF₆ concentrations plotted against time for monitor well and Florida Bay. Injection well water level shown for reference.

Atlantic tide then turned south on the falling tide before reaching the monitor well, as the data suggest.

A second experiment was conducted in August 1996 at the same location. The tidal levels for the Atlantic Ocean, the injection well and Florida Bay are plotted against time in Fig. 4(a). Due to more intense monitoring, the tidal lag between the Atlantic and the injection well noted in the previous experiment is much more evident. A lag time of 1.78 ± 0.38 h was calculated from three observed tidal cycles. A damping of $52 \pm 6\%$ of the Atlantic's tidal amplitude was also observed. The water level in Florida Bay was also monitored and did not vary more than 4.6 cm.

Due to background SF₆ levels from the previous

experiment, both wells and the Bay were monitored for 6 h before injection for SF₆ concentrations and water levels. Residual SF₆ was still present in the injection and monitor wells at concentrations of <14 nM and <3 nM, respectively and did not fluctuate much with time. The elevated value in the injection well could represent SF₆ contamination of the well casing from the previous injections as SF₆ can bind to organic materials such as PVC. No residual SF₆ was detected in the Bay. The injection well was sparged for 10 min with concentrated SF₆ during a low Atlantic tide. It was assumed that this would be sufficient to provide a large signal relative to background concentrations already present in the wells.

The SF₆ results for the August 1996 experiment are

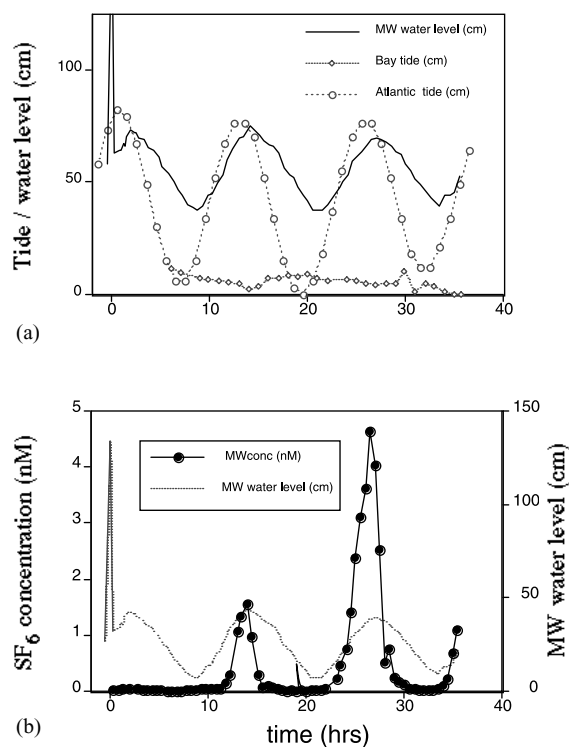


Fig. 5. Results from August 1997 experiment. (a) Tidal/water levels for Atlantic Ocean, monitor well, and Florida Bay. (b) Monitor well's SF_6 concentration plotted with monitor well water level.

shown in Fig. 4(b). After a complete tidal cycle, no change in SF_6 had been observed in either the monitor well or the Bay. This raised concerns about whether the injection well was sparged adequately. The injection well was respurged with concentrated SF_6 gas for 20 more minutes at the next low tide ($t = 0.77$ days) in hopes of respurging the same water mass. No more measurable changes in SF_6 were seen until 1.16 days when the monitor well's concentration rose to 7.35 ± 0.45 nM. A maximum concentration (24.6 ± 1.67 nM) coincided with a low Atlantic tide (1.20 days) when groundwater should have been advected southward. This peak in concentration indicates a transport rate of 0.30 m/h. This is based on the time of the second injection and, as discussed previously, is likely an underestimation. Values returned to baseline after 1.26 days as the tide began to rise and drove the tracer laden plume back to the north. A larger peak was observed at the next Atlantic low tide (1.71 days) with a maximum SF_6 concentra-

tion of 72.2 ± 0.62 nM. By 2 days, values were returning to background values. No further samples were collected until 2.64 days during a falling tide. The SF_6 concentration in the monitoring well at this time (70.4 ± 0.26 nM) was similar to the previous maximum.

Sulfur hexafluoride was not detected in Florida Bay until 1.25 days. Just as the first peak in the monitor well was declining, a concentration of 70.9 ± 31.9 pM was observed in the Bay. This peak declined to 27.1 ± 3.7 pM then increased slightly at 1.46 days to a concentration of 41.1 nM. This double peak may be the result of the multiple injections. After 1.5 days, SF_6 concentrations in the Bay were below our limit of detection. No further traces of SF_6 were detected in the Bay waters for the remainder of the experiment. The maximum concentration observed at 1.25 days corresponds with a groundwater transport rate of 2.30 m/h. This calculation assumes that this peak concentration was from the second injection. If the same is assumed for the second, smaller peak at 1.46 days, a transport rate of 1.59 m/h can be inferred. If this double peak was due to the first injection alone, transport rates of 1.08 and 0.90 m/h can be calculated.

The third and final experiment at this location was during August, 1997. This time, 100 l of water were pumped from the injection well, sparged for 20 min with concentrated SF_6 then pumped back into the well. Unlike the two previous experiments, this injection was conducted during a high Atlantic tide rather than a low. The water level in the monitor well (approximately 3 m south of the injection well) was measured during the injection and increased by more than a meter as the injection slug was pumped into the subsurface. The monitor well water level quickly returned to normal after the injection was completed. The monitor well was sampled for SF_6 and water levels every 30 min while the Bay was sampled for SF_6 every hour. The water level in the Bay was also monitored hourly.

The tidal data are summarized in Fig. 5(a). Once again, a time lag was observed between water levels in the Atlantic and in the monitor well. This lag was estimated to be 1.37 ± 0.27 h during the course of this experiment. The amplitude of the Atlantic tide was dampened by $52 \pm 4\%$ by the time it reached the monitor well, just as it was in the August 1996 experiment. The Bay water levels were out of phase

Table 1

Estimates of groundwater transport rates for septic tank experiments on Big Pine Key and simulated septic tank experiments on Key Largo

Experiment/date	Date	Horizontal transport (rate (m/h))
Septic A1	December 96	—
Septic A2	June 97	—
Septic B	June 97	1.37 and 0.11
Simulated septic (RS-1)	June 96	
Bay		3.28
Monitor well		0.27
Simulated septic (RS-2)	August 96	
Bay		1.59–2.30
Monitor well		0.3
Simulated septic (RS-3)	August 97	
Bay		—
Monitor well		0.21

with the Atlantic tide, however, the amplitude was much smaller (< 14 cm) and coincided with high northerly winds. It is unclear whether this small tidal change in the Bay affected groundwater movement during the course of this experiment.

Background concentrations for the injection well and the monitor well were 0.31 and 0.03 nM, respectively. As in the August 1996 experiment, no increase in the monitor well's SF_6 concentration was observed during the first tidal cycle after injection (Fig. 5(b)). During the next rising tide, monitor well SF_6 concentrations increased along with the tidal level of the monitor well, reaching a peak value of 1.56 nM at 14 h. This yields a transport rate of 0.21 m/h. This may be an underestimation if the plume either moved through the monitor well undetected for the first tidal cycle or moved a little to the north before turning and heading south toward the monitor well. In contrast to the previous two experiments at this site, the monitor well's peak concentration coincided with the highest water level in the monitor well. Recall that injection in this experiment also occurred at high tide. This suggests that over the course of a tidal cycle, net groundwater movement may be small even though the plume may have traveled back and forth a considerable distance. As the tide fell, the SF_6 concentration followed suit, finally reaching background levels at low tide (18.5 h). A second, larger peak was observed with the next high tide. Once again, the maximum SF_6

concentration (4.63 nM) of this peak occurred during the monitor well's highest water level (26.5 h). As the tide ebbed, SF_6 levels dropped to 4.04 ± 0.07 nM at 27 h, then returning to baseline at low tide then began rising with the next flooding tide. These results are similar to the two previous experiments in the respect that peak SF_6 concentrations were observed in the monitor well during the same tidal stage that existed at the time of injection.

The concentrations of samples from the Bay all reflect background values of less than 4 pM, approximately 20 times more diluted than those collected a year earlier. Residual traces of SF_6 were not detected in the Bay before the August 1996 experiment, yet it was detected in the Bay before the August 1997 experiment. This was due to the fact the sampling technique was altered from using syringes to using serum vials between the August 1996 and 1997 experiments, resulting in a lower limit of detection. No significant change in tracer concentrations were observed in the Bay during the August 1997 experiment. This may be attributed to the timing of the injection. During high Atlantic tide, initial transport of the plume should have been towards the Bay. As the Atlantic tide fell, however, the tracer plume moved back to the south towards the monitor well and Atlantic Ocean before ever reaching the Bay.

These injection experiments show that substances injected into the upper portion of the water table in Keys can be transported rapidly (0.21–3.28 m/h) through Key Largo limestone and has the potential to reach surface waters within hours. The groundwaters seem to be driven through the subsurface matrix by tidal pumping, moving north (bayward) as the Atlantic tide rises and to the south (seaward) as the tide falls. A year had passed between the last two Key Largo experiments and slight traces of SF_6 were still present in the Bay before the last experiment, suggesting a long residence time of substances injected into the aquifer. It is unclear how nutrients from septic tanks are affected by this long resident time.

4. Discussion

A summary of calculated transport rates is shown in Table 1. These results suggest that substances injected into the water table beneath the Florida Keys has the

potential to travel rapidly through the porous limestone matrix. The septic tank results from Big Pine Key suggest that during the time of these experiments the plumes from septic tanks in this area of Big Pine Key move in an eastward direction. The lack of any large, reliable SF₆ peaks for site A (Fig. 2(a) and (b)) suggests that the tracer did not travel west toward the well at this site. The presence of low concentrations at site A suggest that a dispersive type of transport reached the well and had a rather long residence time. Six months time passed between injections at site A yet there were still residual traces of SF₆ present before experiment A2. Results from site B (Fig. 2(c)) confirm that advection of groundwater on this part of Big Pine Key is eastward in direction.

The rapid transport rate at site B (1.37 m/h) is an order of magnitude higher than the flow rate of 0.15 m/h (3.7 m/day) reported by Lapointe et al. (1990). Two plausible explanations for this high transport rate are conduit/fracture flow of the wastewater or contamination during the initial sparging process. Although no cores were available for examination from Big Pine Key, previous coring work done by Shinn et al. (1994) at Saddlebunch Keys show that some portions of cores collected had unrecoverable portions in the upper 2 m which could represent conduits, rubble, or sand layers that could have a much higher hydraulic conductivity than Miami oolite. The Saddlebunch Keys are located approximately 30 km west of Big Pine Key and are considered to be in the same geological formation of Miami oolite. It is possible that similar features could also be present on Big Pine Key. A slower groundwater transport rate of 0.11 m/h was calculated from the small peak observed after 10 days at site B. This agrees well with the estimate of Lapointe et al. (1990) and is a most likely representative of the Miami oolite's primary porosity.

The most rapid transport rates found in this study were during the Key Largo experiments with rates of groundwater transport between 0.21 and 3.28 m/h. As mentioned previously, some of these lower rates are probably underestimates due to the bi-directional movement of the plumes. The highest of these rates are most likely due to the high permeability of the Key Largo limestone as well as the presence of conduits in the limestone. Numerous studies cite the large degree of secondary porosity in Key Largo limestone (Vacher

et al., 1992; Shinn et al., 1994; Halley et al., 1995). The majority of the flow through this formation is believed to be via channel or conduit flow. These conduits were originally formed as ancient coral reefs developed vertically. More recently, meteoric diagenesis has contributed to the dissolution of calcium carbonate, resulting in further development of secondary porosity (Vacher et al., 1992). This increase in secondary porosity increases the permeability of the Key Largo limestone and profoundly affects groundwater flow.

The flow rates obtained for the Key Largo experiments can be used to estimate the limestone's hydraulic conductivity using Darcy's law:

$$v = (-K/n)dh/dl \quad (1)$$

where v is the groundwater velocity, K is the hydraulic conductivity, n is the porosity, and dh/dl is the hydraulic gradient. If the porosity, hydraulic gradient, and groundwater velocity are known then one can estimate K . The porosity of the Key Largo Limestone is assumed to be 0.50 (Kump, personal communication). The data from the Key Largo experiments indicate that the hydraulic gradient varies over a tidal cycle. At high tide, we observed groundwater flow towards the bay, indicating that the hydraulic gradient is sloped to the north. At low tide, flow was toward the Atlantic, suggesting the gradient was sloped towards the south. This indicates that the gradient reverses at some point in the tidal cycle. The maximum Atlantic tidal amplitude observed on Key Largo was 0.88 m. If one assumes that the Atlantic's mean tidal level is equal to the bay's mean water level, then one can conclude that the greatest difference in the Atlantic and bay's water levels is 0.44 m at extreme high or low tide, which would establish maximum hydraulic gradients of $\pm 1.02 \times 10^{-3}$ (0.44 m/430 m). Using the highest and lowest rates of groundwater transport (3.28 and 0.27 m/h), one can estimate two extreme values of K as 1602 and 131 m/h, respectively.

The hydrological data obtained from the Key Largo experiments can also be used to estimate a value for the limestone's hydraulic conductivity. In a karstic matrix such as Key Largo limestone, K could vary tremendously depending on local geological features of the limestone (i.e. the presence or lack of conduits). While other methods of estimating K , such as with a

permeameter or a slug test, may usually give more precise estimates that are difficult to conduct in Key Largo limestone because wells typically respond to a slug or a pump test too quickly to be measured. However, Millham and Howes (1995) estimated an unconfined aquifer's transmissivity, T (m^2/h), based on a well's response to the tide using:

$$T = (x^2 S t_0) / (4\pi t_1^2) \quad (2)$$

where x is the well's distance from tidal source (400 m); S is the specific yield of aquifer (dimensionless); t_0 is the tidal period (12 h); and t_1 is the time delay of well's response relative to the tide (average lag for Key Largo experiments = 1.53 h). K (m/h) can then be calculated from its relationship to transmissivity:

$$T = Kb \quad (3)$$

where b is the aquifer thickness. Assuming a specific yield of 0.14 (Johnson, 1967) and an aquifer thickness of 10 m, which is the approximate depth to the Q3 unconformity which may act as a confining layer (Shinn et al., 1994), a value of 914 m/h can be estimated for K .

Dispersive behavior of the plumes may explain some of the results from the August 1996 and 1997 experiments. In each of these experiments, the SF_6 peaks observed for the monitor well were larger the second time they were observed. The results suggest that the SF_6 plumes did not completely travel across the monitor well during these experiments. If they had, then there would be a double peak for the monitor well each time the plume came in contact with the monitor well; one peak as the center of the plume crossed the monitor well in one direction, followed closely by a second peak observed after the tide turned and the most concentrated portion of the plume moved back across the monitor well. Instead, there is only one peak for each associated extreme tide. This suggests that the edges of the plumes came into contact with the monitor well, then turned with the tide before the centers of the plumes could make it to the monitor well. As the plume became more dispersed, a higher concentration of the edge of the plume may have come in contact with the monitor well, resulting in a larger peak concentration of the tracer.

5. Conclusions

The primary purpose of this study was to determine directions and rates of groundwater transport in the Florida Keys. Overall, it appears that transport rates and direction can differ throughout the Keys due to changes in local geology and tidal influences. Transport direction at the study sites on Big Pine Key seems to be eastward in direction and is probably dependent on the hydraulic gradient established by local recharge to the freshwater lens. Transport directions probably vary across Big Pine Key, depending on location and the size of the fresh water lens, which varies seasonally (Hanson, 1980). Conduit flow is the most likely explanation for the rapid transport, 1.37 m/h observed at the second site on Big Pine Key. The lower estimate of 0.11 m/h is comparable to that presented by Lapointe et al. (1990) and most likely represents the primary porosity of Miami oolite.

The most rapid groundwater transport rates were observed during the simulated septic tank experiments on Key Largo. Rates were as high as 3.28 m/h and were closely coupled to the Atlantic tide. The two studies made by Paul et al. (1995a, 1997) gave transport rates ranging from 0.57 to 35 m/h on Key Largo. The lower rates presented here are most likely due to spatial as well as methodological differences. Our site was approximately 400 m from the Atlantic and had no canals nearby whereas their site was adjacent to a canal directly connected to the Atlantic. In addition, their flow rates are obtained by using the first appearance of bacteriophages while ours are calculated using peak tracer concentrations.

Directions of groundwater transport on Key Largo seem to have been north/south in orientation. The observed plumes shifted directions as the Atlantic tide rose and fell. As this "sloshing" movement continued, the plumes seem to become more dispersed. The rate of transport is probably influenced by tidal amplitude with the highest rates corresponding to maximum tidal variations such as those observed during a spring tide. It is unclear at this point what the fate of nutrients placed below the water table may be. Future experiments of this type should utilize bioavailable tracers such as phosphate and dissolved inorganic nitrogen in concert with SF_6 to determine to what extent these nutrients can be stripped from the groundwater either by chemical

adsorption onto the limestone matrix or by utilization by microbial communities present in the limestone.

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