25 Tidal and Meteorological Influences on Shallow Marine Groundwater Flow in the Upper Florida Keys

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INTRODUCTION

Historically, groundwater-management issues in the Florida Keys have not been a major concern of local residents; however, in recent years changes in the water quality of Florida Bay and the health of neighboring coral reefs have focused attention on the possibility that groundwater may play a vital role in the health of marine ecosystems both nearshore and along the reef tract. Groundwater contamination from on-site disposal systems (i.e., septic tanks and cesspools) and wastewater injection has been targeted as a likely source of nutrients and pathogens leading to eutrophication/nutrification of nearshore surface waters (Lapointe et al., 1990; Shinn et al., 1994). In addition to nearshore impacts, it was also believed that contaminants were being transported from onshore areas to the reef tract, as much as 8 km away, by surface- and/or groundwater movement (Shinn et al., 1994).

Creation of the Florida Keys National Marine Sanctuary in 1990 prompted the U.S. Environmental Protection Agency (EPA) to develop a Water Quality Protection Program (WQPP) for the Florida Keys region (EPA, 1991, 1992, 1996). This region encompasses all of the nearshore environments of the Keys, the reef tract, and portions of Florida Bay. The coordination of federal and non-federal agencies through the WQPP has led to the investigation of several groundwater-movement related issues: (1) groundwater flow around wastewater injection wells (Paul et al., 1995a,b; Monaghan, 1996; Corbett et al., 1999); (2) fate and transport of wastewater contaminants to the offshore reef environments (Shinn et al., 1994); (3) septic tank discharge and its impacts on canal systems (Lapointe et al., 1990; Paul et al., 1995a,b); (4) quality and quantity of submarine groundwater discharge (SGD) as well as nutrient loading of surface waters in response to groundwater seepage (Corbett et al., 1999; Shinn et al., in press); and (5) natural groundwater-flow conditions in the Florida Keys (Halley et al., 1994; this study).

In this study, the installation of a circular cluster of paired, multidepth wells on opposing sides of Key Largo and the use of Fluorescein and Rhodamine dyes as groundwater tracers verified that marine groundwater flow occurs from Florida Bay beneath Key Largo and ultimately into the Atlantic Ocean. Weather, bay level, and tidal fluctuations play dynamic roles in controlling groundwater movement in the upper Florida Keys area. This particular area was selected to represent natural gradient-driven flow of groundwater in the absence of any extraneous sources, such as artificial recharge from sewage injection wells.

DESCRIPTION OF STUDY AREA

SITE LOCATION

Key Largo, FL, lies within a subtropical climate with mean January temperatures of 21ºC and mean July temperatures of 28ºC. Annual rainfall for the upper Keys averages about 140 cm, with almost two thirds of the rain occurring between May and October (Halley et al., 1997). The study site is shown in Figure 25.1. The tracer experiments were conducted using pairs of nested wells (two per borehole) at two offshore well cluster sites. The bayside well cluster (BSWC) is located in Florida Bay (25º04.252´N x 80º28.120´W), while the oceanside well cluster (OSWC) is located directly across Key Largo in the Atlantic Ocean (25º03.990´N x 80º27.941´W). The circular clusters of wells are located approximately 60 m and 80 m from the shoreline in 1.1-m and 1.8-m water depth (mean high tide), respectively (Figure 25.1). Well depths are 13.6 m and 6.1 m below rock surface at both sites. These sites were chosen because they straddle a relatively narrow (500-m) unpopulated portion of Key Largo and are unaffected by artificial recharge from shallow sewage injection wells. Four onshore transect wells (18-m deep) were core-drilled to obtain water-table profiles across the island between the well clusters.

HYDROGEOLOGIC SETTING

The Florida Keys region is underlain by one of the most permeable limestones (Key Largo Formation) in the world. The islands have little vertical relief (5 m maximum at Windley Key) and function as discontinuous, semipermeable dams separating the large lagoon of Florida Bay from the Atlantic Ocean. The low relief of the islands and the high permeability of the limestone prevent the development of a well-defined freshwater lens. When combined with meteorological events, these unique conditions result in rapid multidirectional flow patterns within the groundwater system.

The Florida Keys can be divided naturally into two distinct geologic units of Pleistocene age - a coralline boundstone facies of the Key Largo Limestone and the oolitic facies of the Miami Limestone (Miami oolite). The Key Largo Limestone extends from Soldier Key in the northeast to Newfound Harbor Keys to the southwest, a distance of approximately 176 km, and westward beneath the Miami oolite of the Lower Keys (Figure 25.1). The Lower Keys consist of cemented spherical ooids and peloids that begin at Big Pine Key and extend past Key West and beneath the Marquesas Keys in the Gulf of Mexico. Both the Key Largo and Miami oolite formations dip down to the south and southwest (Hoffmeister and Multer, 1968; Perkins, 1977; Shinn et al., 1989; Davis et al., 1992; Halley et al., 1997).

Core data from both well cluster sites depict a vuggy grainstone limestone, typical of reef and back-reef deposits of the Key Largo Formation (Figure 25.2). Core description terminology used in Figure 25.2 and throughout the text is after Dunham (1962). Estimated hydraulic conductivity for this lithologic unit within the Key Largo Limestone ranges from 1400 meters per day (m/d) (Vacher et al., 1992) to 12,000 m/d (Fish and Stewart, 1990). However, horizons of impermeable calcrete, also referred to as caliche, often cap the highly permeable Key Largo Limestone. Generally speaking, five major horizons have been detected within the Key Largo Formation, each horizon being formed during a sea-level lowstand (Perkins, 1977). Where present and continuous, these caliche units create an impermeable barrier to vertical groundwater flow. These calcrete surfaces can form up to 6-cm-thick coatings and can be assumed to have a permeability of several orders of magnitude less than that of the limestone above and below. Core C-1 obtained at BSWC (Figures 25.1 and 25.2) contained the only significant laminated caliche crust horizon in all cores obtained. Lithoclasts or fragments of caliche were observed in other cores, but the presence of a continuous laminated caliche crust was absent (Figure 25.2). This indicates that vertical movement of groundwater is not impeded at these sites.

Owing to a high volume of precipitation and highly porous limestone, a large percentage of rainfall likely infiltrates on land and recharges the water table. However, because of the extreme permeability, tidal pumping, and presence of shallow marine groundwater, the newly recharged freshwater is rapidly mixed with the marine groundwater or is transported laterally and discharged along the coast. Profiles of specific conductance measured at transect wells drilled across the island of Key Largo (Figure 25.1) between the well clusters show a relatively persistent (1- to 2-m thick) brackish lens between the two study sites. Lowest specific conductance of 21.4 milliSiemens per centimeter (mS/cm) was measured in the top 1 m of transect Well C. This corresponds to a salinity of approximately 13 parts per thousand (ppt). At a 5-m well depth, the specific conductance was similar to that of seawater (55.0 mS/cm; 35 ppt), and below 5 m water was hypersaline (59.2 mS/cm: 38 ppt). However, geophysical techniques have revealed localized freshwater lenses around highly populated areas of Key Largo (Ciriello, 1997). Pockets of freshwater lenses were determined to originate from wastewater injection wells and septic tanks, not from natural recharge events such as rainfall.

In addition to the high permeability of the Key Largo Limestone and the role it plays in dispersing freshwater, tides of the Atlantic Ocean also have a great influence on structure of the brackish-water lens beneath the island. The Atlantic Ocean exhibits a typical semidiurnal tide with a range of ~1 m (Figure 25.3). The tidal signal propagates rapidly through the highly permeable island (Halley et al., 1994). Because of the rise and fall of the tides every 6 hours, groundwater dynamics beneath the island are extremely complex. On the bayside of Key Largo, astronomical tides are nearly absent and bay tides instead reflect, for the most part, meteorological (wind) conditions (Figure 25.3) (Smith, 1994).

METHODS

WELL INSTALLATION

Well location was critical for this study, as natural-gradient conditions were essential in obtaining valid groundwater flow data. Absence of artificial influences (septic tank leachate or disposal well effluents) to the groundwater system were key factors for choosing this unpopulated region of Key Largo for the installation of the well clusters (Figure 25.1). BSWC well nests were installed in July 1995; OSWC wells, in February 1996. Ten 7.6-cm holes were core-drilled to a depth of 13.6 m at each site using a hydraulic-powered rotary drill. All drilling and underwater well installations were performed from a 7.6-m-long barge. All wells were constructed of 2.54-cm threaded-PVC pipe and a 1.5-m-long well screen (0.010-inch slot) (Figure 25.4). The deep well screens were set between 12.1 and 13.6 m below the rock surface. In order to complete the deep wells, coarse quartz sand was poured into the borehole, creating a sand pack surrounding the well screen, followed by a slurry of cement forming a plug capping the sampling interval. The shallow wells were inserted into the borehole, alongside the deep well, to a depth of 6.1 m below the rock surface. A plug of quick-setting cement around the well heads and the opening of the hole sealed the borehole from the surface water (Figures 25.4 and 25.5). The central hole was drilled first and completed with a nest of two wells. The eight peripheral well nests were placed in a circular array around the central well nest to create a 60.6-m-diameter well cluster (Figure 25.1).

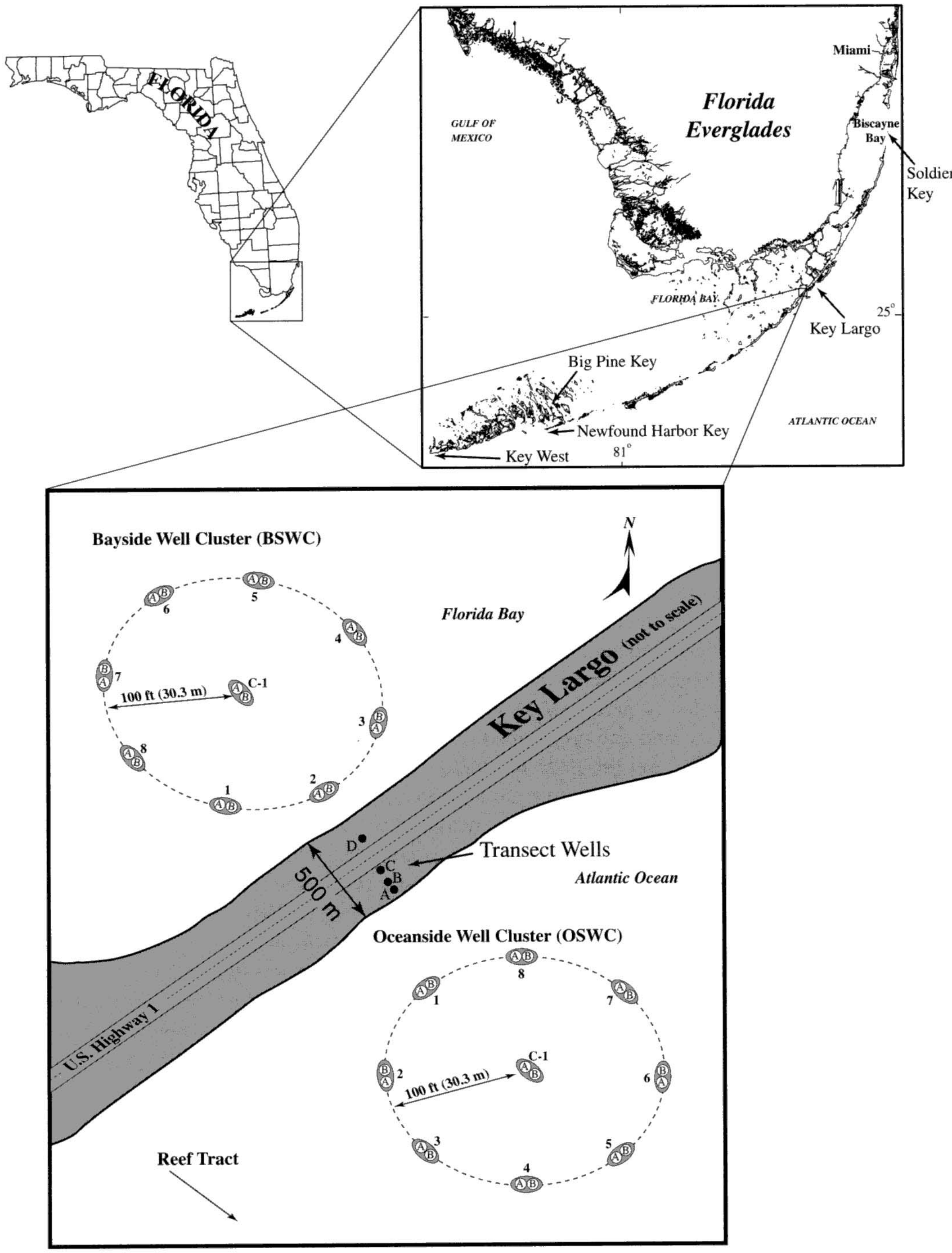

FIGURE 25.1 Site locations of the dye tracer experiments in Key Largo, FL. Layout and position of wells at each well cluster in relation to Key Largo, Florida Bay, and the reef tract are shown for orientation. The central wells, C-lA,B at both Bayside Well Cluster (BSWC) and Oceanside Well Cluster (OSWC), are the sites where dye was injected. The transects of wells located on the island are also shown.

DYE INJECTION AND SAMPLING

Both Rhodamine WT and Fluorescein were used as groundwater tracers. The decision to use them was based on previous work in karst and limestone environments (e.g., Atkinson et al., 1973; Smart and Laidlaw, 1977; Davis et al., 1980; Sabatini and Austin, 1991). Both Rhodamine and Fluorescein are semiconservative groundwater tracers that travel well through limestone because they are not adsorbed onto the limestone and do not degrade in high salinity water (Smart and Laidlaw, 1977). Dye was injected into the central wells of the well cluster and sampling occurred in the surrounding wells. For consistency, at both well clusters the shallow central wells (C-1B) received Fluorescein dye and the deep central wells (C-1A) received Rhodamine WT dye. The initial injection of Fluorescein at OSWC occurred in March 1996. Rhodamine was injected in June 1996. A second injection of both Fluorescein and Rhodamine was conducted in February 1997. The initial dye injection of Fluorescein and Rhodamine at BSWC was in August 1996, and a second injection of both dyes was made in February 1997. In addition to the second injection at BSWC, a known concentration of a sulfur hexafluoride (SF_6) Solution was also injected along with the Fluorescein in the shallow well (C-1B). Samples for SF_6 were collected concurrently with the water for dye analyses and sent to Florida State University's Department of Oceanography Lab, where they were analyzed on a liquid gas chromatograph (LGC). SF_6 is detectable in the picomolar range, making it an ideal groundwater tracer. Care must be taken during sample collection, however, because SF_6 is adsorbed onto and contaminates plastic tubing, as it is highly volatile when in contact with the atmosphere. Copper tubing and dedicated silicon tubing were used during the collection of SF_6 to eliminate or reduce the opportunity for cross-contamination.

Two 55-gal drums were filled with surface seawater for preparing dye solutions. Fluorescein powder (500 g) was added to one drum and 3 L of a 20% liquid Rhodamine solution was added to the second. A small 5-gpm, 12-volt D.C. pump and dye-dedicated tubing were used to inject both dyes into the respective wells. A chaser volume (~50 gal) of ambient seawater was pumped into each well to ensure dye dispersal in the rock. Fluorescein dye issued from small solution holes up to 3 m away at both OSWC and BSWC sites during injection, demonstrating the connectivity between the shallow groundwater and the overlying surface water. Rhodamine dye injected deep (13.6 m), however, was not observed to leak into the overlying surface water.

Subsequent sampling of water from the circular array of wells was accomplished using a portable 12-volt D.C. pump, tubing, and a coupler with O-rings to ensure a tight seal on the underwater wellhead. Collecting water from each well required anchoring a small boat over each site. A diver connected the coupler and tubing to the well head. Each well was purged for at least three well volumes. To eliminate any photodecay of the dyes water samples were collected in amber HDPE bottles. Samples were analyzed in the lab on a Turner Designs Fluorometer following fluorometric procedures according to Wilson (1968) and Aley and Fletcher (1971).

TIDAL MEASUREMENTS

Surface water levels at the OSWC and BSWC were recorded with two pressure transducers attached to the sea floor. The pressure transducers were surveyed in to the nearest benchmarks such that data could be processed relative to a common datum (e.g., North American Vertical Datum of 1988, NAVD88). Measurements of the surface water levels and groundwater pressure allowed some insight into understanding what controls groundwater flow in the Florida Keys. Tidally induced groundwater pressure changes were periodically monitored with an underwater manometer device (Reich, 1996).

RESULTS AND DISCUSSION

Flow velocities obtained under natural-gradient conditions were calculated from breakthrough curves using the first-arrival time rather than the $C_{0.5}$ point along the advective front (Domenico and Schwartz, 1990). The $C_{0.5}$ point takes into account both the dispersion and advection of a tracer in a groundwater flow field. The first-arrival time for obtaining velocity was employed because not all breakthrough curves were sigmoid shaped (i.e., bell-shaped; Parnell, 1986). BSWC-2B (Figure 25.7) is a good example of a sigmoid-shaped curve showing an increase in dye concentration, maximum concentration peak, and then a decrease to near background levels. This indicates that advective flow is strong through these well sites. However, non sigmoid-shaped curves (BSWC-5A; Figure 25.7) are suggestive of low advective flow and higher dispersion of tracer resulting in a slow movement of dye through those well sites.

OCEANSIDE WELL CLUSTER (OSWC)

Data were collected from March 23, 1996, to July 31, 1997. Results after the first injection of Fluorescein in March 1996 and Rhodamine in June 1996 are shown in Figure 25.6. Flow velocities ranged from 0.1 to 1.68 m/d for Fluorescein (shallow injection) and 0.22 to 0.76 m/d for Rhodamine (deep injection). The first arrival of dye (indicated by ◆) at wells 5B and 6A suggests that net groundwater flow was easterly and southeasterly, or in the offshore direction. Dye eventually dispersed in the subsurface and appeared at other wells in the cluster.

Both dyes were injected a second time in February 1997 (see days 238 and 332 in Figure 25.6 for Rhodamine and Fluorescein, respectively). Interestingly, after the second injection, the flow rates increased and direction of flow was to the west. First arrival

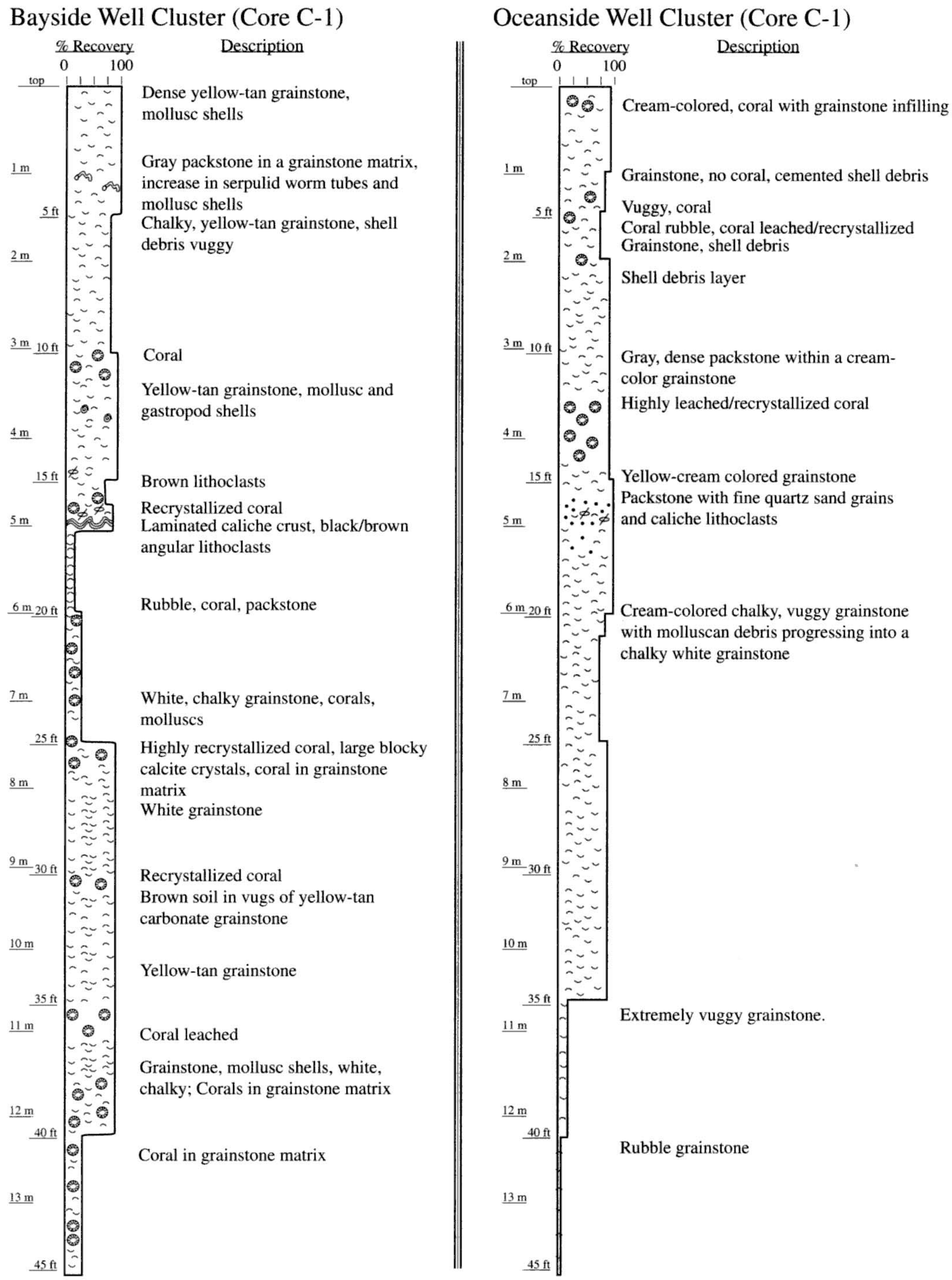

FIGURE 25.2 Generalized description of core C-1 (OSWC and BSWC). Core logs depict typical Key Largo limestone with skeletal material comprising grainstones and packstones along with corals and molluscan shells. Core C-1 at BSWC contains a thick caliche crust (~3 to 5 cm) not present in other cores taken at OSWC or BSWC.

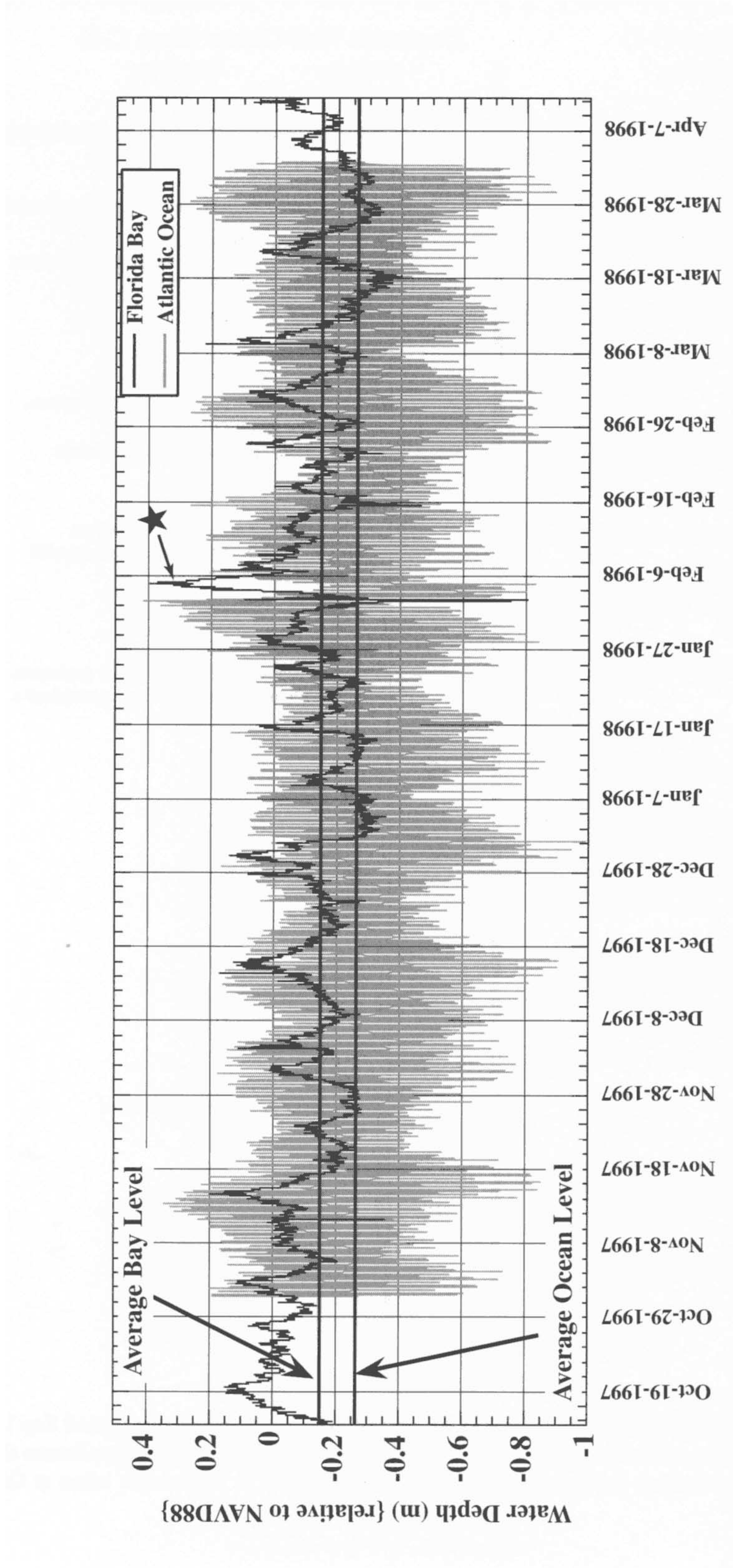

FIGURE 25.3 Fluctuations of water levels for tides for Florida Bay and the Atlantic Ocean. Tides in the Atlantic are semi-diurnal with a range of 1 m and are characteristic of astronomical tides, whereas tides in Florida Bay do not fluctuate with any regularity but vary according to meteorological conditions. The star on February 3 shows peak effects of the Groundhog Day storm that was associated with a severe cold front and winds up to 100 mph. The severe cold front created a drastic swing in bay water level.

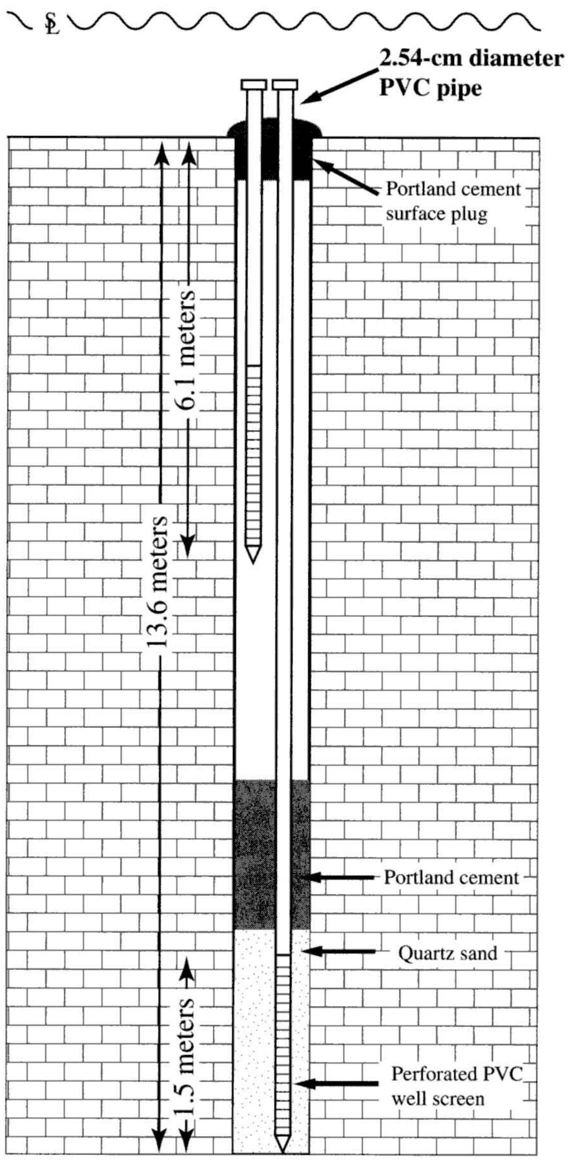

FIGURE 25.4 Installation design for all wells at BSWC and OSWC.

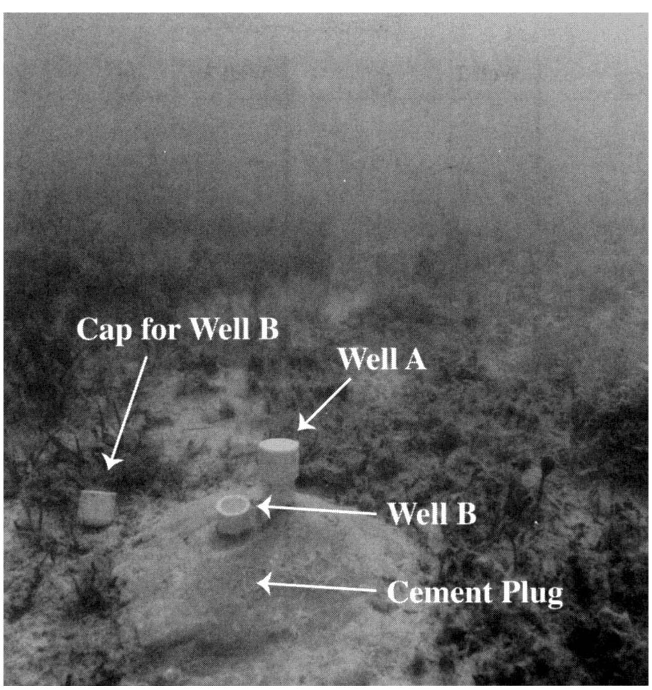

FIGURE 25.5 Photograph of a completed underwater well nest. Each pair of well heads is sufficiently exposed above the sea floor that a coupler and tubing can be attached to sample the groundwater.

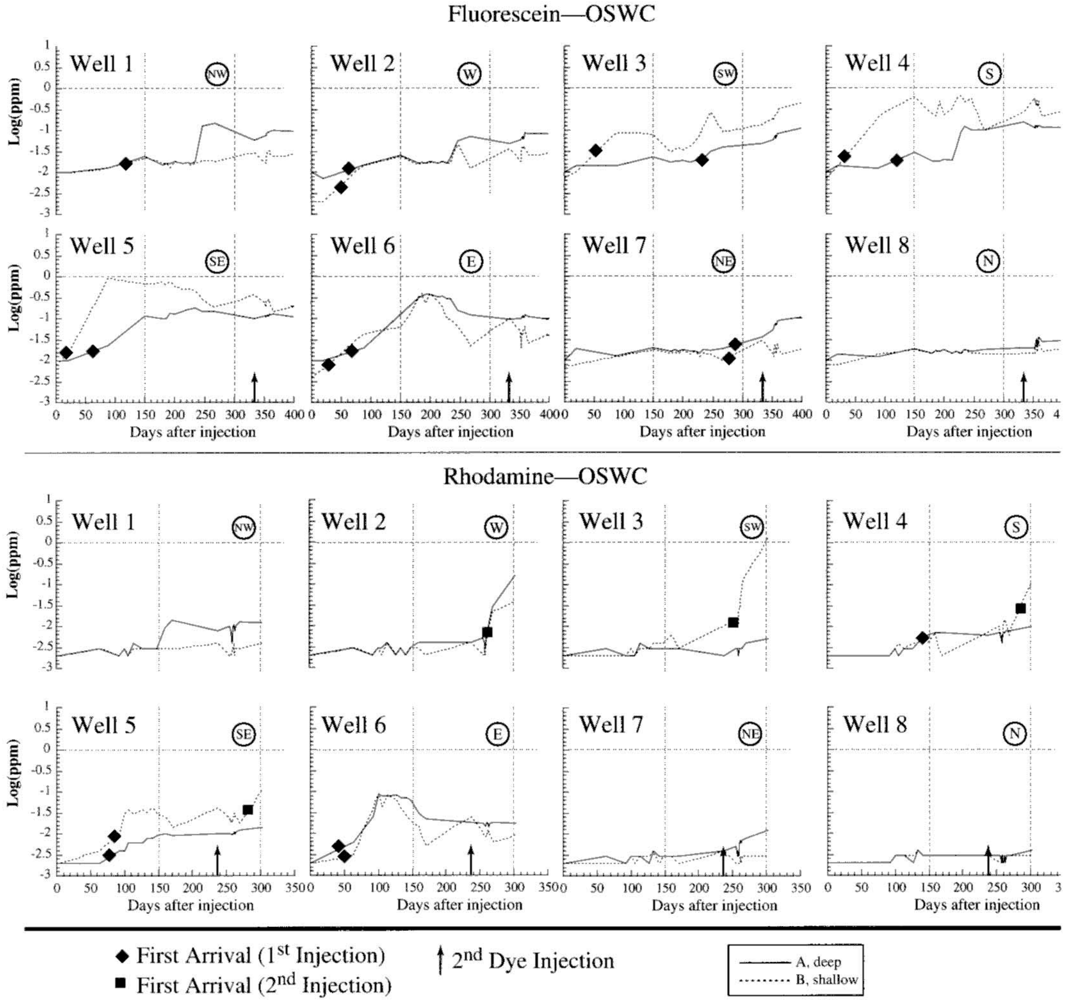

FIGURE 25.6 Breakthrough curves for Fluorescein (March 1996 to July 1997) and Rhodamine (June 1996 to July 1997) at the OSWC. Well numbers are indicated on each chart along with direction from the injection point. Arrival time of the first injection (◆) is used to calculate groundwater-flow velocity. Arrows depict the time of second dye injection (February 1997). A solid box (■) shows first arrival of dye after the second injection. Dye concentrations have been log-normalized so that all data can be displayed on the same scale.

(indicated by a solid box) of Rhodamine was within 16 days at well 313 and 20 days at wells 2A and 2B, resulting in a calculated velocity of 1.9 m/d. No obvious peak of Fluorescein was detected after the second injection.

BAYSIDE WELL CLUSTER (BSWC)

Data at BSWC were collected from August 21, 1996, to July 31, 1997. Breakthrough curves at BSWC are shown in Figure 25.7. Horizontal flow velocity based on the first arrival of dye (indicated by a diamond) ranged from 0.36 to 2.52 m/d for both Fluorescein and Rhodamine. The flow velocity was 1.5 times greater than that observed at OSWC, and the primary direction of flow was in a southeasterly direction.

The arrival of Rhodamine at the shallow wells prior to detection in the deep wells suggests that the vertical-flow component on the bayside of Key Largo is greater than was observed at OSWC. However, the opposite was not true; for example, Fluorescein dye did not appear to move vertically downward at either OSWC or BSWC. The greater upward vertical flow of groundwater at BSWC suggests a greater potential for seepage of nutrient-rich or contaminated groundwater into the surface water than at OSWC. In addition, based on preliminary results from seepage meters, measured seepage rates are greatest at BSWC (Shinn et al., in press). For example, seepage rates collected at BSWC on June 6, 1996, were 38 to 50 L/m^2/day compared to 8 to 20 L/m^2/d obtained on the same date and under the same conditions at OSWC.

Fluorescein and Rhodamine were injected for the second time into the central wells at BSWC, one day after OSWC injection. SF_6 was injected along with Fluorescein. Dye injection occurred at day 182 in Figure 25.7 (indicated by arrow). Patterns in flow rate and direction were similar to those observed at OSWC during the second injection. Flow rates exceeded 3.0 m/d (wells 6A and 6B) and

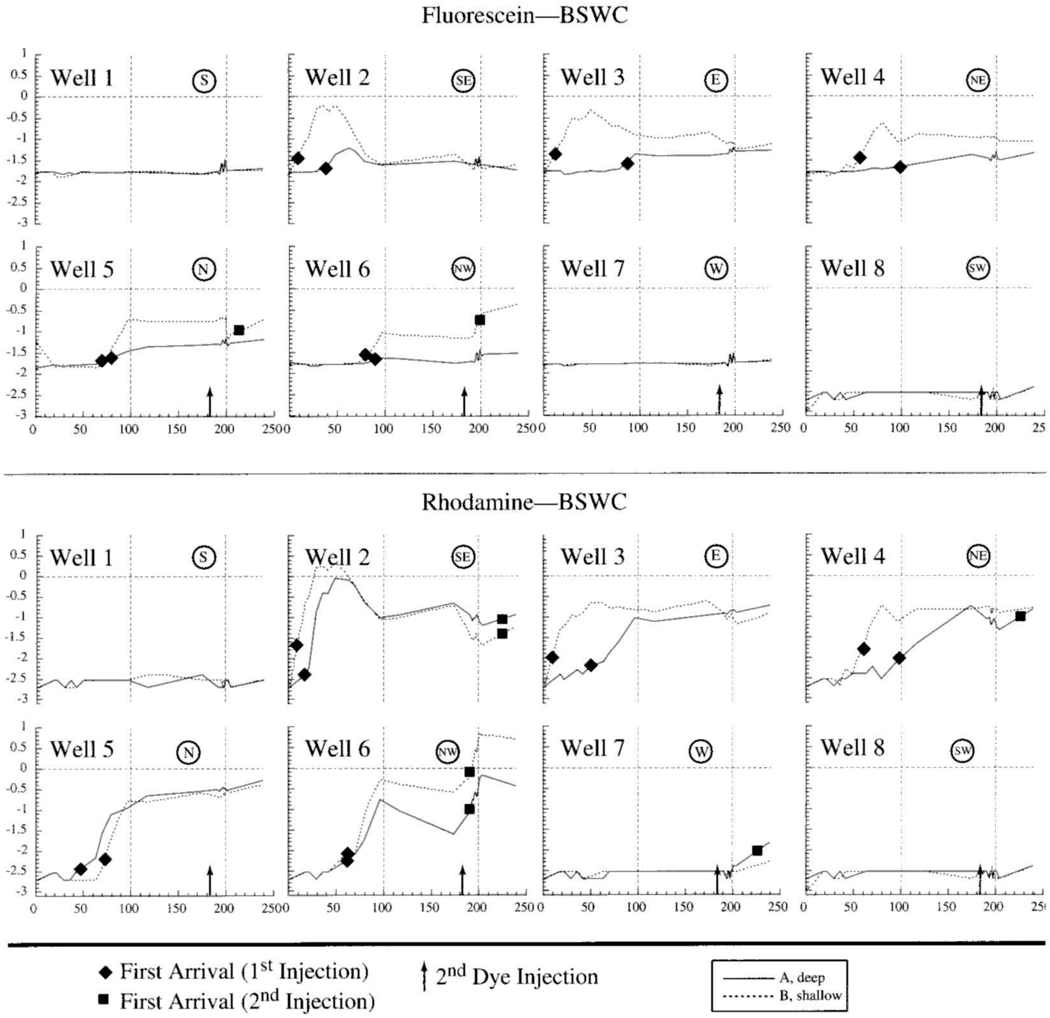

FIGURE 25.7 Breakthrough curves for Fluorescein and Rhodamine (August 1996 to July 1997) at the BSWC. Well numbers are indicated on each chart along with direction from the injection point. Arrival time of the first injection (◆) is used to calculate groundwater-flow velocity. Arrows depict the time of second dye injection (February 1997) of dyes occurred. A solid box (■) shows first arrival after the second injection. Dye concentrations have been log-normalized so that all data can be displayed on the same scale.

the flow direction had reversed to the northwest. SF_6 results showed similar trends with a northwesterly direction and rates of 3.0 m/d. Groundwater flow velocity data from OSWC and BSWC are summarized in Figure 25.8 as a vector diagram. This illustrates the net direction of groundwater flow for both the first and second injection periods.

TIDES AND TIDAL PUMPING

The variability in results from one location to another and from one dye-injection period to another are the result of dynamic controlling factors, such as tides, tidal pumping, and storm events. The result of tidal interaction between bay and ocean create a daily fluctuation in the potential for movement of groundwater beneath the Keys (Shinn et al., 1999). In addition to normal tides, storm winds depress bay or ocean water levels for extended periods of time, resulting in potentially higher flow rates and reverse flow directions.

The most dynamic forcing factor in the Florida Keys is the Atlantic Ocean tides. The Atlantic Ocean water level fluctuates on a semidiurnal tidal cycle: two high and two low tides per day with a tidal range of approximately 1 m. The level of Florida Bay, however, does not fluctuate on a daily tidal cycle; instead, bay water-level fluctuation is driven primarily by meteorological events such as wind speed and direction. The plot in Figure 25.3 displays both Atlantic Ocean and Florida Bay water-level fluctuation over a 6-month period and the average water level at both BSWC and OSWC sites.

It was imperative that water level be compared to a common datum because previous data collected by Halley et al. (1994) and Smith (1994) indicated that Florida Bay water level was, on average, higher than the Atlantic Ocean water level. Pressure transducer data in this study show that water level in this part of Florida Bay is consistently 12 to 15 cm higher than that on the Atlantic

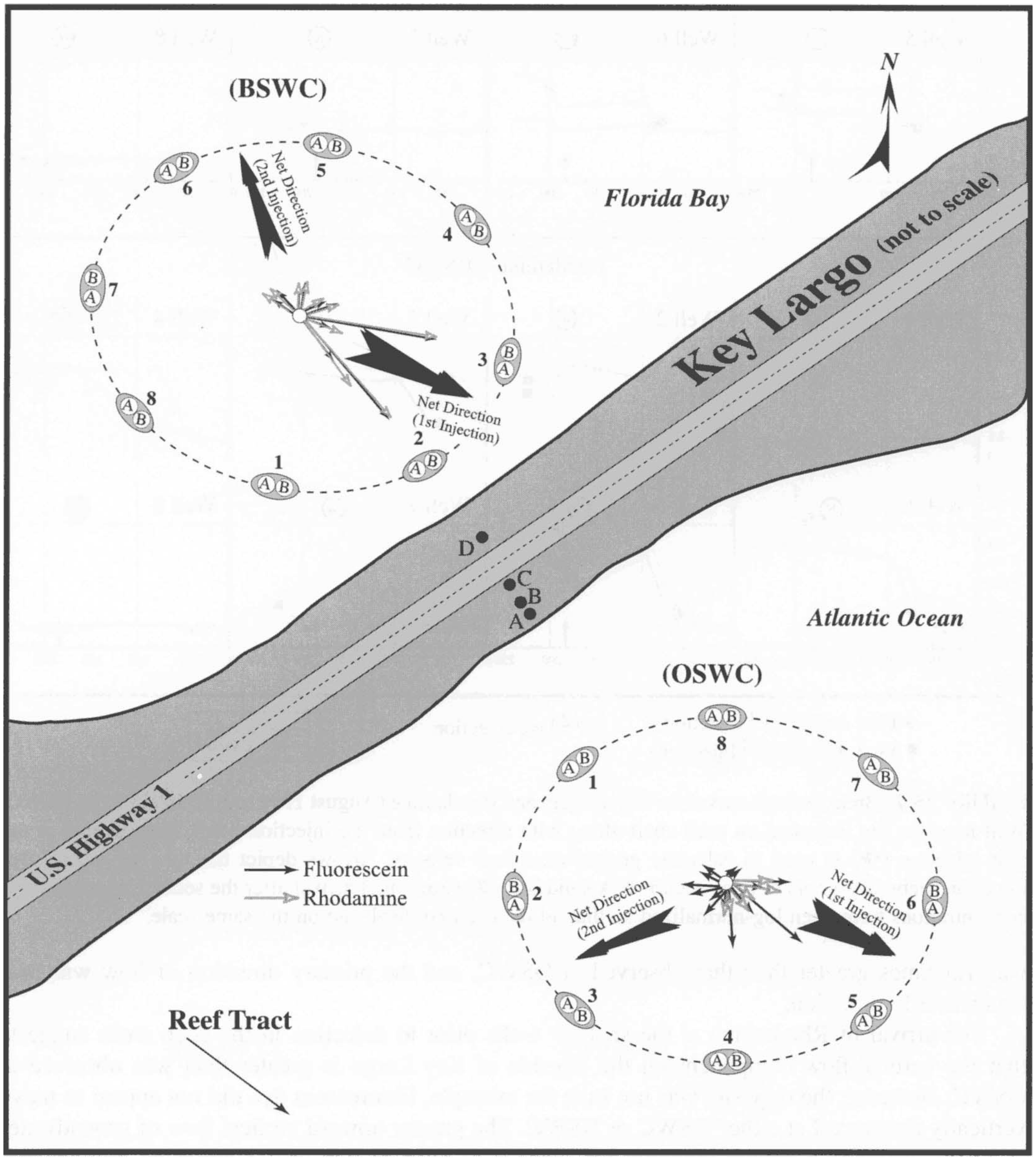

FIGURE 25.8 Vector diagram summarizing the direction and velocity from the breakthrough curves for the first injection experiment. Fluorescein (solid black arrow) and Rhodamine (grey hollow arrow) are to the same scale and represent magnitude of velocity. Note that arrows are longer at BSWC than at OSWC, indicating greater flow rates. Large arrows indicate net direction of groundwater flow observed during both the first and second injection experiment.

side of Key Largo two thirds of the time. The head difference between OSWC and BSWC surface water sets up the potential for groundwater flow to occur from Florida Bay toward the Atlantic. The velocity of bay-to-ocean groundwater flow can be calculated based on Darcy's Equation:

$$v = (K/n)(dh/dl)$$

where v is the velocity (m/d), K is the hydraulic conductivity (m/d), n is the effective porosity (dimensionless), and dh/dl is the hydraulic head gradient (dimensionless). Assuming a conservative hydraulic conductivity of 1000 m/d, an effective porosity of 0.10, and an average difference in head of 0.13 m over a distance of 500 m, a flow velocity of 2.6 m/d is obtained. This flow rate is equivalent to velocity observed from the tracer experiments. This approach was used to calculate flow rates at Davies Reef, Australia, as well as at Eniwetok Atoll, Marshall Islands in the Pacific (Buddemeier and Oberdorfer, 1986).

Advective flow is the primary result of the surface water head gradient, but the greatest influence on dispersive groundwater flow is the direct result of tidal pumping. Atlantic tides fluctuate every 6 hours, four times each day, creating a "pump" that reverses the potential subsurface flow (Parnell, 1986; Serfes, 1991; Underwood et al., 1992). Tidal pumping drives both lateral and vertical groundwater flow (Figure 25.9) and is primarily a nearshore phenomenon that dissipates in magnitude offshore in both the ocean and bay directions (pers. obs.). Observations of tidal pumping and the decrease in amplitude offshore were measured using the underwater manometer (Reich, 1996). Well-head pressures at OSWC and BSWC were measured with the underwater manometer during a rising ocean tide (Figure 25.10). It is apparent that pressures in wells at BSWC are directly linked to tidal fluctuations on the ocean side. Generally, slower horizontal and vertical flow rates were observed on the Atlantic side. Differences between OSWC and BSWC are probably the result of: (1) frictional resistance of flow through the island, and (2) presence of a less saline groundwater lens beneath the island. Groundwater flowing from the bay toward the island is forced to rise and seep into the overlying water as it approaches the island.

STORM EVENTS

Weather events such as winter frontal systems or tropical storms have a dramatic impact on bay and ocean water elevations and also influence the pattern of groundwater flow. Surface water levels at BSWC and OSWC recorded during the passing of Hurricane Georges September 25-27, 1998, show how water levels respond to a shift in wind direction and speed (Figure 25.11). The impact of wind speed and direction on water level is seen most dramatically in Florida Bay. During Hurricane Georges, bay levels dropped ~1 m and the ocean rose ~1 m, which created a head gradient of ~2 m between BSWC and OSWC (Figure 25.11). The cause for such a drop in the bay is its shallow depth - mean water depth is only ~1 m. In addition to its shallow depth, the bay is semi-enclosed, open on the west to the Gulf of Mexico and on the south to the Atlantic through small tidal channels running between the keys.

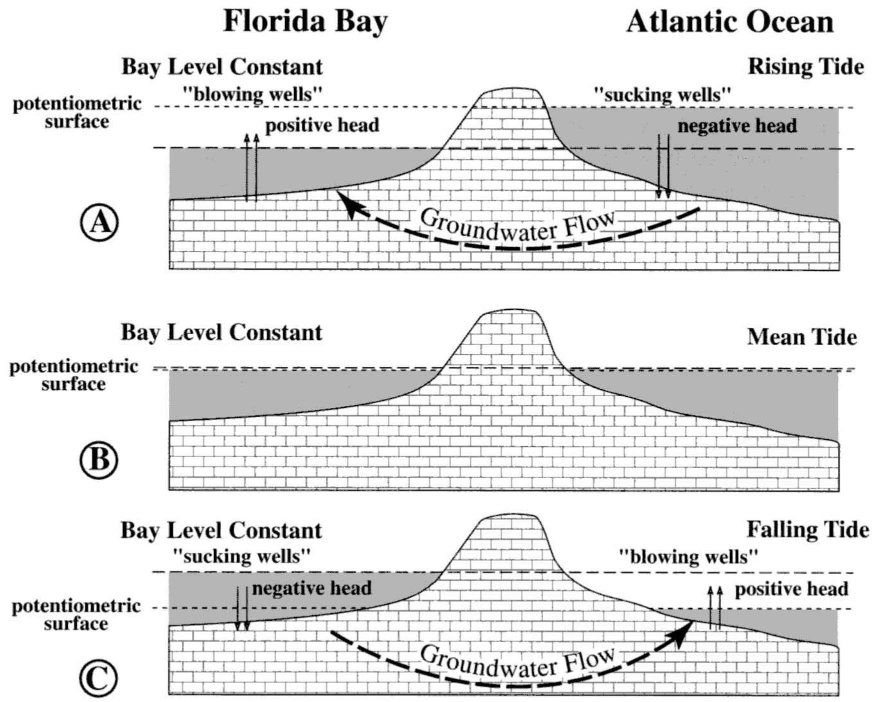

FIGURE 25.9 Fluctuating tidal conditions of the Atlantic Ocean with groundwater flow resulting from tidal pumping. Florida Bay water level remains constant while the Atlantic Ocean fluctuates. Atlantic Ocean tides rise (A), creating a head gradient in the direction of Florida Bay. This is observed in the wells as negative pressure or "sucking" wells on the ocean side and positive pressure or "blowing" wells on the bayside. Between high and low tides (B), surface-water levels are the same on both sides of Key Largo, resulting in no head gradient across the island. As the tide falls on the Atlantic side (C), the head gradient shifts to the Atlantic, providing the potential for ground-water flow in that direction. Monitoring wells display negative pressure or "sucking" on the bayside and positive pressure or "blowing" on the Atlantic side. Groundwater has the potential to flow toward the Atlantic two thirds of the time.

During the second dye injection experiment in February, a cold front passed through the area with 15- to 25-knot winds from the east to northeast. Because of the cold front, dye was detected first in wells OSWC 2A,B and 3A,B and BSWC 5B and 6A,B, opposite to what was observed after the first injection experiment. The groundwater flow direction was to the northwest, and the rate had increased from 1.7 to 1.9 m/d at OSWC and from 2.5 to 3.0 m/d at BSWC. Flow reversal was a direct result of lowering of the bay water level and raising of the ocean water level. The magnitude of Hurricane Georges, a minor Category 2 hurricane, likely represents extreme conditions for measured effects of storms. Events such as strong hurricanes (Category 3 and greater) have a significantly greater impact on groundwater flow than the less severe cold front winds that occurred after the second dye experiment.

Natural groundwater flow can be altered locally where businesses or other facilities have installed shallow sewage injection wells. These systems can inject large volumes of freshwater to depths up to 18 to 27 m (60 to 90 ft). The freshwater is injected into a completely marine groundwater system, and the result is a rapid upward ascent of the treated sewage waters due to the differences between the density of fresh and saltwater. These systems have been shown to create their own freshwater lenses (pers. obs.; Ciriello, 1997). Once the treated sewage waters reach the water table, they are subject to lateral movement and eventually may leak or seep into the nearshore surface waters.

SUMMARY AND CONCLUSIONS

The results presented here demonstrate the significant influences that bay level, daily tidal cycles, and meteorology have on shallow (<14 m) marine groundwater flow in the Upper Keys. The dye tracer analyses, based on the breakthrough curves, demonstrate both horizontal and vertical flow. Horizontal groundwater movement is predominately toward the reef tract (southeasterly flow). A component of vertical flow likely contributes groundwater seepage up into overlying surface waters and along with it the possibility of transporting nutrients or contaminants into coastal nearshore waters. In addition, this study shows that normal groundwater flow rates (2.5 m/d) toward the reef tract are punctuated by higher flow events (3.0 m/d in the reverse direction) during winter cold fronts.

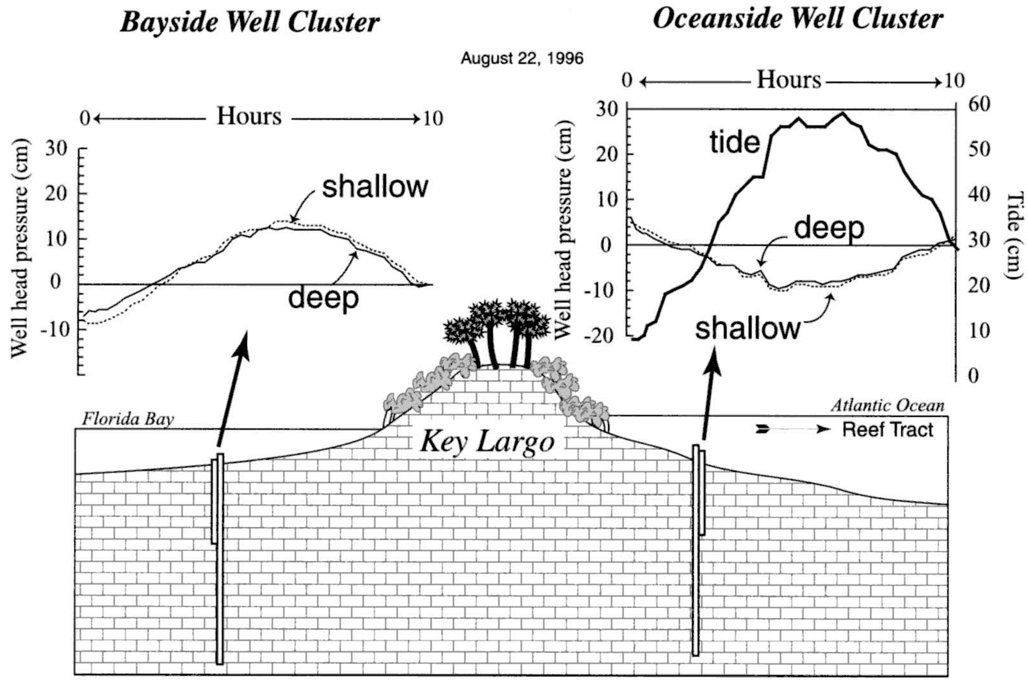

FIGURE 25.10 Pressure in OSWC and BSWC wells during a rising ocean tide. Pressure data were collected with the underwater manometer every 15 minutes for 10 hours. Tide in the bay varied by only 3 cm and therefore is not included in the figure. Notice that the shallow well generally exhibits more positive and negative values than the deep well. This is a result of the limestone dampening the tidal signal with increasing depth.

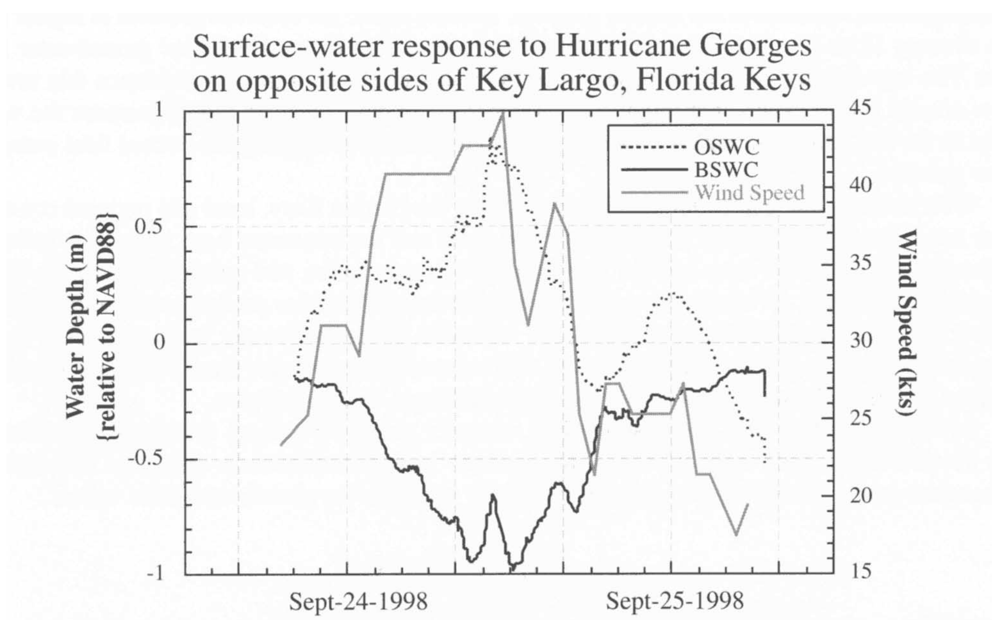

FIGURE 25.11 Water-level response in Florida Bay and Atlantic Ocean during Hurricane Georges. Plotted wind speed shows a direct correlation with height of water level in both the bay and ocean. Wind direction was from the east to southeast according to C-MAN weather station at Molasses Reef.

Based on the data from this study, the greatest forcing factor in the Upper Keys is the difference in water level between Florida Bay and the Atlantic Ocean. Data collected from pressure transducers on either side of Key Largo consistently indicate that the upper Florida Bay water level (averaged over 6 months) is 12 to 15 cm higher than the surface of the Atlantic Ocean. This head gradient over a distance of 500 m would be sufficient to drive groundwater movement at rates comparable to those observed in the tracer experiments. The higher water level on the bayside correlates two thirds of the time with a net direction of flow toward the reef tract. However, during storm events, easterly winds can depress the bay water level while raising the ocean water level, creating a head gradient opposite to the normal gradient. In most cases, the reversed gradient is higher than the average 12 to 15 cm and has the potential to result in a temporarily higher groundwater flow rate. The bay-directed flow rates observed in the tracer experiment provide evidence that reverse flow occurs. Storm events that might push water into the bay, however, would increase the water level in the bay and cause higher flow rates toward the ocean, mimicking the normal tidal pumping flow patterns.

With tourism and residential population rising in the Florida Keys, local and regional concerns over water quality changes of the nearshore and coral reef environments have increased. Influx of anthropogenic nutrients from sewage injection wells, septic tanks, and cesspools increases as the population increases. Evidence provided in this paper as well as other preliminary results from age dating of groundwater (Böhlke et al., 1999) indicates that groundwater seepage occurs in the nearshore. It seems highly likely that once contaminated groundwater discharges into nearshore surface waters, pollutants can also be transported offshore to the reef tract.

In summary, these data demonstrate that, whatever sewage treatment systems are installed in the Florida Keys, what must be taken into account is that both surface discharge and shallow subsurface injection will almost certainly find their way into the nearshore marine waters.

GLOSSARY OF TERMS

Boundstone. A rock unit for which the original components were bound together during deposition.

Calcrete. A dense and often laminated carbonate which can coat the surfaces of limestones. It is formed during exposure of limestone to rain water, resulting in a precipitation of calcium carbonate. Several successions of this precipitation result in a laminated calcrete. Calcrete formation typically takes place beneath a thin soil which can give the calcrete a brownish color. Synonymous with caliche or soilstone crust.

Grainstone. Carbonate rocks that are mud free and grain supported.

Hydraulic conductivity. A measurement describing the rate at which water can move through a permeable unit.

0oids. A spherical carbonate grain formed by precipitating calcium carbonate from seawater; most typically formed in high-energy environments. A rock unit composed primarily of ooids is an oolitic limestone.

Peloids. An oblong-shaped, fine-grained carbonate that may have been produced as fecal matter (pellets) by living animals such as crustacea. Peloids can also form via other mechanisms in warm, shallow seas.

Pleistocene. Period of time in the geologic history of Earth designated as the ice age. It spans a period of time from about 2 million years ago to 10,000 years ago. Large fluctuations in sea level occurred as the ice sheets advanced and retreated.

Vug. A small cavity in limestone; an underground chamber or cavity.

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