Biogeochemistry **38:** 189–205, 1997.

Magnitude and variations of groundwater seepage along a Florida marine shoreline

JAYE E. CABLE*, WILLIAM C. BURNETT & JEFFREY P. CHANTON
*Department of Oceanography, Florida State University, Tallahassee, Florida 32306-3048; jeyoung@nervm.nerdc.ufl.edu; wburnett@mailer.fsu.edu; * Current address: Department of Fisheries and Aquatic Sciences, 7922 NW 71st Street, University of Florida, Gainesville, Florida 32653*

Accepted 6 January 1997

Abstract. Direct groundwater inputs are receiving increasing attention as a potential source of nutrients and other dissolved constituents to the coastal ocean. Seepage into St. George Sound, Florida was measured extensively from 1992 to 1994 using seepage meters. Spatial and temporal variations were documented along a 7-km stretch of coastline and up to 1 km from shore. Measurements were made at 3 transects perpendicular to shore and 1 transect parallel to shore. The general results indicated that seepage decreased with distance from shore (2 of 3 transects), and substantial temporal and spatial variability was observed in seepage flow from nearshore sediments. In addition, trends in mean monthly integrated seepage rates were similar to precipitation patterns measured at a nearby coastal weather station. Based on these measurements, we estimate that the magnitude of groundwater seepage into the study area is substantial, representing from 0.23 to 4.4 $m^3 \cdot sec^{-1}$ of flow through the sediments, approximately equivalent to a first magnitude spring. Although it is unknown how representative this region is with respect to global groundwater discharge, it demonstrates that groundwater flow can be as important as riverine and spring discharge in some cases. Our subsurface discharge rates suggest groundwater is an important hydrologic source term for this region and may be important to the coastal biogeochemistry as well.

Introduction

Groundwater plays an important role in the water balance of many freshwater lakes and may also be an important source of nutrients and other chemical constituents to marine coastal waters. Groundwater inputs have been assessed through direct seepage measurements and water balance calculations and were shown to be significant to lake water budgets (Shaw & Prepas 1990a; Lesack 1995) and to lake nutrient supplies (Connor & Belanger 1981; Brock et al. 1982; Shaw et al. 1990). For example, Brock et al. (1982) demonstrated that groundwater accounted for about 30% of the water budget, 12% of the total phosphorus loading, and about 2% of the total nitrogen budget for Lake Mendota, Wisconsin. In Narrow Lake, Alberta, groundwater contributes ~30% of the water budget and is thought to be the largest single source of phosphorus to epilimnetic waters (Shaw et al. 1990). Lee & Hollyday (1993) estimated that about 36% of total stream flow along Carters Creek, Tennessee, was from groundwater seepage inputs.

Because lakes and streams are relatively smaller-scale semi-closed systems, water balance calculations are more simple in lake settings than in the coastal ocean. The magnitudes of the hydrologic sources and sinks (evaporation, precipitation, stream inputs and outputs) as well as the volumetric change of the water body are easier to obtain. Aquifers lose or gain water to lakes, streams, and coastal waters by several natural mechanisms set up by the hydraulic gradient between the aquifer and these standing bodies of water. Groundwater may enter coastal surface waters as dispersive seepage along shorelines, as point source seepage due to a breach in the confining layer of an underlying aquifer, and as spring discharge. For example, Bokuniewicz (1980) found that 10 to 20% of the freshwater entering Great South Bay, New York was from groundwater which entered as seepage through nearshore sediments. Because of the dispersed nature of such processes, locating and quantifying groundwater inputs is difficult.

Attempts to assess worldwide estimates of submarine groundwater discharge (SGD) have yielded vastly different results. SGD is defined in this paper as including both freshwater discharge from coastal aquifers and seawater recirculating through shelf sediments and continental margins. Many estimates of groundwater discharge, however, were based on rough water balance calculations of the freshwater component only. For example, Garrels & MacKenzie (1967) estimated that groundwater discharge amounts to about 10% of global surface runoff. Nace (1967) arbitrarily set groundwater input to the ocean at about 50×10^4 $m^3 \cdot sec^{-1}$ (about 70% of river discharge), but later, in a more quantitative approach Nace (1970) estimated this groundwater input to be only 0.7×10^4 $m^3 \cdot sec^{-1}$ (about 1% of the total riverine discharge). Zektzer et al. (1973) pointed out in their review of SGD that Nace (1970) probably underestimated the contribution of groundwater to the ocean. Nace's (1970) approach used the world shoreline length and an average discharge rate per unit length of shoreline but neglected deep artesian flow and may have used uncharacteristically low aquifer thicknesses. One of the more recent attempts to estimate the global export of groundwater along continental margins was reported by Cathles et al. (1987) to be less than half of Nace's (1970) value at $< 0.5\%$ of river discharge. Although these reports of SGD vary greatly, they demonstrate it comes in many forms, from seepage into rivers to seepage along marine shorelines, and from "leaky" continental margins to submarine springs.

Groundwater will "seep" into the marine environment along any coastline where the water table and underlying aquifers slope toward the sea. Several factors contribute to the rate of groundwater discharge along a coastline.

Aquifer transmissivity and variations in hydraulic head (the sum of pressure, velocity, and elevation heads) determine flow rates of groundwater through an aquifer, and ultimately, into the ocean. Transmissivity usually controls horizontal flow and is based on the relationship between soil and rock hydraulic conductivity and the saturated thickness of the aquifer. Another factor which influences groundwater flow is the vertical intrinsic permeability of overlying soils and sediments which directly influences the magnitude of groundwater recharge. Discharge measurements, obtained as subsurface fluids exit the sediments along a shoreline, represent the effective flow rate across the sediment-water interface. However, subsurface fluids discharging through nearshore sediments can also include recirculated seawater, whose flow is driven by these groundwater processes. In addition, the reverse of groundwater discharge, salt water intrusion, can occur in regions where domestic water wells have drawn down the water table. For example, the potable water of the Biscayne Aquifer located in south Florida has been significantly impacted by anthropogenic pressures, thus causing passive salt water encroachment to contaminate the aquifer.

Deep confined aquifers are not as efficient at discharging fresh water to the ocean as shallow aquifers, because fewer natural release points are available in that situation. Evapotranspiration and direct seepage are much less likely to occur from these aquifers. In a JOIDES drilling expedition along the southeastern United States coast of the Atlantic Ocean, Manheim (1967) documented the location of several offshore areas of freshened water. These continental shelf ($\sim$120 km offshore) freshwater zones appeared to occur along Eocene strata commonly associated with the continental Floridan Aquifer. However, Manheim (1967) recognized that these freshwater zones may be fossilized groundwater left from a previous low stand of the sea, and they may not have any discharge points.

Many factors control the flow of groundwater into offshore surface waters. However, the magnitude of groundwater discharge is not directly proportional to the length of adjacent coastline. For example, the United States coastline bordering the Atlantic Ocean is twice as long as the U.S. coastline along the Pacific Ocean yet the direct flow of groundwater into the Atlantic is probably several hundred times that into the Pacific (Zektzer et al. 1973). This difference in flow from each coastline may stem from the number and size of adjacent and underlying coastal aquifers, the size of the continental recharge area, and local geology. In addition, Zektzer et al. (1973) and Belyaev (1977) recognized that many rivers are groundwater-fed. The magnitude of riverine discharge to the ocean is relatively well-documented, but Belyaev (1977) reported that as much as 50% of that flow may have a groundwater source. Using a ^{226}Ra budget, Moore (1996) recently demonstrated that direct

SGD to the southeastern U.S. Atlantic Bight is equivalent to about 40% of the freshwater riverine input in the same area.

The discharge of groundwater and recirculated seawater from Florida is impressive due to its huge aquifer systems, long coastline, high precipitation, and karst terrain. The marine limestone and dolomite making up the Floridan Platform contain many underground caverns and tunnels constructed by slightly acidic groundwater flowing through the bedrock. Within this karstic environment exists one of the United States' largest underground freshwater reservoirs, the Floridan Aquifer (Rosenau et al. 1977). Shallow aquifers are present in the sand, clay, and limestone mixtures overlying the limestone bedrock, and these aquifers are usually hydraulically connected with the coastal Atlantic Ocean or Gulf of Mexico.

In this paper we focus on groundwater flow through nearshore sediment using direct seepage measurements. We made extensive measurements of flow using seepage meters between July 1992 and December 1994 to document the temporal and spatial patterns of groundwater seepage in a small area of the northeastern Gulf of Mexico. Quantitative estimates of direct submarine groundwater discharge were obtained by integrating seepage rates from the shoreline out to about 1 km at individual study sites. We show that a volumetrically significant amount of groundwater discharge occurs along a marine shoreline in this area.

Field site and measurement procedure

The field site is located approximately 80 km south of Tallahassee, Florida, near the Florida State University Marine Laboratory (FSUML) in the eastern end of St. George Sound (Figure 1). The topographic slope of St. George Sound in this area results in a water depth reaching about 2 m over 1000 m offshore. Mixed tides occur along this coast with a modest tidal range of about 0.6 m. Much of the bottom sediments in this marine environment are covered by several species of seagrass, including *Thalassia testudinum*, *Halodule wrightii*, and *Syringodium filiforme* (Iverson & Bittacker 1986). In areas where lush seagrass beds are present, the sediments are typically muddy sands. Coarser sand is located in a band near the shoreline and in patches throughout the seagrass beds.

The Floridan Aquifer, the largest aquifer in the southeastern U.S., is found along the northeastern Gulf of Mexico coast in the St. Mark's Formation, a layered marine limestone and dolomite structure of Miocene age (Hendry & Sproul 1966; Rosenau et al. 1977). The St. Mark's Formation ranges from 3 to 7 meters above sea level in the region about 65 km east of the FSUML to about 200 meters below sea level about 130 km west of FSUML. The

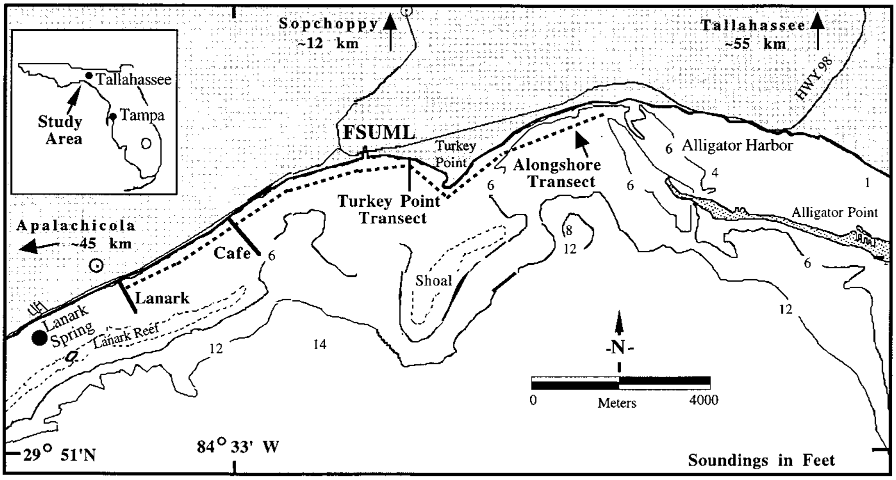

Figure 1. Map of field site located about 80 km south of Tallahassee, Florida, in St. George Sound. Three solid lines and one dashed line show the location of the seepage meter transects.

shallow portions of the St. Mark's Formation expose the Floridan Aquifer at the surface as sinkholes and springs in some locations. The location of the only exposed dolomite in Franklin County, Florida can be found near the marine laboratory (Hendry & Sproul 1966). According to the Florida Geological Survey, aquifer bedrock hydraulic conductivities in Florida have been found to range from 9.7×10^{-3} cm·sec^{-1} for chalky, re-crystallized limestone to 8.0×10^{-7} cm·sec^{-1} for hard dolomite.

Overlying the limestone and dolomite bedrock of the area is a sand, silt, and clay soil mixture which hosts the shallow water table aquifer. Vertical hydraulic conductivities measured on a sediment core collected in the study area at Turkey Point ranged from 2.6×10^{-5} cm·sec^{-1} at 0.3 m below the surface of the sediments to 1.7×10^{-6} cm·sec^{-1} at 3 m below the surface. Sand and clay layers dominated the sediments, with the lowest vertical hydraulic conductivity measured in a clay layer at 2 m in the core (7.4×10^{-7} cm·sec^{-1}). Limestone bedrock was found below 3 m in this region of the coastline based on the core data (L. Rasmussen, pers. comm.). Three nested monitor wells were also installed about 100 m offshore at Turkey Point near a seepage meter transect, and "slug tests" were performed on these wells at 0.5 m, 2 m, and 3 m in the sediments to obtain the in situ horizontal hydraulic conductivities. These conductivities ranged from 2.4×10^{-4} cm·sec^{-1} at 3 m depth to 6.2×10^{-3} cm·sec^{-1} at 0.5 m below the surface, with a average horizontal hydraulic conductivity of 2.8×10^{-3} cm·sec^{-1} for all 3 depths (L. Rasmussen, pers. comm.). The Floridan Aquifer system potentiometric surface of northwest Florida indicates that groundwater is flowing toward the coastline over much of the area between Apalachicola and Alligator Point, Florida (Wagner 1989).

Recharge to the Floridan Aquifer occurs in northern Florida and in neighboring southeastern states via precipitation and runoff (Rosenau et al. 1977). The surficial aquifers are recharged locally by precipitation. Regional precipitation normally peaks from June to October, while the lowest precipitation occurs in November/December and March to May. Annual mean precipitation for the region is 150 cm, as measured from 1964 to 1993 by the National Oceanic and Atmospheric Administration (NOAA) in Tallahassee, Florida. During our three year study period from 1992 to 1994, the mean annual precipitation was 160 cm as measured at the coastal NOAA weather station in Apalachicola, Florida. Precipitation was greatest in 1992 and 1994, while 1993 was considered a relatively dry year. Precipitation data used in this work was collected 45 km west of our study site at Apalachicola, Florida.

Seepage meters, based on a design described by Lee (1977), were used for direct measurements of seepage flow. The meters (0.255 m^2) consisted of the top or bottom 10 to 15 cm of a 55-gallon steel drum placed open-end down into the sediments (Cable et al. 1996). Each 4-L seepage collection bag was prefilled with 1000 mL of seawater prior to attachment to a sampling port on the seepage meter (Shaw & Prepas 1989; Cable et al. 1996). Seepage rate measurements were taken as the change in volume inside the 4-L plastic bag over the known time and area. Results of these measurements may be reported as either a flux ($mL{\cdot}m^{-2}{\cdot}min^{-1}$) or a velocity ($cm{\cdot}day^{-1}$) across the sediment-water interface. All reported seepage rate measurements are the mean daily rate ($\pm\ 1\sigma$) for 3 to 8 approximate hour-long measurements collected at each seepage meter during a single day. All measurements were contiguous and usually covered most of a tidal cycle.

Three transects, each consisting of 5 seepage meters apiece, were installed perpendicular to shore. Each seepage meter in a transect was placed approximately equal distance apart so that the last meter was deployed in a water depth of about 1.5 m (solid lines; Figure 1). “Lanark Transect” was located about 3.5 km west of FSUML and extended 1100 m offshore. “Cafe Transect” was placed about 2 km west of FSUML and the last seepage meter was 620 m offshore. “Turkey Point Transect” was placed less than 0.5 km east of FSUML and extended 480 m offshore. The selection of this area was based primarily on logistics (proximity to FSUML), and we have no reason to believe that it is in any way unusual. Measurements were collected at Lanark and Cafe transects primarily during our summer months (June, July, and August) between 1992 and 1994, while Turkey Point measurements were collected throughout the entire study period.

Another approach to the spatial distribution of groundwater discharge was taken in July 1994 by establishing a temporary transect ("alongshore transect") of 23 meters parallel to shore along the 7-km stretch of coastline from Lanark Transect to Alligator Harbor. We confined our study to the area near FSUML, but we were able to incorporate several different coastal geologic features within the 7-km transect, including marsh, beach, open water, a sound behind several longshore bars, and an area off a sandy spit. From this transect we were able to obtain finer resolution of nearshore seepage areas within our study site. This alongshore transect was approximately 100 m offshore and incorporated the most shoreward seepage meter from the three permanent transects. Eleven seepage meters were first installed between Lanark and Turkey Point and measurements were taken for two consecutive days (27–28 Jul. 1994). The temporary seepage meters were then removed from these sites, and the transect was extended from Turkey Point to Alligator Harbor, where they were measured for the next two consecutive days (29–30 Jul. 1994). All of the seepage meters were placed at a uniform distance from the shoreline ($\sim$100 m), which was far enough from the shore to avoid exposing any of the meters during low tide.

Successive rate measurements at each individual seepage meter during each measurement day were averaged so that the reported rates are a mean ($\pm 1\sigma$) for each station. In order to estimate total flow along the coastline at the perpendicular transects, the individual mean seepage rates were also integrated with distance from shore along the transect using the following relationship:

$$I = \sum_{i=1}^{n} (R_i \cdot d_i)$$

where I is the total seepage flow at the transect for a given set of measurements in units of discharge per length of shoreline ($L \cdot m^{-1} \cdot min^{-1}$); R_i is the mean daily seepage rate ($mL \cdot m^{-2} \cdot min^{-1}$) measured at each station (n = 5) along the transect; and d_i is the distance interval (m) between seepage meters. The mean monthly integrated seepage is then calculated by averaging daily integrated flows from each transect for a given month. This approach assumes that seepage beyond the end of the transects is negligible. Although our results indicate that this negligible seepage is generally the case, we may be underestimating total seepage flow during some time intervals.

Results and discussion

Spatial variations

Variations in sediment hydraulic conductivity and the presence of impermeable clay layers within a sediment column can cause the channeling of groundwater flow. This channeling occurs as groundwater flows along the path of least resistance throughout aquifers to seepage points in lakes, streams, and the coastal ocean. Storm and flooding events can deposit and redistribute sediment and over time this effect may re-route groundwater discharge. These channeling effects in sediments could cause spatial irregularities in seepage flow that result in wide variations within short distances (McBride & Pfannkuch 1975). For example, Shaw & Prepas (1990b) determined that the most sensitive parameter affecting the spatial distribution of seepage measurements within a relatively small area of Narrow Lake, Alberta, was probably due to variations in sediment hydraulic conductivity.

Seepage measurements were first made at the three seepage meter transects during a short time span in August 1992. Groundwater seepage is generally considered to be greatest at the shoreline with an exponential decrease offshore as the hydraulic head on the aquifer is lowered (McBride & Pfannkuch 1975; Lee 1977). However, representative seepage measurements collected at the Lanark transect on 19 and 21 Aug. 1992 did not demonstrate a systematic decrease in seepage with distance from shore (Figure 2). Seepage rates were less than 22 $mL{\cdot}m^{-2}{\cdot}min^{-1}$ (3 $cm{\cdot}day^{-1}$) at all stations along the transect except at 600 m offshore, which had rates approximately twice to three times as great. We do not know why this peculiar pattern is present along this transect. Factors such as sediment inhomogeneity may contribute to this high seepage offshore. For example, it is possible that a semi-permeable clay layer is present at some depth in these nearshore sediments but has been ruptured near the station with the high measured flow.

Results representative of the Cafe (Figure 3A) and Turkey Point (Figure 3B) transects do show a general decrease in groundwater discharge with increasing distance from shore. Although the patterns at each transect differ slightly, the first seepage meter at each of these two transects always yielded a much higher seepage rate than subsequent offshore meters. For example, the seepage rates ranged from 63 ± 15 $mL{\cdot}m^{-2}{\cdot}min^{-1}$ (9 $cm{\cdot}day^{-1}$) on 20 Aug. 1992 to 128 ± 2 $mL{\cdot}m^{-2}{\cdot}min^{-1}$ (18.3 $cm{\cdot}day^{-1}$) on 22 Aug. 1992 at the shoreward most station of the Cafe transect. During this same period, the Turkey Point transect yielded seepage rates for the nearshore station that were indistinguishable at 148 ± 19 $mL{\cdot}m^{-2}{\cdot}min^{-1}$ (21.1 $cm{\cdot}day^{-1}$) and 123 ± 19 $mL{\cdot}m^{-2}{\cdot}min^{-1}$ (17.6 $cm{\cdot}day^{-1}$). The rates observed at the Turkey Point transect in August 1992 turned out to be the highest measured during

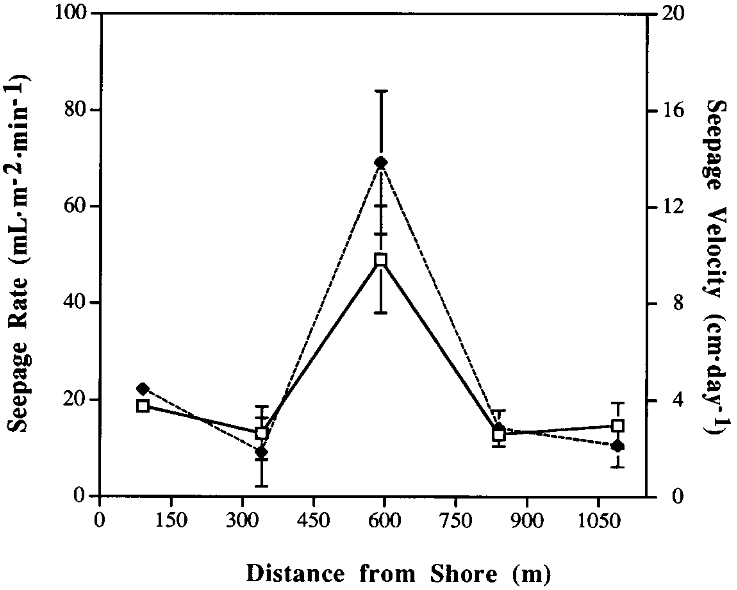

Figure 2. Results from seepage rate measurements made at the Lanark transect on 19 Aug. 1992 (open squares) and 21 Aug. 1992 (closed diamonds) show that seepage patterns do not change significantly on this time scale.

the entire study. Interestingly, although the overall transect seepage rates changed throughout the year, the systematic trend decreasing offshore always remained the same. Turkey Point transect seepage rates decreased appreciably at later time periods from the late summer highs we measured (Figure 3B).

A more detailed method for assessing spatial variations of alongshore seepage was also used during a short time span in July 1994 (Figure 4). Discharge measurements were made at a temporary alongshore transect placed parallel to the coast from the Lanark transect to Alligator Harbor and about 100 m from the shoreline. As observed in 1992 at the Lanark transect, the region at the western end of the study area yielded lower seepage rates. Seepage rates varied between 0 and 50 mL·m^{-2}·min^{-1} (0 to 5.5 cm·day^{-1}) approaching the Cafe transect from Lanark and between 0 to 30 mL·m^{-2}·min^{-1} (0 to 4.3 cm·day^{-1}) beyond Cafe transect to the FSUML. From the marine lab to and around Turkey Point, approximately 4.8 km east of the Lanark transect, seepage rates were very high, reaching to 161 $\pm$ 5 mL·m^{-2}·min^{-1} (23 cm·day^{-1}). East of Turkey Point and approaching Alligator Harbor, seepage rates decreased to less than 16 mL·m^{-2}·min^{-1} (2.3 cm·day^{-1}). The sharp increase in measured seepage flow around Turkey Point is probably related to several factors, including the highly permeable sandy sediments and the shallow depth of the aquifer system in this region. Despite the “patchy” occur-

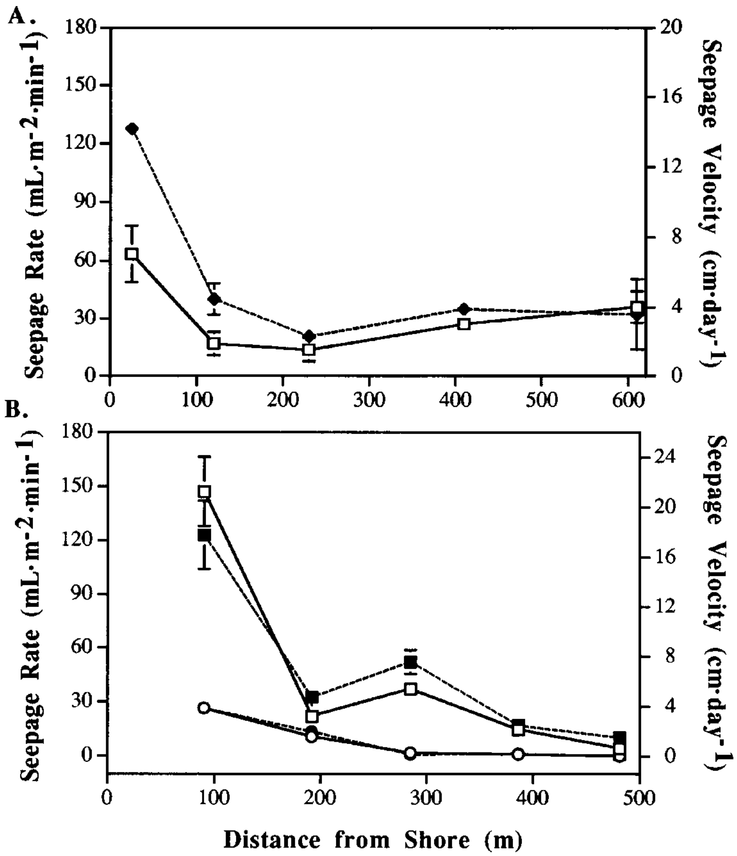

Figure 3. Results from seepage rate measurements at (A) Cafe transect on 20 Aug. 1992 (closed diamonds) and 22 Aug. 1992 (open squares) out to 620 m offshore; and (B) Turkey Point transect for summer (21 Aug. 1992, open squares; 22 Aug. 1992, closed squares) and spring (24 Mar. 1993, open circles; 25 Mar. 1993, closed circles) out to 480 m offshore demonstrate an exponential decrease with increasing distance from shore.

rence and dispersed nature of seepage flow, its widespread distribution along any shoreline could result in a significant regional input of groundwater and recirculated seawater.

Total seepage discharge from the area of each perpendicular transect was calculated by integrating the measured seepage rates from each seepage meter station with distance away from shore. In this manner, integrating the fluid flux by distance results in a discharge rate per unit of shoreline. Integrated seepage discharge from each measurement period was averaged on a monthly basis, and a summary of the mean monthly integrated seepage for each transect is reported in Table 1. Lanark and Cafe transects were measured primarily during the summer months between 1992 and 1994. The integrated seepage discharge

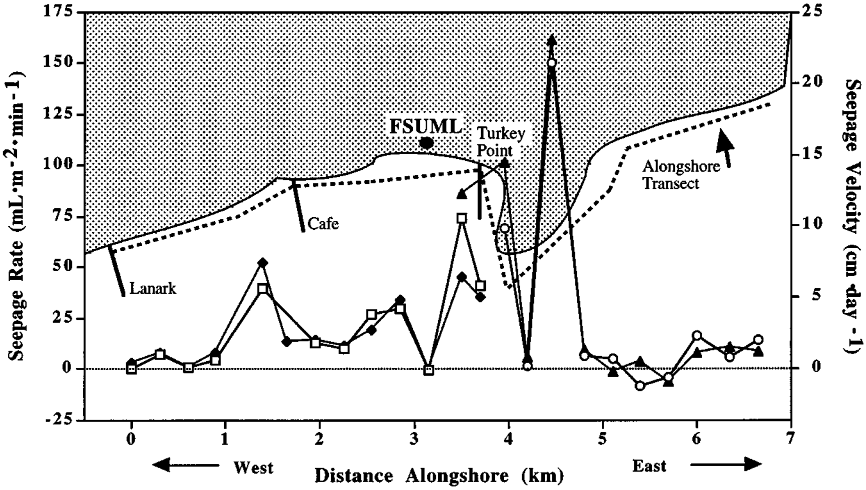

Figure 4. Seepage rate measurement results from the alongshore transect are given versus distance (km) along the coastline from Lanark Transect to Alligator Harbor. Four days of measurements are shown for 27 Jul. 1994 (open squares), 28 Jul. 1994 (closed diamonds), 29 Jul. 1994 (open circles), and 30 Jul. 1994 (closed triangles). A east-west sketch of the coastline is shown in the background to compare the spatial variability of seepage to landform shape.

was generally highest in August, 1992 and 1993 for both transects. The highest integrated seepage at Lanark was measured at 47 ± 28 L·m^{-1}·min^{-1} in August, 1992. Cafe transect integrated seepage was found to be highest in August, 1993 at 42.3 ± 8.4 L·m^{-1}·min^{-1}. Turkey Point transect was measured in August, 1992 (24.2 ± 4.7 L·m^{-1}·min^{-1}), and a more continuous record of seepage discharge was begun in 1993. The highest integrated seepage also occurred in August each year for Turkey Point transect. Total seepage flow through sediments appeared to be highest in 1992 and lowest in 1994 for Lanark and Turkey Point transects. The highest observed integrated seepage flow at Cafe transect occurred in 1993 and this transect was not measured in the summer of 1994.

Temporal variations

Changes in groundwater discharge from an aquifer can vary over time periods from hours to months. For example, McBride & Pfannkuch (1975) suggested that rapid fluctuations in groundwater seepage may occur over time due to changes in lake level and barometric pressure. In addition, in a comparison of seepage measurements in several environments, Lee (1977) demonstrated a distinct relationship between seepage flux and tidal height in Beaufort, North Carolina. Both tidal and seasonal seepage variability was observed in a Barbados coral reef (Lewis 1987) where it was determined that large data sets were

Table 1. Mean ($\pm 1\sigma$) monthly integrated seepage flows are given for Lanark, Cafe, and Turkey Point transects for "n" number of measurement periods during each month. Locations for each transect are given in Figure 1.

Transect	Year	Month	Mean Integrated Seepage ($L \cdot m^{-1} \cdot min^{-1}$)	n
Lanark	1992	April	7.8 ± 4.8	3
		May	7.7 ± 1.1	2
		July	12 ±	1
		August	47 ± 28	4
	1993	July	12.9 ± 2.4	2
		August	22 ±	1
		September	7.7 ±	1
		November	3.9 ±	1
	1994	June	11 ±	1
		July	9.8 ± 3.5	2
		August	8.4 ±	1
Cafe	1992	June	12.40 ± 0.15	2
		August	19.8 ± 6.8	7
	1993	June	35 ±	1
		July	30.6 ± 7.6	5
		August	42.3 ± 8.4	3
		September	39 ±	1
	1994	March	1.6 ±	1
Turkey Point	1992	August	24.1 ± 4.7	3
	1993	March	3.55 ± 0.15	2
		June	12.7 ± 1.7	3
		July	11.87 ± 0.93	3
		August	16.9 ± 3.7	4
		September	12 ±	1
		October	4.8 ±	1
		November	3.2 ±	1
		December	1.2 ±	1
	1994	January	2.05 ± 0.071	2
		February	2.80 ± 0.71	2
		March	2.8 ± 1.1	3
		April	5.0 ±	1
		May	5.5 ±	1
		June	4.8 ±	1
		July	8.1 ± 1.4	3
		August	15 ±	1
		September	15 ±	1
		October	5.55 ± 0.075	2
		November	6.3 ± 0.0	2
		December	1.3 ±	1

necessary to accurately predict temporal variations in groundwater discharge. However, two experiments performed at the Lanark transect in 1992 (Cable et al. 1996) and near the Turkey Point transect in 1993 (Cable & Burnett, unpublished data) did not reveal a discernible relationship between seepage flux, hydraulic head, and tidal height. Mini-piezometers were installed at station 2 of Lanark transect (1992 study) and at station 1 of Turkey Point transect (1993 study) next to the seepage meters. Hydraulic head was measured every 15 to 30 minutes on these piezometers using a manometer designed by Lee and Cherry (1980). The tidal height and seepage rates were also measured during this time, but no relationship was observed between these 3 parameters. It may be that flow through the sandy sediments of the study area responds more to onshore subsurface forcing than changes in tidal height.

A preliminary assessment of the temporal variation of subsurface fluid discharge was performed by comparison of the seepage rates in two different seasons. For example, seepage measurements collected at Turkey Point in August 1992 and the following March are compared here (Figure 3B). Although the trend of approximately exponential decrease in seepage with distance from shore was similar in both cases, the magnitude of flow had decreased significantly in March compared to the preceding August. The mean monthly integrated seepage ($\pm 1\sigma$) during the August 1992 measurement period was 21.4 ± 0.5 L·m^{-1}·min^{-1} but dropped to 3.6 ± 0.3 L·m^{-1}·min^{-1} by the following March. The main control on temporal variations in groundwater flow in this area is precipitation since recharge is governed largely by precipitation and the size of the recharge area.

The mean monthly integrated seepage at the Turkey Point transect, the only site where continuous measurements were made from 1993 to 1994 (Table 1), was compared to monthly rainfall totals to evaluate temporal variations of discharge (Figure 5). A distinct seasonal variation in measured seepage was observed which corresponded to changes in coastal precipitation. In general, the highest and lowest seepage flows occurred during the corresponding high and low precipitation periods. In August when yearly rainfall peaks, groundwater seepage measurements tended to reach their highest discharge. Likewise, when yearly rainfall is the lowest in December, the measured seepage rates were low. However, during the summer months in 1994, a slight “lag time” occurred between the high precipitation and the measured discharge along the shoreline. North Florida and south-central Georgia received 103 cm of rain between June and August of 1994 ($>$ 50% of the total rainfall for 1994), causing severe flooding in many cities and towns along riverbanks and in low-lying areas between Georgia and the coastline. This enormous flux of water likely was discharged to the Gulf of Mexico primarily as surface runoff. High measured seepage fluxes may not have been observed until later

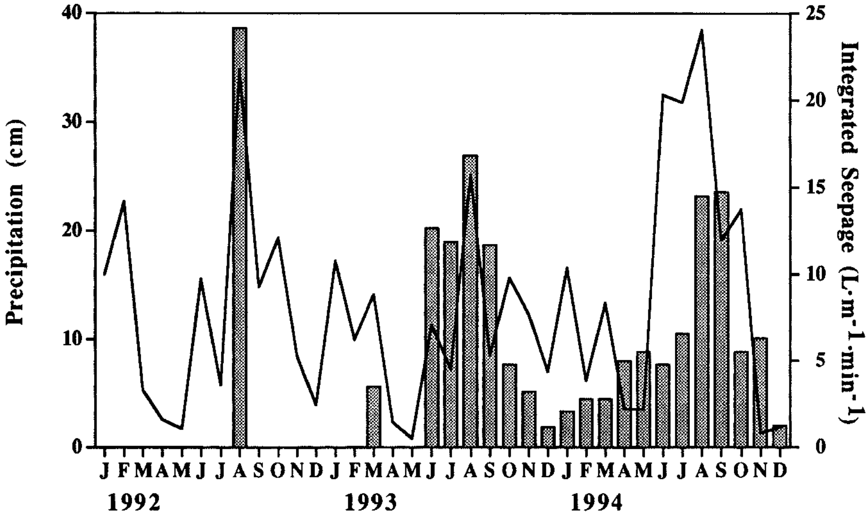

Figure 5. The mean monthly integrated seepage (bars; $L \cdot m^{-1} \cdot min^{-1}$) measured at the Turkey Point transect from August 1992 to December 1994 is shown with monthly total precipitation (solid line; cm) measured at Apalachicola, Florida, from January 1992 to December 1994.

in the summer of 1994 because the main aquifer recharge during this time was occurring farther inland.

Estimates of groundwater flow

Estimates of groundwater discharge into the nearshore waters of the study area are based on the long-term, mean integrated seepage measurements collected at the Turkey Point transect (Table 2). To put these estimates into perspective, we used approximate high, medium, and low integrated values of the seepage flow from this transect (Table 1) to calculate the length of "seeping" coastline required to equal the known average flow from the Apalachicola River and Wakulla Springs. The Apalachicola River is the largest river in Florida with a mean discharge of 720 $m^3 \cdot sec^{-1}$ (Fernald & Patton 1985), while Wakulla Springs is a first magnitude freshwater spring (defined as a spring with $\geq$ 2.8 $m^3 \cdot sec^{-1}$ discharge) in the vicinity with a discharge of 110 $m^3 \cdot sec^{-1}$ (Rosenau et al. 1977). Mean integrated seepage from the Cafe (25 ± 15 $L \cdot m^{-1} \cdot min^{-1}$) and Lanark ($14 \pm 12$ $L \cdot m^{-1} \cdot min^{-1}$) transects were within the range of 2 to 24 $L \cdot m^{-1} \cdot min^{-1}$ found at the Turkey Point transect, which demonstrates these values are at least reasonably representative of both temporal and spatial variations in the area. It is important to remember that Cafe and Lanark transects were sampled during the periods of highest precipitation only, and their mean integrated seepage flows do not include measurements

Table 2. Estimates of the magnitude of groundwater discharge are reported as the length of "seeping" coastline required for an equivalent flow of the Apalachicola River, the largest river in Florida, and Wakulla Springs, a first magnitude spring in the region. The range of mean monthly integrated seepage values were chosen from seepage measurements reported in this paper (*see* Table 1).

	Flow Rate $(L \cdot min^{-1})$[1]	Integrated Seepage $(L \cdot m^{-1} \cdot min^{-1})$	Approx. Length of Coastline Required to Support Flow (km)
Apalachicola River	4.3×10^7	24	1,800
		8	5,400
		2	22,000
Wakulla Springs	6.6×10^6	24	280
		8	830
		2	3,300

[1] Flow rates for the Apalachicola River and Wakulla Springs are equivalent to 720 $m^3 \cdot sec^{-1}$ and 110 $m^3 \cdot sec^{-1}$, respectively.

during lower flow periods. The alongshore transect, which only addressed seepage flow within 100 m of the shore, revealed seepage rates ranging from 0 to 161 $mL \cdot m^{-2} \cdot min^{-1}$. The highest seepage rates were found east of the sandy spit known as Turkey Point.

The entire length of Florida's coastline including the Atlantic coast around the Keys to Alabama on the Gulf of Mexico coast is roughly 13,600 km (Morris 1995). According to the U.S. Coast and Geodetic Survey, this shoreline length includes all bays, sounds, and other bodies of water to the head of tidewaters or to a point where waters narrow to 30 m. If the seepage estimates made here are representative of Florida, during times of high SGD flow the length of coastline required to equal Wakulla Springs flow is only about 280 km or 2% of the entire Florida coast. A similar calculation shows that only about 13% of Florida's coastline is required for seepage flow to equal the discharge of the Apalachicola River. On the other hand, during low seepage flow it would require a length of "seeping" coastline approximately 1.5 times as long as Florida to equal the flow from the Apalachicola River. The fact that the medium flow rate would produce something equivalent to the Apalachicola River over the coastline of Florida is significant. Stated another way, groundwater discharge along the study area's 7-km stretch of coastline ranged from 0.23 to 4.4 $m^3 \cdot sec^{-1}$. This flow is even more impressive when you consider that these estimates include only nearshore seepage without contributions from submarine springs or offshore seepage. Given the fact that Florida contains one of the world's largest natural underground freshwater reservoirs (the Floridan Aquifer), it is likely that large fluxes of groundwater enter the ocean through a combination of seepage and spring flow.

The magnitude of direct groundwater discharge into the ocean is an important but elusive link in the world's hydrologic budget which needs to be better quantified. The dispersed nature of seepage flow makes this task difficult, time-consuming, and labor intensive. Seepage is shown in this report to be volumetrically significant in one area of the northeastern Gulf of Mexico. It is likely that this process is important in many other areas as well, at least within areas such as Florida which is characterized by karstic geology. Significant ecological implications can arise from the study of this subsurface discharge of groundwater or recirculated seawater into coastal waters. Although this region clearly represents only a small portion of the global picture, it demonstrates that this flow can be as important as river and spring discharge in some areas.

Acknowledgments

Funding for this project was awarded to WCB and JPC by the National Science Foundation (OCE-91-01797) and Earthwatch, Inc. Climatological data was provided by the National Oceanographic and Atmospheric Administration stations in Apalachicola and Tallahassee, Florida. Thanks to Linda Rasmussen for allowing JEC to measure vertical hydraulic conductivities on her sediment core collected at Turkey Point, Florida, and for providing us with her slug test results for horizontal hydraulic conductivity. We thank G. Bugna, R. Corbett, P. Cable, M. Schultz, and many Earthwatch volunteers for their assistance in the field. The kind and helpful efforts by the marine lab staff at Turkey Point, Florida are greatly appreciated. We thank two anonymous reviewers for their helpful comments and suggestions.

References

Belyaev AV (1977) Integrated dependence of the water budget of the principal geographical zones of the world, Akad. Nauk. SSSR ser. geograph. No. 1. Summarized In: World Resources 1990-91, Ch 10, "Freshwater," Oxford University Press

Bokuniewicz H (1980) Groundwater seepage into Great South Bay, New York. Estuaries and Coastal Marine Science 10: 257–288

Brock TD, Lee DR, Janes D & Winek D (1982) Groundwater seepage as a nutrient source to a drainage lake: Lake Mendota, Wisconsin. Water Research 16: 1255–1263

Cable JE, Burnett WC, Chanton JP, Corbett DR & Cable PH (1996) A field evaluation of seepage meters in a coastal marine environment. Estuarine, Coastal and Shelf Science, in press

Cathles LM & members of Working Group 3 (1987) Fluid circulation in the crust and the global geochemical budget. In: Report of the Second Conference on Scientific Ocean Drilling, COSOD II (pp 67–86). Strasbourg, France

Connor JN & Belanger TV (1981) Groundwater seepage in Lake Washington and the Upper St. John's River, Florida. Water Resources Bulletin 17(5): 799–805

Fernald EA & Patton DJ (1985) Water Resources Atlas of Florida. Florida State University, Tallahassee, Florida, 291 pp

Garrels RM & MacKenzie FT (1967) Evolution of Sedimentary Rocks. Norton & Co

Hendry C & Sproul C (1966) Geology and groundwater resources of Leon County, Florida. Florida Geol. Surv. Bull. No. 47: 1–178

Iverson RL & Bittacker HF (1986) Seagrass distribution and abundance in eastern Gulf of Mexico coastal waters. Estuarine, Coastal and Shelf Science 22: 577–602

Lee DR (1977) A device for measuring seepage flux in lakes and estuaries. Limnol. Oceanogr. 22: 140–147

Lee DR & Cherry JA (1978) A field exercise on groundwater flow using seepage meters and mini-piezometers. J. Geological Educ. 27: 6–10

Lee RW & Hollyday EF (1993) Use of radon measurements in Carters Creek, Maury County, Tennessee, to determine location and magnitude of ground-water seepage. In: LCS Gundersen & RB Wanty (Eds) Field Studies of Radon in Rocks, Soils, and Water (pp 237–242). C K Smoley Publishing Co

Lesack LFW (1995) Seepage exchange in an Amazon floodplain lake. Limnol. Oceanogr. 40(3): 598–609

Lewis JB (1987) Measurements of groundwater seepage flux onto a coral reef: Spatial and temporal variations. Limnol. Oceanogr. 32(5): 1165–1169

Manheim FT (1967) Evidence for submarine groundwater discharge of water on the Atlantic continental slope of the southern United States, and suggestions for further research. New York Academy of Sciences Transactions, ser. 2 29: 839–853

McBride MS & Pfannkuch HO (1975) The distribution of seepage within lake beds. United States Geological Survey J. Res. 3: 505–512

Moore WS (1996) Large groundwater inputs to coastal waters revealed by ^{226}Ra enrichments. Nature 380: 612–614

Morris A (1995) The Florida Handbook. Peninsular Publ. Co., Tallahassee, Florida, 763 pp

Nace RL (1967) Are we running out of water? US Geological Survey Circ. 536: 7 pp

Nace RL (1970) World Hydrology: status and prospects. In: World Water Balance (pp 1–10), I. *Symposium for the Association of Internationale D'Hydrologie Scientifique Publication* No. 92

Rosenau J, Faulkner G, Hendry C & Hull R (1977) Springs of Florida. US Geol. Surv. Bulletin No. 31: 1–461

Shaw RD & Prepas EE (1989) Anomalous, short-term influx of water into seepage meters. Limnol. Oceanogr. 34: 1343–1351

Shaw RD & Prepas EE (1990a) Groundwater-lake interactions: II. Nearshore seepage patterns and the contribution of ground water to lakes in Central Alberta. J. Hydrology 119: 121–136

Shaw RD & Prepas EE (1990b) Groundwater-lake interactions: II. Accuracy of seepage meter estimates of lake seepage. J. Hydrology 119: 105–120

Shaw RD, Shaw JFH, Fricker H & Prepas EE (1990) An integrated approach to quantify groundwater transport of phosphorus to Narrow Lake, Alberta. Limnol. Oceanogr. 35: 870–886

Wagner JR (1989) Potentiometric surface of the Floridan aquifer system in the northwest Florida water management district. Northwest Florida Water Management District Water Resources Map Series 89-001

Zektzer IS, Ivanov VA & Meskheteli AV (1973) The problem of direct groundwater discharge to the seas. J. Hydrology 20: 1–36