Eogenetic Karst Hydrology: Insights from the 2004 Hurricanes, Peninsular Florida

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Abstract

Eogenetic karst lies geographically and temporally close to the depositional environment of limestone in warm marine water at low latitude, in areas marked by midafternoon thunderstorms during a summer rainy season. Spring hydrographs from such an environment in north-central Florida are characterized by smooth, months-long, seasonal maxima. The passage of Hurricanes Frances and Jeanne in September 2004 over three field locations shows how the eogenetic karst of the Upper Floridan Aquifer responds to unequivocal recharge events. Hydrographs at wells in the High Springs area, Rainbow Springs, and at Morris, Briar, and Bat Caves all responded promptly with a similar drawn-out rise to a maximum that extended long into the winter dry season. The timing indicates that the typical hydrograph of eogenetic karst is not the short-term fluctuations of springs in epigenic, telogenetic karst, or the smoothed response to all the summer thunderstorms, but rather the protracted response of the system to rainfall that exceeds a threshold. The similarity of cave and noncave hydrographs indicates distributed autogenic recharge and a free communication between secondary porosity and permeable matrix—both of which differ from the hydrology of epigenic, telogenetic karst. At Briar Cave, drip rates lagged behind the water table rise, suggesting that recharge was delivered by fractures, which control the cave’s morphology. At High Springs, hydrographs at the Santa Fe River and a submerged conduit apparently connected to it show sharp maxima after the storms, unlike the other cave hydrographs. Our interpretation is that the caves, in general, are discontinuous.

Introduction

Many karst springs are well known for their rapid response to rainfall (e.g., Birk et al. 2006). Such springs are characterized by “fast-response hydrographs” (White 2005, 298), which show individual storm peaks that return quickly to base flow levels. In contrast, other karst springs have “slow response hydrographs showing only wet or dry periods” (White 2005, 298). We have shown from a survey of many large springs (Florea and Vacher 2006) that the slow-response springs are typical of eogenetic karst, whereas the fast-response springs typify telogenetic karst.

From the perspective of the flashy hydrographs of telogenetic karst, the explanation of the smooth hydrographs of eogenetic karst is that the “contributions of individual storms have been averaged out and that only the rise and fall of discharge with seasonal wet and dry periods is reflected in the hydrographs” (White 2005, 568). Similarly, we wrote, “The cumulative effects of all the precipitation events during the wet season drive the changes in discharge at these (eogenetic) springs” (Florea and Vacher 2006, 358). We will present evidence in this paper of a different explanation. Although seasonal rainfall is an expected feature of areas where eogenetic karst is located (Jordan 1984), the smooth hydrographs can logically be seen to be the product of the long, drawn-out response to a few major storms as opposed to the sum of the near daily rainfalls of the rainy season.
Hurricanes Frances and Jeanne were discrete, identifiable recharge events in the Florida peninsula and provided an opportunity to study how eogenetic karst responds to recharge-generating rainfalls. The result of the study is clearer hydrologic distinction between eogenetic and telogenetic karst.

Eogenetic Karst

The terms “eogenetic” and “telogenetic” were applied to karst (Vacher and Mylroie 2002) to draw a parallel with the first and third of the three time-porosity stages defined by Choquette and Pray (1970). According to the Choquette and Pray scheme, the eogenetic and telogenetic stages are before and after the reduction of primary depositional porosity by burial diagenesis. Thus, the hallmark property that distinguishes eogenetic and telogenetic karst is the magnitude and relative significance of the continuum of matrix (intergranular) porosity—effectively, matrix permeability. Not surprisingly, matrix permeability of karst limestone varies roughly inversely with geologic age (Florea and Vacher 2006): the older the limestone, the more likely it has experienced burial diagenesis. In the globally distributed examples of carbonate aquifers compiled by Budd and Vacher (2004), for example, the matrix hydraulic conductivities of the five Cenozoic aquifers, log $K$ (m/s) = $-5.5 \pm 1.5$, differ by 4 orders of magnitude from the matrix hydraulic conductivities of the seven Paleozoic and Mesoozoic aquifers, log $K$ (m/s) = $-9.5 \pm 1.5$.

Cenozoic carbonate aquifers and eogenetic karst are not randomly distributed around the world. Reasonably, they occur in the same general region where carbonate sediments are forming now—that is, broadly, silicilastic-deprived, low-latitude (tropical to subtropical) settings not far from warm, marine water. Indeed, according to the original usage of Choquette and Pray (1970; e.g., 216), the eogenetic zone is a “net depositional realm” and the telogenetic zone is a “net erosional realm.” Extension of the terms to karst by emphasizing the magnitude of matrix porosity blurs that distinction but does associate eogenetic karst with the geography of marginal marine carbonate deposition.

Where, then, do eogenetic meteoric diagenesis and eogenetic karst occur? One locale is isolated, small carbonate islands (Vacher 1997), including low reef islands of atolls and barrier reefs, low eolianite islands such as Bermuda, low platform islands such as Tongatapu and Grand Cayman Island, uplifted atolls such as Nauru and Niue, and high–reef composite islands such as Barbados and Guam. Another is the exposed portions of isolated or attached carbonate platforms such as the Bahama Banks and the Florida and Yucatan peninsulas, including their associated small islands (e.g., San Salvador, the Florida Keys, and Cozumel, respectively).

The rainfall characteristics of such places reflect their low-latitude locations and proximity to warm marine water. Many examples fall into the Aw (tropical, dry winter) climate (Koeppen classification, e.g., Aguado and Burt 2004), where the seasonality results from the summer poleward shift of the Intertropical Convergence Zone (ITCZ). Some occur in Cfa (humid subtropical), on the west side of the subtropical anticlines. Generalizing, then, the habitat of eogenetic karst typically includes a rainfall regimen dominated by frequent thunderstorms, whether they be due to the ITCZ, easterly waves entrained within the trade winds, or local convection—and, of course, infrequent tropical cyclones (hurricanes). As a result, the amount and character of rainfall are typically seasonal, with convective thunderstorms during the summer and tropical cyclones during the late summer and early fall. In Barbados (13° N), for example, the rainy season is May through November. At Heron Island (23° S, southern Great Barrier Reef), the rainy season is December through June.

In our comparison of spring hydrographs of eogenetic vs. telogenetic springs (Florea and Vacher 2006), we found a seasonality in the spring discharge in areas of eogenetic karst. That study, which was based on long-term records of spring discharge and rainfall, indicated a rather long lag time between the height of the rainy season and the culmination of the spring discharge—90 d in the case of Silver Springs, Florida. We interpreted the lag time to be a measure of the moderating effect of the large storage in the permeable matrix pore space of the eogenetic karst of west-central Florida. We now have field data from that eogenetic karst that allow association of changes in spring discharge and cave water levels to particular rainfalls. The data shed light on how the seasonality of rainfall that typifies the climate of eogenetic karst connects to the hydrology of eogenetic karst itself.

The field area, peninsular Florida, is well suited to make the connection. Low, small, carbonate islands, which in some ways could be considered the archetype of eogenetic karst, are particularly unsuited. The reason is that the whole of a small, low, permeable, eogenetic karst island is affected, and analysis of water levels is confounded, by low-frequency (seasonal) sea level fluctuations (e.g., Bermuda, see Rowe 1984). Moreover, the dynamics of a lagging “interface” come into play. Neither of these complications affects the Florida interior.

Study Area

Geology

The Upper Floridan Aquifer (UFA), one of the world’s classic regional aquifers (Back and Hanshaw 1970; Fetter 1994, 293–303), underlies all of peninsular Florida. It is unconfined or semiconfined north of about Tampa (Figure 1). Where it is unconfined, the UFA is part of an active, modern karst characterized by sinkholes (Tihansky 1999), extensive cave-scale porosity (Florea 2006a), and 33 first-magnitude springs (Scott et al. 2004). This regional karst includes Alachua, Gilchrist, Marion, and Citrus counties (Figure 1), the area of our study.

The carbonates in which the karst is developed are the Ocala (Late Eocene) and Suwannee (Oligocene) limestones. They formed when what is now the Florida peninsula was an isolated bank and silicilastic sediments from the north were diverted into a now filled seaway (Back and Hanshaw 1970). Porosity of the Ocala Limestone averages about 30% (Loizeaux 1995). Mean matrix permeability is on the order of $10^{-6}$ m/s (Florea 2006b).
Mapping of caves in the study area has revealed the character of the elements of secondary porosity in rocks of the UFA (Florea 2006a, 2006b). Detailed surveys of caves such as Briar Cave (Figures 1 and 2) document an architecture composed of laterally extensive, tabular cavities at several levels with vertical connections provided by dissolved out fissures conforming to approximately NE–SW and NW–SE fractures. The importance of the fracture porosity is underscored by the ubiquity of solution-enlarged, soil-filled fractures in the epikarst exposed in quarry walls. Significantly, the caves of the cave levels are not interconnected. They likely do not represent an integrated system of conduits leading to springs. Cave passages often end in blind pockets, progressively narrowing fissures, and collapses. Sediments from younger units commonly choke caves and fill drilled cavities in west-central Florida. These sediments, as noted by Back and Hanshaw (1970, 366), would "reduce permeability enough to retard flow and generate a higher head (water table)."

Although less common, conduit flow does occur in the karst of Florida. In one documented example, along the Santa Fe River in our study area (Figure 3), conduit flow between a sinking stream and a river rise some 5 km downstream has been established by scuba diving, dye tracing, and other means (e.g., Martin et al. 2006; Martin and Portell 2002; Screaton et al. 2004). The spring hydrograph is marked by dramatic changes in spring discharge that are directly linked to river stage and precipitation events (Screaton et al. 2004). It differs from the smooth hydrographs of typical eogenetic karst presented in Florea and Vacher (2006). Chemographs at the rise document rapid exchange of water between conduit and matrix porosity (Martin and Dean 2001) and attest, in general, to the easy communication between the three elements of the triple-porosity system of eogenetic karst.

Another sinking stream and river rise conduit system is documented in the Woodville Karst Plain (WKP) and Wakulla Springs in the Florida Panhandle (Figure 1). Cave divers have mapped approximately 60 km of partially connected underwater conduits in the WKP (Loper et al. 2005). This conduit system is of a magnitude not documented elsewhere in Florida.

Rainfall

With the highest elevation about 100 m and no point of land as much as 100 km from warm marine water, the Florida peninsula is ideally situated for summer thunderstorms. Maps in introductory textbooks showing the distribution of thunderstorms in the continental United
States indicate “by far the greatest incidence is over central Florida, where thunderstorms occur on average more than 100 days per year” (Aguado and Burt 2004, 334). For our study area, the incidence is more than about 75 thunderstorm days per year according to a state map based on the 30-year period, 1948 to 1977 (Jordan 1984). According to the same data compilation, there are 1.2 to 1.5 thunderstorms per thunderstorm day; the duration is 1.0 to 1.8 h per thunderstorm; 70% to 80% of the thunderstorm days occur during the 4-month period of June to September; and about 20 thunderstorm days occur during the peak months of July and August. The peak occurrence of these thunderstorms is in the midafternoon, with 60% to 70% of the thunderstorms occurring between 2:00 p.m. and 7:00 p.m. (Jordan 1984).

The summer thunderstorms create a strong seasonality in Florida’s rainfall. Some 40% of the approximately 140 cm/year rainfall of Florida occurs in June, July, and August (Martin and Gordon 2000). There is also a secondary maximum in the late winter that is associated with the southern penetration of middle latitude weather systems (Jordan 1984). This secondary maximum increases northward and particularly into the panhandle. According to maps in Jordan (1984), the warm-season (June to September) rainfall averages about 18 cm or more per month in our study area, and the cold-season (December to March) rainfall averages 9 cm per month, for a warm-season/cold-season rainfall ratio of about 2. For comparison, the ratio is about 1.4 in the western panhandle.

Unlike the frequent, short-lived thunderstorms, hurricanes and tropical storms have huge rain areas, sometimes exceeding 400 km in diameter. They move slowly and can take days to pass a given locality. The result is that tropical systems contribute significantly to the rain totals in the months that they occur, which in Florida is typically in the late summer and early fall. According to the summary in Jordan (1984), on average about 20 tropical storms and hurricanes per decade crossed the shore or came within 200 km of it in the 90-year period ending in 1980, and 61% of them occurred in September and October. A map in the same reference shows that about 30% of the long-term average rainfall for the month of September in the study area came from tropical storms and hurricanes.

By any measure, 2004 was an unusual year for hurricanes in Florida. Four major hurricanes crossed the state during a 6-week period. Frances made landfall on September 5 as a Category 2 storm, and Jeanne made landfall on September 26 as a Category 3 storm (Figure 1). They followed nearly identical paths across the peninsula (Figure 1). They covered thousands of square kilometers, producing flooding rainfalls that affected our entire study area. In addition, feeder bands from Hurricane Ivan, which made landfall in the panhandle, brushed our study area during the time between Frances and Jeanne. These storms provided us the opportunity to obtain hydrographs from eogenetic karst in which specific recharge events can be identified and witness how the karst aquifer responded.

**Data Acquisition**

The data are from three locations (Figure 1): Morris Cave in the Radar Hill Quarry, Citrus County; Briar Cave, Marion County; and a 540-km² area of Gilchrist and Alachua counties, the High Springs Water Gap (HSWG), south of the Santa Fe River (Figure 3). Exploratory water level monitoring was under way at all three locations before the hurricanes arrived and, after the hurricanes, was extended well into the following dry season.

Pressure transducers at all sites provided hourly water level data. At Morris Cave, precipitation data were collected hourly with an on-site rain gauge. We used on-line weather stations for daily rainfall amounts from Ocala for Briar Cave (5 miles outside of town) and from the town of High Springs for HSWG. We supplemented the water level and precipitation data at Briar Cave with hourly drip rate measurements from the matrix porosity of the vadose zone using a tipping bucket rain gauge. Finally, at Briar Cave and in the HSWG, we obtained daily measurements of discharge from the combined vents of Rainbow Springs (28 km from Briar Cave, USGS Station no. 02313100) and the Santa Fe River (at the northwest corner of High Springs study area, USGS Station no. 02321500; Figure 3). These data are available from the USGS on-line data archives.

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Figure 3. Map of the HSWG study area in Alachua and Gilchrist counties. Black dots are the locations of individual monitoring sites. Open circles along the Santa Fe River are the locations of springs. Dashed lines are prehurricane water levels in the Floridan Aquifer. The shaded region in the western portion of the study area delimits the outcrop of the Miocene Hawthorn Group and the dark polygons in this region are lakes.
Site Details and Limitations

The entrance to Morris Cave is a recent collapse feature exposed in the Radar Hill Quarry. The large cave entrance is adjacent to a water retention pond. Storm events produce rapid runoff on the surface of the reclaimed quarry, and on occasion, the pond overflows into the cave causing erosion and sediment transport. More than 2 m of sediment accumulated in the cave during the study period. The sediment buried and eventually destroyed the in-cave instrumentation.

Briar Cave is in a vastly different setting than Morris Cave—no quarry and only a small, natural entrance. Briar Cave is an air-filled cave with more that 1 km of surveyed passage (Figure 3). Access to Briar Cave was limited to one Sunday per month by request of the landowner. Our power systems failed several times after December 2004, causing periods of interrupted data. By March 2005, mineral precipitation on the rain gauge collecting drip rate data prevented further measurements.

The well-instrumented HSWG is an ongoing study funded by the Florida Department of Environmental Protection to monitor ground water flow conditions in the vicinity of the large springs on the Santa Fe River. The study consists of seven water level monitoring sites (PW-2 through PW-8) managed by Karst Environmental Services Inc. The seven sites lie at various distances from the Santa Fe River (Figure 2; Table 1). PW-6 is an aquifer-sustained pool in Bat Cave, an air-filled cave with more than 1 km of surveyed passage. PW-5 is in Bradley Sink, a site of discrete recharge to the Floridan Aquifer. The other five sites are drilled wells. One of them, PW-2, intersects a 3-m-high submerged cavity.

All but one monitoring site in the HSWG study provide a continuous record during the period of study. The exception is PW-6, Bat Cave, where four important months (July 18 to November 12, 2004) of data are missing because a rodent in the cave chewed apart the cable from the piezometer.

Results

The time series data (Figure 4) capture the effects of both localized rain events of the summer rainy season in August of 2004 and the widespread precipitation from the hurricanes that followed that September:

- At Morris Cave (Figure 4A), the cave at the quarry, thunderstorm-induced, short-duration, high-amplitude spikes with an amplitude of more than 2 m and an average duration of 4 d are superimposed on a long-term (multimonth) variation of approximately 2 m that started with Hurricane Frances.
- At Briar Cave (Figure 4B), the water table variation contains two distinct step-ups that occur after each hurricane. Overall, the variation is similar to the long-term variation at Morris Cave. The amplitude is approximately 2 m and the peak water level occurs 41 d after Frances. The discharge at nearby Rainbow Springs follows a similar pattern. The vadose drips from the matrix porosity inside the cave follow a later schedule (Figure 4B).
- Among the seven monitoring sites in the HSWG (Figure 4C), only the well closest to Santa Fe River (PW-2) has a storm-spiked pattern like that of the river. PW-4 and PW-5 show two step-ups like the pattern at Briar Cave. The other sites show a smooth rise and maximum like the main signal at Morris Cave (Table 1).

The time series data in Figure 4 also document the contrast in the areas covered by the different types and amounts of rainfall. The hurricanes covered the whole area. Hurricane Frances dumped 28 cm in 2 d at Morris Cave, 28 cm in 3 d at Ocala, and 34 cm in 3 d at High Springs; Hurricane Jeanne followed with 18 cm in 1 d at Morris Cave, 5 cm in 1 d at Ocala, and 16 cm in 2 d at High Springs. In contrast, the other recorded rainfalls, in particular the August rainfalls, illustrate the localized nature of the normal summer rains. For example, a storm on August 7, 2004, at High Springs produced 3.5 cm of precipitation. This same storm did not occur at either Morris or Briar Caves. The next day, 5 cm of rain fell during 4 h in the afternoon at Morris Cave, while no precipitation occurred at either Briar Cave or High Springs.

The typical summer rainfalls register conspicuously on the hydrograph at Morris Cave, where water overflows into the cave from a pond at a quarry. These same summer rainfalls do not produce short-term changes in the water level at

<table>
<thead>
<tr>
<th>Site</th>
<th>Distance from the Santa Fe River (km)</th>
<th>Change in Water Level, Pre-Frances to Post-Jeanne (m)</th>
<th>Time from Event to Peak Water Level in Figure 4 (d)</th>
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<tr>
<td>Santa Fe</td>
<td>0</td>
<td>—</td>
<td>Frances 6 Jeanne 5</td>
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<td>PW-2</td>
<td>3</td>
<td>2.2</td>
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<td>PW-3</td>
<td>5</td>
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<td>PW-4</td>
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<td>PW-8</td>
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The summer thunderstorms in our record of Florida rainfall apparently did not appreciably recharge the aquifer. They did not register on the water table. By contrast, the hurricane rainfalls affected the water table and did so promptly (Figure 4). Without question, they were recharge events.

The difference in the scale of the two types of rainfall can be shown by a simple calculation. For Hurricane Frances alone, the 30 cm of rainfall over the 8770 km$^2$ of the four-county study area amounts to approximately 2.5 x 10$^9$ m$^3$ of water. In contrast, 5 cm of rainfall from a thunderstorm affecting an area 25 km in diameter would produce 2 orders of magnitude less water or approximately 2.5 x 10$^7$ m$^3$. Thus, it would take about 100 of these thunderstorms to deliver the same amount of water to the four counties.

The hydrographs make clear that it is the hurricanes that are responsible for the post-thunderstorm seasonal high in the water levels of 2004. The amplitude of this maximum is consistent with that interpretation. Assuming no loss to evapotranspiration during the days of the storms, the two hurricane rainfalls amounted to a potential recharge of roughly 50 cm. At many of the sites, the water table rise was about 2 m, suggesting a specific yield of about 25%. This compares to the matrix porosity of about 30% for these limestones (Loizeaux 1995).

Our finding of the ineffectiveness of the summer thunderstorms for recharge confirms a similar finding by Martin and Gordon (2000) from a 1-year study (1996 to 1997) of a nearby field site in Alachua County. Only 10% of the 52-cm June to August rainfall recharged the aquifer. In contrast, 46.4 cm (75%) of the year’s recharge occurred during a large storm in October and a second large storm in April.

**Time Lag between Rainfall and Peak Response**

Hurricane Frances initiated and Hurricane Jeanne augmented a rise in water levels that lasted through the fall months to a seasonal maximum approximately 40 d after the hurricanes. This 40-d lag between the rainfall and the peak of the response is based on the identification of the recharge-generating rainfall events.

In contrast, cross-correlation between 852 months of rainfall and spring discharge data at Silver Springs (Marion County) produced a time lag of 90 d (Florea and Vacher 2006, Table 2). This statistically derived result is undoubtedly incorrect because it is blind to the fact that many of the rainfalls contributing to the rainy season do not recharge the aquifer. The statistical 3-month lag from the peak rainfalls of July and August to the culmination of the spring discharge likely also reflects the occurrence of numerous September and October recharge events due to tropical storms and hurricanes over the 70-year period of record.

**Significance of Fractures**

Not counting the anomalous spikes from the artificial inflows at Morris Cave, the cave hydrographs (Morris Cave, Briar Cave, and Bat Cave [PW-6]) consist of broad, draw-out responses to the recharge events characteristic of diffuse rather than conduit flow (e.g. Hobbs and Smart 1986). They are synchronous with each other and, moreover, synchronous with the well (noncave) hydrographs, indicating that the recharge is broadly distributed rather
The two wells in the HSWG that experienced a 3-m rise in water level and is marked by a chain of lakes (Figure 3). The Hawthorn is within the HSWG; it contains the aquifer (Back and Hanshaw 1970). An erosional remnant from overlying Hawthorn confining beds that confine the conduits is that they become choked with sediment eroded (Florea 2006a). This interpretation fits the findings from exploration and mapping of subaerial, formerly submerged caves in the area. Why do the other cave hydrographs not communicate easily with the highly permeable matrix porosity? PW-2, on the other hand, is clearly a conduit—there is synchronicity in the well, and the hydrograph emerges with the water level at Briar Cave (Figure 4B). The recharge transport revealed at Briar Cave is widespread and can explain why all the hydrographs started their rise at the same time (Figure 4).

Character of the Saturated Zone

One of the striking features of the water table hydrographs (Figure 4) is how similar so many of them are; another is how this similarity holds regardless of the presence or absence of caves at the monitoring site. At many monitoring localities, including all three cave sites (Morris Cave, Briar Cave, Bat Cave), a water-filled sinkhole (Bradley Sink), and two of the noncave sites (PW-4 and PW-8), the hydrographs began to rise promptly with Hurricane Frances and rose to approximately 2 m above prehurricane conditions some 40 d later. It certainly does not appear that two storm pulses passed through a system of connected conduits en route to springs while being effectively disconnected from low-permeability rocks enclosing the conduits. Instead, the synchronous cave and noncave water level variations suggest that the cave porosity communicates easily with the highly permeable matrix porosity. PW-2, on the other hand, is clearly a conduit—there is a 3-m-high cavity in the well, and the hydrograph emulates the river. Why do the other cave hydrographs not look more like PW-2? The answer, we believe, is that the caves are discontinuous, that the norm for caves in this karst is that they are not conduits (Florea 2006b). This interpretation fits the findings from exploration and mapping of subaerial, formerly submerged caves in the area (Florea 2006a).

One of the reasons that the caves do not serve as conduits is that they become choked with sediment eroded from overlying Hawthorn confining beds that confine the aquifer (Back and Hanshaw 1970). An erosional remnant of the Hawthorn is within the HSWG; it contains the water table and is marked by a chain of lakes (Figure 3). The two wells in the HSWG that experienced a 3-m rise rather than a 2-m rise are either in the erosional remnant (PW-7) or next to it (PW-3). The lower specific yield of the siliciclastic sediments in the uneroded unit (PW-7) or reworked into the cavernous porosity (PW-3) could account for the different response and explain the occurrence of the steep gradient in the neighborhood of known open conduits explored by cave divers at Ginnie Springs along the Santa Fe River (Figure 3).

Discussion and Conclusions

Our findings have some broad implications to karst hydrology that, we believe, warrant further discussion. First, they support the concept of a threshold for rainfalls that produce recharge in eogenetic karst. Second, they suggest that it is relevant to draw a distinction between caves and conduits in eogenetic karst.

The summer thunderstorms that characterize the rainy season in our study area did not noticeably recharge the aquifer, whereas the hurricanes certainly did. Martin and Gordon (2000) similarly found at a nearby location that summer rainfalls were inconsequential in comparison to two rainfalls in the dry season. Farther away in Barbados, Jones and Banner (2003) found from comparison of oxygen isotope concentrations in rainfall and ground water that the rainfalls of the rainy season did not recharge the aquifer unless they exceeded 19.5 cm in a month, which they called a threshold. Applying the technique to Puerto Rico and Guam, they obtained uncannily similar thresholds of 19 and 20 cm/month, respectively. If an even approximately similar threshold applies to our field area, where summer rainfalls average 18 cm/month (Jordan 1984), many summer months will not have recharging rainfalls. In general in eogenetic karst, it cannot be assumed that a rainy season, which is a common feature to these areas, equates to a recharge season. If seasonal variations of temperature and thus potential evapotranspiration are also significant, the rainy season will coincide with the high potential evaporation season. Both derive from the high-sun season.

The distinction between caves and conduits is relevant because the prevailing view of caves in karst hydrology is heavily colored by the perspective of epigenic karst in telogenetic limestones. Thus (White 1988), “Seen in true context, the theory of cave origins is nothing more than the theory for the development of the conduit permeability of a carbonate aquifer.” More recently, Klimchouk and Ford (2000, 46) define karst as “… an integrated mass-transfer system in soluble rocks with a permeability structure dominated by conduits dissolved from the rock and organized to facilitate the circulation of fluid” (following Huntoon 1995). These views are appropriate for epigenic telogenetic karst. In eogenetic karst, however, it is not appropriate to assume that water courses through the limestone via a system of integrated conduits among a diffuse continuum of fracture permeability in otherwise uninvolved, low-permeability rock. Rather, eogenetic karst features permeable rock. This permeable matrix contains fractures and caves. Some of the caves are connected and form conduits. Some are former conduits that are now choked with sediment that they are disconnected. Many formed as and remain simply chambers (Mylroie and Carew 2000). All
permeability elements—matrix, fractures, caves that are conduits, caves that are not conduits—come into play in the hydrology of eogenetic karst.

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