GEOPHYSICAL RESEARCH LETTERS, VOL. 39, L24401, doi:10.1029/2012GL053933, 2012

Visualization of conduit-matrix conductivity differences in a karst aquifer using time-lapse electrical resistivity

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Received 19 September 2012; revised 7 November 2012; accepted 8 November 2012; published 19 December 2012.

[1] In the karstic upper Floridan aquifer, surface water flows into conduits of the groundwater system and may exchange with water in the aquifer matrix. This exchange has been hypothesized to occur based on differences in discharge at the Santa Fe River Sink-Rise system, north central Florida, but has yet to be visualized using any geophysical techniques. Using electrical resistivity tomography, we conducted a time-lapse study at two locations with mapped conduits connecting the Santa Fe River Sink to the Santa Fe River Rise to study changes of electrical conductivity during times of varying discharge over a six-week period. Our results show conductivity differences between matrix, conduit changes in resistivity occurring through time at the locations of mapped karst conduits, and changes in electrical conductivity during rainfall infiltration. These observations provide insight into time scales and matrix conduit conductivity differences, illustrating how surface water flow recharged to conduits may flow in a groundwater system in a karst aquifer. **Citation:** Meyerhoff, S. B., M. Karaoulis, F. Fiebig, R. M. Maxwell, A. Revil, J. B. Martin, and W. D. Graham (2012), Visualization of conduit-matrix conductivity differences in a karst aquifer using time-lapse electrical resistivity, *Geophys. Res. Lett.*, *39*, L24401, doi:10.1029/2012GL053933.

1. Introduction

[2] Karst aquifers are used by 25% of the world's population for drinking water resources and comprise around 40% of the groundwater of United States [*Ford and Williams*, 2007]. While karst aquifers provide important water resources world-wide (e.g., southeastern Appalachian mountains; mid-west USA; Yucatan peninsula; southwestern China; circum-Mediterranean region), they are generally poorly understood due to the spatial and temporal complexity of the flow patterns caused by widely varying porosity and permeability and the organization of the conduit and matrix system. Traditional groundwater approaches (e.g., so-called Darcian approaches that assume laminar flow) poorly represent flow paths and rates within karst conduits and their surrounding matrix [*Ford and Williams*, 2007; *Rosenberry and LaBaugh*, 2008]. Conduits control flow in the aquifer, while matrix porosity stores most of the water, which leads to a high degree of uncertainty in flow paths locations, travel times, nutrient dynamics, and dissolution of the soluble minerals comprising the aquifer. The interconnectedness of surface water with groundwater leads to a vulnerability of these aquifers to contamination, limitations of their sustainability, and difficulties in their management [*Veni et al.*, 2001]. Understanding interactions between flow in conduits and storage in matrix porosity is thus crucial. These fundamental hydrologic processes have long been studied in the Upper Floridan Aquifer of the Santa Fe River basin in Florida, the field site for this work [*Bailly-Comte et al.*, 2010; *Gulley et al.*, 2011; *Martin and Dean*, 1999, 2001; *Martin and Screaton*, 2001; *Martin et al.*, 2006; *Moore et al.*, 2009, 2010; *Screaton et al.*, 2004].

[3] Hydrogeophysics has been a growing field in karst hydrology that has been used in part to improve understanding of distribution of secondary porosity [*Jardani et al.*, 2007; *Legchenko et al.*, 2008; *McGrath et al.*, 2002; *Sumanovac and Weisser*, 2001; *van Schoor*, 2002]. Electromagnetics, gravity, and ground penetrating radar are generally considered the most suitable methods for detecting karst conduits and other large cavities [*Chalikakis et al.*, 2011; *Thomas and Roth*, 1999]. The highly irregular soil and subsurface bedrock complexity in karst systems has been suggested to limit electrical resistivity tomography [*Chalikakis et al.*, 2011; *Thomas and Roth*, 1999]. To our knowledge, no previous geophysical field experiment has successfully applied time-lapse electrical resistivity tomography (ERT) in karstic systems, to study conduit-matrix conductivity differences.

[4] Karst watershed dynamics have been explained using conductivity, thermal and chemical data, most commonly at springs [*Bailly-Comte et al.*, 2011, 2010; *Martin and Dean*, 1999, 2001; *Martin and Screaton*, 2001; *Martin et al.*, 2006; *Screaton et al.*, 2004]. Recent work, largely based on differences in discharge at river sinks and springs where rivers rise to the surface, suggests that allogenically recharged surface water may exchange with groundwater in matrix porosity during high flow [*Martin and Screaton*, 2001] (Figures 1d and 1e). At baseflow, water stored in matrix porosity discharges to conduits. Consequently water discharging at baseflow exhibits high electrical conductivity (up to ~500 μS/cm) as a result of equilibration with soluble minerals of the aquifer. During high flow, surface water with low electrical conductivity (~50 μS/cm) can drain into the subsurface through sinkholes and reversing springs [*Gulley et al.*, 2011]. Differences

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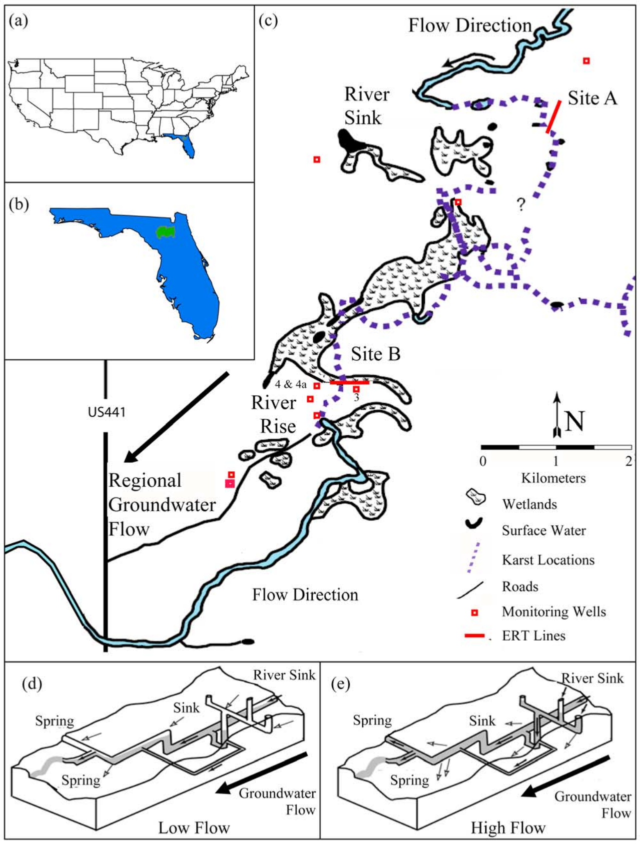

Figure 1. (a) Region of the United States of the study area in blue and (b) the Santa Fe River basin in the green region of Florida. (c) Santa Fe River sink-rise system, with the Santa Fe River shown in blue. The Santa Fe River is captured by a karst window and follows a network of karst conduit (denoted by dashed lines) until it reappears five kilometers downstream. ERT study locations are shown with red lines and denoted by Site A and Site B. (d) Hypothesis of baseflow in a karst conduit system. (e) Hypothesis of high-flow in a karst conduit system. Adapted from *Bailly-Comte et al.* [2011], *Langston et al.* [2012] (With kind permission from Springer Science+Business Media: Interactions of diffuse and focused allogenic recharge in an eogenetic karst aquifer (Florida, USA), Hydrogeology Journal, 20, 2012, 767–781), and *Martin and Screaton* [2001].

in electrical conductivity between the surface water and groundwater produce variable conductivity water in the conduits depending on the fraction from each source [*Grasso and Jeannin*, 2002; *Hess and White*, 1988].

[5] During low flow conditions, flow through the Santa Fe River Sink-Rise system takes 3–5 days, while during high flow conditions travel times can be less than 24 hours [*Martin and Dean*, 1999; *Screaton et al.*, 2004]. Differences in discharge from the Santa Fe River Sink and Santa Fe River Rise indicate storage of water in the matrix, but penetration depths into the matrix are unknown [*Moore et al.*, 2009]. With large differences between electrical conductivities of the surface water and groundwater, we expect time-lapse ERT to record variations in resistivity within matrix and conduits. ERT should be able to distinguish low conductivity water derived from surface runoff as it flows into conduits and displaces high conductivity groundwater of the matrix porosity. Measurements taken over time should allow for the first time subsurface observations of water conductivity differences between the conduits and matrix and how these differences changes through time.

2. Methods

2.1. Field Site

[6] Our test site is located in the Santa Fe River watershed, north-central Florida, USA (Figures 1a and 1b). The Santa Fe River watershed is underlain by the Floridan aquifer system, which is confined by Miocene Hawthorn Group siliclastic rocks in it eastern half but where the Hawthorn Group has been removed by erosion in the western half the Floridan aquifer system is unconfined. The Floridan aquifer system is comprised of a sequence of thick pre-Miocene age dolomite and limestone and is split into the Upper and Lower Floridan Aquifers by the Middle Confining Unit. The boundary between the confined and unconfined Floridan aquifer system is classified as semi-confined (defined as where the Hawthorn Group is 0 to 30 m thick [*Scott*, 1988]). At this boundary, the Santa Fe River is captured by a sinkhole (Santa Fe River Sink, Site A) connected to water-filled conduits that lead to a first magnitude spring (Santa Fe River Rise, Site B) about 5 kilometers to the south (Figure 1c). Approximately 10,000 meters of these conduits have been mapped by cave divers and dye and thermal tracing has connected the Santa Fe River Sink with the Santa Fe River Rise [*Hisert*, 1994; *Martin and Dean*, 1999; *Screaton et al.*, 2004]. Wells have been installed to the depths of the conduits and to the water table in the gap between the Santa Fe River Sink and Santa Fe River Rise that allow monitoring the variations in the electrical conductivity of the groundwater [*Moore et al.*, 2009].

[7] To remotely sense changes in conductivity away from the wells, we set up two electrical resistivity tomography survey lines across locations of known conduits (red lines in Figure 1c). One survey line was located ~1 km downstream of the Santa Fe River Sink (Site A). The second survey line was placed ~200 m upstream of the Santa Fe River Rise (Site B). Electrical conductivity of surface water may decrease by up to 400 μS/cm (~90% decrease in electrical conductivity) during precipitation events [*Bailly-Comte et al.*, 2011]. To test if ERT can be used to detect these changes non-intrusively and therefore estimate the positions of the conduits, we collected nearly 2 months of time-series ERT data. These data sets were inverted using a time lapse inversion algorithm recently introduced by [*Karaoulis et al.*, 2011], providing visualization of resistivity changes through time. This inversion process is a finite element approach where resistivity changes are modeled in areas where significant changes are expected.

2.2. Geophysical Experiment Setup and Processing

[8] At both sites, ERT electrodes were emplaced with bentonite clay (to decrease the contact resistance of the ground electrode contacts) at 5 m spacing for the duration of the time-lapse experiment. Measurements for ERT were made with an ABEM system using a Wenner array.

[9] Data was processed using MATLAB®. Raw resistance data were filtered to within acceptable ranges that were seen in field observations of conductivity. The inversion process is described in the auxiliary material. Data sets were considered to be acceptable when the errors were <10%. The

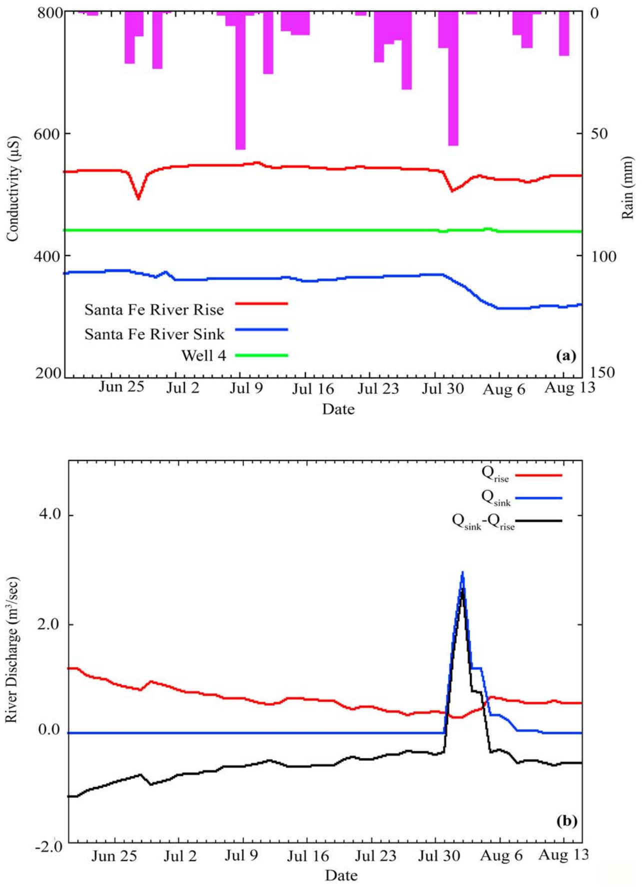

Figure 2. (a) Precipitation and conductivity in O'Leno State Park, conductivity is shown for groundwater at well 4, Santa Fe River Sink and Santa Fe River Rise. (b) Discharge from the Santa Fe River Sink and Santa Fe River Rise and the difference between these flows for the time period of June 23rd through August 15th.

filtered data were then inverted simultaneously and a time-lapse inversion model output error was $\sim$5%.

3. Results and Discussion

[10] We compare here the electrical resistivity tomography observations that were collected over a 2-week time period (July 27th to August 8th) when rain events changed electrical conductivity at the sampling and observation locations (Figure 2a). Rain during this time averaged from 20-50 millimeters per day (Figure 2a) reducing surface water conductivity by $\sim$15% at both the Santa Fe River Sink and Santa Fe River Rise. These changes in conductivity reflect allogenic recharge from the confined portion of the basin and flow through the conduit system [*Martin and Dean*, 2001] Groundwater conductivity varies by less than 10 μS/cm in Well 4 with no response to the rain events (Figure 2a). Well 4 is used to estimate the regional specific conductivity of groundwater because it has the smallest variance in composition of all the monitoring wells, which is interpreted to indicate little mixing with allogenic water [*Moore et al.*, 2010] and due to its proximity to our electrical resistivity tomography lines. During our entire study period there is discharge from the Santa Fe River Rise; however, there is only discharge at the Santa Fe River Sink between July 31st and August 10th (Figure 2b). The difference in discharge between the Santa Fe River Rise and Santa Fe River Sink is shown on Figure 2b, where a negative difference reflects draining of groundwater matrix and a positive difference reflects a recharge event. During our electrical resistivity tomography data collection period, groundwater consistently drains into the karst conduits until a recharge event occurs (August 1st to August 5th). Other large rain events have been observed during this time frame, however these events did not generated flow at the Santa Fe River Sink or a subsequent recharge event. Using an estimate of a 20-meter conduit, 20% porosity and an even distribution of recharge a mixing depth of conduit water can be estimated. For this rain storm low conductivity water could penetrate the groundwater matrix out to a distance of 8 meters.

[11] Subsurface resistivity for both Sites A and B are shown in Figure 3 at six times during the time period of July 27th through August 8th. Locations of conduits mapped during cave-dive exploration are projected on the cross-sections of electrical resistivity (plain closed lines in Figure 3). These projections are scaled to be 20 m in diameter. This corresponds to the average size of the conduits estimated by *Screaton et al.* [2004], although cave diver descriptions of the conduits indicate conduit diameters are locally variable (M. Poucher, personal communication, 2004). A highly resistive shallow layer is seen on all surveys (>4000 ohm m), which corresponds to an approximately 1 to 3 m thick layer of drained undifferentiated Plio-pleistocene sands overlaying the limestone of the Upper Floridan Aquifer. Distinct resistivity anomalies occur at the estimated locations of the projected conduits at both ERT lines. These anomalies reflect contrasts in electrical resistivity, which we interpret to be caused by the differences between the resistivity of the water in the conduits and the water in the matrix porosity. Similar anomalies in resistivity occur in locations that have no known conduits and may represent unidentified conduits. The same magnitude of resistivity changes are not seen in these other locations, suggesting they may be minor flow pathways of smaller conduit size or less well connected to the main conduit, limiting the amount of low-conductivity water that enters them. A clearer signal is seen at Site B than at Site A, likely due to the proximity of the karst conduit to the highly resistive layer at Site A. This proximity may cause some distortion and smearing of the resistivity signal.

[12] Both sites show responses to changes in the resistivity of the Santa Fe River Sink water resulting from the August 1st rain event (Figure 2), but their magnitudes are different (Figures 4 and 5). The resistivity value increases by nearly 150 ohm-m at Site A; point C is located in the middle of the projected conduit (Figure 4). The surrounding area also has increased resistivity, but by only 50 to 75 ohm-m. Resistivity also increases at all of the points selected from Site B, but the increases are smaller than at Site A and each point increases by only around 20 ohm-m (Figure 5). The larger differences in variations in resistivity at Site A than Site B may result from the proximity of Site A to the Santa Fe River Sink and the source of low conductivity rain water. Alternatively, differences in the size of the conduits, or increased dissolution surrounding the conduits [*Moore et al.*, 2010] may alter the way that conduit and matrix waters mix. Figure 5c shows point resistivity values through time for interpreted minor flow

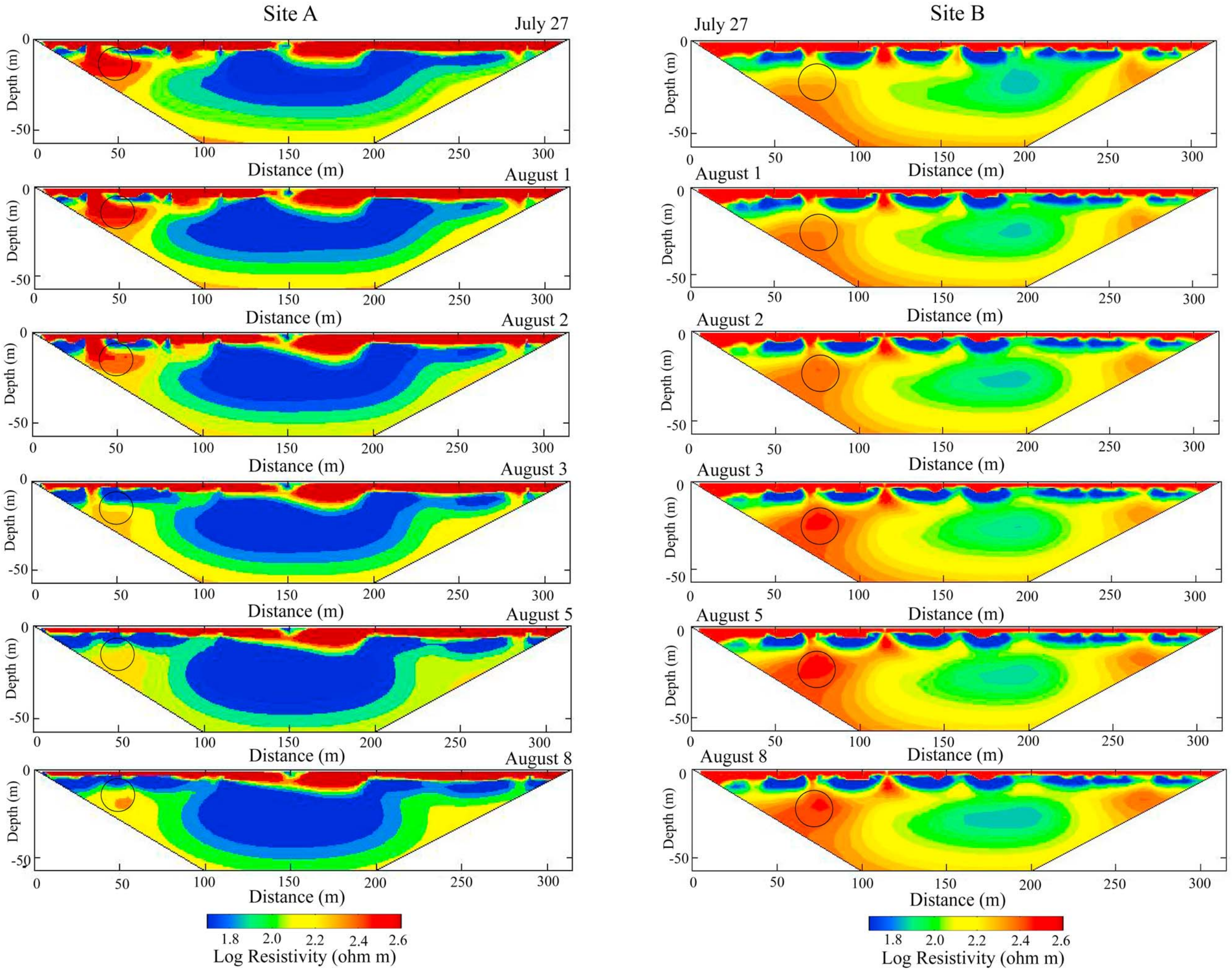

Figure 3. Electrical resistivity tomography inversions for Site A and Site B. Spatial distribution of resistance (ohm m) over time between July 27th and August 8th. Estimated karst conduit locations are shown by black circles and are not to scale. Resistivity values (ohm m) are shown in log space.

pathways at Site B (Area 2), in a pattern similar to those at known conduit locations (Figures 4b and 5b). However, these locations show a smaller magnitude change (∼10 ohm-m) in resistivity compared to other pathways, indicating they receive less of the low-conductivity water.

[13] The smaller increase in resistivity with distance from the estimated location of the conduit may reflect propagation into the surrounding matrix porosity of allogenically recharged low-conductivity water in the conduit. The minimum change in resistivity occurs about 20 meters on either side of the maximum change; this distance may reflect the penetration depth of water into the matrix porosity. Using a volumetric flux calculation with constant porosity and recharge, we estimated mixing out to 8 meters. While these estimates differ (i.e., 8 meters from a volumetric flux and 20 meters from an ERT anomaly), the exact diameter of the conduits at these locations is unknown, recharge distribution may not be constant along the karst conduit, and preferential flow may change mixing penetration. By these assumptions, mixing out to 20 meters is possible. The distance water flows into the matrix will depend on the magnitude of precipitation, antecedent elevations of the water table, and thus variations in head gradients between the conduit and the matrix porosity. However, due to inversion processing and smoothing this decrease in resistivity with distance may be an artifact of the model and has yet to be verified.

[14] Although both locations show a similar increase in electrical resistivity, the peak resistivity at Site A occurs on August 2nd (Figure 4) while the peak at Site B occurs three days later on August 5th (Figure 5). This lag may represent the transit time for the pulse of low conductivity water from the August 1st rainstorm to pass through the system. The three day lag estimated here matches very well with thermal tracer measurements of flow time for the sink-rise system at these river stages [*Martin and Dean*, 1999]. Once the pulse of rainwater has discharged from the conduit network, the conduits begin to drain the matrix again and the conduit water would be comprised of a mixture of groundwater and surface water (Figures 3 and 4). A different temporal signal is seen at the minor flow paths (Figure 5c). Here, peak resistivity is seen around Aug 8th which lags by 3 days the peak resistivity observed at the known location of the conduit (Figure 5a). This delay could reflect the poor hydrologic

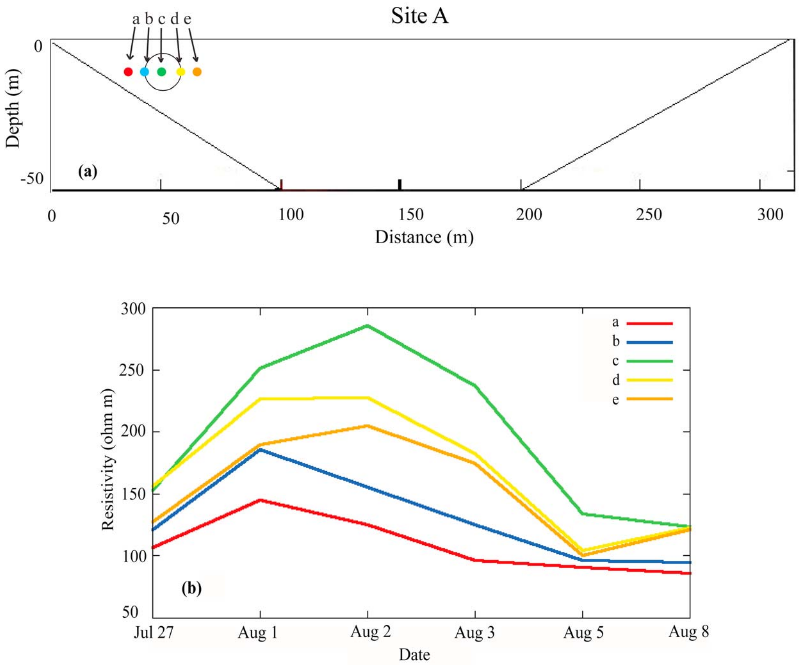

Figure 4. Point resistivity (ohm m) measurements through time for Site A. (a) Locations of the points with respect to the subsurface profile and (b) a plot of resistivity data. Point C is in the middle of the projected conduit shown on Figure 3, Point B and D are at +/− 10 meters from Point C, Points A and E are +/− 20 meters from Point C.

connection with the main conduit and thus a longer residence time for the low-conductivity water to reach this location.

4. Conclusions

[15] In this study, we used time-lapse ERT observations in an area with known locations of water-filled conduits to quantify temporal and spatial changes in electrical resistivity to assess conductivity differences of water between conduits and matrix porosity. During baseflow conditions we see karst conduits have a mixture of surface water and groundwater, resulting from conduits draining highly conductive matrix water and mixing with less conductive surface water. After a rain event dilutes the conductivity of the surface water, resistivity increases at the location of the conduit. This increase in resistivity is seen out to a distance of

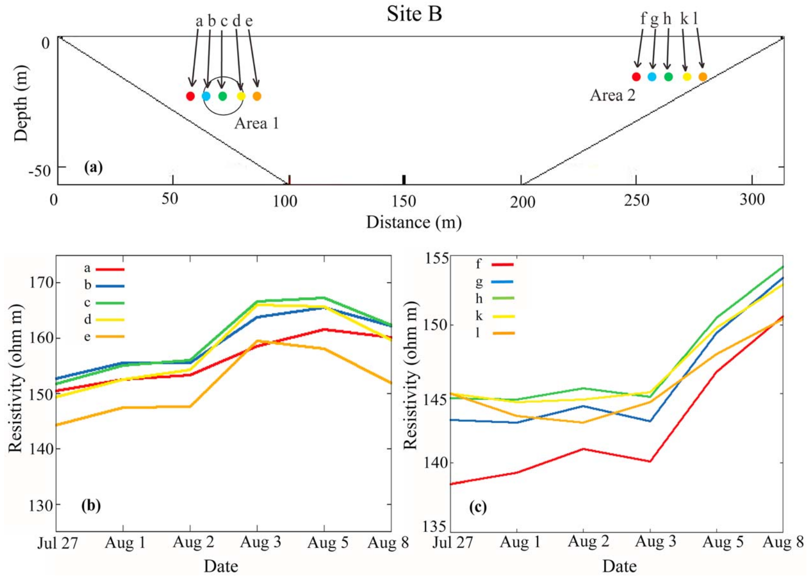

Figure 5. Point resistivity (ohm m) measurements through time for Site B. (a) Locations of the points with respect to the subsurface profile and plots of resistivity through time for (b) Area 1 and (c) Area 2. Area 1 is where a mapped karst conduit is, with Point C being the center of the projected conduit, point B and D +/− 10 meters from the center, and Point A and E +/− 20 meters from the center. Area 2 is where an interpreted karst conduit is, with Point H being the center of the projected conduit, point G and K +/− 10 meters from the center, and Point F and L +/− 20 meters from the center.

20 meters, which may indicate penetration of conduit water into the groundwater matrix. However, the inversion processes could cause this resistivity pattern. Conduit water penetration has yet to be verified. Our time-lapse geophysical experiment visualizes differences in conduit-matrix conductivity and temporal dynamics of the karst system [*Martin and Dean*, 1999; *Martin and Screaton*, 2001], which is a fundamental advancement in understanding karst systems. Understanding these dynamics has a direct impact on understanding water flow, quantity and quality (e.g., nutrient cycling and drinking water resources) in karst systems, which are crucial to the world's populations drinking supply.

[16] **Acknowledgments.** This work was funded by the National Science Foundation (EAR-0854516) and supported by the Colorado School of Mines and the University of Florida. We thank O'leno State Park staff for allowing us to work inside the park.

[17] The Editor thanks the anonymous reviewer for his/her assistance in evaluating this paper.

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