CHAPTER 4

Quantifying potential recharge through thick soils in mantled sinkholes using ERT data

ABSTRACT

We quantified potential recharge through thick soils in mantled sinkholes using differential electrical resistivity tomography (DERT). Conversion of time-series 2-D ERT profiles into 2-D modeled soil moisture profiles using a numerically optimized form of Archie's Law allowed us to monitor soil moisture differences over time. These results were combined with Penman-Monteith daily potential evapotranspiration (PET) and daily precipitation data to quantify potential recharge through thick soil profiles. Potential recharge calculated from three sets of time-series ERT data indicated that precipitation contributing to potential recharge only occurred during brief periods when precipitation exceeded PET. Over the study duration, potential recharge amounts calculated from changes in soil moisture ranged from 19% to 31% of cumulative precipitation. Spatial distribution of infiltration showed that a significant amount occurred on sinkhole flanks, though overland flow also caused higher amounts of infiltration in sinkhole bottoms. Results also indicated that soil filled sinkholes can both transmit water rapidly to an underlying aquifer and store and slowly release water as a result of slower infiltration.

INTRODUCTION

Recharge and infiltration are important hydrologic processes which are difficult to understand and quantify at the field scale. The process of water movement from the surface into the subsurface is defined as infiltration, while recharge is defined as water which is added to an aquifer (Scanlon et al., 2002). Recharge can be further separated into actual recharge and potential recharge. Potential recharge usually refers to water which has infiltrated to a depth at which it may be assumed to recharge an aquifer at some time in the future (Scanlon et al., 2002). Exceptions to this assumption are in arid regions or in areas with extremely deep unsaturated zones. Understanding where, when, and how much water recharges an aquifer is critical information for understanding groundwater quality and quantity (de Vries and Simmers, 2002). An important reason for obtaining a better understanding of infiltration and recharge is that the ability to model transport of dissolved contaminants through the unsaturated zone requires information about where, when, and how infiltration and recharge are occurring.

Recharge occurs at variable rates via different mechanisms depending on geologic, climatic, biologic, and geomorphic settings. In many settings, recharge is a relatively slow process resulting from diffuse infiltration of precipitation through soils and underlying bedrock. One notable exception is in many karst settings where a significant portion of the recharge entering an aquifer can occur as direct recharge via sinking streams flowing through conduits which are open to the surface. While this process (sometimes referred to as rapid or point-source recharge) can quickly add large amounts of water to a karst aquifer, an extension of the same conduit system which rapidly introduced water to the aquifer may also rapidly remove it. Rapid recharge is often cited as one reason why karst aquifers are extremely sensitive to contamination, and sinkholes, in particular, are targets of concern as a potential source of significant contamination (Lee and Krothe, 2001; Stephenson et al., 1999). Sinkholes are usually considered part of the epikarst, which is the uppermost portion of a karst system and contains both unsaturated and saturated conditions and may contain a significant amount of the storage capacity in a karst system (Doctor et al., 2006; Klimchouk, 2004; Lee and Krothe, 2001; Perrin et al., 2003). The epikarst also has the ability to transmit water relatively rapidly if infiltrating water bypasses matrix flow through soils by flowing through preferential flowpaths (Maloszewski et al., 2002; Perrin et al., 2003).

In karst settings, sinkholes are often modeled conceptually as sources of rapid recharge (White, 2003; White et al., 1995). However, characterizing soil filled sinkholes as sources of rapid recharge may not be entirely accurate, and soil filled sinkholes could actually be considered an end member in a sinkholes classification scheme. This scheme can very generally be considered to range from sinkholes with no soil and an open conduit, to sinkholes containing thick clay-rich soils and no openings. Thick clay- and silt-rich soils, in particular, have the capacity to store and slowly release large amounts of water, in addition to allowing water to pass relatively rapidly through the unsaturated zone via macro-pores such as old root casts, burrows, and soil fractures (Iqbal and Krothe, 1995; McKay et al., 1993). Adding to the complication of the sinkhole system is the fact that overland flow after heavy rainfall events is funneled to the bottom of the sinkhole where it is forced to infiltrate, overflow, evaporate, or transpire. Even small sinkholes may capture runoff from larger areas. In sinkholes with relatively unobstructed connections to conduits, recharge is rapid. However, in soil filled sinkholes without open connections to underlying conduits, runoff ponds may form temporarily and much of this water can infiltrate relatively slowly through the soils. A significant portion of this water will recharge the aquifer as somewhat delayed and temporally distributed recharge by way of temporary storage and later slow release by the soils. In this way, thick soils in the unsaturated zone over a karst aquifer can be a significant source of slowly released water which sustains base-flow in a karst hydrologic system. The diversity of infiltration processes in soil filled sinkholes ultimately means that they have the potential to provide recharge to an aquifer at slow, intermediate and rapid rates, and cannot simply be modeled as a source of rapid recharge.

Many methods have been developed for estimating or measuring recharge at different spatial scales (Scanlon et al., 2002). For large scales, recharge can be modeled using mass-balance models which may incorporate measurements of soil water, stream and spring hydrographs, well levels, precipitation, stable isotopes, and potential evapotranspiration (Das Gupta and Paudyal, 1988; Doctor et al., 2006; Sophocleous, 1991). Geographic information systems are also useful tools for regional recharge modeling, especially for use with readily available data such as soil types, topography, land cover and climatic parameters (Dripps and Bradbury, 2007). At smaller scales, tools such as lysimeters provide good estimates of recharge, though they are subject to large spatial variations in estimated recharge due to localized heterogeneities in soils and vegetation (Chapman and Malone, 2002).

Unfortunately, quantifying amounts and rates of infiltration and recharge at intermediate scales (10s to 100s of m) is extremely difficult using traditional methods. Geophysical methods are excellent tools to use at these scales because of their scalability and mobility. Electrical techniques such as electrical resistivity tomography (ERT) are particularly well suited for work in the unsaturated zone because of their ability to penetrate to useful depths with reasonable resolution in the field and their high sensitivity to changes in electrical properties resulting from changes in soil moisture (Michot et al., 2003; Sheets and Hendrickx, 1995; Sreedeep and Singh, 2005). The primary objectives of this study were to quantify the timing and amount of infiltration and potential recharge through sinkholes with thick soil mantles. We accomplished these objectives using changes in soil moisture derived from differential ERT over a time period of approximately five months.

FIELD SITE

Our research site at the Virginia Tech Kentland Experimental Farms in Montgomery County, Virginia contains two well-developed sinkhole plains formed in ancient New River terraces (**Figure 4.1a**). The sinkholes are generally broad and shallow, allowing easy access for agricultural activities, and contain no bedrock outcrops. Thick terrace deposits mantle sinkholes with soils characterized as weathered fluvial terrace materials deposited by the ancient New River, which have developed over the underlying Cambrian aged Elbrook Formation limestone and dolostone bedrocks. Soils are classified by the USDA-NRCS as Guernsey silt loam, Unison and Braddock soils, and Unison and Braddock cobbly soils (USDA-NRCS, 2006). Both sinkhole plains have numerous sinkholes of similar size and shape. Two sinkholes were chosen for more detailed analysis in our study. Sinkhole #1 is in a higher and older terrace deposit and contains highly weathered soils to depths exceeding 12.2 m. Sinkhole #5 is formed in a lower and younger terrace and contains soils which are not as mature. In Sinkhole #5, bedrock was reached in most augered holes at depths between 3.4 and 7.6m below land surface. Instrumentation installed at the field site consists of monitoring wells (which do not reach the saturated zone), time domain reflectometry (TDR) access-tubes used to obtain small-scale soil moisture measurements, and permanent carbon electrode arrays for ERT measurements.

Sinkhole formation at both sites appears to be the result of two mechanisms. First, soil-piping, down-slope movement and slumping are together moving soils from the surface into the subsurface. A second, and perhaps more important, mechanism seems to be dissolution of bedrock and subsequent slumping of sediments into the resulting bedrock depression. Evidence for this can be found in cobble layers and other soil layers which are laterally continuous in sinkhole flanks, but slope towards the sinkhole bottoms and become deeper below the surface with proximity to the sinkhole bottom (**Figure 3.11**).

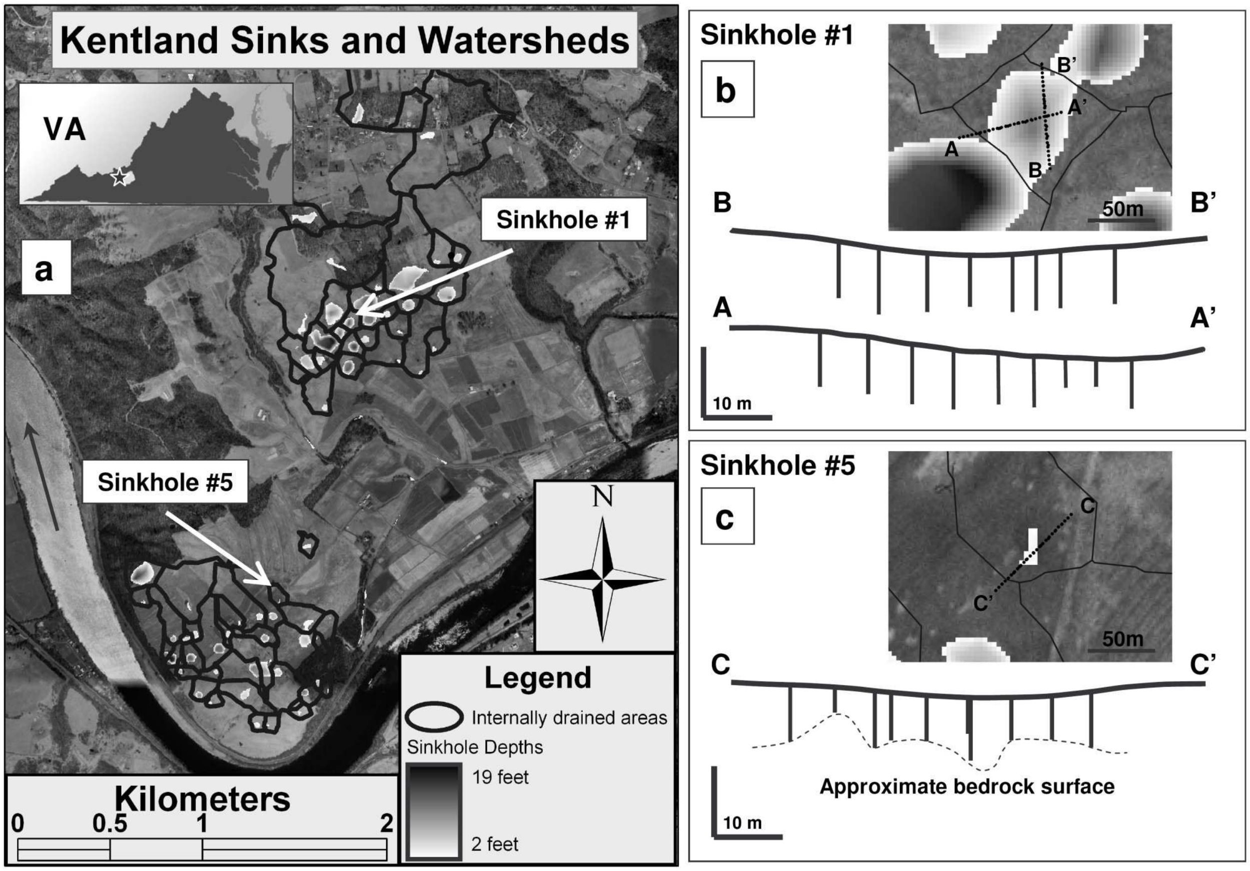

Figure 4.1 Field site and locations of ERT profiles
a) Virginia Tech Kentland Experimental Farms at Whitethorne, Virginia, USA. **Figure 4.1a** shows study sinkholes #1 and #5 and catchment areas (adjacent polygons) for each sinkhole within the two sinkhole plains. Aerial imagery © 2002 Commonwealth of Virginia. Sinkhole #1 is in the higher, older terrace. b) and c) show the location and orientation of instrumentation installed in transects across both sinkholes. Upper image in the diagrams is a map view of the sinkhole, while the lower portion of the diagrams shows profile views of monitoring wells, TDR access-tubes and other instrumentation installed along each transect. Note that depth of bedrock was not determined in Sinkhole #1.

Vegetation at the site is dominated by grasses. In the upper sinkhole #1, fields are used for hay and grazing. During the study period grass was either mowed or grazed. In the lower sinkhole #5, the site was covered by grasses and weeds which were kept mowed to < 50 cm in height.

METHODS

Our approach to quantifying potential recharge in soil-filled sinkholes involved measuring temporal variations in soil moisture derived from differential ERT measurements. In soils, potential recharge occurs when the rate of precipitation exceeds the rate of potential evapotranspiration (PET) and water moves below the root depth. By assuming a 1.5m root depth for grasses, and further assuming that soil moisture which infiltrated to depths below 1.5m had moved below the depth of influence by PET, we defined potential recharge as changes in soil moisture in the soil profiles below -1.5m (**Figure 4.2**). We compared cumulative changes in three ERT-derived soil moisture profiles with rates of cumulative precipitation and PET for the same study period to identify periods when either PET or infiltration was the dominant process. We compared the amounts of water added to the entire profile thickness vs. the portion lying below -1.5m by investigating the relationships between PET, precipitation and the amount of water added or lost within the upper 1.5m of the profiles.

ERT and soil moisture

Dipole-dipole ERT data were collected 11 times between May 17, 2006 and October 9, 2006 for each of the three different transects across the two study sinkholes **(Figure 4.1):** two in sinkhole #1 and one in sinkhole #5**.** Data were collected using permanently installed arrays of 25 carbon ERT electrodes per transect (Schwartz and Schreiber, In review) , 72m in length. We used permanent carbon electrodes to ensure very high quality ERT data and to minimize errors which would have resulted from slight variations in soil-electrode electrical contact and location if we had installed and removed electrodes each time measurements were made. Volumetric soil moisture was calculated for a portion of each of these profiles (**Figure 4.3**) by converting dipole-dipole ERT data into soil moisture using a modified and numerically optimized form of Archie's Law (Schwartz et al., *In review;* Shah and Singh, 2005) which includes the important effects of clay content on bulk soil conductivity, and a Mehlich 1 extractable Ca + Mg proxy for pore-

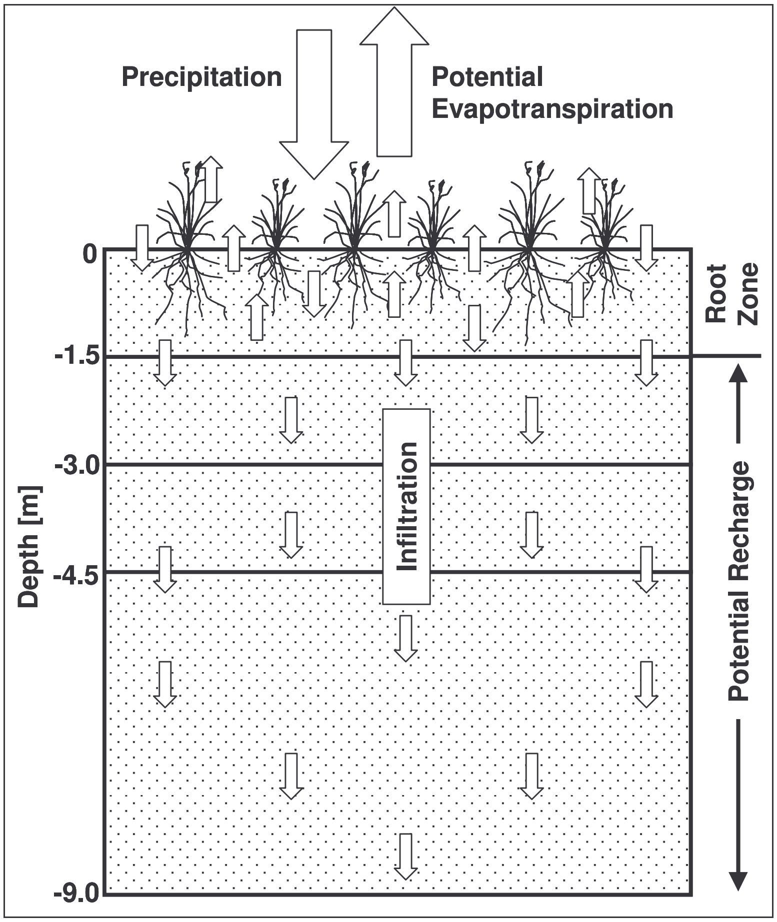

Figure 4.2 Conceptual model of vadose water movement and model layers
Conceptual diagram of the processes modeled and methods used to calculate potential recharge in unsaturated soil profiles.

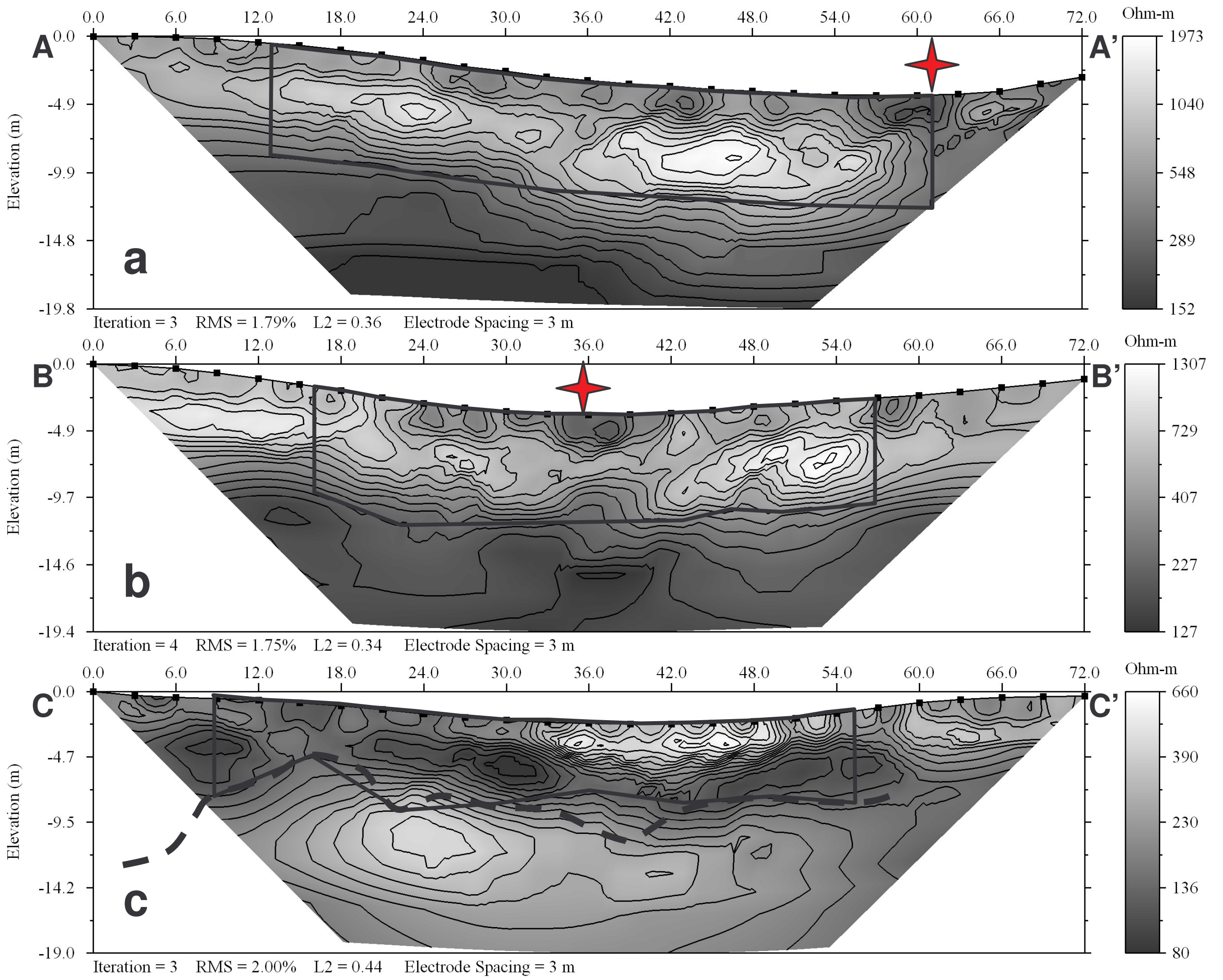

Figure 4.3 ERT profiles

ERT profiles for each transect showing contoured resistivity values and portions of each profile where time-series moisture data were modeled. a) and b) show transects across sinkhole #1 while c) is across sinkhole #5. The bedrock-soil interface in c) is shown as a dashed line. Stars indicate the point where a) and b) intersect. A, A', B, B', C and C' represent transect endpoints as shown in **Figure 4.1**. Also note that the resistivity scales are not the same for each profile water conductivity. The proxy assumes a relationship between the dominant cation species in the soil and equilibrium pore-water conductivity.

Changes in soil moisture for 10 time intervals from May 17 to October 9, 2006 were obtained by calculating the difference in ERT-derived volumetric soil moisture relative to the initial dataset collected on May 17, 2006. These changes were calculated as m^3 of water added or subtracted from the three soil profiles (**Figure 4.3**) by assuming a 1m profile thickness. Because we calculated volumetric moisture content, conversion of these data into a volume of water added or subtracted from the profile (relative to the initial profile) was done by summing the volumetric moisture changes for each of the 0.5 x 0.5m model cells contained in a 1m thick profile.

Recharge calculations

Potential recharge was calculated by using a simple mass balance model and a 1.5m root depth (**Figure 4.2**). Increases in the soil moisture below this depth represented water which was available to potentially recharge the underlying aquifer. Decreases in soil moisture in the interval below -1.5m represented water which moved downward to the region below and could also be called potential recharge. To better understand rates of infiltration and the timing of potential recharge, we divided ERT-derived soil moisture profiles into intervals of 0 to -1.5m, -1.5 to -3.0m, -3.0 to -4.5m, and below -4.5m in depth, to monitor rates of infiltration and potential recharge based on the timing of a wetting front which moved from the upper to lower depth intervals (**Figure 4.2**). This also allowed a more detailed investigation of differences between the two sinkholes.

PET modeling and precipitation

We used the Penman-Monteith model (Allen et al., 1998; ASCE-EWRI, 2002; Howell and Evett, 2004; Snyder and Eching, 2006) with a tall grass reference to calculate daily PET at our field site. The Penman-Monteith model is the standardized method for calculating potential evapotranspiration using standard climatic data and has been shown to be widely applicable worldwide (Allen et al., 1998). If needed, the model can be adjusted for crop or vegetation conditions at a particular site which may differ from the reference crop used in the model. We used a model developed by Snyder and Eching (2006) which simulates reference evapotranspiration for both short and tall grass canopies. Their model uses the standardized form of the Penman-Monteith equation (ASCE-EWRI, 2002) to calculate daily reference values. Required data were derived from hourly data recorded at our field site on the Virginia Tech Kentland Farms (VT, 2007), and include daily maximum and minimum temperature, average wind speed, global solar radiation (corrected to net solar radiation), and daily maximum and minimum relative humidity. Hourly precipitation data were also recorded at this weather station. Cumulative PET and precipitation were both converted into m^3 of water by multiplying the modeled or measured amount by each profile's length and assuming a profile thickness of 1m. PET was not assumed to be actual evapotranspiration (AET), and AET was not directly modeled in this study. Except for periods when the rate of precipitation is greater than the rate of PET, PET is assumed to be greater than AET.

RESULTS AND DISCUSSION

PET, precipitation, and soil moisture

Figure 4.4 shows the relationship between cumulative modeled PET, cumulative precipitation, and cumulative ERT derived changes in soil moisture in each profile over the study period. When the slope of the cumulative precipitation data is less than the slope of cumulative PET, no deep infiltration or recharge occurs. Conversely, when the slope of cumulative precipitation is greater than the slope of cumulative PET, potential recharge can occur in unfrozen soils, but only if infiltrating water moves below the depth of influence from ET processes. Three important time intervals can be described in our data based on these relationships between cumulative precipitation and cumulative PET. The first time interval is a period of drying which lasts from day-137 until day-173. During this time, most of the water removed from the soil profiles is due to ET. There is evidence that water is also being removed through the bottom of the soil profile. For example, **Figure 4.5** shows the timing of addition or removal of water from each depth interval described above. In profiles for sinkhole #1 (**Figure 4.5 a and b**) the interval between -1.5m and -3.0m showed a slight decrease in soil moisture between day-137 and day-173. There is a corresponding increase in water in the interval below -4.5m. Since both these intervals are significantly below the depth at which ET would be a factor, we concluded that this water has

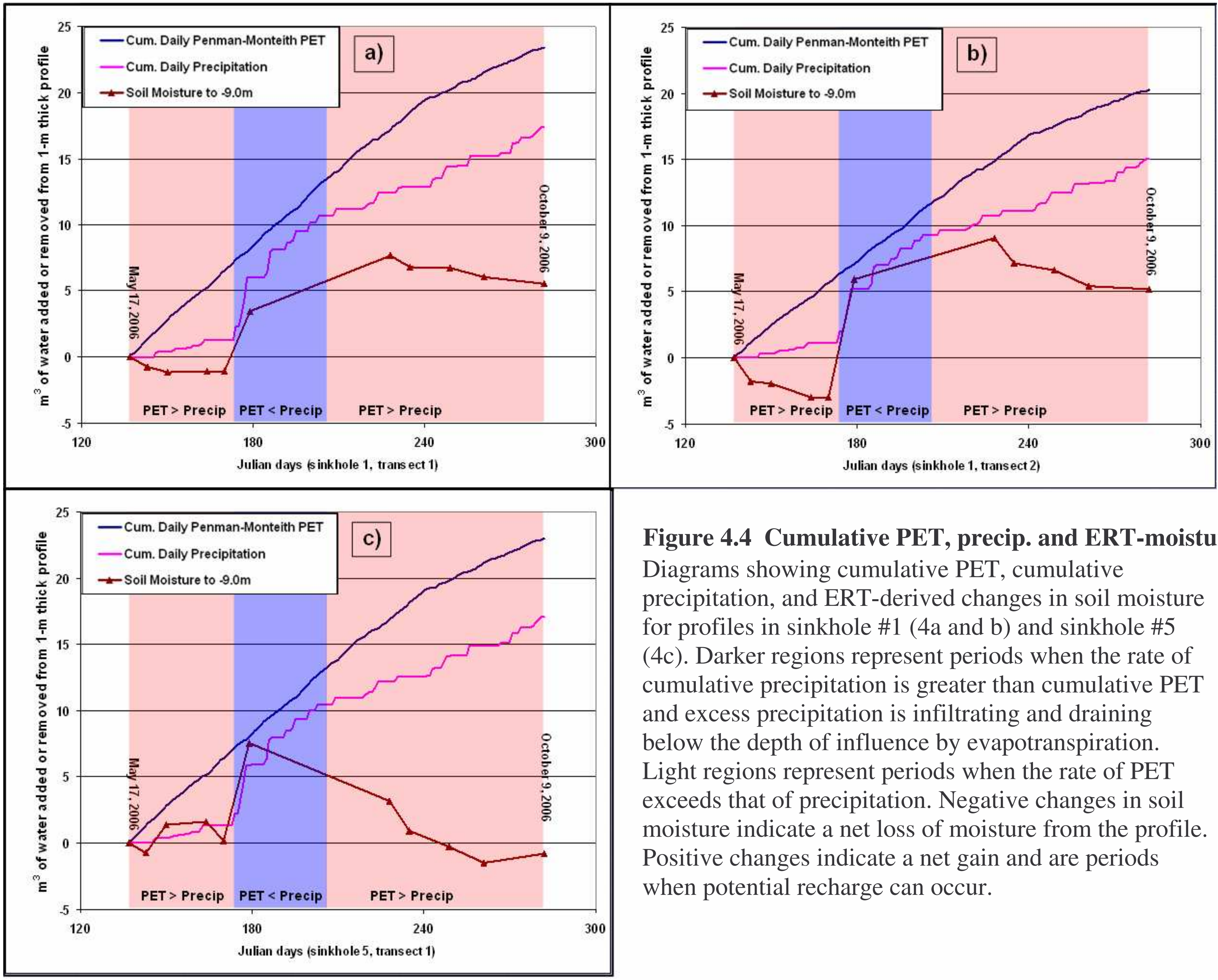

Figure 4.4 Cumulative PET, precip. and ERT-moisture Diagrams showing cumulative PET, cumulative precipitation, and ERT-derived changes in soil moisture for profiles in sinkhole #1 (4a and b) and sinkhole #5 (4c). Darker regions represent periods when the rate of cumulative precipitation is greater than cumulative PET and excess precipitation is infiltrating and draining below the depth of influence by evapotranspiration. Light regions represent periods when the rate of PET exceeds that of precipitation. Negative changes in soil moisture indicate a net loss of moisture from the profile. Positive changes indicate a net gain and are periods when potential recharge can occur.

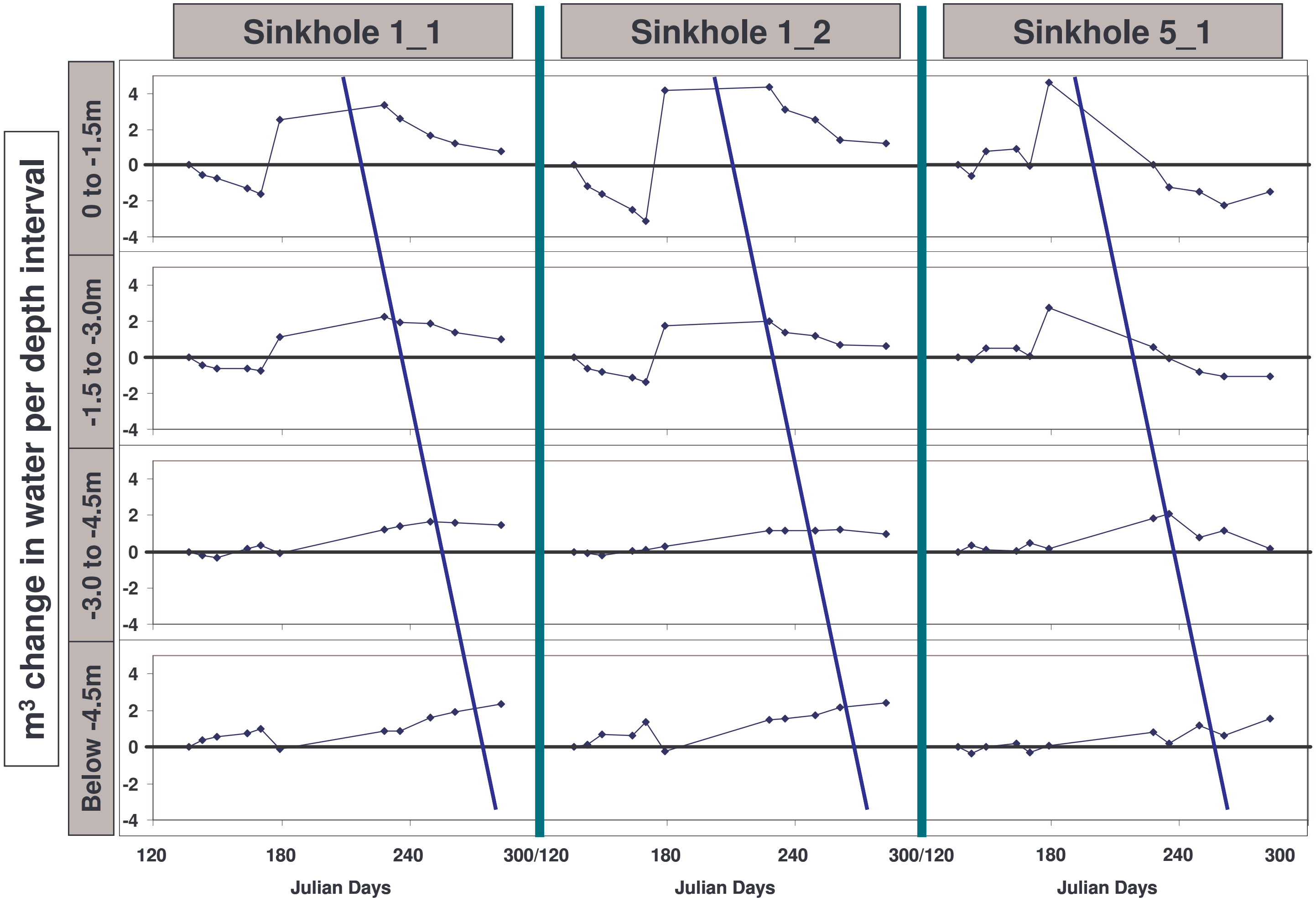

Figure 4.5 ERT-derived moisture changes by depth interval
Changes in ERT-derived soil water for each sinkhole transect by depth interval. Note a slight loss in water content in profiles for sinkhole #1, a) and b), between -1.5m and 3.0m and a corresponding increase below -4.5m. This indicates that a small amount of water was moving downward during this time interval and probably represents the motion of a wetting front from a previous rain event. Sinkhole #5 c) does not clearly show the same pattern. Diagonal lines show the progression of a wetting front as detected by the time required for water to be added to sequentially deeper intervals in the profiles.

moved downward in the soil profile. The water is likely part of a wetting front which was introduced by rainfall prior to the first ERT measurements.

On day-173, a period of significantly increased precipitation began in which the rate of cumulative precipitation was greater than or equal to the rate of cumulative PET. This trend continued until day-204 when the rate of cumulative precipitation decreased and was again less than the cumulative PET slope **(Figure 4.4)**. During this time interval, excess water infiltrated to depths below the influence of ET and could be assumed to contribute to potential recharge **(Figure 4.5 a, b and c)**.

After day-204, conditions returned to a state in which precipitation could be entirely removed from the system by ET processes (**Figure 4.4**). Changes in ERT derived soil moisture for each 9m-thick soil profile, and analysis of changes occurring in individual depth intervals showed that moisture losses primarily occurred in the upper 1.5m of each profile (**Figure 4.5**). This supported our hypothesis that moisture above -1.5m would primarily be removed by ET during periods when PET was greater than precipitation, but water below -1.5m would continue to move downwards.

Figure 4.6, Figure 4.7, and **Figure 4.8** show the spatial distribution of increases or decreases in volumetric soil moisture over time in each 2-D profile. Patterns of change support the idea that infiltration and recharge processes are not homogeneous, especially in sites with heterogeneous soils. One pattern which was clearly apparent is that a significant amount of infiltration occurs in the topographically lowest region of the sinkholes. This is likely the result of increased infiltration during heavy rain events which caused overland flow to pond in the bottom of the sinkholes. Patterns apparent in **Figure 4.6, Figure 4.7,** and **Figure 4.8** also support the idea that large amounts of water infiltrate on the flanks of sinkholes. For example, in **Figure 4.6** and **Figure 4.7** (sinkhole #1)**,** there is an increase in soil moisture along the entire length of the profile with localized regions of higher soil moisture. **Figure 4.8** (sinkhole #5) does not show this pattern as clearly and it appears that more water has infiltrated at the lowest portion of the sinkhole. This could be due to a) either slightly different vegetation in sinkhole #5 or b) different soil characteristics (higher silt and clay content) (Schwartz et al., *In review*). Runoff and

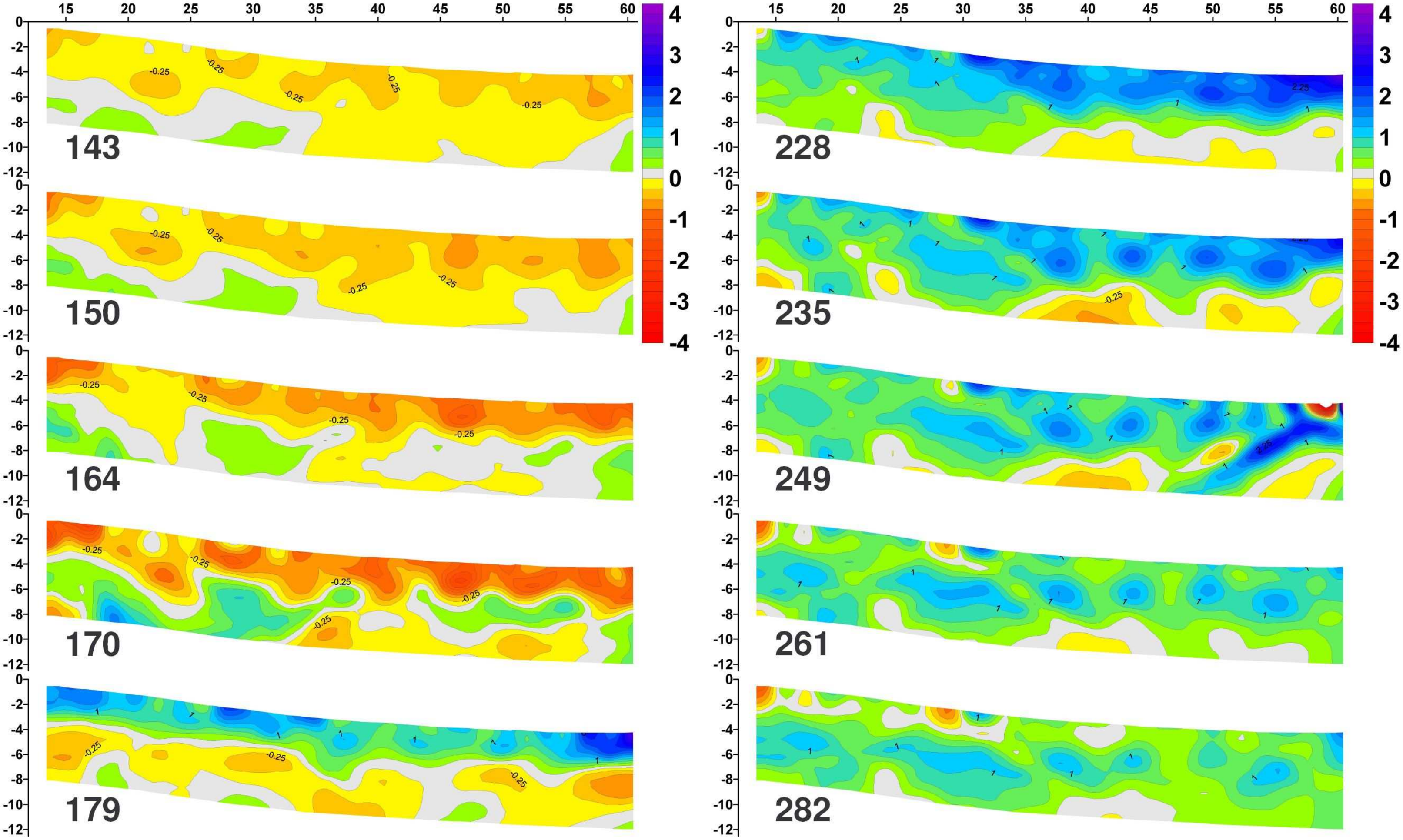

Figure 4.6 Profiles of moisture change over time in sinkhole #1, profile #1
Temporal and spatial changes in soil moisture relative to a baseline model on day-137 (May 17, 2006) in sinkhole #1, transect #1as modeled using time-series ERT data. Warm colors represent decreases in volumetric moisture content and cooler colors represent increases in volumetric soil moisture content. Scales on the X and Y axes are in [m]. Numbers in the lower left of each profile are Julian days. The baseline profile was measured on Julian day-137. Large rain events occurred between day-173 and day-187, with PET < Precip between day-173 and day-204.

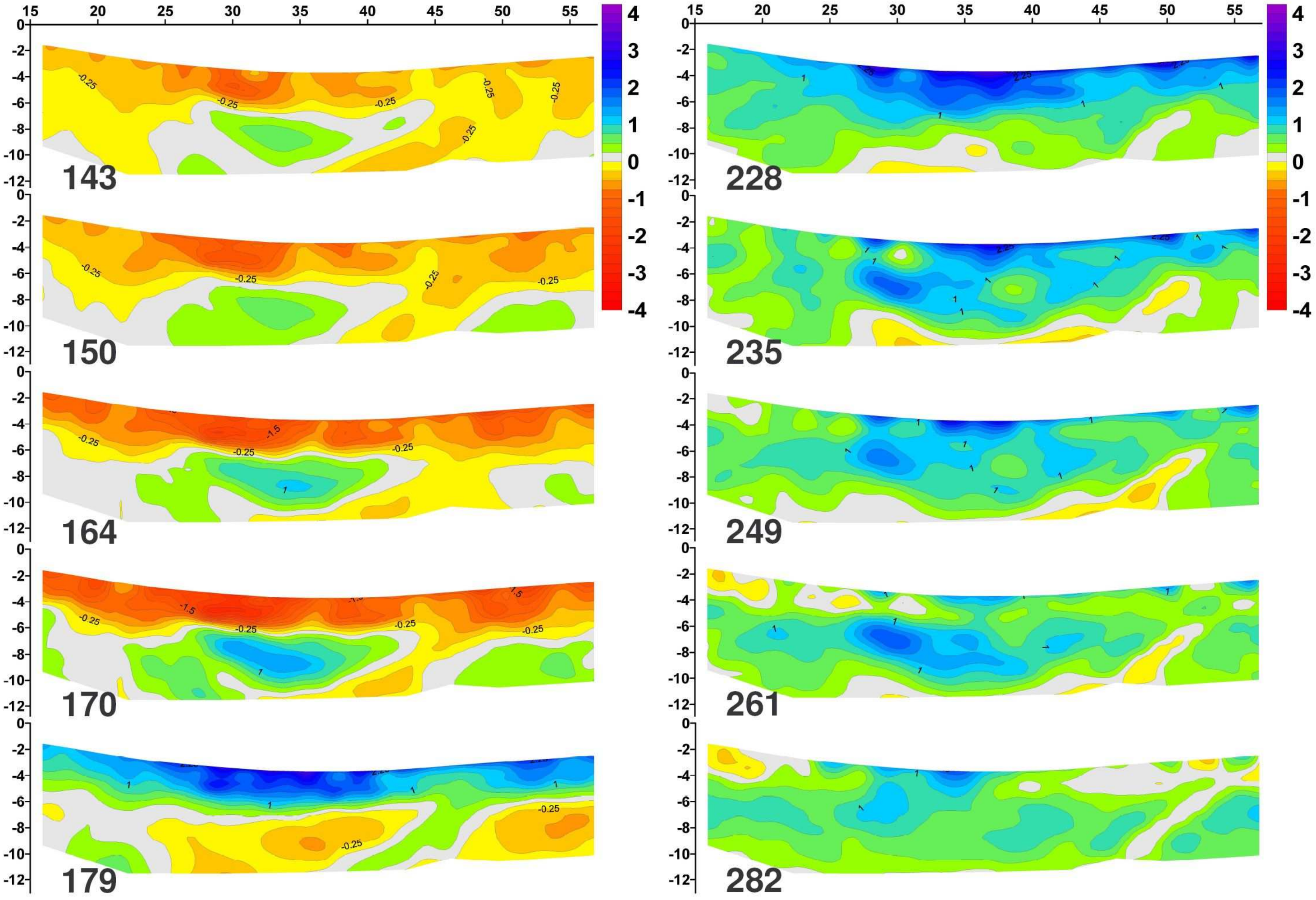

Figure 4.7 Profiles of moisture change over time in sinkhole #1, profile #2
Temporal and spatial changes in soil moisture relative to a baseline model on day-137 (May 17, 2006) in sinkhole #1, transect #2as modeled using time-series ERT data. Warm colors represent decreases in volumetric moisture content and cooler colors represent increases in volumetric soil moisture content. Scales on the X and Y axes are in [m]. Numbers in the lower left of each profile are Julian days. The baseline profile was measured on Julian day-137. Large rain events occurred between day-173 and day-187, with PET < Precip between day-173 and day-204.

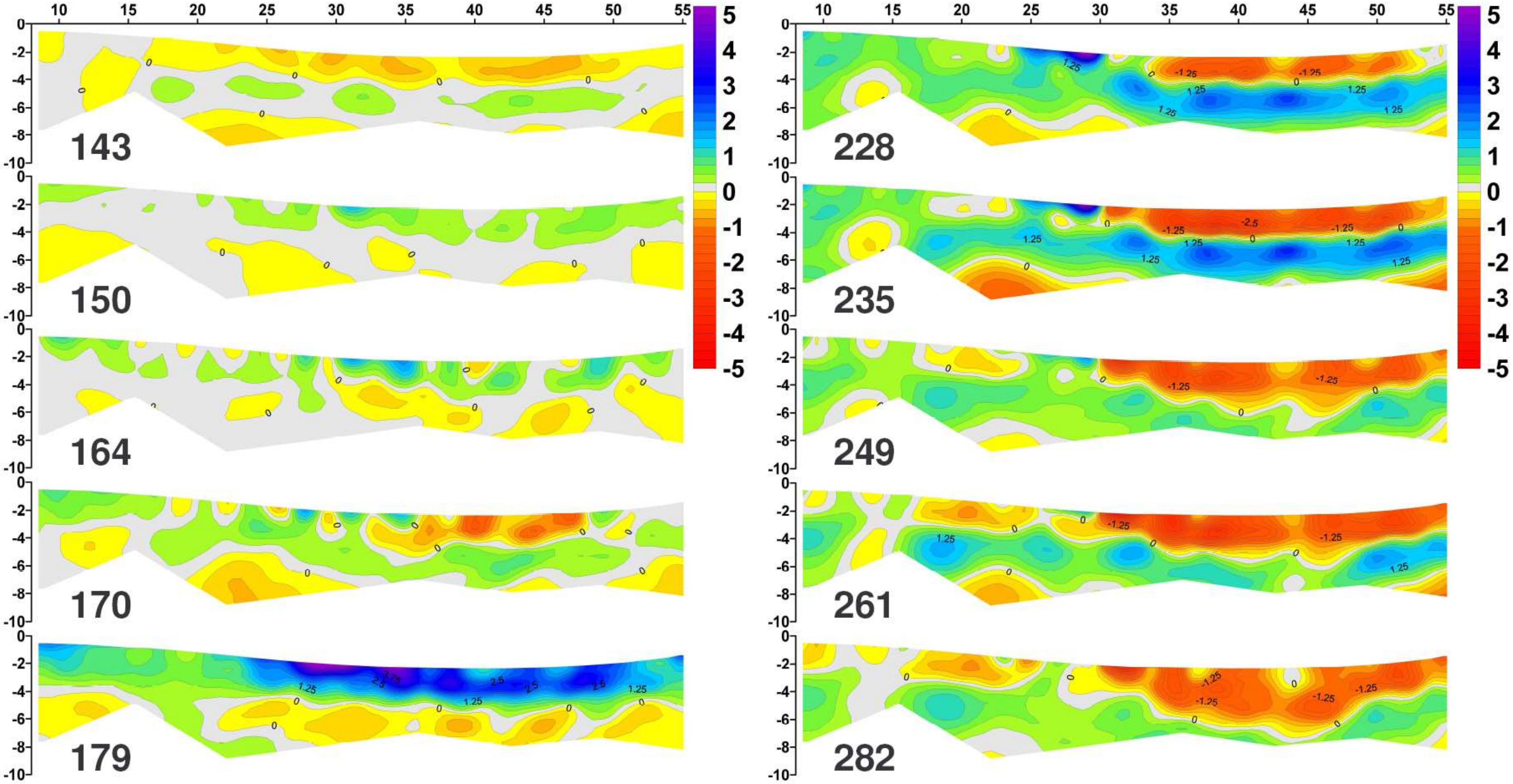

Figure 4.8 Profiles of moisture change over time in sinkhole #5, profile #1
Temporal and spatial changes in soil moisture relative to a baseline model on day-137 (May 17, 2006) in sinkhole #5, transect #1as modeled using time-series ERT data. Warm colors represent decreases in volumetric moisture content and cooler colors represent increases in volumetric soil moisture content. Scales on the X and Y axes are in [m]. Numbers in the lower left of each profile are Julian days. The baseline profile was measured on Julian day-137. Large rain events occurred between day-173 and day-187, with PET < Precip between day-173 and day-204.

ponding in the lowest part of sinkhole #5 may also have been greater than in sinkhole #1. We observed evidence of ponded water 20-30 cm deep in the lowest point of sinkhole #5 after a heavy rain. The amount of infiltration which occurs in the bottom of the sinkhole vs. the flanks is controlled by rates of precipitation (which would influence runoff), physical properties of the soils (which control rates of infiltration), type and amount of vegetation and preceding soil moisture conditions (which also influence how much and how fast infiltration occurs).

Recharge

We calculated recharge using a simple mass balance in each of the three 2-D profiles (**Figure 4.2** and **Figure 4.5**). **Figure 4.9** shows cumulative PET, precipitation, change in water content for the entire profile thickness, and change in water content for the profile below -1.5m. By assuming that any addition or removal of water to the interval below 1.5m in depth represented either recharge (by passing through the bottom of the profile) or potential recharge (by being added to the profile), we were able to quantify recharge. **Table 4.1** presents the amounts of water added to each profile below -1.5m. Our calculations indicate that between 19 and 31% of precipitation between day-173 and day-204 (June 22 to July 23) infiltrated to a depth where it can be considered potential recharge. Based on published estimates of annual recharge as a percent of precipitation (Delin and Risser, 2007), these values are reasonable. It is worth pointing out that this occurred during the summer growing season when PET was very high and recharge rates are normally very low. However, as others have shown, recharge is extremely variable temporally and is dependent upon many different factors such as geology, climate, antecedent moisture conditions, physical and chemical soil parameters, and rates of precipitation and overland flow. (Delin and Risser, 2007; Delin et al., 2007; Dripps, 2003; Nolan et al., 2007).

Unfortunately, we do not have data for the time interval between day-179 and day-228. In**,** **Figure 4.5** and **Figure 4.8,** we see evidence that a significant portion of precipitation which fell of sinkhole #5 probably passed quickly through the profile and was not detected by our measurements. For example, in the profile for sinkhole #5 (**Figure 4.4**), there was a rapid increase in the volume of infiltrated water in the soil profile, but by day-228 the moisture content had already decreased to approximately half of the initial increase at day-179. It is very likely that much of this water had already passed through the entire profile by day-228. In addition to

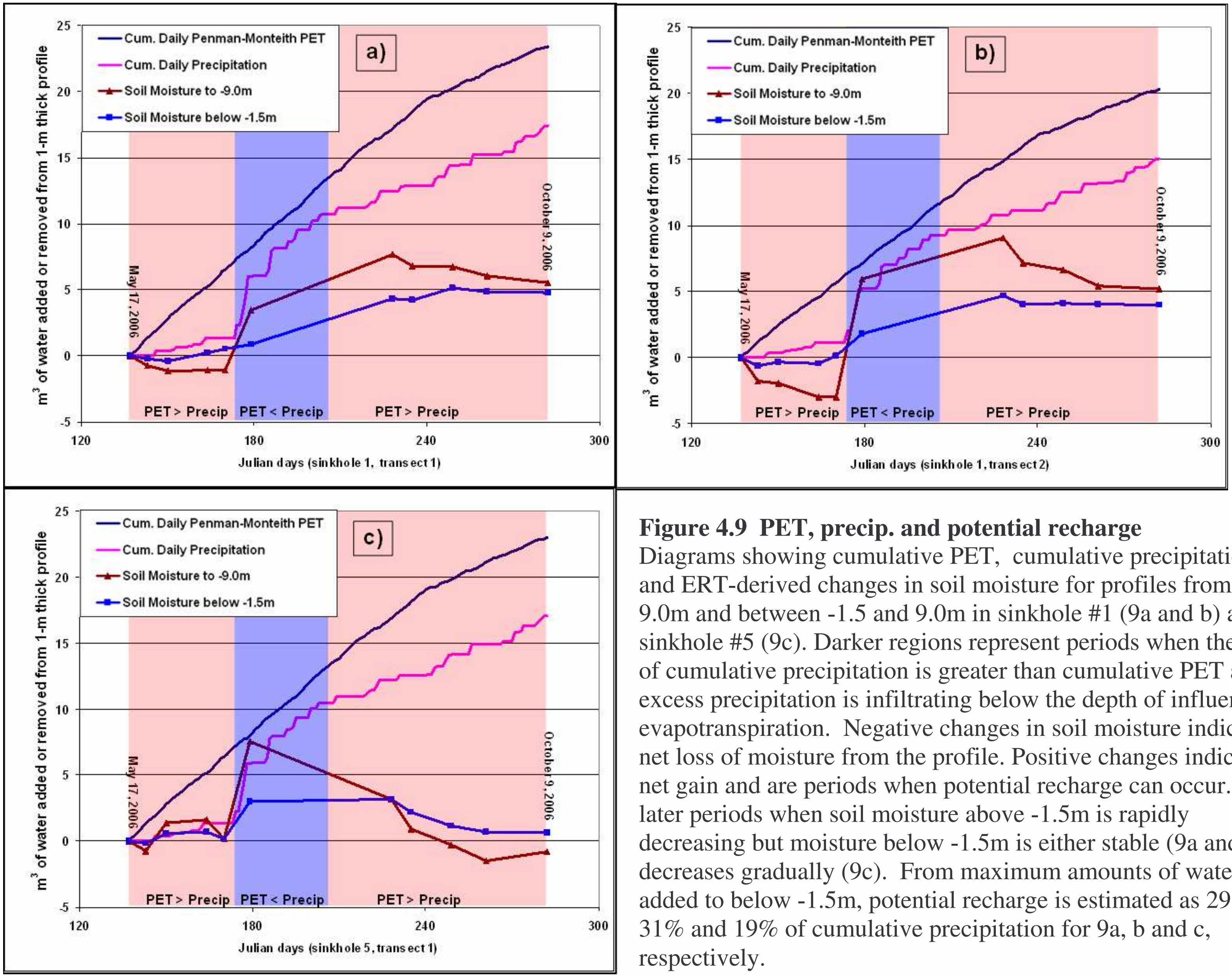

Figure 4.9 PET, precip. and potential recharge
Diagrams showing cumulative PET, cumulative precipitation, and ERT-derived changes in soil moisture for profiles from 0 to -9.0m and between -1.5 and 9.0m in sinkhole #1 (9a and b) and sinkhole #5 (9c). Darker regions represent periods when the rate of cumulative precipitation is greater than cumulative PET and excess precipitation is infiltrating below the depth of influence by evapotranspiration. Negative changes in soil moisture indicate a net loss of moisture from the profile. Positive changes indicate a net gain and are periods when potential recharge can occur. Note later periods when soil moisture above -1.5m is rapidly decreasing but moisture below -1.5m is either stable (9a and b) or decreases gradually (9c). From maximum amounts of water added to below -1.5m, potential recharge is estimated as 29%, 31% and 19% of cumulative precipitation for 9a, b and c, respectively.

measuring a much smaller percent of precipitation as recharge for this profile (**Table 4.1**) when compared to those in sinkhole #1, ERT derived moisture changes shown in **Figure 4.8** indicate that the wetting front moved through these soils much faster than it did in sinkhole #1 (**Figure 4.6** and **Figure 4.7).**

Our ERT-derived results compared well with the expected timing and amounts of infiltration and potential recharge using cumulative Penman-Monteith PET and precipitation data (**Figure 4.9a, b,** and **c**). ERT results for the three profiles show several similarities and differences. In all three profiles, the ERT-modeled increase in water content over the entire profile thickness was consistent with nearly 100% infiltration during the intense rain events. In **Figure 4.9b** and **c**, the increase in ERT-derived moisture is greater than the cumulative precipitation which fell over the profiles. We believe this is the result of overland flow from the adjacent sinkhole flanks which shed large amounts of water. Overland flow is not represented in the cumulative precipitation data shown in **Figure 4.4** and **Figure 4.9**. Enhanced infiltration at the bottom of the sinkholes was measured by ERT profiles which cross the bottom of the sinkhole. Evidence to support this hypothesis can be found in **Figure 4.9a** where the increase in ERT-derived soil moisture is nearly identical to the precipitation which fell during the intense rain events beginning on day-173, but is significantly less than the infiltration measured in **Figure 4.9b**. The profile shown in **Figure 4.9a** ends at the bottom of the sinkhole and did not measure moisture changes across the entire width of the bottom as the profile shown in **Figure 4.9b** did.

Even though the two profiles in sinkhole #1 show different amounts of water infiltrated, both **Figure 4.9a** and **b** show that similar amounts of water were added to the depth interval below -1.5 m, with approximately 30% of cumulative precipitation contributing to potential recharge. When only compared to the interval where the rate of precipitation equaled or exceeded the rate of PET (day-173 to day-204), approximately 50% of this precipitation contributed to potential recharge. Results from sinkhole #5 were different from sinkhole #1, though it appeared that a similar amount of water infiltrated and contributed to potential recharge below -1.5 m. The main difference between sinkhole #5 and #1 was that the rate at which water passed through the soil profile was much higher. This is evident by the temporal distribution of soil moisture in both the entire profile and at depths below -1.5m (**Figure 4.9c). Figure 4.8** clearly shows this difference as well, with a well-defined wetting front moving downward quickly. After the rate of precipitation decreased to less than that of PET at day-204, the near-surface lost moisture rapidly (especially in silty soils filling the lowest potion of the sinkhole). By day-282, there was almost no evidence of this water remaining.

CONCLUSIONS

The most important result of this research is that we were able to model field scale spatial and temporal distribution of soil moisture in three profiles from 41 to 47 m in length and 9 m in depth using 11 sequential sets of ERT data. We did this by using a modified form of Archie's Law to convert 2-D ERT data into 2-D soil moisture and then measuring differences in modeled soil moisture content over time. This model and these methods are described in Chapter 3. From these data we derived potential recharge amounts for each profile. We also showed that these results are in good agreement with the results expected after examining the relationships between cumulative PET and precipitation over the monitored time interval.

We have shown that soil-filled sinkholes can retain and slowly transmit significant amounts of water after a recharge event. At the same time, we also saw evidence that a portion of infiltrating water probably moved through the unsaturated zone relatively quickly (but not what might be considered rapidly), especially in sinkhole #5. These results refute the assumption that all sinkholes should be treated simply as a source of rapid infiltration and recharge and suggest that for the purposes of understanding infiltration and recharge, in certain cases soil-filled sinkholes should be treated more like surrounding upland areas where diffuse infiltration dominates. However, these conclusions are not valid in cases where overland flow forces concentrated infiltration of both water and potential contaminants at the bottom of sinkholes. For the purposes of better management practices, soil-filled sinkholes should still be treated as sources of potential contamination, even though the rate of transport through the unsaturated zone may be somewhat attenuated. For the purposes of characterizing the hydrogeology of mantled sinkholes and karst settings, these results indicate that soil-filled sinkholes have a significant capacity to store and slowly release water to the underlying aquifer.

One advantage of using this hydrogeophysical method to quantify potential recharge is that it is relatively easy to apply to field scale studies. After basic soil properties have been measured, the method is non-invasive and can be used over any time interval desired. There are often large discrepancies between results of small-scale recharge estimates or measurements and regional-scale results. For field-scale studies, the methods we present are an alternative to scaling large or small scale results down or up to obtain intermediate-scale estimates.

ACKNOWLEDGEMENTS

We acknowledge funding for this research from: US Department of Education GAANN Fellowship, Virginia Water Resources Research Center, Cave Conservancy Foundation, Cave Research Foundation, National Speleological Society, Geological Society of America, West Virginia Association for Cave Studies, and the Virginia Tech Graduate Research Development Program. We thank Ankan Basu, Mike Beck, Lee Daniels, Beth Diesel, Bruce Dunlavy, Frank Evans, Brad Foltz, Marty Griffith, Mary Harvey, Ashley Hogan, Danielle Huminicki, Stuart Hyde, Rachel Lauer, Steve Nagle, Jeanette Montrey, Wil Orndorff, Zenah Orndorff, Dave Rugh, Cori and Zachary Schwartz, Jim Spotila, Brett Viar, Dongbo Wang, and Brad White for their assistance both in the field and in the lab.

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Table 4.1

Results of recharge calculations showing amount of water added to each profile below -1.5m (derived from ERT data), amount of precipitation which occurred over each profile, and percent of precipitation which infiltrated below -1.5 m and can be assumed to represent recharge. Time interval represented is between May 17 and October 9, 2006, but note that potential recharge only occurred over the time interval from day-173 to day-204.

Sinkhole # and profile	Recharge (m^3)	Precipitation (m^3)	Recharge as % of precipitation
#1, profile 1	5.1	17.4	29
#1, profile 2	4.7	15.1	31
#5, profile 1	3.2	17.1	19

CHAPTER 5

FUTURE RESEARCH

Introduction

Over the course of research for this dissertation, data were collected which were not used or presented in results discussed in the previous chapters, but were instead used for initial sinkhole characterization and to provide background data for later more in-depth research. The following pages discuss some of this work by research topic and outline future work which could build on the work already done at this field site.

Numerical modeling

The data presented in Chapter 4 for the summer and early fall of 2006 showed measurable increases in ERT-derived soil moisture in all three sinkhole profiles **(Figures 4.7, 4.8 and 4.9)**. However, a similar study which only measured ERT changes in sinkhole #1, profile #1 was conducted during fall of 2005 (**Figure 5.1**). When these results are compared to the results of the 2006 study, it is apparent that antecedent moisture conditions are very important in determining how much precipitation infiltrates. During spring and summer of 2005, below average precipitation was recorded at the site **(Figure 5.2)**, which led to drier than normal antecedent moisture conditions at the time the 2005 study began. This likely was a significant factor which contributed to a continuous loss of soil moisture over the study period (September 5, 2005 to January 9, 2006) (**Figures 5.1** and **5.3).** Additionally, rain events which did occur during this time interval were not as intense as those which occurred during the 2006 study and most of the water was probably held within the root zone and removed relatively quickly by evapotranspiration (ET) before it could infiltrate to below the root zone and become potential recharge.

Without precipitation during the winter and spring of 2006, the very short periods of intense rainfall received during summer of 2006 may not have infiltrated to the depths that they did (below root depths) and the overall trend would have been either one of little change in soil moisture or of continued soil moisture loss via both ET and potential recharge moving slowly downward. It would be interesting to examine in more detail how antecedent soil moisture impacts the spatial and temporal distribution of soil moisture using numerical modeling.

To study long-term variations in seasonal infiltration and potential recharge in soil-filled sinkholes, ERT-methods could be used. However, high-resolution long-term data collection would be required, which would be an onerous task. As an alternative, a 2-D unsaturated zone hydrologic model such as HYDRUS-2D (Simunek et al., 1999) can be constructed to simulate unsaturated flow, which will provide information on long term changes in soil moisture and recharge. The model would include hydraulic parameters derived from the measured soil properties, precipitation, potential evapotranspiration (PET), and periodic ERT-derived moisture data. ERT-derived soil moisture distribution can be used as both initial conditions for the model and as calibration data for later time-steps in the model results. By combining numerical methods with ERT-derived data, the accuracy of the model will be significantly improved and long-term estimates of infiltration and recharge can more easily be simulated. I plan to continue these sinkhole moisture studies by performing the study outlined above.

Compare results from inside a sinkhole with a similar study outside a sinkhole

The work I have already presented focused on infiltration and potential recharge within two soil-filled sinkholes. These results give some indication that these processes might differ when compared to non-sinkhole environments with thick soils. However, to really make comparisons between what occurs in a sinkhole and outside of a sinkhole, a similar study will need to be done on an upland area around a study sinkhole. This work is not possible with the data I have already collected and would require additional instrumentation. This may be the subject of a future research proposal.

Compare results from a soil-filled sinkhole with a soil-filled sink containing an open drain

Another useful study would be to monitor infiltration and recharge in soils in a sinkhole which also contains an open drain. This experiment would allow a comparison between infiltration and slow recharge in the soil-filled sinkhole vs. runoff and rapid infiltration in the sinkhole with an open drain.

Process 3-D ERT data

I collected nearly 100 ERT profiles in six different sinkholes at Kentland Farms. These profiles were arranged is order to facilitate 3-D inversion at a later date when I might have access to 3-D inversion software. I will soon have access to this software and plan to use these data to generate true 3-D models of resistivity in the sinkholes. For sinkholes #1 and #5, in particular, I have detailed physical data which will help me interpret these models in terms of general soil properties and depth to bedrock.

Soil profile characterization

Depending on interest from potential collaborators, I may continue to investigate the physical and chemical properties of the 470 soil samples I collected at depths up to 9m. Ancient New River terrace deposits which mantle the karst plains at the Virginia Tech Kentland Experimental Farms have not been well characterized at depths below 3m. The samples I collected preserve information which can be used to better understand the age, weathering history, parent materials, and depositional environments of the sediments which now form the soils found in these terraces. As an example, some work has been done to characterize mineralogy of clays and other size fractions of these soils (Harris et al., 1980). This research suggested that clay mineralogy changes with depth and soils transition from containing more hydroxy-interlayered vermiculite near the surface, to more kaolinite with increasing depth. If this is true, and the trend in increasing kaolinite with depth continues or remains constant, this could be useful in efforts to further refine the extractable cation model of pore-water conductivity used in the modified form of Archie’s Law which is discussed in Chapter 2.

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Simunek, J., M. Sejna, and M.T.v. Genuchten. 1999. The HYDRUS-2D software package for simulating two-dimensional movement of water, heat, and multiple solutes in variably saturated media. Version 2.0, IGWMC - TPS - 53. International Ground Water Modeling Center, Colorado School of Mines, Golden, Colorado:251pp.

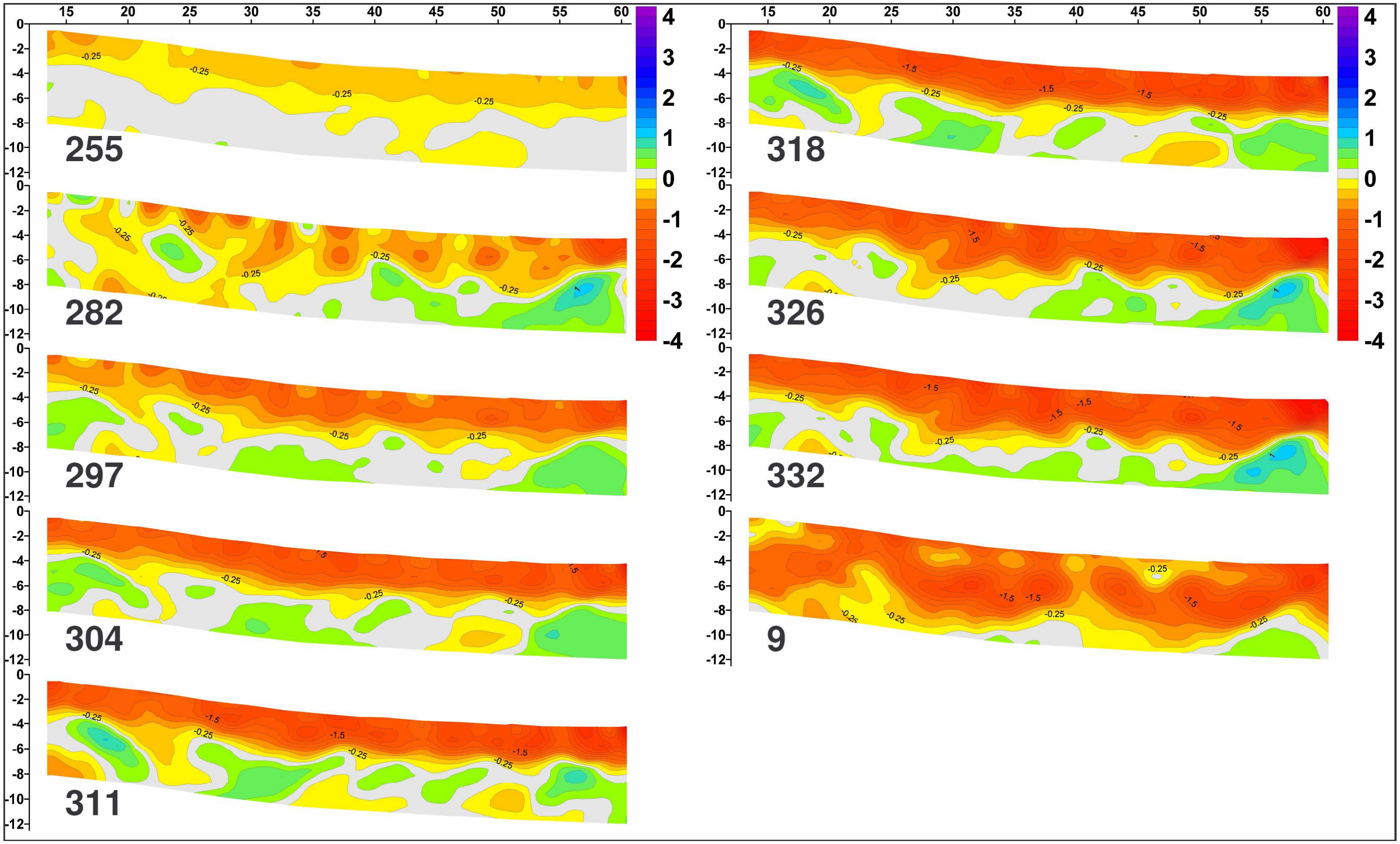

Figure 0.1 ERT-derived changes in soil moisture during fall of 2005

Temporal and spatial changes in soil moisture from Sept 5, 2005 to January 9, 2006 in sinkhole #1, transect #1 as modeled using time-series ERT data. Warm colors represent decreases in volumetric moisture content and cooler colors represent increases in volumetric soil moisture content. Scales on the X and Y axes are in [m]. Numbers in the lower left of each profile are Julian days. The baseline profile was measured on Julian day-248. These profiles show that 1) rainfall during this period did not significantly contribute to potential recharge, and 2) that much of the observed decrease in moisture below -1.5m in depth is the result of continuous downward movement of moisture over time, which resulted in relative decreases in soil moisture during the study.

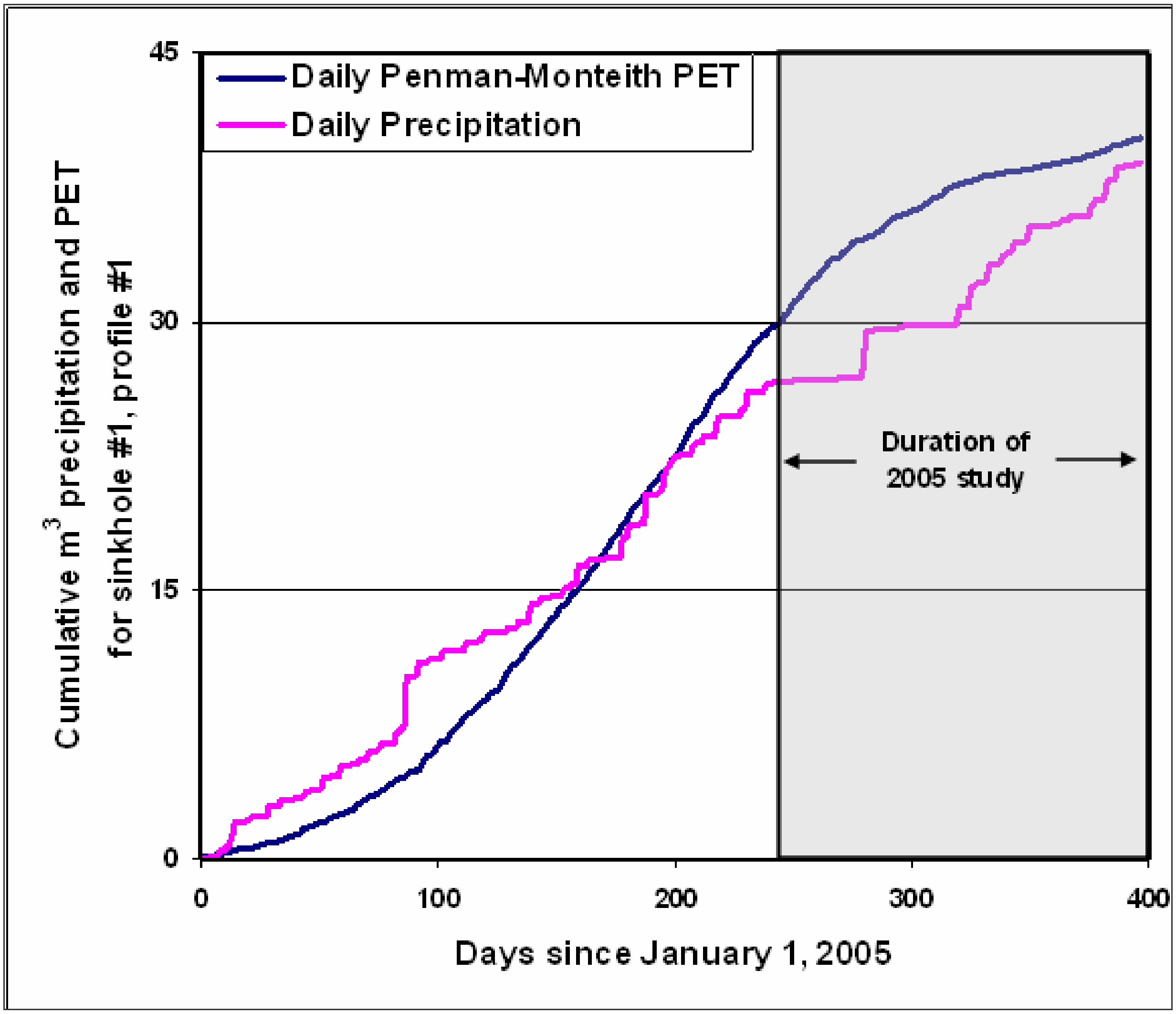

Figure 0.2 Cumulative precipitation and PET during 2005
Diagram showing cumulative precipitation and Penman-Monteith modeled PET for sinkhole #1, profile #1. Note that for much of the year prior to the 2005 study the rate of PET exceeded the rate of precipitation.

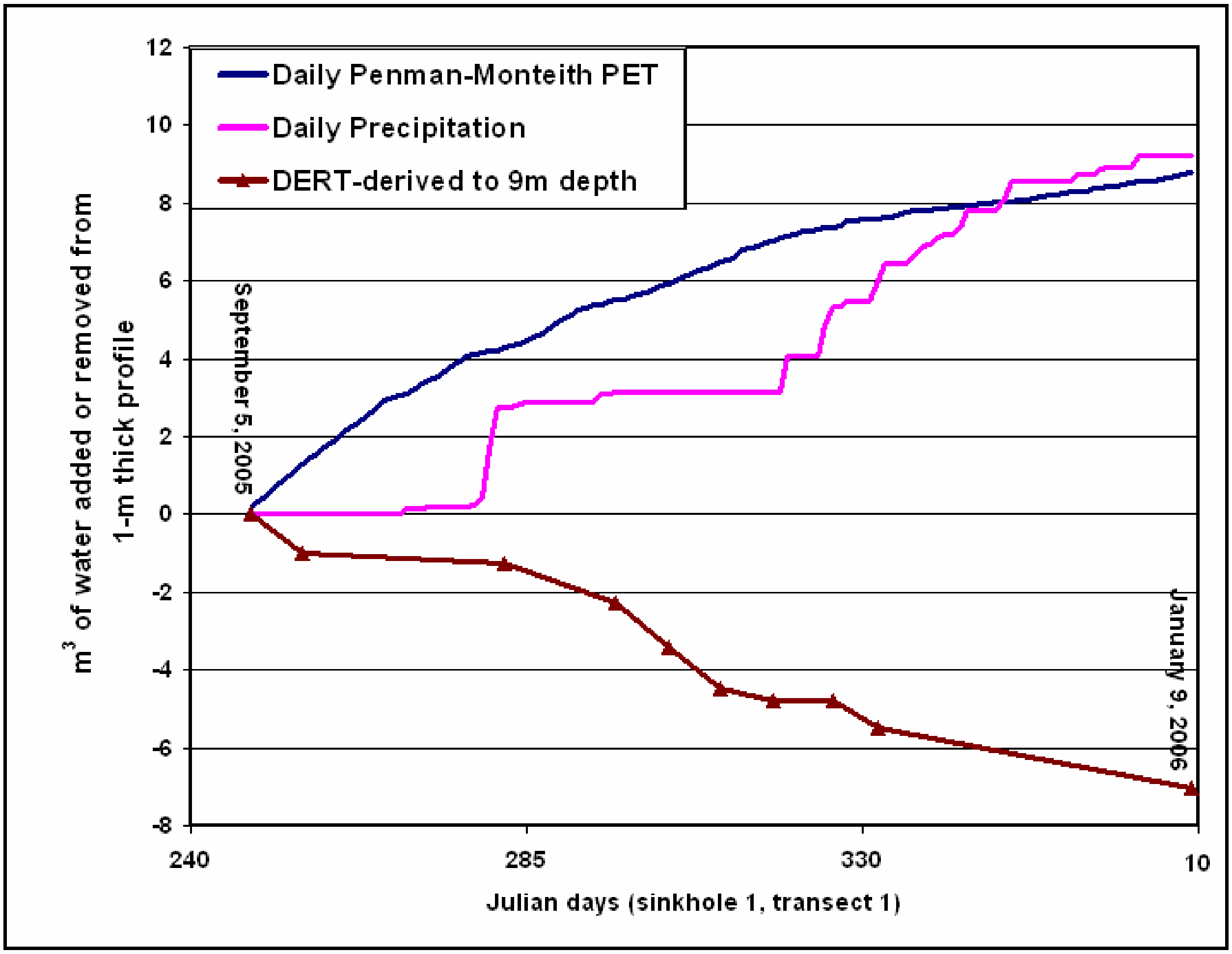

Figure 0.3 Cumulative precip, PET, and ERT-moisture for 2005 study
Diagram showing loss of volumetric soil moisture in sinkhole #1, profile #1 between September 5, 2005 and January 6, 2006 as modeled using ERT-derived changes in soil moisture. Also shown are cumulative precipitation and modeled Penman-Monteith PET for the same period.

VITA

Benjamin F. Schwartz

EDUCATION

Virginia Polytechnic Institute and State University, Blacksburg, VA
Ph. D. Geosciences, *expected fall 2007.*
Dissertation: *Quantification of Infiltration and Recharge through Soil-filled Sinkholes using Electrical Resistivity tomography and Time Domain Reflectometry*
[Advisor: Dr. Madeline Schreiber]

Radford University, Radford, VA
B. S. Geology, May 2003 - *Summa cum Laude*

Professional Experience

2001 - 2003	Full time summer employee for Virginia Department of Conservation and Recreation, Division of Natural Heritage, Karst Program in Radford, VA. Primary duties included delineation of karst drainage basins in VA with dye tracing, water sampling, geologic field observations and interpretation. Managed and compiled data in a GIS and wrote annual progress reports for the project.
2000 - 2001	Part time employee at Anderson and Associates Surveyors and Engineers, Blacksburg, VA. Performed high precision GPS surveys in SW VA. Position also required extensive CAD work.
1995 - 1999	CNC machinist for Nicholson Precision Instruments, Gaithersburg, MD. Specialized in prototyping and machining small close tolerance parts made with aluminum, plastics and exotic materials. Also specialized in precision mold making and molding of complex silicone rubber gaskets. Managed all daily operations of an independent satellite machine shop.
1991 - 1995	Party chief, rodman and courthouse researcher for Jeffery Hiner, Land Surveyor, Monterey, VA. Primary duties related to rural land surveying.

Teaching and Mentoring Experience

2007	Supervising and mentoring a geology major during a 4-credit undergraduate research project at Virginia Tech dealing with analysis of discharge data recorded at an ebb and flow karst spring. Objectives include flow period characterization, choosing an appropriate method for time-series analysis, developing a model to predict flow periods based on average discharge, writing a final report, and presenting results at the 2007 Geological Society of America annual meeting in Denver.
Fall 2005	Wrote a field guide for, organized, and led a two-day karst hydrology field trip to Bath County, VA for a graduate level Karst Hydrology class at Virginia Tech. The field trip was a critical link between classroom exercises, instruction, and discussion and the 'real-world' aspects of karst geology and hydrogeology. The trip included a trip into one of the largest caves in Virginia to observe a karst hydrologic system from the inside.
Spring 2004	Laboratory Instructor for Groundwater Hydrology, Virginia Tech. Taught labs for upper-level undergraduates and graduate students. Re-organized and edited several lab sections

and wrote new lab sections for a karst hydrology lab exercise and field trip, as well as a hydrogeophysics lab section that included demonstration and application of Electrical Resistivity Tomography equipment to characterizing shallow hydrogeology.

Fall 2003 Laboratory Instructor for three sections of Physical Geology, Virginia Tech. Duties included writing and administering exams and quizzes, and assigning all grades.

Virginia Tech Service

2004 - 2006 Member (2004-2005) and Chair (2005-2006) of Graduate Student Liaison Committee, Virginia Tech Department of Geosciences. Responsibilities included: communicating graduate student concerns and issues to the department; assisting with developing annual questionnaires for anonymous graduate student feedback; and working with the Graduate Student Research Symposium (GSRS) committee to make the GSRS more beneficial to both graduate students and faculty.

2006 Assisted with the departmental graduation ceremony and party, including setting up and removing equipment, tables and chairs.

Spring 2005 Assisted the Laboratory Instructor for Groundwater Hydrology with two field-centered lab exercises.

2005 Taught the Geophysics laboratory instructor how to set up and operate the department's Electrical Resistivity Tomography equipment.

2004 - 2005 Assisted with annual fall field trips for incoming graduate students, Virginia Tech Department of Geosciences. Described local karst hydrology and geology at several stops on the field trip, as well as described my research at the VT Kentland Farms.

2003 - 2005 Assisted with yearly karst field trips for Groundwater Hydrology class. Duties included driving vans and helping to describe karst hydrology and geology at several stops

Professional Service

2005 Assisted with a four-day Project Underground (describe/define this) workshop and field trip for VA earth science teachers where the primary emphasis was on how to incorporate karst science into SOL materials. Presented an invited talk about my research on sinkhole hydrology and hydrogeophysics and discussed how this current research could be incorporated into classroom materials.

2003 - present Project co-manager: Powell Mountain Karst Preserve. Responsibilities include: managing access for research and exploration to several caves (including the longest and deepest cave in VA) lying within the PMKP – owned by the Cave Conservancy of the Virginias (CCV); managing and compiling all field notes, scientific data and maps for the project in hard copy and digital formats; and compiling annual reports of activities and accomplishments for the CCV and the National Forest Service.

1997 – 2003 and 2006 – 2007 Director - Board of directors for Butler Cave Conservation Society. Responsibilities include a variety of duties related to operating a non-profit organization, as well as serving on many committees.

1993 - present	Director - Board of directors for Virginia Speleological Survey. Duties include coordinating and managing research and exploration in several regions of Virginia

Grants and Awards

2007	$145 Southeast Division Geological Society of America travel grant.
2007	$13,386 Cave Conservancy of the Virginias. *The Role of Epikarst in Controlling Recharge, Water Quality and Biodiversity in Karst Aquifer Systems of Virginia*
2007	$20,000 Virginia Water Resources Research Center grant. *The Role of Epikarst in Controlling Recharge, Water Quality and Biodiversity in Karst Aquifer Systems of Virginia*
2007	VT College of Science Runner-up Award for Outstanding Grad Student of the Year.
2006	$15,000 Cave Conservancy Foundation's Ph.D. Graduate Fellowship in Karst Studies. *A multi-method approach to characterizing sinkhole hydrogeology and recharge mechanisms in agricultural settings.*
2006	$90 Southeast Division Geological Society of America travel grant.
Fall 2006	Full Research Assistantship and other funding - co-wrote grant proposal with Dr. Madeline Schreiber. Submitted to: Virginia Water Resources Research Center.
Spring 2006	Byron N. Cooper Graduate Fellowship award. Full Research Assistantship funding for one semester. Dept. of Geosciences, Virginia Tech.
2005	$5,000 Cave Research Foundation's annual Karst Research Fellowship. Presented annually to one student who proposes an outstanding karst-related research project.
2005	$2,000 National Speleological Society's Ralph W. Stone Award and Fellowship.
2005	$2,000 Geological Society of America research grant.
2005	$100 Geological Society of America travel grant.
2005	Award: GSA outstanding research proposal. One of 19 from 720 applications.
2005	$250 and award: GSA Hydrogeology Division outstanding research proposal. One of three.
2005	$300 Research grant from West Virginia Association for Cave Studies.
2005	$250 Research grant from Virginia Tech Graduate Research Development Program.
2004	Awarded a US Dept. of Ed. GAANN Fellowship. Provided full Research Assistantship funding and some travel and equipment funds for three semesters.
2004	$100 Geological Society of America travel grant.

2003	$4,600 Research grant from Cave Conservancy of the Virginias for equipment. *Can Cave Sediments Predict Past Flood Magnitudes?*
Spring 2003	Deans Scholar – Geology Department – Radford University
2000	$5,000 Cave Conservancy Foundation's Undergraduate Fellowship in Karst Studies.
1999	Fellow award - National Speleological Society.

Peer-reviewed Publications

Schwartz, B. F., Schreiber, M. E. and Rimstidt, J. D., 2006, Calibrating access-tube TDR soil moisture values using measured physical and chemical soil parameters. Submitted to *Soil Science Society of America Journal.*

Schwartz, B. F. and Schreiber, M. E., 2005, New Applications of Differential Electrical Resistivity Tomography and Time Domain Reflectometry to modeling infiltration and soil moisture in agricultural sinkholes. Proceedings of the *10th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst.* September 2005.

Other Publications

Orndorff, W., Hypes, R., Lucas, P., Fagan, J, Zokaites, C., Orndorff, Z., Lucas, C., **Schwartz, B.**, 2005, Protecting Virginia's Caves and Karst through the Environmental Review Process. Proceedings of the *National Cave and Karst Management Symposium*, November 2005.

Schwartz B. F., Schreiber M. E., and Orndorff W., 2004. Hydrologic characterization of sinkholes in agricultural settings: Implications for best management practices. *Proceedings of the 2004 Virginia Water Resources Research Symposium*, Blacksburg, Virginia, Oct 4-6, 2004.

Schwartz, B. F., 1999, Exploring Barberry Cave. *National Speleological Society News*, September, v. 57 no. 9. A report documenting the history of exploration in Barberry Cave, Bath County, Virginia.

Schwartz, B. F., 1999, Project Caving and Permanent Rigging. *National Speleological Society News*, October, v. 57 no. 10. A technical report dealing with solutions to problems encountered with rigging in long-term project caving.

Schwartz, B. F., 1993 - present, Reports, maps and articles in *The Virginia Cellars,* the official publication of the Virginia Speleological Survey.

Publications in preparation

Schwartz, B. F., Orndorff, W. D., Futrell, S. M., Lucas, P. C., The Caves and Karst of Virginia. Chapter for Caves and Karst of North America. A book being published prior to the 2009 International Congress of Speleology held in Kerrville, Texas.

Ficco, M. J., Davis, N. W., White, W. B., **Schwartz, B. F.** Geology of the Chestnut Ridge Cave System, Bath County, Virginia. Book chapter being prepared for a publication compiling and presenting 50 years of research and exploration by the Butler Cave Conservation Society in the Burnsville Cove, Virginia.

Schwartz, B. F., Schreiber, M. S., Comparison and evaluation of Time Domain Reflectometry and Electrical Resistivity Tomography as tools for modeling soil moisture at the field scale. In preparation.

Schwartz, B. F., Schreiber, M. S., Quantifying Potential Recharge through Thick Soils in Mantled Sinkholes Using ERT Data. In preparation.

Conference Presentations

Hyde, S., **Schwartz, B.**, Lucas, P., 2007, Characterizing discharge signals and flow mechanisms at a Virginia ebb and flow karst spring. Poster presentation at the *Geological Society of America annual meeting,* October, 2007

Schwartz, B., Schreiber, M., 2007, Field scale soil moisture measurements using TDR-calibrated ERT data. Oral presentation at the *Geological Society of America annual meeting,* October, 2007

Schwartz, B., Schreiber, M., 2006, Examining temporal changes in soil moisture in a karst sinkhole using differential ERT and TDR. Oral presentation at the *Virginia Water Science and Technology Symposium*, November, 2006

Schwartz, B., Schreiber, M., 2006, Integrating Differential Electrical Resistivity Tomography and Time Domain Reflectometry as a tool for modeling soil moisture and infiltration in sinkholes. Oral presentation at the *Geological Society of America annual meeting,* October, 2006

Schwartz, B., 2006, An update on Omega Cave System: the last 6 years of exploration and discovery in Wise County, Virginia. Oral presentation at the *National Speleological Society annual meeting,* August, 2006

Schwartz, B., Schreiber, M., 2006, Integrating Differential Electrical Resistivity Tomography and Time Domain Reflectometry as a tool for modeling soil moisture and infiltration in sinkholes. Poster presented at the *SEG 2006 Hydrogeophysics Workshop.* August, 2006

Schwartz, B. F., 2006, Techniques for measuring soil moisture in sinkholes. Oral presentation at the *Graduate Student Research Symposium*, Virginia Tech Dept. of Geosciences, March, 2006

Schwartz, B. F. and Schreiber, M. E., 2005, Using TDR and 2D Differential ERT to monitor changes in soil moisture in mantled agricultural sinkholes. Oral presentation at the *Geological Society of America Annual meeting,* October, 2005

Schwartz, B. F., 2005, A multi-method approach to characterizing sinkhole hydrogeology and recharge mechanisms in agricultural settings. Oral presentation at the *Graduate Student Research Symposium*, Virginia Tech Dept. of Geosciences, March, 2005

Schwartz, B. F., Schreiber, M. E., Orndorff, W. D., 2004, Hydrologic Characterization of Sinkholes in Agricultural Settings. Oral presentation at the *Geological Society of America annual meeting,* November 2004.

Schwartz, B. F., Schreiber, M. E., Orndorff, W. D., 2004, Hydrologic Characterization of Sinkholes Using a Multi-method Approach. Oral presentation at the *Virginia Water Resources Research Center symposium,* October 2004.

Schwartz, B. F., Schreiber, M. E., Orndorff, W. D., 2004, Hydrologic Characterization of Sinkholes Using a Multi-method Approach. Poster presented at *Geological Society of America NE-SE meeting,* March 2004.

Orndorff, W. D**., Schwartz, B. F.**, Orndorff, Z. W., 2004, Patterns of Karst Hydrological Systems Developed in Ordovician-aged Carbonates of the Southwestern Virginia Valley and Ridge. Oral presentation at the *Geological Society of America NE-SE meeting,* March 2004.

Schwartz, B. F., 2004, Hydrologic characterization of sinkholes using a multi-method approach. Oral presentation at the *Graduate Student Research Symposium*, Virginia Tech Dept. of Geosciences, March, 2004

Invited Presentations

Schwartz, B. F., March, 2007, Integrating Differential Electrical Resistivity Tomography and Time Domain Reflectometry as a tool for modeling soil moisture and infiltration in sinkholes. Weekly seminar speaker at USGS, Reston, Va.

Schwartz, B. F., November, 2006, Karst, hydrology and geophysics - (How to turn a sinkhole into a complex hydrogeophysical problem). Weekly seminar speaker at Eastern Tennessee State University, Department of Physics, Astronomy and Geology, Johnson City, TN.

Schwartz, B. F., 2006, Karst, hydrology and geophysics - (How to turn a sinkhole into a complex hydrogeophysical problem). Weekly seminar speaker at Appalachian State University, Department of Geology, Boone, N.C.

Non-thesis Research

2006 - *Characterizing a complex ebb-and-flow karst spring in Bath County, Virginia*. We are currently collecting field data that will allow us to investigate relationships between average flow rates and several overlapping ebb-and-flow signals. Mechanisms for causing this behavior are also being investigated and modeled.

2003 - *Delineation of the subterranean Doe Creek, Clover Hollow, Sinking Creek and Little Stony Creek drainage basins in Giles County, Virginia, with the use of multiple fluorescent water tracers.* This research project fulfilled a research requirement for the Karst Hydrology course offered through Western Kentucky University and the Center for Cave and Karst Studies.

2002 - *Features controlling the speleogenesis, and the speleogenetic sequence, of Doe Mountain Cave in Giles County, Virginia*. This project fulfilled a research requirement for the Karst Geology course offered through Western Kentucky University and the Center for Cave and Karst Studies.

2003 - *Current: Can Cave Sediments Predict Past Flood Magnitudes?* This project is in progress and is investigating the relationship between flow velocities needed to move boulders through hydraulic lift tubes, and the magnitude of catastrophic flood events required to achieve this.

2002 - Independent Study Project: *Analysis of an Igneous Intrusion in a Highland County, Virginia, cave.*

2002 - *Microgravity survey across a portion of Hatteras Island, NC.* – This study measured extremely small variations in gravity across the island and is part of a larger geo-physical and hydrological study of this barrier island.

General Speleology:

- Eighteen years of experience in studying, exploring, surveying, and documenting caves.
- Many published maps and written works on caves, and caving techniques and equipment, in Virginia, other states, and other countries.

Professional Affiliations

Geologic Society of America
American Geophysical Union
National Speleological Society