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DELINEATING THE SUBSURFACE: USING SURFACE GEOPHYSICS TO IDENTIFY GROUNDWATER FLOW PATHS IN A CARBONATE AQUIFER

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This study examines stream loss in a small tributary of the Youghiogheny River known as Hoyes Run in Garrett County, Maryland. The stream bounds the pit of the Deep Creek limestone quarry, operated by Keystone Lime Company. During low flow, the stream abruptly terminates in a swallet, leaving approximately 100 m of dry streambed. In addition to geophysically investigating this swallet, our study located two other zones of loss active during periods of higher flow. Multiple resistivity profiles using the SuperSting™ Resistivity System were generated along the zone of stream loss and compared with results of ground penetrating radar (GPR) and electromagnetic conductivity (EM) profiles in the same location. Dye trace using Fluorescein™ confirmed the flow path of water from the stream into the quarry. Geologic examination of the area reveals several sizable known caves developed in the same limestone sequence; however, there are no known cave entrances in the immediate vicinity. Our study shows that surface geophysics coupled with hydrologic and geologic analysis can locate possible flow paths for groundwater in a karst aquifer, even in the absence of obvious karst surface expression. Borehole confirmation is slated before remediation measures are executed.

INTRODUCTION

Pollution and alteration of surface and subsurface hydrology increasingly threaten karst areas. In order to protect these fragile and dynamic watersheds, efficient diagnostic methods must be adapted for use in complex karst settings. The use of surface geophysical techniques to delineate possible flow paths of clean water in karst aquifers is a relatively new adaptation of existing technology.

Stream loss at Hoyes Run associated with the Deep Creek Quarry has impacted trout populations significantly since returning to operation in 1997. Since 1998, overall trout populations in Hoyes Run have declined from an estimated 669/km to 291/km in 2002 (Klotz and Pavol, 2003). Significant volume loss and thermal and sediment fluctuations have been cited as direct causes of this dramatic decrease. Protracted drought conditions as quantified by the Palmer Drought Severity Index for the county have contributed to the problem. The objective of this study was to apply several methods of near-surface geophysical analysis to a stream loss problem near a limestone quarry, ultimately to distinguish between solution cavities containing air, sediment and water in order to best delineate groundwater flow paths.

The study region consisted of the streambed and surrounding region of Hoyes Run, a small tributary of the Youghiogheny River. The loss of the entire volume of Hoyes Run, a previously pristine trout stream with neutral pH and low sediment load, was observed associated with a swallet that had developed in the streambed. An analysis of the geology and groundwater flow path suggested that water infiltrated the quarry at several seep zones that occurred along bedding contacts in the Loyalhanna Limestone. It seemed likely that the stream was following the altered hydraulic gradient from its bed and into the quarry at these seeps.

Downstream water quality was severely impacted due to this loss zone. Dry sediment from the exposed channel becomes highly mobile due to wind and flashy rain conditions. Additional sediment inputs occur due to insufficient residence time of rinse waters in the settling pond as well as turbulent erosion as the overflow discharge pipe. The settling pond is also improperly shaded, so it adds thermal fluxes to the downstream area, an additional problem in maintaining the diverse and abundant trout population.

One of the goals of this research is to determine the groundwater flow paths so a grouting solution could be initiated to restore the stream volume. This would simultaneously improve the quality of water in the downstream portion beyond the swallet and reduce energy expenditure associated with dewatering activities.

PREVIOUS STUDIES

Although surface geophysical methods such as resistivity and ground penetrating radar have been used extensively in carbonate bedrock areas, they have traditionally been limited to detection of cavities that are air or sediment filled, or sinkholes. By using a combination of traditional geology and hydrology, coupled with the application of surface geophysics, less uncertainty in data interpretation can be achieved.

Limitations noted for electrical geophysical methods by Keary et al., (2002) include the observations that interpretations are often ambiguous and must be correlated with a secondary method and that assessment of geologic controls are necessary to discriminate between valid alternative interpretations of the data. In addition, interpretation is generally limited to simple structural configurations, such that any deviations from these simple situations may be impossible to interpret. Topography and the effects of near-surface variations can also mask the effects of deeper variations (Keary et al., 2002).

Geophysical studies of karst have generally not emphasized detection of indirect indicators of deeper conduits, or mapping of recharge features, such as soil pipes or filled collapse features overlying active karst conduits (Ahmed, 2002). Combined methods of electromagnetics (EM) and ground penetrating radar (GPR) were used by Benson and La Fountain (1984) to identify soil piping and deep cavity detection with some success. Cooper and Ballard (1988) used microgravity, spontaneous potential, various downhole methods, sonar, resistivity, and ground penetrating radar over known targets with varying results. Yuhr et al., (1993) found that "Although there is a strong correlation between the resistivity of limestone and natural water in residence in a limestone aquifer, when employed in the vertical dipole mode, EM measurements are capable of detecting dissolution enlarged joints."

Use of EM and resistivity to characterize subsurface karst features were compared by Pazuniak (1989) with varying degrees of success in identifying linear fracture trends and areas prone to sinkhole development. The effect of groundwater was not evaluated, however. Zhou et al. (2000) used dipole-dipole electrical resistivity tomography for defining depth to bedrock of mantled karst in southern Indiana. McGrath et al., (2001) undertook a comparison of resistivity and microgravity with favorable results and a high level of data correlation between the two methods. Dunscomb and Rehwoldt (1999) used 2-D resistivity in a variety of karst terrains with a good deal of success in locating known cave and sinkhole features, as well as confirming suspected fault zones or clay-filled cavities. Resistivity methods yield useful information in water exploration and surveying despite a considerable decrease of resolution with depth (Sumanovac and Weisser, 2001).

Pringle et al., (2002) successfully utilized ground penetrating radar (GPR) to delineate sediment-filled caves that were appropriate for archaeological excavation. They compared the findings of a GPR survey to a resistivity survey in the same location. While they did not find a correlation between shallow-surface anomalies detected by resistivity and deep anomalies detected by GPR, they determined that the presence of high resistance solid limestone close to the ground surface masked the effects of any structures located at depth.

In summary, subsurface exploration of karstic terrains is dependant upon the geophysical method selected and its appropriateness to the subsurface conditions. While a homogenous medium may be an ideal circumstance for effective results from GPR, 2-D resistivity may provide poor results. Similarly, 2-D resistivity is much more successful in identifying shallow features, even when a clay-rich layer is present which would otherwise negate the radar signal of GPR. A variety of geophysical technologies are required to construct a reasonable model of the subsurface.

GEOLOGY AND HYDROLOGY

The study area is in the Sang Run quadrangle in Garrett County, Maryland (Figure 1), within the Appalachian Plateaus province. The quarry is leased by the Keystone Lime Company and is known as the Deep Creek Quarry. Topographically, it is situated on a knob that is bordered on the southeast by Hoyes Run, a small tributary of the Youghiogheny River. The area consists of a very gently dipping Mississippian age limestone, dolostone, sandstone and shale units (Brezinski, 1989) (Figure 1D). The basal unit exposed in the quarry is the Loyalhanna member of the Greenbrier formation. Quarrymen suggest, however, that the Burgoon Sandstone of the Purslane formation may be exposed at the quarry floor and refer it to as the "blue sand" while the Loyalhanna is referred to as the "blue lime." However, the flooded pit does not permit investigation of this transition to differentiate between strata at this level.

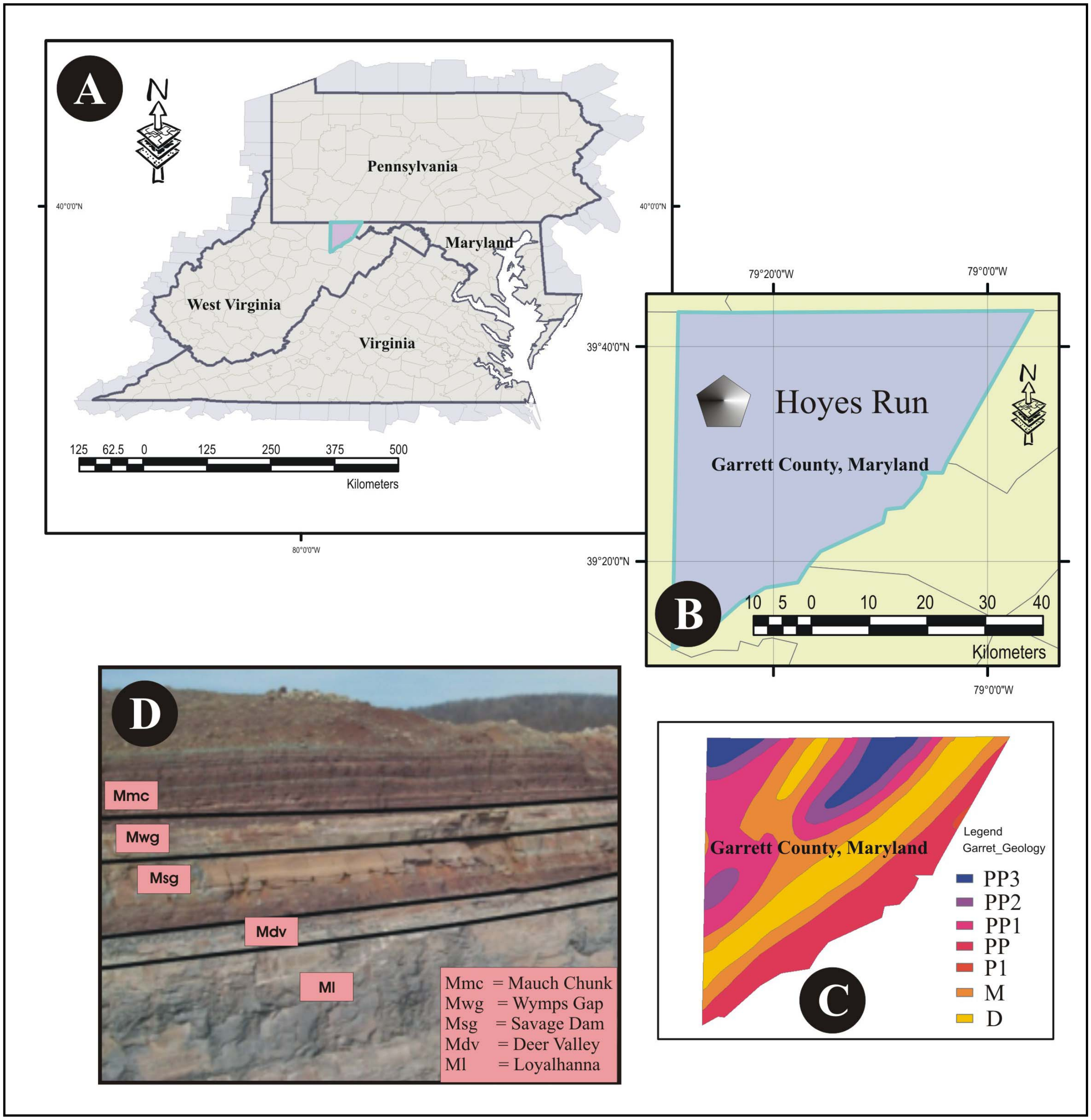

Figure 1. (A) Regional map of the study region showing Garrett County, Maryland. (B) Approximate location of the Deep Creek Quarry in Garrett County, Maryland. (C) Geological Map of Region from Schruben et al., (1994). (D) Stratigraphy of the area is well exposed along the quarry high wall from Brezinski, (1989).

The Hoyes Run watershed is fluviokarstic, with minimal karst surface expression, although springs do appear in the area in both the Deer Valley and Loyalhanna Limestone members in the Hoyes Run watersheds. Sinkholes have not been located except where associated with the stream loss noted in this study.

The quarry walls exhibit strongly regular joint sets that are nearly orthogonal and average N29° E and N48° W respectively, related to a regional structural feature, the Accident Dome anticline. These joint sets act as conduits for groundwater flow, creating a series of interconnected passages at near right angles that result in maze-like formation of solution channels and caves. Accident Dome is an anticlinal structure located on the Allegheny Plateau. It is an obvious continuation of the deformation that created the Ridge and Valley Province just to the east. This deformation was a result of repeated orogenies that created the Appalachian Mountains. Most likely structural deformation in the area occurred during the Allegany Orogeny, approximately 300-280 Ma.

John Friend Cave (also known as Friend's Saltpeter Cave) is developed in the Loyalhanna Limestone, and occurs northwest of the quarry at the base of Gap Hill. It is the only known cave in the area to have significant passage development and appears to be hydrologically unrelated to the drainage system surrounding the quarry. This is due to the fact that the topography is the geomorphologic result of fluvial downcutting along the limbs and axis of an asymmetric domal structure (the Accident Dome anticline) such that Ginseng Hill occurs on the northwest limb of the fold while the quarry is situated on the southwestern plunge, or slightly closer to the axis. It appears that Hoyes Run and the local groundwater flow path trend SW towards the Youghiogheny River, failing to interact with drainage associated with Ginseng Run. Therefore Ginseng Run functions as a surface, and most likely a subsurface, drainage divide isolating John Friend Cave from any groundwater associated with the Hoyes Run area.

Water chemistry in the watershed is generally quite good, and has for years supported significant trout populations (Klotz and Pavol, 2002). Samples taken during extremes of flow, from near drought to bank full conditions, indicate relatively stable temperature (~ 14° C), pH (~6.2) and total dissolved solids (TDS) (~688 mg/L) upstream from the quarry area. However, downstream water quality beyond the overflow pipe of the settling pond is significantly different with temperature readings as high as 18° C, one anomalous pH value of 8.9, and several TDS measurements over 9000 mg/L.

GEOPHYSICAL STUDIES

A resistivity survey using the dipole-dipole method at 3 m spacing (Figure 2) indicated several anomalous areas of increased resistivity. Stream loss was confirmed at the known swallet, coinciding at approximately 70 m. However, a second anomaly was noted at approximately 87 m. A visual inspection of the area confirmed that the stream was entering a small swallet in the stream bank at an area where the lower limestone unit contacted the upper redbed that was functioning as a confining unit for the Loyalhanna Limestone. This survey also revealed what was likely an extremely irregular limestone contact with possible pinnacles and areas of possible caves.

On a later date, surveys with the EM-31 were performed on 5 m and 10 m centers. A significant rain event resulted in near bank full conditions of the stream. Taking readings along the same traverse, data indicated subtle variations of several millisiemens per meter (mS/m) in the vertical and horizontal dipole modes. Although extremely subtle, this correlated with a resistive signal on the resistivity survey, and suggested a possible void space at depth. These surveys, however, failed to detect the second zone of stream loss. This was attributed to the sensitivity of the instrument at the selected location, which was several meters on the opposite bank from the area of interest. It is also possible that the loss zone was temporarily occluded by sediment due to consistent higher flow. The likelihood of a cavity occluded by clay fill was low as the anomaly was recorded as resistive, suggesting that it was air filled. It is likely that clay or water would have produced a more conductive signal.

EM-34 surveys with both 10 m and 20 m coil separation on 5 m centers were repeated for the stream traverse. In both data sets, there is a considerable drop off of conductivity in approximately the zone of stream loss. The results for the 20 m coil separation do seem to indicate the possibility

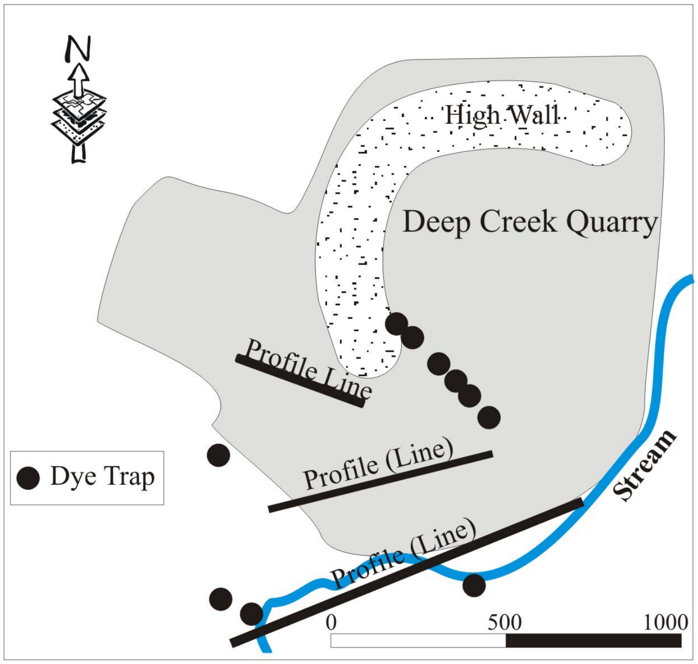

Figure 2: Location map of Deep Creek Quarry showing geophysical survey locations and dye trap locations.

of resistive anomalies at depth. Unfortunately, the subtle variations in the observed readings do appear to correspond with EM-31 and resistivity profiles for the same location. It is interesting to note the spike in conductivity on all EM surveys at approximately location 30-32 (~150 m along the traverse). These anomalous readings coincided with an electric fence that was deactivated for each of the studies.

The same profile was utilized along the stream for GPR evaluation. This study was conducted when the stream was at such extreme low flow that it was impossible to gauge. Findings correlated with the location of the primary anomaly (swallet) at 70 m, but also failed to detect the secondary loss zone. The study did, however, detect an area of stream loss that was previously not recorded (Figure 3). The loss occurred at a prominent outcrop of limestone bedrock at approximately 63 m, and appeared to have been treated with cement to prevent water loss. Although this zone had been visually examined on several occasions, no apparent loss had been noted. Visual inspection after GPR indicated a small amount of disturbed sediment disappearing into a void in the bedrock. It is apparent that in some instances high clay content in the soil interrupted the radar signal completely, and no subsurface imaging was obtained.

While the electrical methods both confirmed resistive anomalies at approximately 9 - 10 m below the surface, in this study GPR data did not quantify the depth of the anomaly. Upon completion of the comparative methods along the selected traverse, the results ranged from subtle definition of anomalies (GPR and EM) to well defined spatially (resistivity). It was determined on this basis to utilize resistivity for future studies.

A second resistivity line was completed approximately 30 m north of the first line, and approximately 8 m higher in elevation (Figure 4). This traverse was selected because it represented an intermediate contour midway between the stream and the quarry pit. The dipole-dipole survey was completed using 2 m spacing with the 56 electrode array. Data inversion revealed several negative

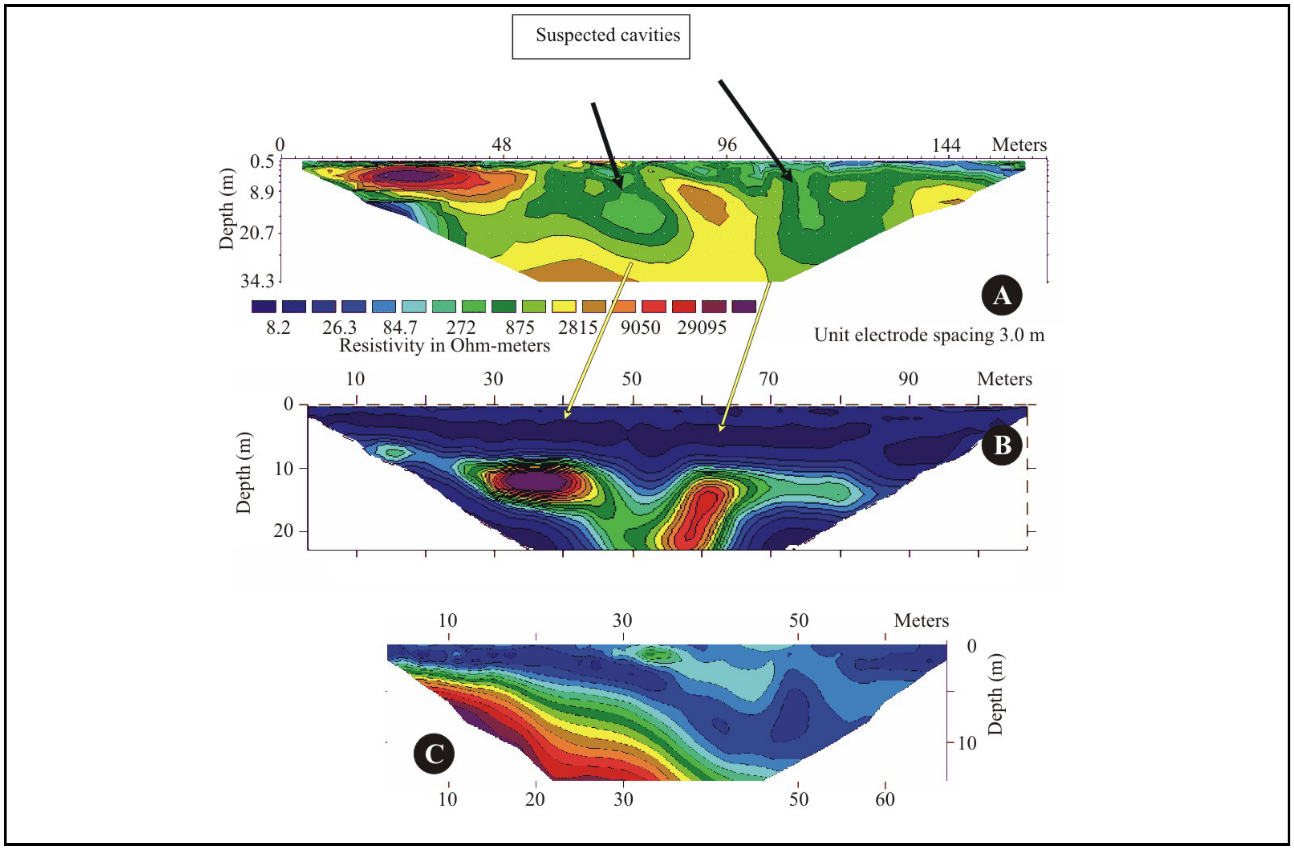

Figure 3: Data from line one (stream profile) was correlated across all three selected geophysical methods.

values that were discarded in further processing. Overall the error rate of the survey was low, with a low percentage of error at ~5-8%. This profile revealed two very large anomalous features that appeared to represent solution cavities (Figure 4). The pinnacled karst bedrock was evident, and was buried under a large volume of relatively homogenous and conductive material. These highly resistive anomalies had subtly different signal response such that the easternmost anomaly appeared extremely resistive, suggesting an air filled void, while the larger anomaly seemed slightly more conductive towards its center, suggesting a void with residual clay fill. These characteristics are being interpreted as two parallel passages that may or may not be hydrologically connected. However, the easternmost cavity appears to be communicating water from the stream to the quarry pit as it has likely been flushed of all sediment fill. This sediment appears to remain in the larger void. Although the clastic material deposited in caves comes from many sources, fluvial transport is the only significant removal mechanism (White, 1988).

A third resistivity profile was conducted along the inclined access road to the quarry pump. A total of 56 electrodes at 2 m separation were used. The electrode placement was difficult due to the large amount of loose overburden, and the highly compacted nature of the material on the access road. Additionally a large pile of rock and soil debris almost 2 m in height interrupted the survey. This profile did indicate a gentle gradient of reducing conductivity, and clearly shows the stratigraphy of the bedrock beneath the fill. The contact with the Loyalhanna limestone can clearly be seen (Figure 4C). Unfortunately the survey location did not coincide with locations of suspected voids.

There were two caves located when the quarry moved its highwall. Repeated charges failed to produce rock fracture. Upon inspection it was noted that a large solutional fissure was widened. Manual digging and the use of a backhoe revealed the cavities, occurring along joint trends and both measuring approximately 1-3m in width and as much as 7m in depth. Their linear extent could not be determined as unfortunately very little remained after the quarry rock removal. The passages found in the quarry pit were likely solutional features on the basis of the absence of breakdown. Evaluation of the remaining channels suggested two parallel, sinuous passages both approximately 7m in length and 3-4 m in width. They appeared to be approximately 5-6 m in depth and were completely sediment filled.

We propose that the speleogenesis of these two features were as follows: Solutional passages formed along regional jointing. Later, Pleistocene fluctuations of sea level caused the passages to be inundated by water. Subsequent lowering of the water table resulted in slow percolation of vadose water carrying extremely fine sediments. These sediments eventually nearly filled the cave passage. Additional elevation of the water table after melting of last glacial ice and subsequent erosion resulted in local base level to be at the level of Hoyes Run, flooding the sediment choked passages. Finally, the present quarry activity resulted in a local cone of depression in the water table that slowly emptied the cavities of water, while sediment was not transported out because either flow was not turbulent enough, or there is a lack of sufficient fracture below the caves to allow the sediments to be removed.

Only one of the two caves noted on resistivity surveys seems to be communicating water pirated from Hoyes Run into quarry pit. This is likely a zone of turbulent flow, resulting in transport of sediments from the easternmost cavity, allowing for more open cavity to appear on survey. This scenario correlates well with the sediment-filled cavities located in the pit area.

This confirmed the likelihood of additional solution passages occurring in the Loyalhanna formation at roughly the same elevation after correcting for dip as those that appeared on the 2nd

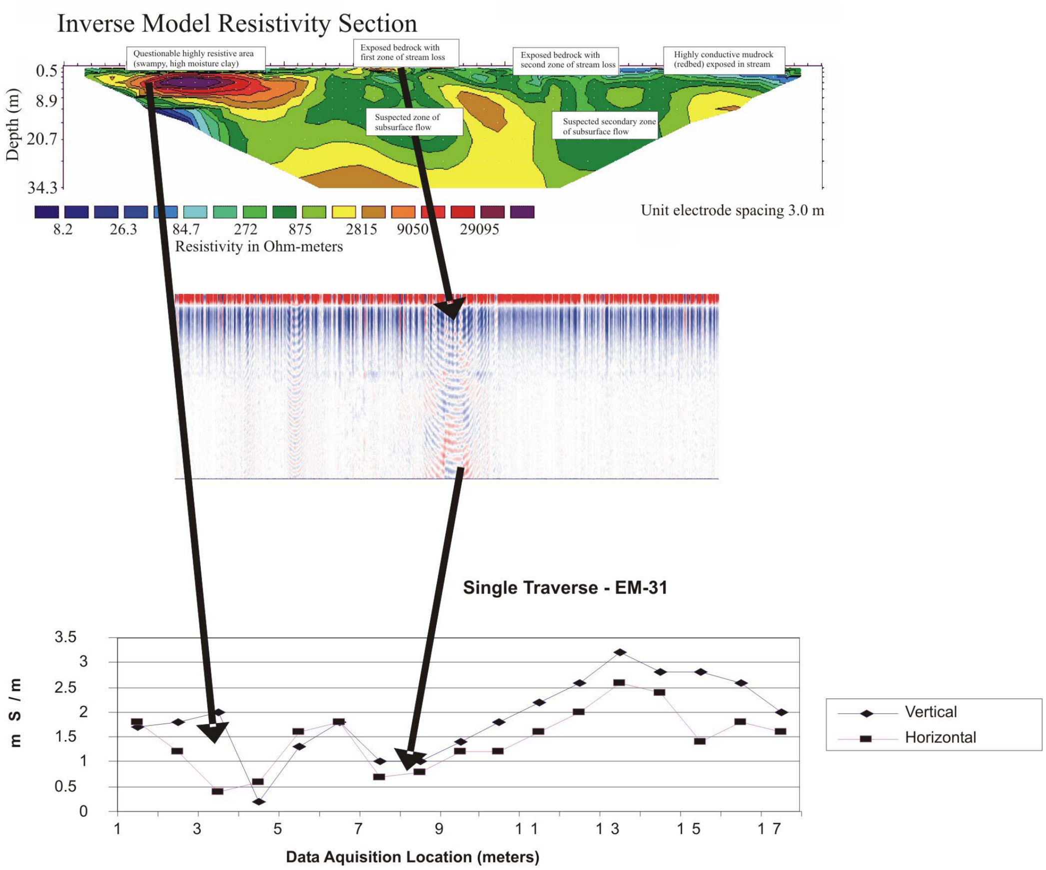

Figure 4. Pseudosections created by inversion of raw resistivity data for all three survey lines.

resistivity profile. Confirming the groundwater flow path along geologic strike from the stream to the quarry pit was required to determine if these cavities were pirating the stream, taking it to the artificial water table as efficiently as the karst system would permit it. A dye trace was completed to test this hypothesis.

During a period of high stream volume, a dye trace utilizing Fluorescein^{TM} dye was conducted to verify the suspected surface and groundwater interaction. After obtaining permission from Garrett County Department of Health as well as Maryland Department of Natural Resources, a protocol established by the Environmental Protection Agency (EPA) and adopted by the National Speleological Society (NSS) was adapted for use at the site.

Due to the poorly accessible location of the resurgent water, a number of methods were attempted at the collection point. It was finally determined that the best approach was to utilize more dye than calculated for, and to place dye receptors immediately beneath the cascade in the quarry pond. A total of 248.8 g of Fluorescein^{TM} dye was utilized. This amount, while greater than the calculated amount (31.1 g based on recommended dilution of 0.37 kg. /1.61 km of travel per NSS standards), was selected so that dilution could be minimized and a visual trace could be conducted. Fluorescein^{TM} dye was mixed with water from the stream. Due to extremely low temperatures (ambient air temperature -6° C, water temperature 6° C), mixing was incomplete as Fluorescein^{TM} is not particularly soluble at low temperatures.

Due to flashy stream conditions, a background fluorescence study could not be conducted; therefore, an additional trap was placed upstream, approximately 5 m away from the dye injection site to assess background fluorescence. Dye traps were placed in selected locations and the mixed dye was injected directly into the main swallet utilizing a 20.3 cm piece of 10.2 cm diameter PVC conduit. This encouraged most of the dye to enter the swallet with only a small amount being swept downstream with the current.

Due to weather conditions, dye traps were not changed until the third day following dye injection. Traps were collected according to protocol, and field analyzed for the presence of Fluorescein^{TM}. A total of four of the six traps located in the quarry pond tested strongly positive for Fluorescein^{TM}. A second trap was intentionally cross-contaminated for comparison with all traps, resulting in a distinct contamination spot, but an overall weakly positive fluorescence.

The control trap was negative for presence of Fluorescein^{TM}, as was the trap at the settling pond overflow valve. However, the trap located at the pump pipe outlet did fluoresce under UV light, indicating that dilution of the dye did occur, but not significantly enough to result in a negative trace. The presence of dye at this location confirmed the validity of the positive results from the quarry pit, as the only transport mechanism for water into this location was, indeed, from the quarry pit itself.

CONCLUSIONS

While all selected geophysical methods were able to detect known and unknown anomalous stream loss, electrical methods (especially resistivity) seemed best able to characterize the extent and depth of these variations. However, ease of use of the EM-31, coupled with its correlation to other methods, makes it an excellent choice for use in initial characterization of a similar condition. In the inhomogeneous, highly stratified environment of this study, resistivity proved far superior in characterizing suspected targets.

Subtleties in signal response of highly resistive bodies such as caves are not readily interpretable for groundwater flow path detection. However, this study has revealed that when coupled with hydrologic and geologic assessment, a reasonable hypothesis of groundwater flow path can be inferred from a resistivity survey, especially when turbulent flow conditions exist. The dynamic nature of groundwater flow in karstic aquifers is not easily modeled, but possibly geophysical techniques could be adapted to trace waters that have been injected with attenuation-enhancing salts. It is clear that electrical geophysical methods will become more and more relied upon for assessment of karst groundwater conditions in the future.

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