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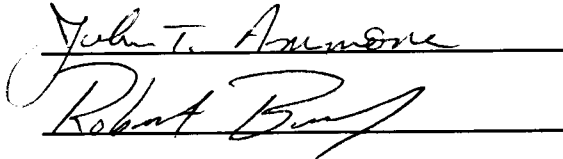
I am submitting herewith a thesis written by Joseph Cole Reagan entitled "An Examination of Methodologies to Assess High-Resolution Noninvasive Sensing of Near-Surface Perched Water". I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Agricultural Engineering Technology.



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We have read this thesis

and recommend its acceptance:



Accepted for the Council:



Associate Vice Chancellor
and Dean of The Graduate School

**AN EXAMINATION OF METHODOLOGIES TO ASSESS HIGH-RESOLUTION
NONINVASIVE SENSING OF NEAR-SURFACE PERCHED WATER**

A Thesis

Presented for the

Master of Science

Degree

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Joseph Cole Reagan

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To:

My parents, Ed and Anne Reagan, for the encouragement, support, and love they provided throughout my academic career. To my sister, Cari Reagan, for the strength and understanding that only a little sister could provide. To Tracey Odum, for her emotional support, love, and advice.

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Abstract

Previous studies have proven the rate that pollutants move through the soil is directly related to the rate that water moves through the soil. The rate that water moves through the soil increases under saturated conditions due to increased macropore flow. When an impermeable layer exists in a soil, the downward movement of water is restricted. If a saturated layer of soil exists above an unsaturated layer, a perched water table forms. A perched water table creates saturated conditions and increased macropore flow above the impermeable layer in the soil profile. Therefore, a perched water table may provide a rapid pathway for pollutants to nearby water resources.

Ground Penetrating Radar (GPR) is proposed as a tool that will noninvasively sense underground perched water. The research objectives of this study are to identify a perched water table in a shallow sandy loam soil lying atop sandstone bedrock, and to validate statistically the developed technique with the use of blind tests. Previous exploratory studies at the Environmental Research Tract (Plateau Experiment Station) are built on, refined, and developed to map morphological features that influence subsurface perched water. Perched water produces an area of signal scatter that occurs near the perched water surface within GPR data. Extensive lab processing of the data attempts to apply filtering methods to the data. The filtering processes aspire to divide the data into low and high frequencies, thus better distinguishing the actual perched water table surface and the orientation of this surface (e.g., slope). Blind tests are used to validate the filtering techniques developed in the lab and to ensure a non-biased interpretation. At present, results have not provided a repeatable method that can enhance the perched water surface so that it can be accurately measured.

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List of Abbreviations and Symbols

σ	Relative dielectric constant
$\sigma_{avg.}$	Average relative dielectric constant
σ_o	Overall relative dielectric constant
λ	Wavelength
A	Mineral horizon that formed at the soil surface
B	Horizons which have formed below an organic (O), mineral (A), or elluvial (E) horizon, and are dominated by the obliteration of all or much of the original rock structure
C	Mineral horizons or layers that are little altered by soil forming processes
ψ	Soil water pressure potential
FFZ	First Fresnel Zone
GPR	Ground Penetrating Radar
GPS	Global Positioning System
SIR	Subsurface Interface Radar
TT	Two Way Travel Time
DSP	Digital Signal Processor
AC	Alternating Current
DC	Direct Current
PES	Plateau Experiment Station

Chapter 1

Introduction and Objectives

1. Significance

With increasing urban and industrial expansion into rural areas in the 1990's, the assurance of the quality of Tennessee's rural water supplies remains questionable. Effects of urban runoff and irresponsible environmental practices are easily seen through developments of contaminated waters. Society's contact with these contaminated waters results in the spread of waterborne diseases. Also, pollution is a noticeable deterrent to most natural ecological systems. Many contaminants responsible for pollution seep unknowingly through the vadose zone into local water supplies. Therefore, the need for better soil water monitoring devices is essential to determine the pathways that contaminants travel.

Perched water, often conducive to contaminant travel, is a pathway to be considered. A perched water table forms when a low permeability layer lies below a layer with higher permeability. The low permeability layer can be a naturally forming fragipan with contrasting soil textures, or aquic moisture regimes. The low permeability layer can be due to the presence of plinthite mottles or continuous-phase plinthite bodies. In areas with shallow soils that resemble those found on the Cumberland Plateau, bedrock is a feature that can perch water.

In contrast to a perched water table, the true water table is the upper surface of the groundwater at that level in the ground where the water is at atmospheric pressure (Soil Sci.

Soc. Am., 1978). When a perched water table occurs, the soil conditions below the restricting layer are unsaturated. Where as, all soil below the surface of a true water table is completely saturated.

Surface-applied chemicals and fertilizers are foreseen by society as one source of pollutants. Therefore, examination of farming practices is an area of interest when studying contamination pathways. More site-specific technologies are being introduced to farmers, for example, the use of Global Positioning Systems (GPS) allows farmers to perform much more precise practices during crop production. The application of surface-applied chemicals and fertilizers can be monitored in the field and the areas that require more or less attention can be addressed appropriately. Important information needed to enhance and ensure the precision of these practices lies beneath the soil surface. In particular, areas with potential to perch water during continuous infiltration events are of great interest and concern. The spatial variability in soils, needs to be identified and examined within a particular location for perched water problems.

When there is increased use of irrigation systems or increased surface application of domestic and animal waste effluent, offsite surface and subsurface flow of contaminants caused by perched becomes a major concern. A perched water table generally forms under continuous infiltration events, whether it is a lengthy rainfall or irrigation. When a perched water table forms, the soil above the impeding layer becomes saturated. Under saturated conditions, macropore flow increases considerably. Macropores are large pores or channels in soil that formed from worm channels, decomposed roots, or increased preferential flow of water through soil pores.

Perched water tables have the potential to increase macropore flow within a soil. In addition, water perched at or near the surface will increase surface runoff. Surface runoff caused by perched water occurs when there is very little gradient to induce subsurface lateral water movement. Surface runoff can cause erosion and can also transport pollutants found on the soil surface to nearby lakes or streams, thus contaminating these water supplies.

2. Ground Penetrating Radar Overview

Ground Penetrating Radar (GPR), a relatively new technology, has been developed to aid in the gathering of subsurface soil information. A main area of GPR application is in soils. The information that GPR can gather is not only accurate, but is also noninvasive. Therefore, GPR requires much less labor intensive practices than many conventional methods that would be used during studies of this nature.

While radar waves can be used in different areas of scientific and military application, GPR is specifically designed for use when dealing with earthen materials. Ground penetrating radar emits a broad band of radar waves in frequencies that best penetrate earthen materials. The capability of GPR to penetrate a particular material is based on the material's electrical properties, primarily its relative dielectric constant (σ) and electrical conductivity (ρ). Radar waves penetrate a medium until they reach a layer that has contrasting electrical properties than of the previous layer. As the differing layers of the material are encountered by the radar waves, the waves are partially absorbed by the material, partially refracted away from the antenna, reflected back to the antenna, and they continue to penetrate. Therefore, many different factors must be considered before deciding to obtain GPR data.

Depth of penetration is one factor to be considered. Penetration depth of GPR is limited by the number and the strength of changes in electrical properties within a medium. Penetration depth is also limited to the ρ of the material. Electrical conductivity in an earthen material is stimulated by (1) porosity and degree of water saturation, (2) amount and type of salts in solution, (3) the amount and type of clay, and (4) scattering (Doolittle and Collins, 1995). Penetration depth is also determined by the frequency of the antenna used.

The antennas used with GPR produce radar waves that range in frequency from 10 to 1000 MHz. The lower the frequency of the antenna, the greater the depth of penetration. While the lower frequency antennas' penetration depths are greater, they often retain less detailed information since the larger wavelength (λ) cannot resolve the small changes in electrical properties between layers.

When information lies relatively near the surface of the material, a higher frequency antenna is usually preferred. The high frequency antennas smaller λ can resolve minimal changes in the electrical properties between layers. Using higher frequency antennas allows detailed information to be gained, which can be an advantage. Though the data are more detailed, the higher frequency antennas are limited in penetration depth. The lack of penetration depth is caused by the smaller λ becoming attenuated due to its encountering numerous changes in σ within a medium (The Finnish Geotechnical Society, 1992).

A primary electrical property of the soil that affects GPR's capability is the soil's σ . The sharper the change in σ between soil boundaries, the greater the amount of radar waves reflected back to the antenna. The σ of dry soil ranges between 2.5 and 6. The highest value of σ , 81, is the value of water. Therefore, soil water content is a significant factor in

determining a soil's σ . Other factors that affect a particular soil σ are related to the soil chemical and physical properties. These properties include: (1) bedding, (2) cementation, (3) voids, (4) faults, (5) intrusions, and (6) man-made metallic structures (Johnson et al., 1979).

3. Objectives

The research objectives of this study were to identify a perched water table in a shallow sandy loam soil lying atop sandstone bedrock, and to validate statistically the developed technique with the use of blind tests. Previous exploratory studies that used GPR technology to map soil morphological features that influenced perched water beneath the agricultural landscapes of the Cumberland Plateau (e.g., bedrock and soil horizons) were built on, refined, developed, and tested.

Chapter 2

Literature Review

1. Perched Water Tables

In order to predict the fate of agricultural chemicals in soils, there was a need for a better understanding of the physical, chemical, and biological processes that governed water and chemical movement under a wide range of conditions (Jaynes, 1991). Jaynes (1991) found that the rate at which pollutants moved through the soil was directly related to the amount and rate at which water moved through the soil. The flow rate of water through the soil increased under saturated conditions due to increased macropore flow.

A major concern was that agricultural chemicals or domestic pollutants may quickly find their way to a nearby source of clean water. One way these agricultural chemicals and/or other domestic pollutants enter water supplies is via turbulent macropore flow induced by perched water. Aubertin (1971), using a fluorescent dye, showed that macropores could conduct water at rates as fast as 10 m in 30 min under saturated conditions. Aubertin (1971) found these saturated conditions could occur prematurely when a perched water table formed. Rahe et al. (1978) used antibiotic-resistant strains of *Escherichia coli* to study the movement of bacteria in perched water tables on the hillsides in western Oregon. They found the movement of these strains to be at least 15 m in 1 h in the upper horizons of the soil.

Hammermeister et al. (1982b) proved perched water tables potentially provided a means that pollutants from agricultural and domestic sources could have entered surface

waters and consequently degraded the quality of these waters. These pollutants moved very rapidly through perched waters, allowing very little time to solve a known problem. Weyman (1973) concluded from a review of field studies and from his own work that for subsurface flow to occur, there must be an underlying zone of lower hydraulic conductivity. The low hydraulic conductivity layer would restrict the downward movement of water through the soil causing it temporarily to perch. If enough lateral gradient existed down slope, subsurface flow could occur.

The existence of a low-permeability clay layer in a high-permeability sand formation could lead to the formation of a discontinuous saturated lens, with unsaturated conditions existing both above and below the clay layer (Freeze and Cherry, 1979). Freeze and Cherry (1979) determined the infiltration rate of the upper layer was greater than that of the lower, less permeable layer. When an infiltration event occurred, the infiltrating water would reach the less permeable layer at rates too high for a particular soil layer to manage, thus perching the water temporarily.

In recent years, results from a wide range of field and laboratory studies indicated that solutes commonly did not move by simple piston flow. Instead, solutes traveled much faster through the soil via preferential flow paths (Jaynes et al., 1988). Preferential flow (i.e., macropore flow) in soil affected transport behavior of water and solutes in the field so that not only the prediction, but even the quantitative measurement of the water and solute distribution became difficult. Jury et al. (1986a,b) found accelerated movement of some moderately to strongly absorbing pesticides occurred through the involvement of extensive macropore flow.

2. Restricting Layers

The impermeable layer that restricts the downward movement of water could be caused by the presence of a fragipan or an argillic horizon containing high percentages of clay. Soils containing continuous phases of plinthite or numerous plinthite mottles also had the potential to perch water under excess soil moisture (Carlan et al., 1985). In addition to these, soils that have a shallow depth to bedrock could likely perch water. Not only was perched water information valuable in the prediction of contaminant transport, but also from an agricultural production stand point. Since perched water tables had the potential to exist for months, information about perched water tables was very valuable to farmers. Farmers were concerned about the depth to the water table in the spring that governed soil behavior in relation to early crop development (Bouma et al., 1980).

Fragipan

Parlange et al. (1989) defined a fragipan as a loamy clay horizon with very low organic matter and a greater bulk density than the overlaying layers. A fragipan, when dry, appeared to be cemented and could be almost totally impenetrable to roots, air, and water (Hillel, 1982). Franzmeier et al. (1989) reported an approximate 100-fold decrease in the saturated hydraulic conductivity of a fragipan relative to overlaying horizons in a soil in southeastern Indiana. During periods of infiltration events, the possibility existed of a perched water table or an episaturated layer forming in a soil that contained a fragipan. Episaturation was defined by Vepraskas (1992) and Soil Survey Staff (1992) as the condition in which a soil was periodically saturated in one or more layers that overlaid unsaturated horizons within 2

m of the soil surface.

Daniels and Fritton (1994) commented that nearly one-third of Pennsylvania's soils contained fragipans. They also stated that with the lack of advancement to provide urban-fringe housing public sewer systems, the problems arising from subsurface mounding of sewage effluent caused by fragipans would continue to grow. Mounding of sewage effluent was due to infiltration rates exceeding the capacity of the fragipan and the existence of extremely small lateral gradients beyond the zone of saturation. They found when very small lateral gradients were present, the restriction of water movement caused by a fragic horizon would cause the fluid to actually surface due to mounding of the fluid. In Pennsylvania and in other areas where fragic horizons occur, the mounding of sewage effluent problems began with the inconsistency of the common percolation test. The percolation test was often required by law in many states before a sewage disposal permit could be issued. The test was commonly used to design and size sewage disposal systems. They concluded that a problem with the percolation test was that it determined the soil's vertical hydraulic conductivity at a single depth and might or might not take into account the vertical hydraulic conductivity of the fragipan layer.

Under some conditions, like those found on the landscapes of northern Idaho, episaturated conditions could occur for extended periods of time. McDaniel and Falen (1994) indicated that episaturated conditions could develop as early as December and persist into May. They also confirmed that during this time the quantities of water contained in the perched zones of saturation could have represented as much as 58% of the seasonal precipitation received.

Plinthite

Blume et al. (1987) stated plinthite was an Fe-rich, humus-poor material that hardened irreversibly upon repeated wetting and drying. Perched water tables formed in some soils due to the presence of continuous-phase plinthite bodies or the presence of numerous plinthite mottles (Carlan et al., 1985). Plinthite restricted the downward movement of water and therefore had the capability to form a perched water table. Many coastal plain soils are characterized by rapid surface infiltration and reduced permeability in subsurface horizons due to plinthite (Asmussen and Ritchie, 1969; Fiskell and Perkins, 1970; Asmussen, 1975).

In the coastal plain regions, center pivot irrigation systems are a common farming practice. A major concern of farmers in this region is the efficiency of these irrigation systems. Blume et al. (1987) explained that due to the relatively high surface infiltration rates and the increased levels of plinthite, the efficiency of irrigation was greatly reduced. Recurring perched water tables allowed for rapid lateral movement of water along the top of these plinthic horizons. Besides the concern of irrigation efficiency, Blume et al. (1987) found these perched water tables allowed rapid lateral movement of surface applied chemicals and fertilizers by means of shallow subsurface flow or by surface runoff.

Bedrock

Bedrock, generally a low-conductive material, is another vadose zone constituent that has the capability to perch water. Soils that resemble those found on the Cumberland Plateau with shallow depths to bedrock face this predicament. During periods of heavy rainfall, temporarily saturated zones (i.e., perched water tables) often develop over less permeable

regions of subsoil or rock (Hammermeister et al., 1982a).

During an experiment on the hillsides in western Oregon, Hammermeister et al. (1982a) found that problems related to perched water were direct effects of near-surface impermeable bedrock. They found that at a particular site, there was a statistically significant difference in vertical hydraulic conductivity between the A, B, and upper portions of the C horizons. Though there was a difference in hydraulic conductivity, they determined bedrock was responsible for the perched water. For the same regions, the soil water pressure potentials (ψ) in the B and upper portions of the C horizon would temporarily rise. But, Hammermeister et al. (1982a) concluded that conditions for creating and maintaining a perched water table were much more favorable in regions of impermeable bedrock. From their studies on hillslopes, the contribution of subsurface flow from upslope regions increased the possibilities of a perched water table forming and increased its duration.

3. Effects on Water Supplies

Perched water tables potentially provide a means by which pollutants from agricultural and domestic sources could enter clean water supplies and consequently degraded the quality of these waters (Hammermeister et al., 1982b). The main water supplies that are in jeopardy from pollution via perched water are the nearby streams and ponds. Many farms have ponds or lakes used to water livestock. Other times naturally occurring streams are used as the water supply. There are residents in rural areas that extract water from streams for everyday household use.

Perched water may increase the movement of certain negatively charged fertilizers

when they are not absorbed by plant life. Nitrate (NO_3^- -N), which is commonly applied to crops in fertilizers, does not become absorbed by soil particles due to its negative charge, and therefore can move freely in soil through soil solution (Tisdale et al., 1993). NO_3^- -N became a pollutant when accumulations of 10-ppm were found in drinking water (Michna and Bourodimos, 1973) and if found in higher concentrations could cause Methemoglobinemia (Blue Baby Syndrome) in infants.

Lowery et al. (1982) found that the predominant cause of overland flow from sloping land was ephemeral perched water tables. They stated that the cause of the perched water was due to restricting B and C horizons in the soil, thus inducing surface runoff. With more strict regulations and laws on the applications of chemicals and fertilizers and better handling instructions with these farming aides, there was much less over application to the land than in years past. These best management practices have reduced much of the degradation of water supplies due to surface runoff, but the fact remained that there was still some pollution caused by agricultural and domestic sources. Perched water was thought to be an area of concern relating to these sources of pollution.

4. Soil Water Detection Methods

Prior to this study, there have been other methods used in order to detect water in soil (West and Black, 1970; Bouma et al., 1980; Crestna et al., 1985; Parlange et al., 1989). Some of these methods were a more conventional type, while other studies used more electrically dependent detection methods. Each method seemed to have its own advantages and disadvantages.

The disadvantages to many conventional methods are (1) they take a considerable amount of time and manpower when employed properly and (2) spatially limited due to the lack of study area they covered. The conventional methods also fell short on accuracy level. The accuracy level was affected by too many factors that occurred naturally and could not be accounted for (i.e., macropore flow, perched water). Bouma et al. (1980) suggested that shallow unlined boreholes should not be used to observe water tables because they formed artificial storage basins for macropores that conducted water into the borehole more rapidly than the water moves out of the borehole. They also suggested that deep unlined boreholes were affected by heavy rainfall due to lack of storage capacity of macropores. A macropore's lack of storage capacity was many times affected directly by a soil layer with low hydraulic conductivity that caused a perched water table. Macropore flow also affected piezometer readings. Bouma et al. (1980) found that some piezometers did not contain water during saturated conditions because naturally occurring macropores were not continuous through the sidewalls of the tubes.

A more complex system used to determine water in soils was with the use of a platinum oxygen cathode. The cathode's measurements were affected by a large number of factors interacting to produce a degree of variability between individual measurements. West and Black (1970) stated that if changes in oxygen flux among the three phase (soil, air, and water) system and the two phase (soil and water) system were sufficiently precise to enable the differentiation of the two systems, the technique could have had application in locating water tables in soils. In their study, West and Black (1970) discovered that in a well-drained soil the probability of detecting the water table was high. Yet under poorly drained soils there

was a higher probability of finding an isolated saturated zone occurring above an actual water table. McIntyre (1967) pronounced that the oxygen flux measured with the platinum cathode in a dry soil was an underestimation of the true flux. This suggested some question as to the accuracy of the cathode readings under saturated conditions, which generally occur when dealing with a perched water table.

Crestna et al. (1985), doing research for their study of the detection of water in soil with a computed tomographic (CT) scanner, discovered that gamma-ray absorption and neutron probe methods could be used for dynamical studies of water in soil, but they do not take into account soil inhomogeneities and do not evaluate three-dimensional (3-D) profiles of water content and motion. However, their study concluded the CT scanner did actually take into account soil inhomogeneities and they were also able to generate 3-D information. Petrovic et al. (1982), collecting data with a CT, were unable to obtain consistent results in measuring soil water content. While Crestna et al. (1985) had some luck determining quantitative water content, they found problems obtaining a function of position when a large number of absorption measurements had been taken. Aside from the problem of obtaining a function of position, Crestna et al. (1985) were able to determine real-time studies of water motion in soil up to 1.6 mm/s. This technique could possibly provide a considerable contribution in determining macropore flow rates within a perched water table.

Two methods commonly used by soil scientists and geologists to determine soil characteristics are electromagnetic conductivity meters (EM) and Ground Penetrating Radar (GPR). Each of these tools provided accurate data, have a major advantage of gathering this data nonintrusively, and are much less spatially limited in the field than other detection

methods. The fact that data obtained with these two methods were gathered nonintrusively is an advantage. The soil the data are collected from is in its natural state and has not been altered by intrusive probing. Both devices have been used to help gather a wide variety of soil data.

The EM used electromagnetic energy to measure apparent conductivity of earthen materials (Doolittle et al., 1994). The EM had been successfully used to identify characteristics in sodium-affected soils. For example, an EM was used to delineate between saline and nonsaline soils found in loess-derived soils in West Tennessee (Ammons et al., 1989). These two soils were difficult to separate during field mapping, but with the aid of an EM the separation in the two soils was much more easily identified. Also, the EM was used effectively in south-central Illinois to map the depth to the natric horizons (Nettleton et al., 1994). The EM had also proven to be useful for determining the depth to claypan in Mexico soils that were under similar management practices (Doolittle et al., 1994).

The one major disadvantage when using an EM was that for optimum output a medium that was relatively constant throughout a given area was required. Soil properties of one variable dominating over the properties of other variables provided for the greatest success when using an EM (Cook et al., 1989). When data were taken in this manner, with the basis on the dominant soil variable, assumptions were made on all other variables.

5. Ground Penetrating Radar Applications

One relatively new technology developed over the years to assist procedures in collecting soil information was Ground Penetrating Radar (GPR). To the present date, GPR

has been successfully used in mapping many subsurface features. The ability to map these features provides a better understanding of the interactions that take place in the vadose zone. Some of the features mapped can possibly contribute to the formation of a perched water table.

The ability to distinguish soil horizon characteristics was a major accomplishment of GPR. GPR allowed scientists to determine the spatial variability of soils (Collins and Doolittle, 1987). Many times, soil horizon formation, development, and other soil constituents could directly affect water movement within a soil. The ability to gather horizon data without any excavation or soil disturbance allowed for soil water testing in its natural state. The capability of GPR to provide this information nonintrusively saved considerable amounts of time and effort (Schellentrager et al., 1988).

Information concerning depth to bedrock was another source of information easily and accurately attained with GPR. Hamlett (1995) compared GPR with the use of manual rock probes to determine depth to bedrock. He discovered GPR to be much more consistent in locating bedrock. Hamlett (1995) found that many times large rocks suspended above bedrock would cause inaccuracies in the probe data. He also concluded, that on the Cumberland Plateau, deposits of mudstone would stop the penetration of the rock probe therefore, misrepresenting the actual depth to sandstone bedrock.

On the Cumberland Plateau, bedrock lays relatively near the surface (≈ 1 m). Depending on soil conditions and the antenna used, locating bedrock at depths greater than 1 m is possible. Under most conditions, GPR could commonly obtain data at depths ranging between 3 and 10 m. If ideal conditions existed, information that lays at depths of at least 20

m could be gathered (Johnson et al., 1979). Birkhead et al. (1996) determined that the accuracy of GPR in determining depth to bedrock in their study gave r^2 values equal to 0.85. The ability to map information dealing with both soil horizons and bedrock could be very beneficial when locating perched water.

The potential for GPR to be used as a tool for shallow subsurface hydrologic investigations was dependent on the performance of GPR for locating a water table and underlying restricting layers (Smith et al., 1992). Truman et al. (1988) found the ability of GPR to locate depth to the water table correlated highly with their physical measurements. They determined the correlation was high due to the difference in σ between the water table and soil interface. Truman et al. (1988) stated that water caused abrupt interfaces in soil due to its high σ . Birkhead et al. (1996) also obtained high levels of accuracy in determining depth to the phreatic surface. Their studies generated r^2 values equal to 0.97 when GPR values were compared with depth to a phreatic surface in augered boreholes. The accuracies they attained were also attributed to the relatively high σ of the soil water. The top of the phreatic surface was accented much more because of the decline in soil water content above the phreatic surface for the coarse-textured material.

The use of GPR allowed for observation of the extent and behavior of the water table on a more spatially continuous basis than was possible with conventional methods (Truman et al., 1988). When the determination of a definite water table, natural or perched, with GPR becomes more developed, information on wetting front movement could be magnified. Smith et al. (1992) discovered extensive monitoring well networks installed to determine mass storage and flow within soils could be costly and very labor intensive. They also stated that

these large well networks interfere with normal agricultural field sampling. The development of GPR to identify saturated zones of soil nonintrusively could prove beneficial when determining storage and wetting front movement. Once this technique was developed, the use of GPR could potentially be used to identify paths for preferential flow by monitoring soil water movement in the vadose zone. Once preferential flow path information was obtained, the ability to determine the fate and transport of pollutants could be assessed. Also, determination of animal waste lagoon seepage could become easier with GPR, than was found by Brune et al. (1988), when there was a better understanding of the hydraulic interaction in soil.

Conventional sampling techniques, unlike GPR, were intrusive methods of obtaining soil data. In relatively soft sediments, the spade and auger were the main conventional sampling tools. Each of these tools was slow, tedious, and provided incomplete data due to limited sites of observation and generally covered small survey areas. An important advantage GPR had over these conventional sampling techniques was providing a continuous record of underground features (Hubbard et al., 1990). Ground penetrating radar could provide this information without any excavation or disturbance of soil. Also, GPR provided for a much more efficient means of collecting soil data. Schellentrager et al. (1988) used GPR to update soil surveys in Florida. Ground penetrating radar proved to increase the number of transects studied, decrease the manpower required to perform the study, decrease the total number of hours spent in the field, and also decrease the total cost of the project when compared with the conventional soil survey method.

Chapter 3

Materials and Methods

1. Site Location and Description

Data obtained during this study were taken from two plots. These plots are located at the Environmental Research Track of the Plateau Experiment Station in Cumberland County, TN (Figure 3.1). The Environmental Research Track is adjacent to the Clyde M. York 4-H Camp. The soils in each plot are sandy-loam soils of the Lily series (Fine-Loamy, siliceous, mesic Typic Hapludult). The first plot contained a naturally occurring water table that was observed both physically via monitoring wells and with the use of GPR. The data from the plot was compared, contrasted, and used to develop the method to detect perched water. A second plot was installed to perform an unbiased blind test to ensure the validity of the procedure.

Plot 1

Plot 1 lies approximately 5 m from a nearby creek at the edge of a narrow stretch of woods and contains a naturally occurring water table generated by lateral subsurface flow from upslope regions of the plot (Figure 3.2). The water table can be visually observed in an excavated soil pit at the lower end of the plot. The plot is 9-m long and approximately 5-m wide. No alterations were made to the plot except the addition of a water monitoring system, the excavated soil pit, and removal of any vegetation and ground cover that would cause

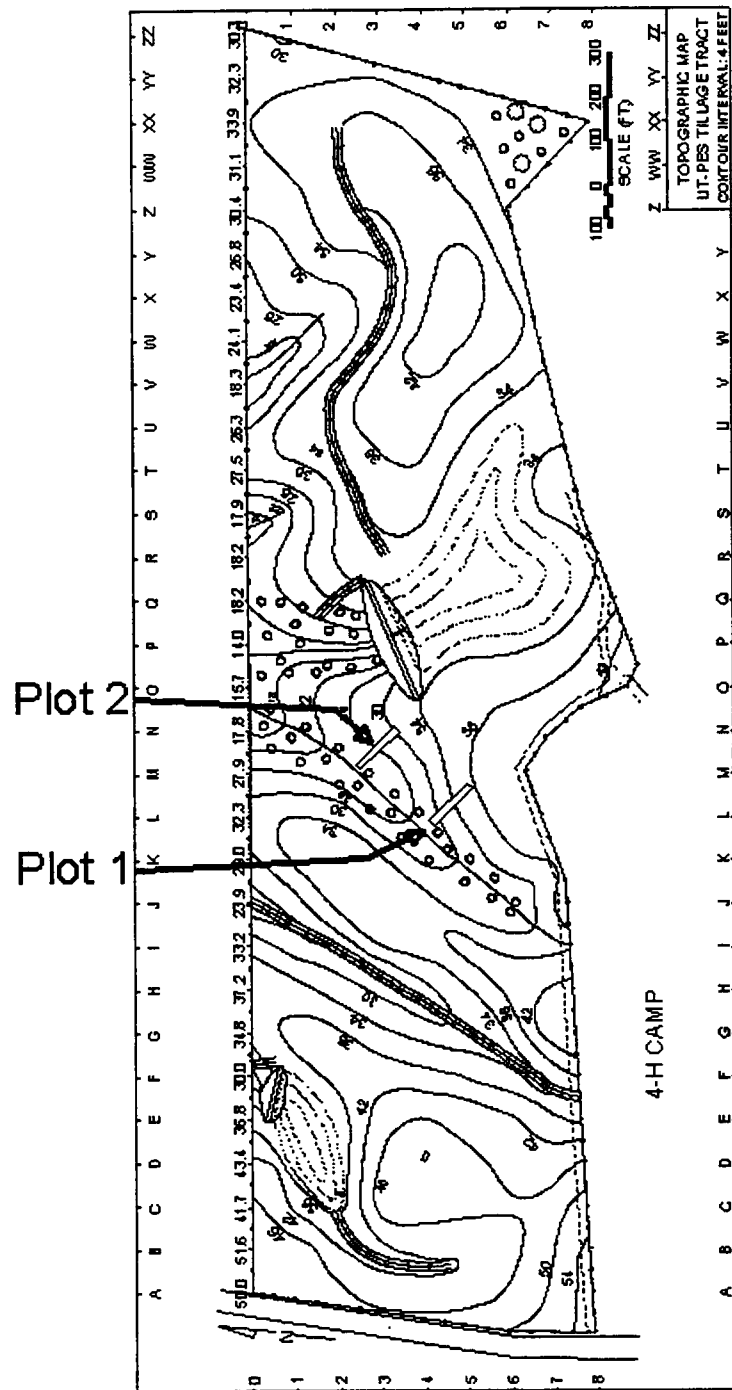


Figure 3.1 Positioning of Plot 1 and Plot 2 within the Environmental Research Tract at the Plateau Experiment Station.

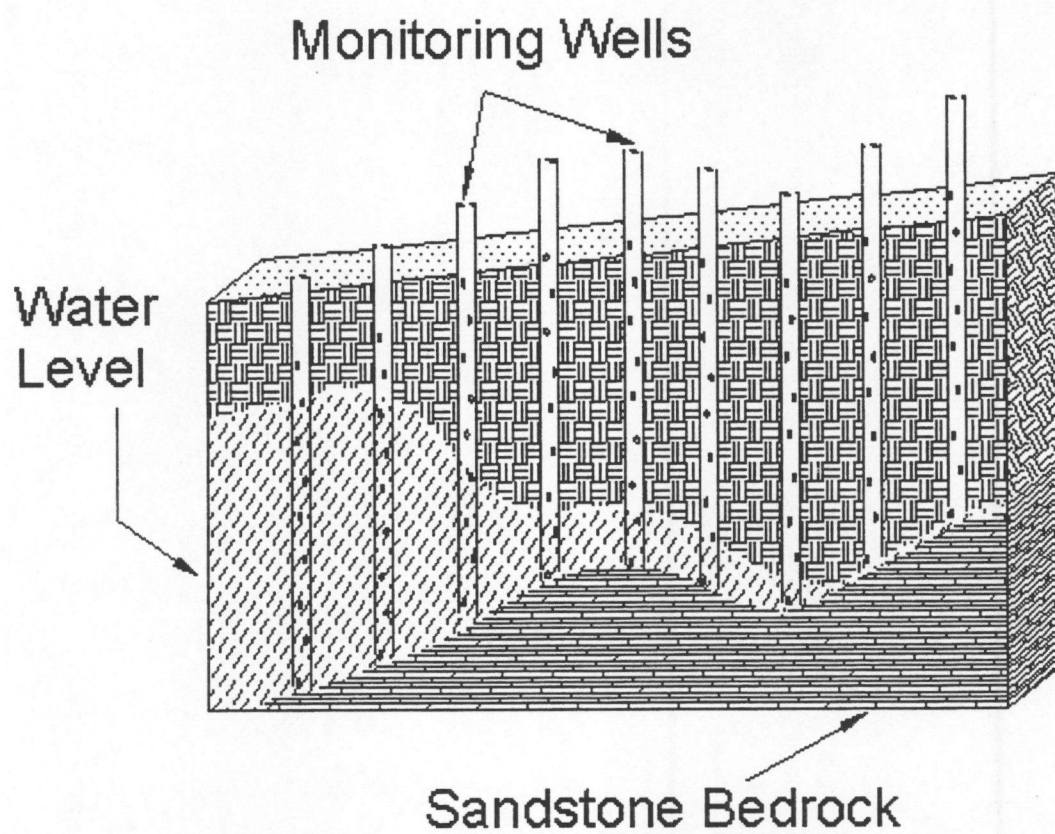


Figure 3.2 Approximate orientation of the water table, bedrock, and monitoring wells at Plot 1.

rough or uneven terrain.

Plot 2

Plot 2 was 7-m long and approximately 2-m wide. Plot 2 was along the edge of the same small stretch of woods as Plot 1 and was located approximately 50 m away from Plot 1. The water table was also generated by the same small creek as Plot 1.

2. Water Monitoring and Water Application

Plot 1

Plot 1, being long and narrow, had a single row grid pattern with 1-m spacing between grid points. Monitoring wells were installed at each of the grid points. Each well was installed with the use of a hand auger. The well holes were cored to a depth that allowed the well pipes to rest atop the sandstone bedrock. The wells consisted of 1.9-cm dia. polyvinyl chloride (PVC) pipe. Each pipe had 0.2-cm diameter holes drilled along its length 10 cm apart to allow free flow of water into and out of the wells. The wells were also left open at each end to enable an accurate measurement of the water level in the plot.

The water level in each well was measured with an electric measuring ruler that consisted of an open circuit at its tip attached to a buzzer at the opposite end. When the device was lowered into the wells and contact with water was made, the circuit was completed, causing the buzzer to sound. When the buzzer sounded, the ruler attached to the sensor was read to find the depth of the water in each well. The water table at Plot 1 was naturally occurring from a nearby wet-weather stream, and therefore no additional water was

added to the plot.

Plot 2

Plot 2 was installed for the sole purpose of performing a statistical comparison. Plot 2 was installed similar to Plot 1 (Figure 3.3). All ground cover and vegetation were removed to provide a smooth surface to obtain the GPR data. Monitoring wells were installed to rest atop sandstone bedrock. The wells were evenly spaced on a 1-m grid pattern.

3. Instrumentation Review

GPR Setup

A Subsurface Interface Radar System 10-A (SIR-10A) mainframe was used while collecting GPR data throughout this study (Figure 3.4). The SIR-10A was manufactured by GSSI, Inc. located in North Salem, NH. The programs that the mainframe operated were DOS based, and the components that made up the mainframe were very similar to a modern personal computer. These components consisted of a Cyrix motherboard, a math coprocessor, a digital signal processor, and the system's firmware.

During calibration, system inputs were obtained from a standard keyboard. During data collection, when a grid point was passed, a mark was placed at that point in the data either by a hand marker attached to the antenna or by one of the function keys on the keyboard. Though GPR provides a continuous profile of subsurface features and conditions, discrete observation points are needed to locate the radar image and to evaluate soil characteristics within a site (Brune et al., 1988).

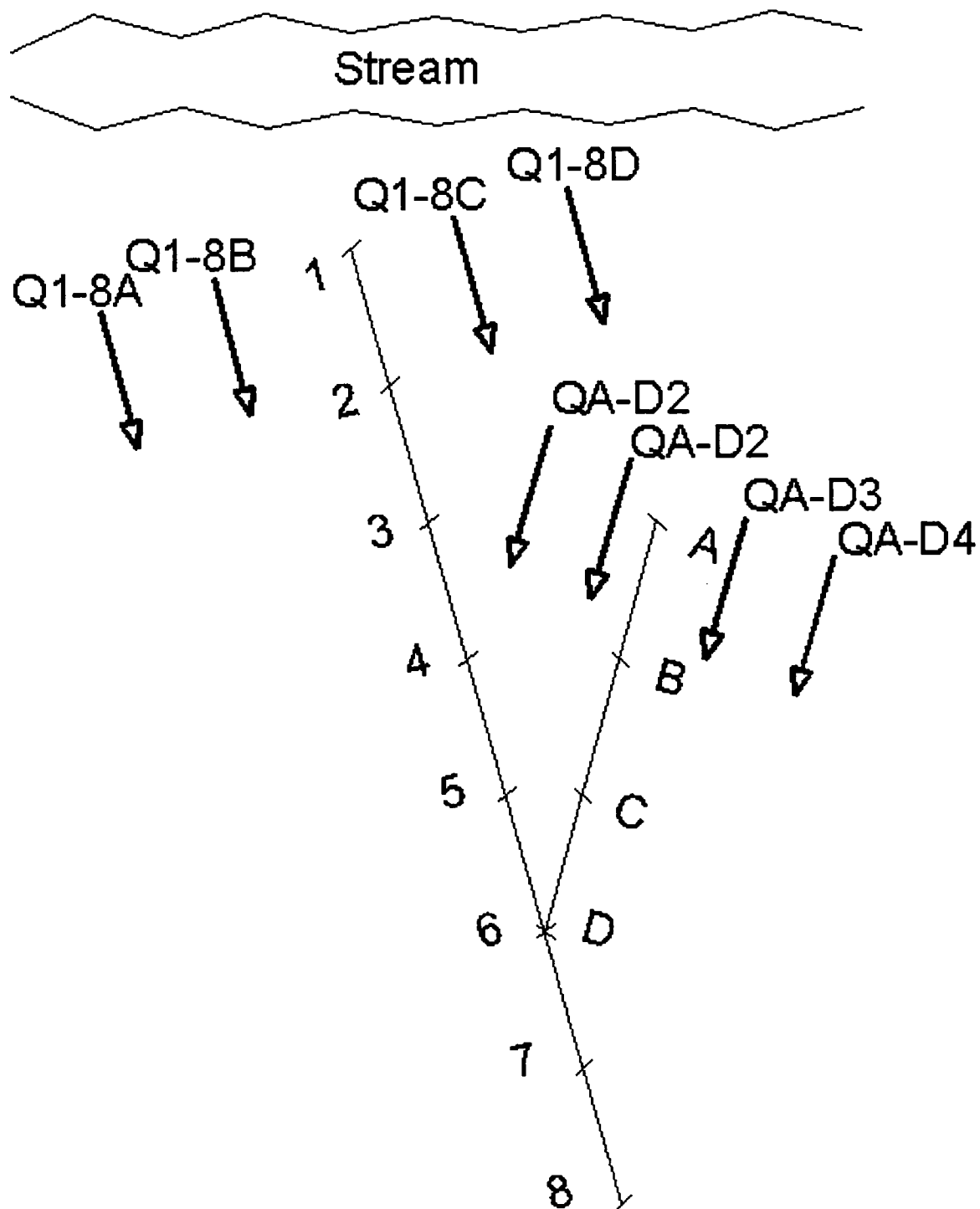


Figure 3.3 Orientation and labeling of monitoring wells spaced 1 m apart at Plot 2.

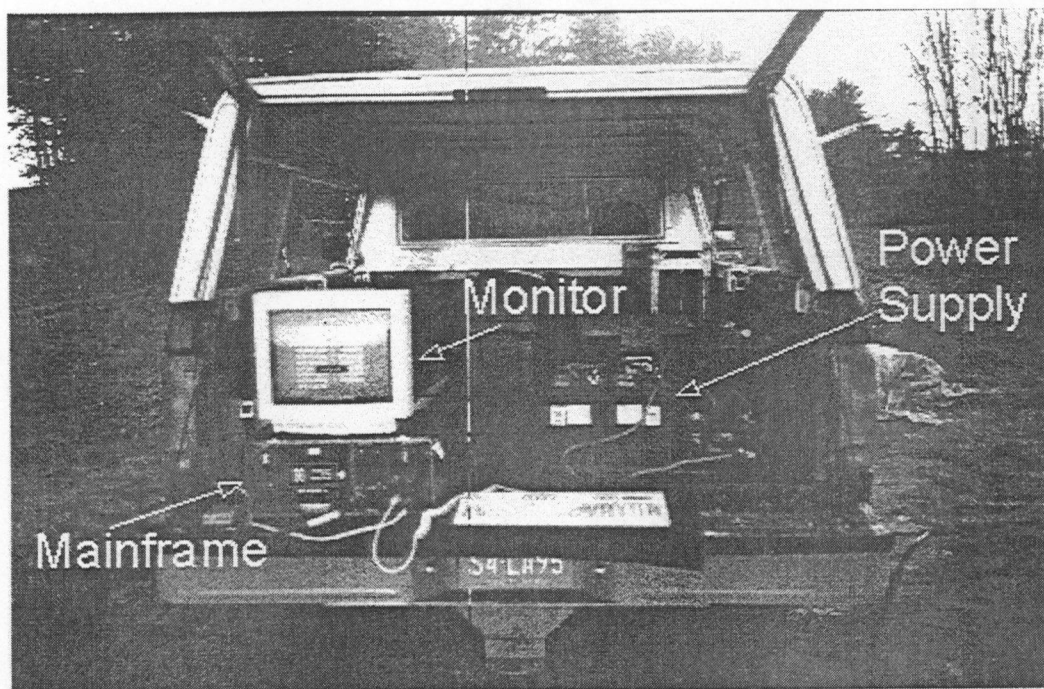


Figure 3.4 Setup of mainframe, monitor, and power supply in the field.

The type of radar output could be chosen from two different methods: by viewing the data on a VGA monitor and/or by storing the data to an internal tape drive. Radar output could be visually displayed on a VGA monitor that allowed for visualization of data in the field without actually storing the data to memory. When calibrating the system in the field, viewing the data on the screen was generally the method of choice. Once the system was calibrated, data output could be stored to an internal 2.3-GB Exabyte 8-mm tape drive while also being viewed on the VGA monitor. The advantage of storing the data to the tape drive was the ability to evaluate the data at a later date.

A large assortment of antennas existed for GPR data collection. The antenna sizes ranged from 10 to 1000 MHz. To obtain the high resolution data required for this study, a 900-MHz antenna (Model 3101D) was chosen. The antenna was attached to the system mainframe via a 15-m antenna control cable. During field operation, the antenna was secured to a PVC towing device.

Because there were no nearby sources of power, this study used a portable and reusable supply of electricity by wiring two 12-V deep-cycle batteries together in parallel. In turn, the power from these two batteries was converted from DC current to AC current by a DC/AC power inverter. The AC current from the inverter supplied both the VGA monitor and the system mainframe. When the two batteries were fully charged, six to eight hours of field data could be collected. Because the two plots in this study were relatively small and easily accessible, the radar system and the power supply were both run from the rear of a covered truck to reduce the effects of environmental hazards (e.g., rain, cold temperatures).

4. Data Collection Summary

Plot 1

Plot 1 consisted of a natural water table generated by a nearby creek. No additional water was added to the plot from outside sources other than rainfall. Measurements were taken in each of the nine wells using the previously described technique. Water level readings were taken two different ways. First, the amount of water above bedrock was measured in each well. Second, the depth to water below the soil surface was taken. Taking measurements both ways ensured correct determination of where the water level was actually located in the soil profile. These physical measurements were to be used in correlation with the GPR data.

Plot 2

Physical measurements taken at Plot 2 were taken by a neutral party. The neutral party withheld the measurements until all GPR data had been gathered and processed. Again, no additional water was added to the plot. The water table was generated from a nearby wet-weather stream. The data taken at Plot 2 were used exclusively for statistically comparing the procedure developed at the previous plot.

SIR-10A Settings

The SIR-10A provided several optional settings used under different field situations and with different antennas. The GPR interpreter used information obtained during previous GPR work on the Cumberland Plateau along with the SIR System-10A user's manual (GSSI, 1993) and some predetermined settings for the particular antenna (e.g., frequency, pulse

width) to determine the proper settings to be used to collect perched water information with a 900-MHz antenna.

The SIR-10A had the ability to utilize high and low pass filters in order to remove particular frequencies from the GPR data. The removal of unwanted frequencies would better identify a certain type of radar reflection. A high pass filter would remove low frequency data and allow high frequency data to pass through the filter, while a low pass filter would remove high frequency data allowing low frequency data to pass through the filter. The three types of vertical high and low pass filters that the SIR-10A made available were Infinite Impulse Response (IIR), Finite Impulse Response (FIR), and Triangle filters.

The three filter types each used vertical high and low pass filters in different ways. The main difference between the IIR and the FIR filters was that the IIR had a nonlinear phase response while the FIR had a linear phase response. The Triangle filter worked by sliding a triangle shaped weighting function over the data to remove high or low frequencies. Of these three filter types, the only one that the SIR System-10A user's manual cautioned the reader about was the Vertical IIR High Pass Filter. It stated that when obtaining GPR data this filter must be set to remove the low frequency noise before the gains were applied to the data. The removal of this low frequency noise controlled tilt within the data.

The GPR interpreter decided to utilize IIR filter settings similar to those recommended by the SIR System-10A user's manual and not to apply any other filters to the data while in the field. Further and more extensive filtering procedures were applied to the GPR data once back in the lab. The GPR interpreter could utilize the same filters that the SIR-10A provided by implementing a GPR interpretation program, Radan for Windows 1.4 (GSSI, 1997).

The SIR-10A constituents that made up the settings for the IIR filter were the number of poles needed and the frequency needed for the high and/or low pass filter. The number of poles for the IIR filter ranged from 1 to 4 for both the high and low pass filter. The higher the number of poles, the greater the suppression of unwanted frequencies. The recommended number of poles was 2. Setting the number of poles equal to 1 was not recommended because the filter may become tilt sensitive thus, over saturating the signal. Setting the number of poles to 3 or 4 meant that computation was approximately doubled that of the value equal to 1 or 2.

The recommended frequency setting value for the Low Pass Filter was 1.5 times that of the dominant cycles/scan of the data. The value for this setting can range from 1 to 255, the lower the number the stronger the filter. The cycles/scan value was calculated by dividing the range of the GPR signal by the antenna signal pulse width. The range used in this study was 30 ns/scan. The pulse width of the 900-MHz antenna was 1.1 ns/cycle. Therefore, the IIR Low Pass Filter Setting for the data taken was calculated to be 41. Knowing that the conductivity (ρ) of a loamy soil increased from 1.1×10^{-4} mho/m dry to 2.1×10^{-2} mho/m wet (GSSI, 1992), it was theorized that the perched water table was increasing the soil conductivity at the water table surface. The increased ρ at the water table surface caused high frequency scattering of the radar signal. Therefore, to allow more of the high frequency signal to pass through the filter, a higher value of 54 was given to the IIR Low Pass Filter. The value of 54 was chosen based on previous encouraging experimental water table work done on the Cumberland Plateau (Hamlett, 1995).

The recommended frequency setting value for the High Pass Filter was equal to 0.25

times that of the dominant cycles/scan of the data. For the research done on the Cumberland Plateau during this study, the value for the High Pass Filter was calculated to be 7. The SIR System-10A user's manual stated that this value should be initially used for the IIR High Pass Filter and should be increased or decreased until no tilt remained in the data. A value too high could cause useful data to be filtered out. A value of 4 was found to be sufficient to remove low frequency noise that caused tilt within the data.

Data Collection

Once water level measurements were taken at each well location, the SIR-10A system was calibrated using the previously described settings. Some settings, such as the gain, changed due to the present soil characteristics that may have been affected by the current soil water content. The radar antenna used during this study had a 900-MHz center frequency. A high frequency antenna restricted the depth of penetration, but the small λ ensured the depiction of very slight changes in the soil σ . Using the high frequency antenna produced the significant level of resolution needed for this study.

The well locations at each plot were evenly spaced on a 1-m grid pattern. The grid pattern was used as a guide to acquire the GPR data. Each row of wells was used as a transect by which the radar antenna was pulled. The pattern was sufficiently dense to ensure that complete data sets of each plot were taken. At each well location, a mark was inserted into the data from the keyboard. The mark allowed distinct identification of location inside the plot within the GPR data. The keyboard was used instead of the common procedure of using a hand marker. During the study, using the hand marker caused interference with the

radar waves that were emitted from the top of the antenna, that produced unwanted static in the data.

5. Blind Test

Throughout the study, all physical measurements taken were made available to the GPR interpreter. The information was needed to develop the calibration technique for determining perched water and bedrock within GPR data. Because the GPR interpreter had never observed perched water within GPR data, the water characteristics and radar reflection were calibrated using the physical measurements taken in the field. These physical measurements verified possible filtering methods used to sense perched water.

Though knowing the physical measurements during interpretation of the data supplied an effective calibration technique, there was the possibility for the interpretation to be biased. In order for the results of the study to maintain unbiased conclusions, a blind test was performed. Plot 2 was installed to serve this purpose. Radar and physical depth measurement data were gathered without the interpreter being present. Information such as location of plot, presence or absence of water, and direction of pull were withheld from the GPR interpreter. Once the Two-way Travel Time (TT) to the perched water table reflection for each well location in the data had been determined and submitted to the neutral party, three physical depth measurements were requested (shallow, moderate, deep). These measurements were used to calculate the overall relative dielectric constant (σ_o). The σ_o was in turn used to calculate water level depth measurements for all the marked well locations in the radar images.

6. Image Interpretation Procedure

A GPR annotation program, Radan for Windows 1.4 (GSSI, 1997), was used to process the GPR data in order to identify the perched water level within the profile. The water level was brought out of the data with the use of a Finite Impulse Response (FIR) boxcar filter. The FIR filter used a maximum value of 1023 scans horizontal low pass boxcar filter to remove any high frequency noise that was in the data. The FIR filter also applied a value between 66 and 99-MHz vertical low pass boxcar filter to remove any high frequency noise. Some filtered data consisted of numerous discontinuous reflections. When this occurred, a FIR filter with a value of 1023 scans horizontal low pass boxcar filter was used for a second time to remove the discontinuous reflections.

Knowing the relationship between depth and soil σ_o , and the equations used to determine the σ_o , the following procedure was used to calculate the depth to the perched water based on the TT and three ground truth measurements. Two points will define an exponential line, but after observation of previous data that used all data points to define the exponential change in σ_o , three points better defined the same line.

Hamlett (1995) found an exponential decrease in σ_o with depth when performing research on the Cumberland Plateau. Hamlett (1995) used the iron pipe method to calibrate and determine the σ_o for the soil profile. Three iron pipes were buried in the soil profile at three different depths. Using the known depth to the pipe and the TT, the σ_o could be calculated for the three depths. Therefore, the value of the σ_o used depended on the depth at which desired information was located.

Smith et al. (1992), using a 120-MHz antenna to locate a water table with GPR, found

one monitoring well measurement was adequate for calibration to predict the actual water table surface. But, Smith et al. (1992) also noted that using three monitoring wells produced a calibration that was more accurate than the one well calibration and that using six wells did not improve the results achieved by using three wells. Smith et al. (1992) compared these findings to the iron pipe method. Smith et al. (1992) buried iron pipes at two and three different depths in an unsaturated soil profile. They found that the iron pipe method consistently underestimated the actual depth to the water table due to differences in soil water content between the two calibration techniques.

Procedure

Prior to gathering GPR data, physical measurements were taken for depth to water table and depth to bedrock at each well location. These measurements were taken by someone other than the GPR interpreter to prevent a biased interpretation. Once the GPR data had been obtained, the data had all excess information removed from the beginning and from the end of the data set, and were then horizontally normalized. The previously determined filtering procedure was then applied to the data to bring out the perched water table. Also, the same data interpretation technique described before was applied to the data.

By changing the σ_0 of the filtered GPR data to equal zero, the depth scale of the data could be read in nano seconds (ns). Therefore, all depths to perched water in the filtered GPR data were recorded as the TT to the water level and back to the antenna. The three ground truths were chosen by the GPR interpreter based on the GPR data. A shallow, a medium, and a deep depth to the perched water table allowed for the best calibration for the σ_0 within the

soil profile. After processing the data, the GPR interpreter was provided physical measurements from three of the well locations from which he/she chose. The depth to the perched water was known in both length (m) and in its TT (ns) for the three ground truth locations. Knowing the physical measurements of these locations, the interpreter used these measurements to determine the σ_o for the three ground truth locations by using the following equation:

$$\sigma_n = \frac{(ns/m)^2}{43.56} \quad (\text{eq. 3.1.})$$

where:

σ_n = relative dielectric constant $n = 1, 2, \text{ and } 3$
 ns = TT in nano seconds
 m = depth in meters

Once the σ_n was calculated at each ground truth location ($\sigma_1, \sigma_2, \sigma_3$), the physical depth to perched water was plotted against the σ_o on an XY graph. An exponential trend line was fit to the three points to determine the exponential equation for change in σ_o with a change in depth (Figure 3.5). The graph produced a best-fit line with an equation that was used to calculate a σ_o for a given depth. Using the exponential equation produced by the depth vs. σ_o graph and after determining the limits of the 900-MHz to be approximately 0.75 m (Figure 3.6), values were used to calculate the TT of the perched water table. These values ranged from 0.0 m to 0.75 m on a 0.03 m increment scale.

$$\sigma_o = ae^{(b \cdot m)} \quad (\text{eq. 3.2.})$$

where:

σ_o = overall relative dielectric constant

a = constant

b = constant

m = depth (m)

The following equation could be generated by setting σ_n equal to σ_o and solving for ns:

$$ns = \sqrt{(ae^{(b \cdot m)} \cdot 43.56)} \cdot m \quad \text{eq. 3.3.}$$

where:

ns = TT in nano seconds

a = constant

b = constant

m = depth (m)

Once the TT for the range of depth increments was calculated, the TT was plotted against the range of depths in TableCurve™ v2.03 (Jandel Scientific, 1994) on an XY graph and all possible equations were fit to the line (Figure 3.7). It was determined that for several tests one particular equation, which had similar components to the previously used equations, continuously had high r^2 values ($r^2 \approx 0.99$). The equation was chosen to determine the depth to perched water given the depth in nano seconds.

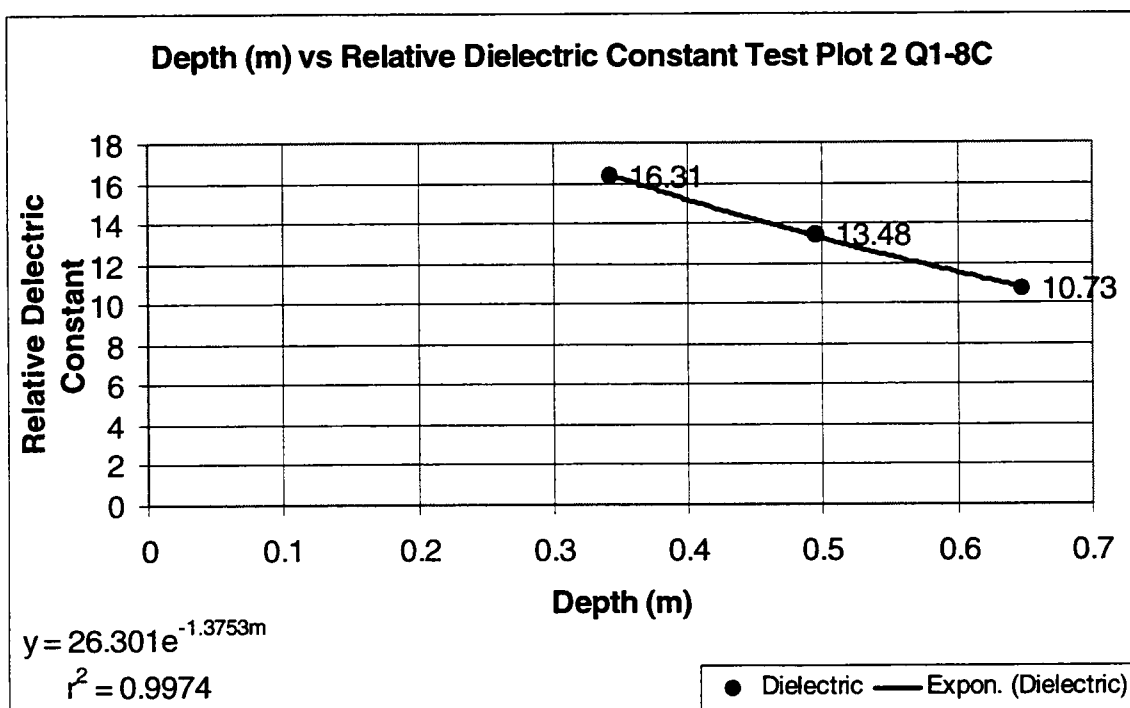


Figure 3.5 Exponential change in relative dielectric constant with a change in depth.

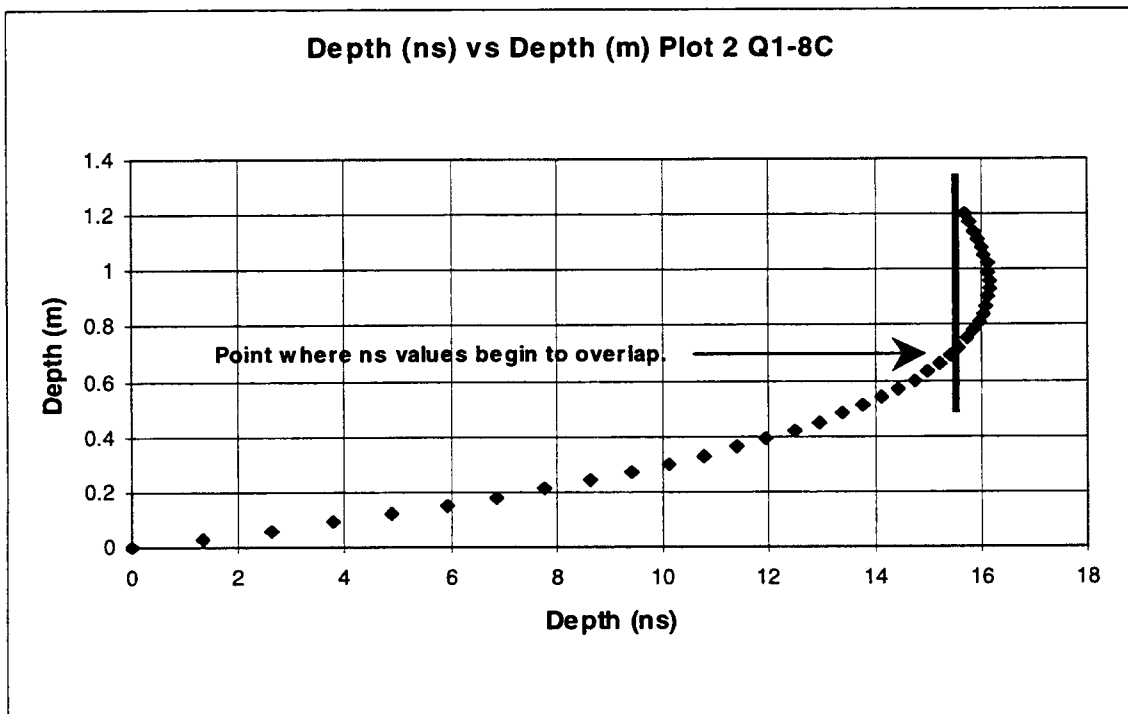


Figure 3.6 Illustration of the maximum depth of penetration of the 900-MHz antenna.

$$\ln(y)=c+d\sqrt{x} \quad (\text{eq. 3.4.})$$

where:

y = depth (m)

c = constant

d = constant

x = depth (ns)

Using the empirical equation derived by TableCurve™ v2.03 (Jandel Scientific, 1994) and the depth to perched water taken from the filtered GPR image in ns, the actual depth to perched water was calculated in meters. Once the depths were calculated for each well location and given to the neutral party, the true physical measurements were then given to the GPR interpreter. These two sets of data were statistically compared to each other using a statistical program (Appendix A) executed in SAS® v6.12 (Proprietary Software, 1996) (Saxton, 1997).

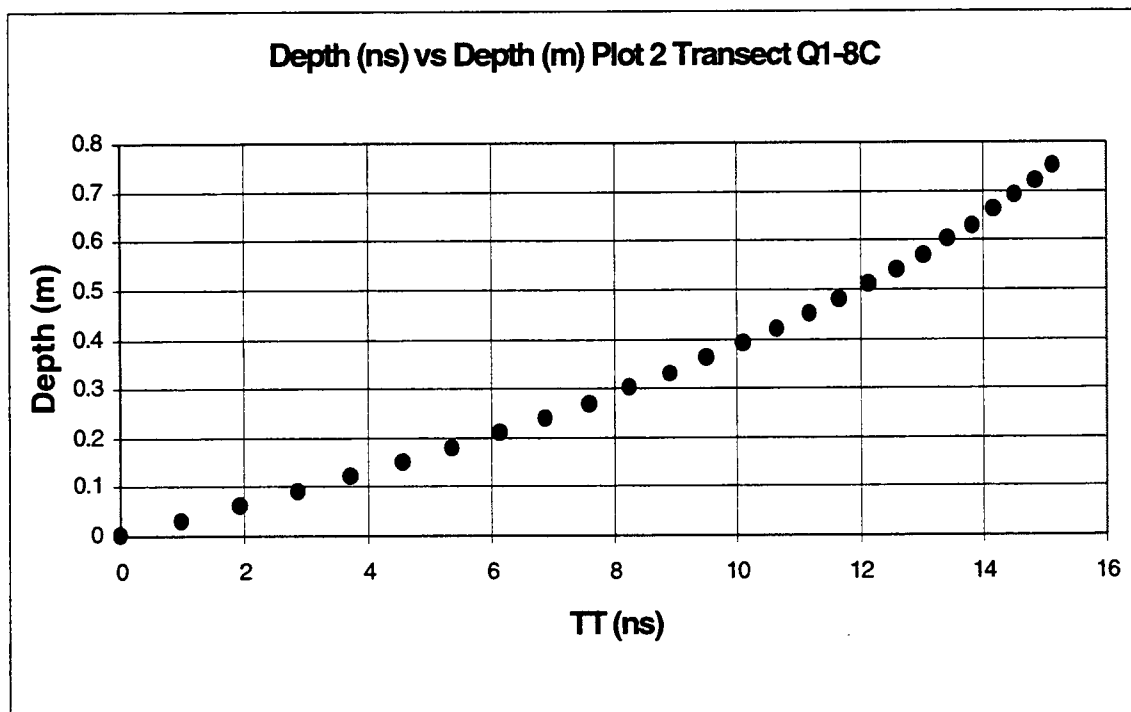


Figure 3.7 Calculated TT (ns) vs predetermined range of depths (m).

Chapter 4

Results and Discussion

1. Interpretation Results

When interpreting radar data, many cases allowed identification of soil characteristics based on distinct radar reflections. At Plot 1, the determination of the water level within the plot was not identified by a single strong reflection. Instead, the water level was identified in the GPR profile as an area of reflections that became scattered. The shallow depth at which the area occurred ruled out the signal scattering due to the antenna reaching its depth of penetration limits. A common depth of penetration for a 900-MHz antenna appeared to be 1 m. Had the scattering of the radar signal begun at ≈ 1 m or deeper, the signal scattering possibly could have been due to most of the signal being absorbed or reflected by layers in the soil profile. Instead, the signal became scattered at a depth that was within a reasonable depth for the 900-MHz antenna. The ρ of a sandy soil ranges in value from 1.4×10^{-4} mho/m dry to 6.9×10^{-3} mho/m wet and a loamy soil ranges from 1.1×10^{-4} mho/m dry to 2.1×10^{-2} mho/m wet. Thus, scattering was attributed to increased ρ due to an increase in soil water content at the perched water surface.

Blind Tests

The development and use of a blind test proved to be essential when ensuring that a subjective technique was scientific and repeatable. During the initial blind test, a single

calibration point was used to determine a single σ_o for the entire soil profile. Results provided reasonable r^2 ($r^2 \approx 0.84 - 0.88$) values, but an unacceptable correlation between physical measurements and GPR measurements (Figure 4.1 and 4.2). After further research, it was determined that assuming a single σ_o was inaccurate because the q changed with depth. Instead, three calibration points were used to calculate the average relative dielectric constant ($\sigma_{avg.}$) for the soil profile. The $\sigma_{avg.}$ gave a better representation of the actual σ for a given depth based on the TT to the particular soil feature reflection. Also, the use of the very top of the radar reflection to determine the depth to perched water was inaccurate. Instead of using the top of the reflection to obtain measurements, the top should have been used for the radar reflection until the reflection started to become banded. Once the reflection became banded, the bottom band at each mark should be used to determine the actual depth. Though the blind test failed to confirm the procedure was accurate, it provided a valuable consideration to be used for future blind tests and other research.

During the second blind test, instead of withholding all critical information from the GPR interpreter to ensure an unbiased outcome, the direction of pull was known. The direction of pull gave the interpreter a notion about the general slope of the perched water surface. The direction of the pull was uphill and away from the water supply, thus, suggesting an increase in depth from the soil surface to the perched water surface as the antenna was pulled farther from the creek (Figure 4.3, 4.4, and 4.5). Tables 4.1 - 4.3 provided the calculated depth to perched water, the statistical results for the second blind test, and the constants derived by the best-fit equations. The procedure generated excellent statistical results for the blind test, but the direction of pull was known by the interpreter.

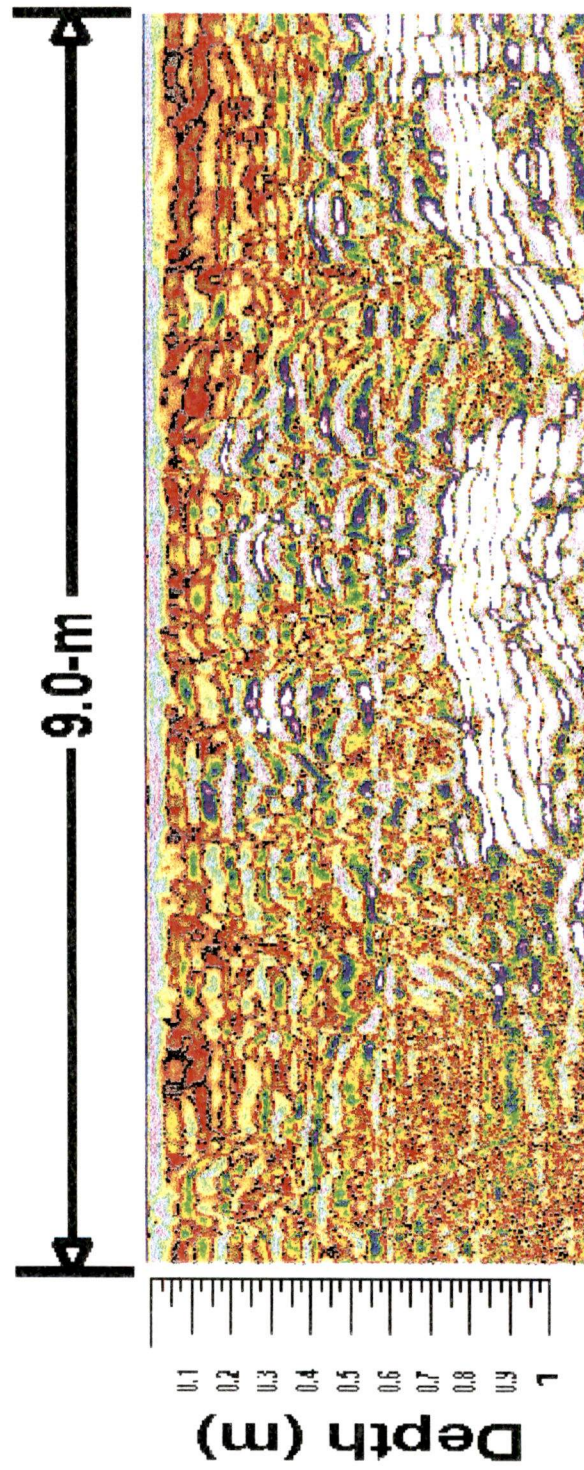


Figure 4.1 GPR data of Plot 1 prior to the filtering process.

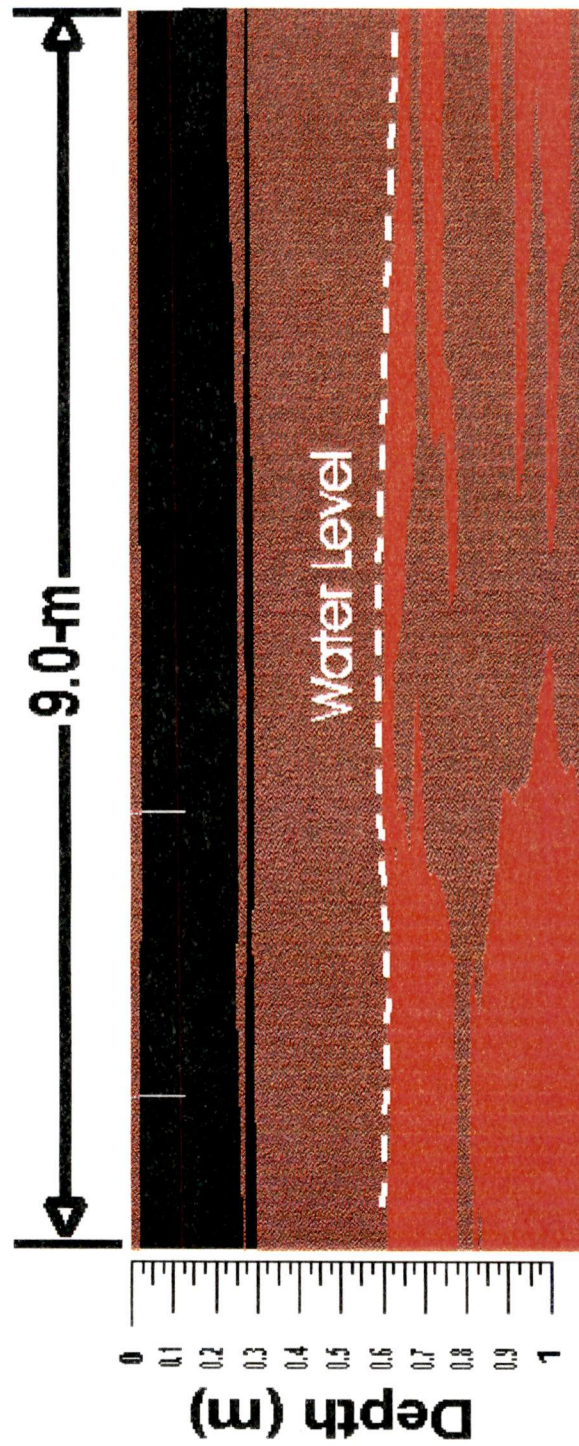


Figure 4.2 Filtered GPR data of Plot 1 using a single point for calibration of σ_0 depicting the water level. Interpreter knew the direction of pull.

Therefore, this was not actually a blind test. But, in order to test the particular procedure under different soil moisture contents and at a different plot, the same step-by-step process was performed on previous data taken at Plot 1 and at Plot 2. The direction of pull was also known for these interpretations. Tables 4.4 - 4.6 provided the calculated depth to perched water, the statistical results, and the constants derived by the best-fit equations for previously taken data.

When collecting data to be used for a third blind test, improper system settings were used. The different settings proved to change the appearance of the GPR images after filtering. These changes in appearance altered the interpretation of the data significantly.

A final blind test was performed on a set of previously interpreted data. The GPR interpreter was unaware of this fact and the data had been randomized by reversing the direction of some of the data files. Eight images were viewed, filtered, and interpreted in the presence of two witnessing neutral parties. Of the eight images, only three were interpreted correctly.

Detection of Restricting Layers

Bedrock produced a radar reflection in the GPR images at Plot 1 that was readily seen by the interpreter. Because GPR requires a well-trained interpreter to depict soil characteristics and because the data had to be presented to others, bedrock needed to be more easily identified. To visualize the bedrock surface better, a FIR filter was also applied to the data. The FIR filter used the minimum value (3 scans) horizontal high pass boxcar filter to remove some of the flat-lying ringing system noise in order to make the bedrock more visible

(Figure 4.6).

Though the same radar settings were used and very similar soil conditions existed, data taken at Plot 2 did not produce the same bedrock reflections as were seen in the Plot 1 data. The data taken at the plot could not be filtered in order to sufficiently bring out the bedrock.

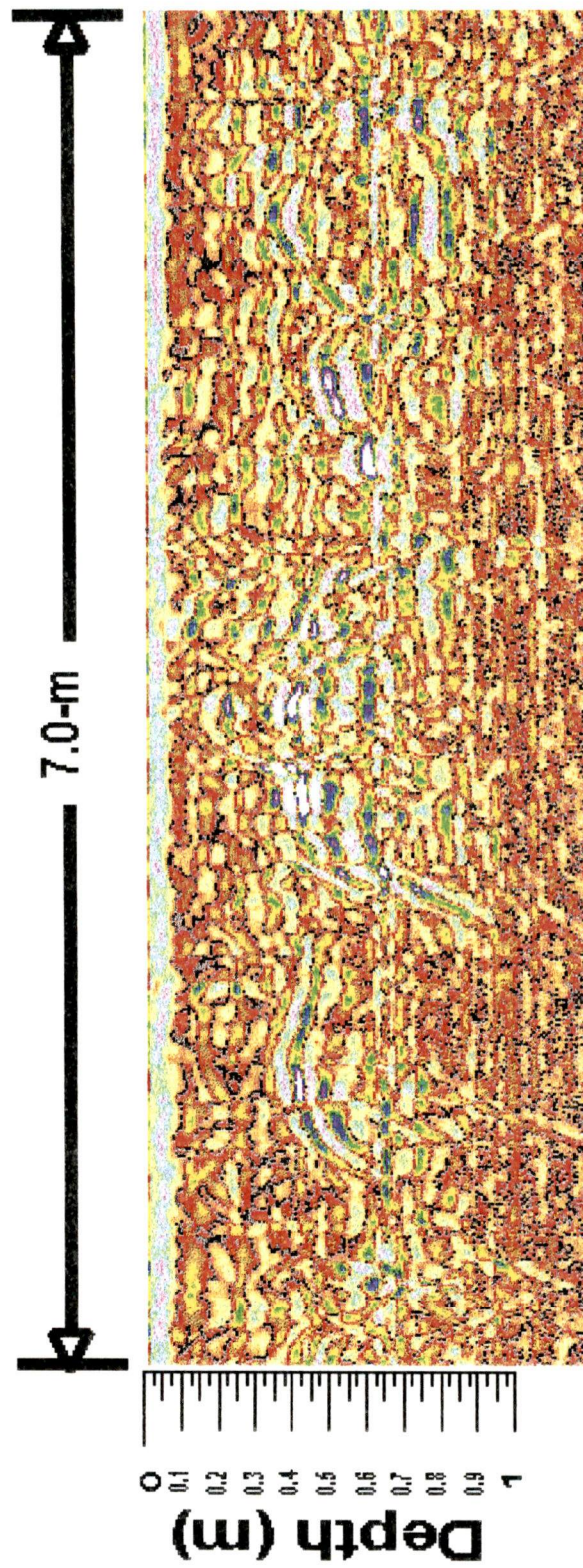


Figure 4.3 GPR data of Plot 2 prior to the filtering process.

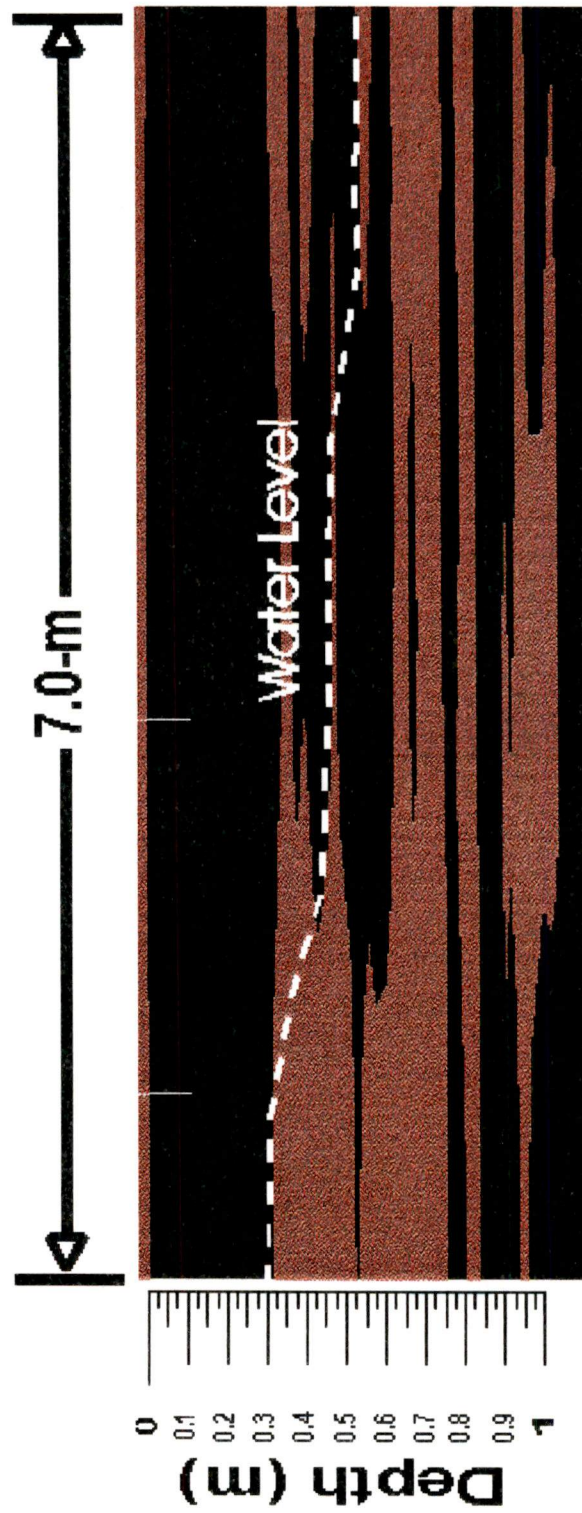


Figure 4.4 Filtered GPR data of Plot 2 illustrating the perched water table surface using three points for calibration. The interpreter knew the direction of pull.

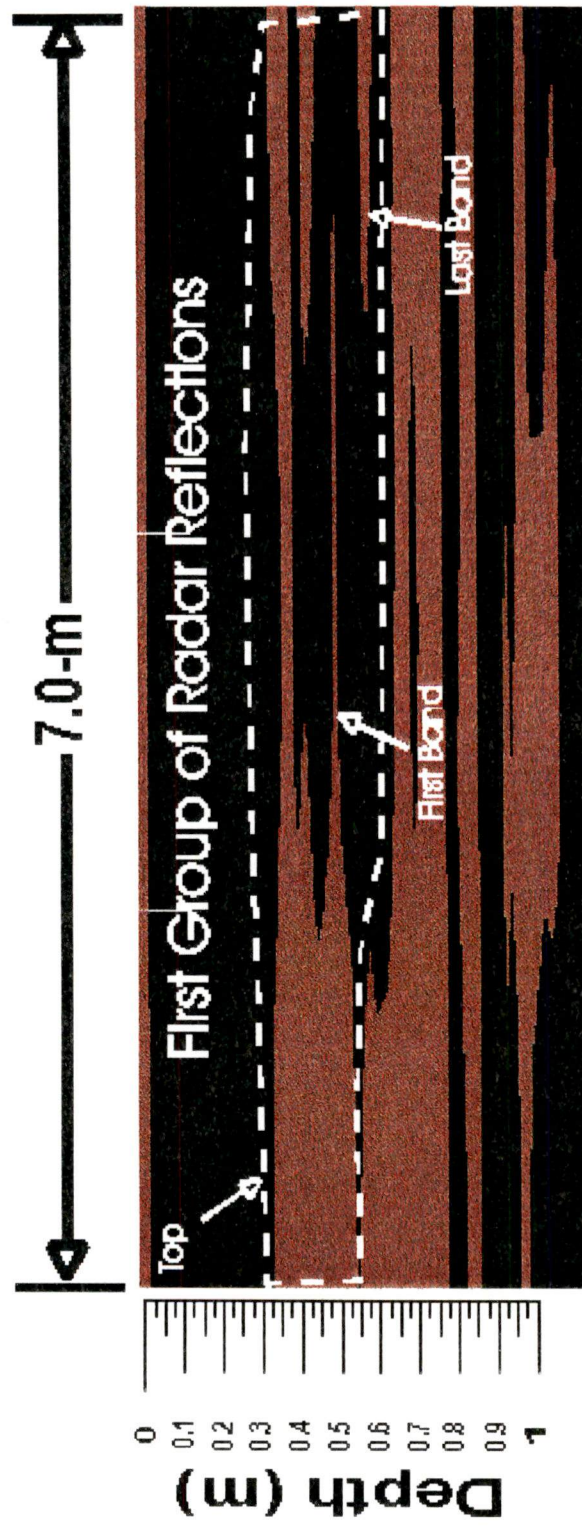


Figure 4.5 Filtered GPR data of Plot 2 showing first set of radar reflections and bands used to determine depth to perched water when the direction of pull was known.

Table 4.1 Calculated depth to perched water and the physical measurements to perched water for Plot 2 taken 5/09/97, with GPR interpreter knowing the direction of pull.

Well I.D.	Physical(m)	Q1-8A(m)	Q1-8B(m)	Q1-8C(m)	Q1-8D(m)
1	0.330	0.345	0.341	0.331	0.327
* 2	0.343	0.349	0.348	0.334	0.329
3	0.381	0.469	0.442	0.349	0.410
* 4	0.495	0.543	0.475	0.551	0.523
5	0.572	0.594	0.619	0.579	0.562
*† 6	0.648	0.637	0.670	0.579	0.632
7	0.737	0.694	0.791	0.721	0.662
8	0.762	0.718	0.791	0.738	0.662

* Ground Truth Wells

† Same well as D in Table 4.2

Table 4.2 Calculated depth to perched water and the physical measurements to perched water for Plot 2 taken 5/09/97, with GPR interpreter knowing the direction of pull.

Well I.D.	Physical	QA-D1(m)	QA-D2(m)	QA-D3(m)	QA-D4(m)
A	0.343	0.378	0.351	0.368	0.332
B	0.356	0.378	0.364	0.469	0.335
C	0.483	0.436	0.571	0.540	0.571
† D	0.648	0.579	0.586	0.621	0.603

† Same well as 6 in Table 4.1

Table 4.3 Statistical results from blind test and constant values derived from best-fit lines 5/09/97, with GPR interpreter knowing the direction of pull.

Transect	r ²	Intercept	Slope	a	b	c	d
Q1-8A	0.95	-0.1	1.16	40.52	-2.28	-4.93	1.25
Q1-8B	0.98	0.01	0.93	26.56	-1.52	-3.98	0.97
Q1-8C	0.96	0.003	1.01	26.30	-1.38	-3.84	0.91
Q1-8D	0.96	-0.08	1.19	25.20	-1.24	-3.72	0.87
QA-D1	0.97	-0.19	1.47	26.56	-1.52	-3.98	0.97
QA-D2	0.81	-0.01	0.99	26.56	-1.52	-3.98	0.97
QA-D3	0.88	-0.14	1.20	26.56	-1.52	-3.98	0.97
QA-D4	0.84	0.05	0.89	26.56	-1.52	-3.98	0.97

Table 4.4 Calculated depth to perched water, and the physical measurements to perched water for Plot 1 taken 3/16/97 using transect N1-N9B for calibration, with GPR interpreter knowing the direction of pull.

Well I.D.	Physical (m)	N1-N9B (m)
1	0.63	0.67
2	0.60	0.67
3	0.60	0.67
4	0.66	0.84
5	0.69	0.85
6	0.79	0.92
7	0.91	0.89
8	0.84	0.87
9	0.81	0.89

Table 4.5 Calculated depth to perched water, and the physical measurements to perched water for Plot 2 taken 4/18/97 using transect Q1-8C for calibration, with GPR interpreter knowing the direction of pull.

Well I.D.	Physical (m)	Q1-8C (m)
1	0.38	0.43
2	0.41	0.45
3	0.46	0.49
4	0.53	0.50
5	0.66	0.60
6	0.78	0.74
7	0.81	0.76
8	0.88	0.76

Table 4.6 Statistical results from blind test and constant values derived from best-fit lines 3/16/97 and 4/18/97 respectively, with GPR interpreter knowing the direction of pull.

GPR Transect	r^2	Intercept	Slope	a	b	c	d
N1-N9B	0.69	0.001	0.90	50.37	-1.60	-4.07	0.86
Q1-8C	0.97	-0.188	1.35	49.13	-2.11	-4.68	1.09

Table 4.7 Blind test of Plot 2 data taken 5/09/97 randomized as to perched water table presence and/or elevation trend (no water, level, increasing, or decreasing elevation), with GPR interpreter neither knowing direction of pull nor that it was a previously interpreted data set.

	GPR Transect	Actual	Interpreter	Correct
	Q1-8A	decreasing	decreasing	Yes
*	Q1-8D	increasing	none	No
*	Q1-4A	increasing	decreasing	No
	Q1-8C	decreasing	decreasing	Yes
*	Q1-8B	increasing	increasing	Yes
*	Q1-4C	increasing	decreasing	No
	Q1-8B	decreasing	increasing	No
*	Q1-8D	increasing	decreasing	No

* Transects reversed

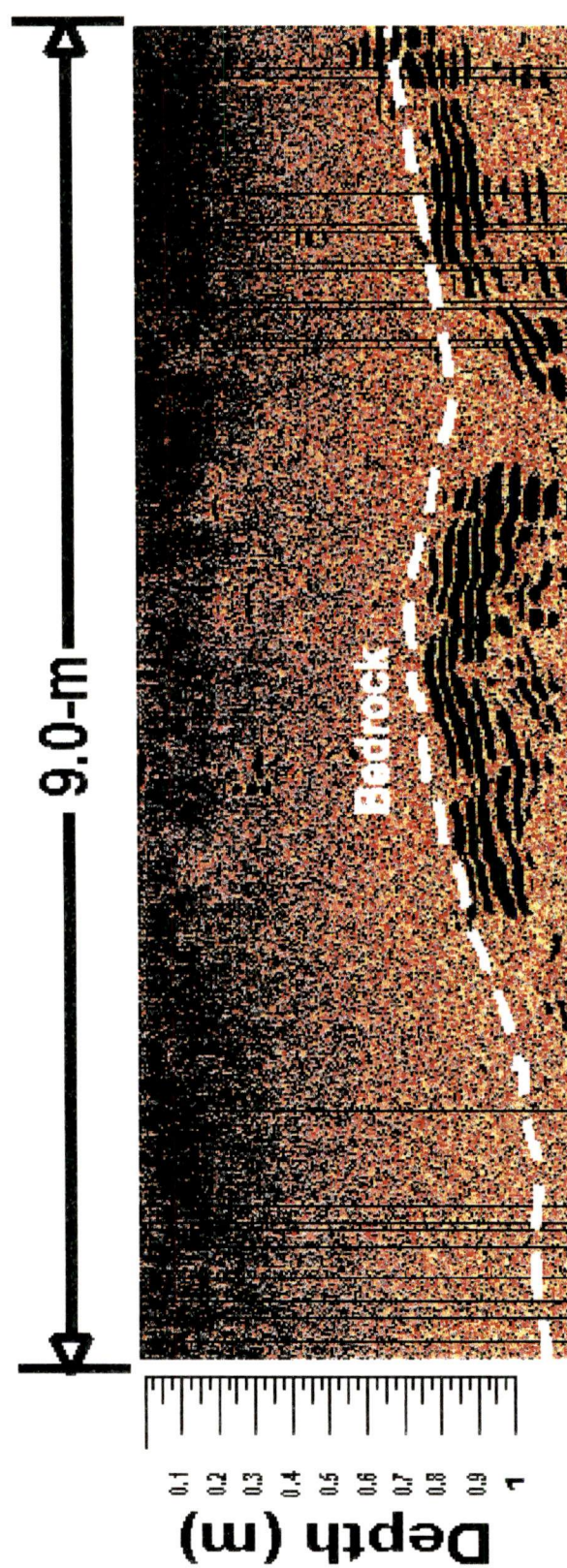


Figure 4.6 Filtered GPR data of Plot 1 illustrating the orientation of bedrock

Chapter 5

Recommendations

Many problems that occur with perched water are within the top 1 m of the soil, but the need to obtain perched water information at a greater depth could present itself. Currently the radar antennas range between 10 and 1000-MHz, but there is a relatively large jump from 500 to 900-MHz with nothing between. Therefore, an antenna with a frequency in the 600 to 700-MHz range would be needed. This range of antenna frequency would allow for greater depth of penetration than the 900-MHz, but still give a high level of resolution.

The fact that the bedrock could be randomly depicted with the high frequency antenna illustrates the spatial variability of the soils on the Cumberland Plateau. Also, to expand the possible uses of GPR in other agricultural areas that experience perched water problems, more data need to be collected in soils with restricting layers other than bedrock (e.g., plinthite, fragipans).

The largest problem with using the higher frequency antennas is the size and weight of the antennas. The antenna used in this study, 900 MHz, is 8x18x33-cm long and weighs approximately 2.3 kg. The small size and weight of the antenna tend to make the method impractical for large scale field use. Due to the small weight of the antenna, rough terrain causes the antenna to lose contact with the ground surface and distort the radar output. A solution to the problem would be to add weight to the antenna somehow and possibly stabilize the antenna so that it is more rigid during data gathering. One suggestion to possibly

correct the problem would be to construct a sled to harness the antenna. Not only would the sled add weight to the antenna, but if the sled were constructed in a way that provides support to the sides of the antenna, the antenna would become more stable during travel. The sled would protect the antenna from abrasions caused by extended use and rough terrain. The sled would also provide a way to pull the antenna more easily with an all terrain vehicle or a small tractor.

Blind Test

The calibration performed during this research used the physical measurements taken in the field. Though the GPR interpreter could have tried to maintain unbiased intentions, the fact still remained that the actual depth to perched water was known when observing the GPR images. Therefore, the only possible way to accurately test the validity of the derived technique was to predict perched water with the use of GPR blindly. The blind test provided an excellent method to prove repeatability of previous calibration techniques in an unfamiliar field situation.

Chapter 6

Summary

The research objective of this project was to identify a perched water table atop sandstone bedrock and identify the restricting layer. Once the method was developed, the procedure was to be enhanced and improved in order to identify perched water under natural soil settings on a repeatable occurrence. To determine the technique was repeatable, a blind test was performed.

Though many times water within a soil profile may produce a very strong and distinct radar reflection, Plot 1 determined that when dealing with perched water the reflection does not always occur. In order for a distinct radar reflection to occur, a sharp change in σ must be present. When a perched water table formed, it was usually proceeding an infiltration event. This means that the overall soil water content would be higher than usual for the entire soil profile. Therefore, the actual perched water surface will not have a σ much different from the above soil.

Instead of causing a distinct reflection, perched water was displayed in a GPR image as an area of data where the signal became scattered. This same type of reflection was usually seen when an antenna had reached the limits of its penetration depth. In the data obtained for this project, the scattered signal began much higher in the GPR image than it would be for the antenna's maximum depth of penetration.

The area within the radar image that depicted the perched water could vaguely be seen without any filtering of the data. But, to be able to measure the actual surface of the perched

water accurately, an attempt was made to filter out information other than that of the perched water table. With the use of Plot 2, blind tests were performed in order to validate the filtering techniques used to identify the perched water surface. The validation of the techniques used was essential because the interpretation of GPR images was very subjective. At present, no blind test has been successful in proving the methods developed were scientific and repeatable. However, each blind test attempt has provided insight to problems with the techniques used. One test failed due to use of a single σ_0 when the σ_0 actually decreased exponentially with depth. A second test failed because prior knowledge of the direction of pull was known by the GPR interpreter. These test results produced excellent correlation between the physical measurements and the GPR interpretation. However, the results could not be repeated when the direction of pull was not known by the interpreter. Previously gathered and processed data were presented unknowingly to the interpreter with the data randomized prior to interpretation. Only three of eight images were explained correctly for presence or absence of perched water and/or the slope. A third test failed due to improper hardware settings during data collection.

The detection of restricting layers (e.g., bedrock) was easily attained within Plot 1. Plot 2 did not provide the same results. The maximum depth of penetration for the 900-MHz antenna was found to be less than 1 m when attempting to detect perched water. The higher soil water content found when dealing with perched water attenuated the radar signal much faster than under dry conditions. The results from this project performed on the Cumberland Plateau found that to detect a restricting layer beneath a perched water table 1 m or deeper, a lower frequency antenna should be used. A lower frequency antenna would provide greater

depth of penetration, but would lose the ability to detect narrow changes in σ .

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Appendices

Appendix A

Statistical program used to compare physical and GPR calculated perched water depths.

```
options ls = 64 ps = 72;
      data Q1-8B;
      input gpr physical;
      diff = gpr - physical;
cards;

;
proc print data = Q1-8B;
      title "Difference between GPR Water Level and Physical Water Level";
proc univariate data = Q1-8B;
      var = diff;
run;
proc reg;
      model physical = gpr;
run;
proc plot; plot physical * gpr
run;
```

Appendix B

Raw Data File Names

Date	File Name
6/17/96	CRSV6_17_96
3/16/97	CRSV3_16_97
4/18/97	CRSV4_18_97
5/9/97	CRSV5_9_97

GPR Data Used in Figures				
Figure	Raw Data	Corel Draw	Presentations	WordPerfect
4.1	N1-9A.DZT	PLOT2GPR.CDR	PLOT2GPR.WPG	GPR-FIG.WP6
4.2	N1-N9AFIL.DZT	PLOT2FIL.CDR	PLOT2FIL.WPG	GPR-FIG.WP6
4.3	Q1-8B.DZT	PLOT3GPR.CDR	PLOT3GPR.WPG	GPR-FIG.WP6
4.4	Q1-8BFIL.DZT	PLOT3FIL.CDR	PLOT3FIL.WPG	GPR-FIG.WP6
4.5	Q1-8BFIL.DZT	BANDING.CDR	BANDING.WPG	GPR-FIG.WP6
4.6	PLT2BEDA.DZT	PLOT2BED.CDR	PLOT2BED.WPG	GPR-FIG.WP6

Other Figures				
Figure	AutoCAD/Excel	Corel Draw	Presentations	WordPerfect
3.1	CRV-TOPO.DWG	CRV-TOPO.CDR	CRV-TOPO.WPG	ACADFIG.WPD
3.2	PLOT2CAD.DWG	PLOT2CAD.CDR	PLOT2CAD.WPG	ACADFIG.WPD
3.3	PLOT3CAD.DWG	PLOT3CAD.CDR	PLOT3CAD.WPG	ACADFIG.WPD
3.4	NA	SIR10SCN.CDR	SIR10SCN.WPG	SCAN-FIG.WPD
3.5	5/9/97.XLS	NA	NA	CHPTR3.WPD
3.6	5/9/97.XLS	NA	NA	CHPTR3.WPD
3.7	5/9/97.XLS	NA	NA	CHPTR3.WPD

Appendix C

Plot 2 Perched Water Ground Truth Conversions 5-09-97 Transect Q1-8B

Color Table = 1

Color Transform = 2

FIR LP Vertical = 66 MHz

FIR LP Horizontal = 1023 scans

Overall Dielectric Constant = 1.0

FIR LP Horizontal = 1023 scans (Second Time)

ns/ft = 2 * SQRT Dielectric Constant

Ground Truth Information

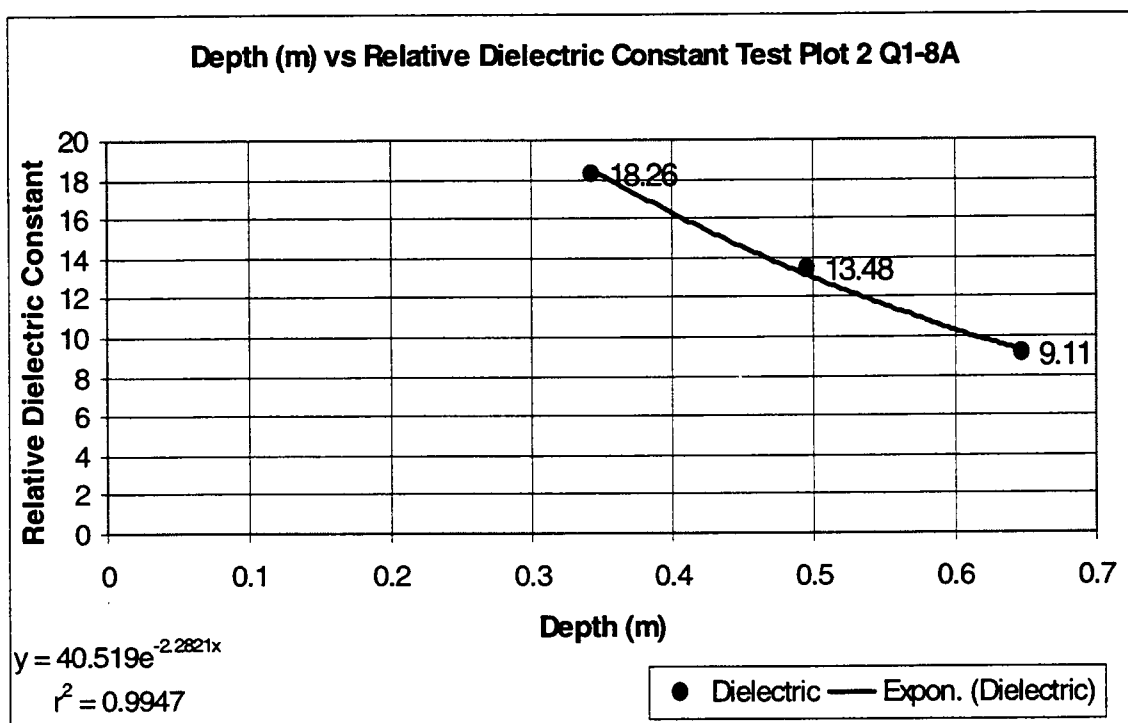
	Well I.D.	Depth (in)	Depth (ft)	Depth (cm)	Depth (m)
	2	13.5	1.125	34.29	0.3429
	4	19.5	1.625	49.53	0.4953
	6	25.5	2.125	64.77	0.6477

Q1-8B

	Well I.D.	Depth (ns)	Depth (m)	Dielectric
	2	9.67	0.3429	18.26
	4	12	0.4953	13.48
	6	12.9	0.6477	9.11

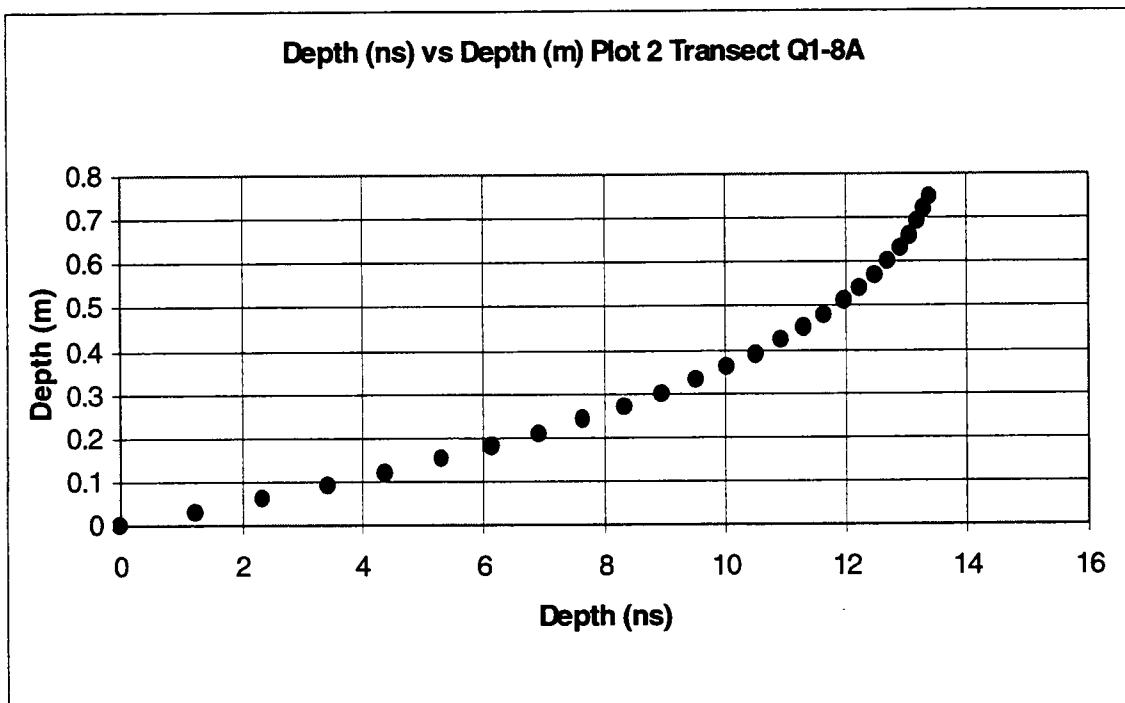
Table Curve Information

lny=a+bx^(0.5)					
		Parameters	Values	Std Error	T Value
Eqn	lny=a+bx^(0.5)	a	-4.928832006	0.138781093	-35.51515495
Eqn #	33	b	1.246663863	0.039866767	31.27075403
r2	0.989966817				
DF Adj r2	0.989094366			95% Conf Lim	95% Conf Lim
Fit Std Err	0.023457566			-5.215323623	-4.642340389



Perched Water
Q31-8B (a = 40.519 b = -2.282)
 $\text{SQRT}(a \cdot \exp^{(b \cdot x)} \cdot 43.56) \cdot x$

Depth (m)	Depth (ns)
0	0
0.03	1.217947727
0.06	2.35392567
0.09	3.412071348
0.12	4.396336642
0.15	5.310495599
0.18	6.158151928
0.21	6.942746189
0.24	7.667562692
0.27	8.33573612
0.3	8.950257874
0.33	9.513982175
0.36	10.0296319
0.39	10.4998042
0.42	10.92697586
0.45	11.31350848
0.48	11.66165342
0.51	11.97355653
0.54	12.2512627
0.57	12.49672026
0.6	12.71178512
0.63	12.8982248
0.66	13.05772229
0.69	13.19187972
0.72	13.30222191
0.75	13.39019974



Equation $\ln y = a + bx^{0.5}$

$$Y = \text{EXP}(a + b * \text{SQRT}(X))$$

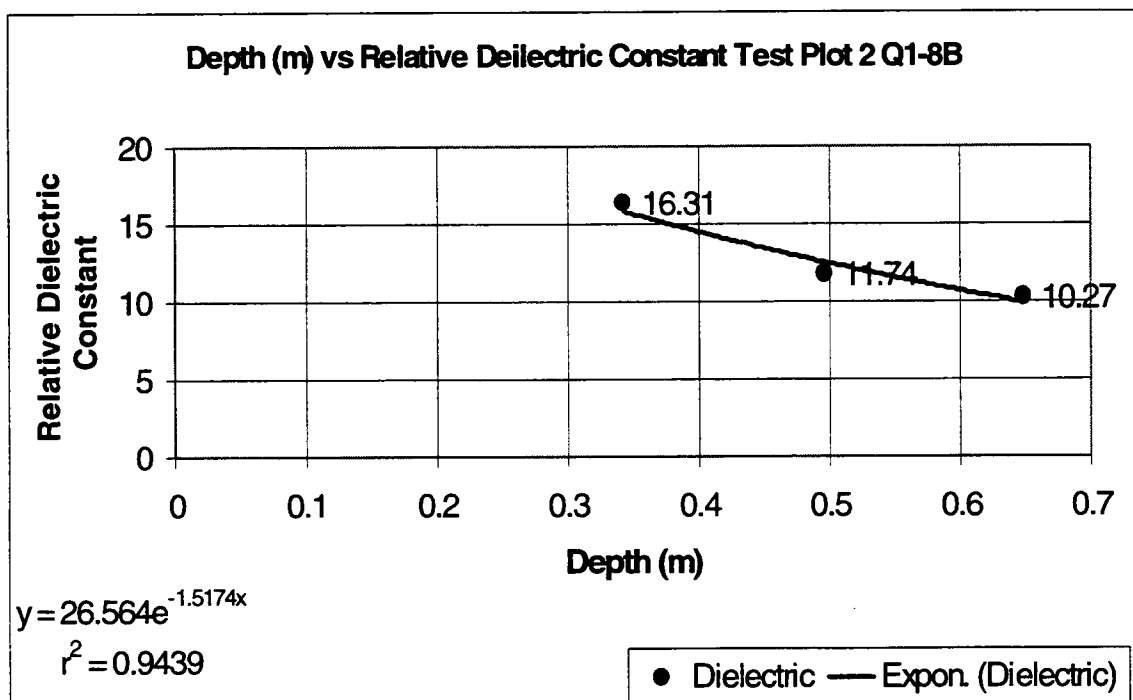
Q1-8A

a -4.928832006
b 1.246663863
X Depth (ns)

Q1-8B

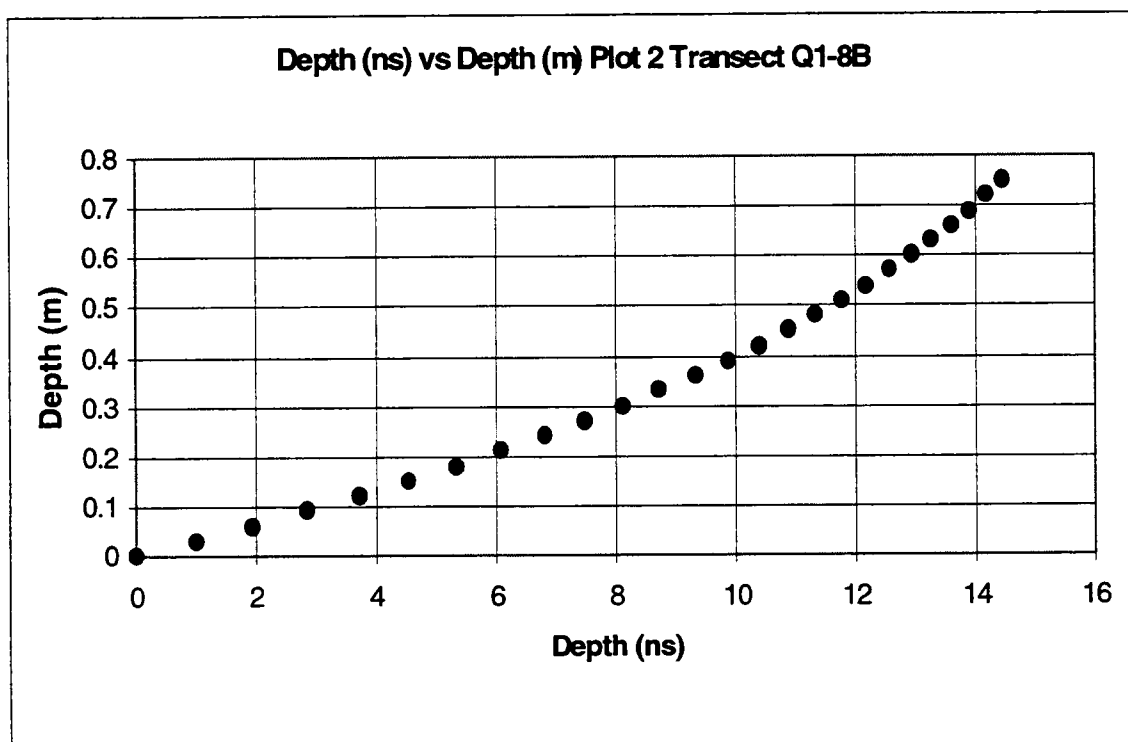
Well I.D.	Depth (ns)	Calculated Depth (m)	Ground Truth (m)	Well Information (m)	Inches	Centimeters
1	9.61	0.345		0.330	13.000	33.020
2	9.67	0.349	0.343	0.343	13.500	34.290
3	11.2	0.469		0.381	15.000	38.100
4	12	0.543	0.495	0.495	19.500	49.530
5	12.5	0.594		0.572	22.500	57.150
6	12.9	0.637	0.648	0.648	25.500	64.770
7	13.4	0.694		0.737	29.000	73.660
8	13.6	0.718		0.762	30.000	76.200

Plot 2 Perched Water Ground Truth Conversions 5-09-97 Transect Q1-8B					
Color Table = 1					
Color Transform = 2					
FIR LP Vertical = 66 MHz					
FIR LP Horizontal = 1023 scans					
Overall Dielectric Constant = 1.0					
FIR LP Horizontal = 1023 scans (Second Time)					
ns/ft = 2 * SQRT Dielectric Constant					
Ground Truth Information					
	Well I.D.	Depth (in)	Depth (ft)	Depth (cm)	Depth (m)
	2	13.5	1.125	34.29	0.3429
	4	19.5	1.625	49.53	0.4953
	6	25.5	2.125	64.77	0.6477
Q1-8B					
	Well I.D.	Depth (ns)	Depth (m)	Dielectric	
	2	9.14	0.3429	16.31	
	4	11.2	0.4953	11.74	
	6	13.7	0.6477	10.27	
Table Curve Information					
		lny=a+bx^(0.5)			
		Parameters	Values	Std Error	T Value
Eqn	lny=a+bx^(0.5)	a	-3.977703496	0.03733309	-106.5463249
Eqn #	33	b	0.966433391	0.010635103	90.87202947
r2	0.998784317				
DF Adj r2	0.998678606			95% Conf Lim	95% Conf Lim
Fit Std Err	0-Jan-00			-4.054771756	-3.900635237



Perched Water
Q31-8B (a = 26.564 b = -1.5174)
 $\text{SQRT}(a \cdot \exp^{(b \cdot x)} \cdot 43.56) \cdot x$

Depth (m)	Depth (ns)
0	0
0.03	0.997532259
0.06	1.950167741
0.09	2.859421976
0.12	3.726765021
0.15	4.553622737
0.18	5.341378036
0.21	6.091372091
0.24	6.804905514
0.27	7.483239503
0.3	8.127596956
0.33	8.739163558
0.36	9.319088834
0.39	9.868487179
0.42	10.38843885
0.45	10.87999096
0.48	11.34415839
0.51	11.78192472
0.54	12.19424315
0.57	12.58203734
0.6	12.94620226
0.63	13.28760502
0.66	13.60708568
0.69	13.90545801
0.72	14.18351025
0.75	14.44200587



Equation $\ln y = a + b x^{(0.5)}$
 $Y = \text{EXP} (a + b * \text{SQRT}(X))$

Q1-88

a -3.9777035
b 0.96643339
X Depth (ns)

Q1-88

Well I.D.	Depth (ns)	Calculated Depth (m)	Ground Truth (m)	Well Information (m)	Inches	Centimeters
1	9.02	0.341		0.330	13.000	33.020
2	9.14	0.348	0.343	0.343	13.500	34.290
3	10.7	0.442		0.381	15.000	38.100
4	11.2	0.475	0.495	0.495	19.500	49.530
5	13.1	0.619		0.572	22.500	57.150
6	13.7	0.670	0.648	0.648	25.500	64.770
7	15	0.791		0.737	29.000	73.660
8	15	0.791		0.762	30.000	76.200

QA-D1

Well I.D.	Depth (ns)	Calculated Depth (m)	Ground Truth (m)	Well Information (m)	Inches	Centimeters
	9.67	0.378		0.343	13.500	34.290
	9.67	0.378		0.356	14.000	35.560
	10.6	0.436		0.483	19.000	48.260
	12.6	0.579	0.648	0.648	25.500	64.770

QA-D2

Well I.D.	Depth (ns)	Calculated Depth (m)	Ground Truth (m)	Well Information (m)	Inches	Centimeters
1	9.2	0.351		0.343	13.500	34.290
2	9.43	0.364		0.356	14.000	35.560
3	12.5	0.571		0.483	19.000	48.260
4	12.7	0.586	0.648	0.648	25.500	64.770

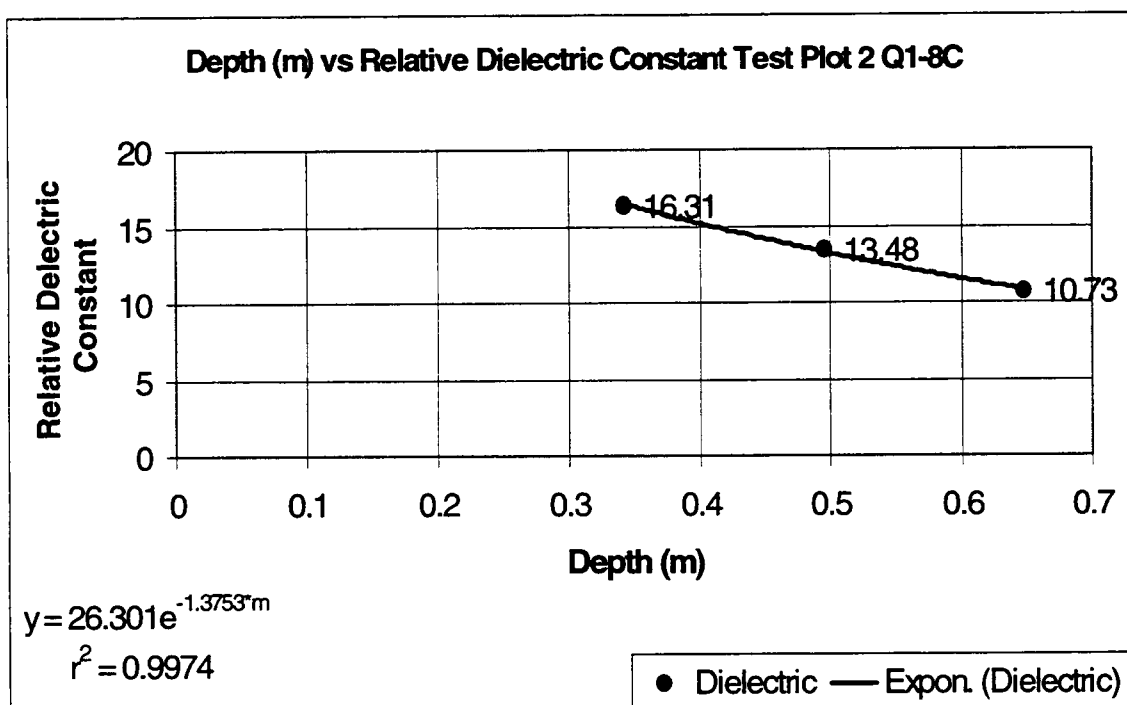
QA-D3

Well I.D.	Depth (ns)	Calculated Depth (m)	Ground Truth (m)	Well Information (m)	Inches	Centimeters
1	9.49	0.368		0.343	13.500	34.290
2	11.1	0.469		0.356	14.000	35.560
3	12.1	0.540		0.483	19.000	48.260
4	13.2	0.627	0.648	0.648	25.500	64.770

QA-D4

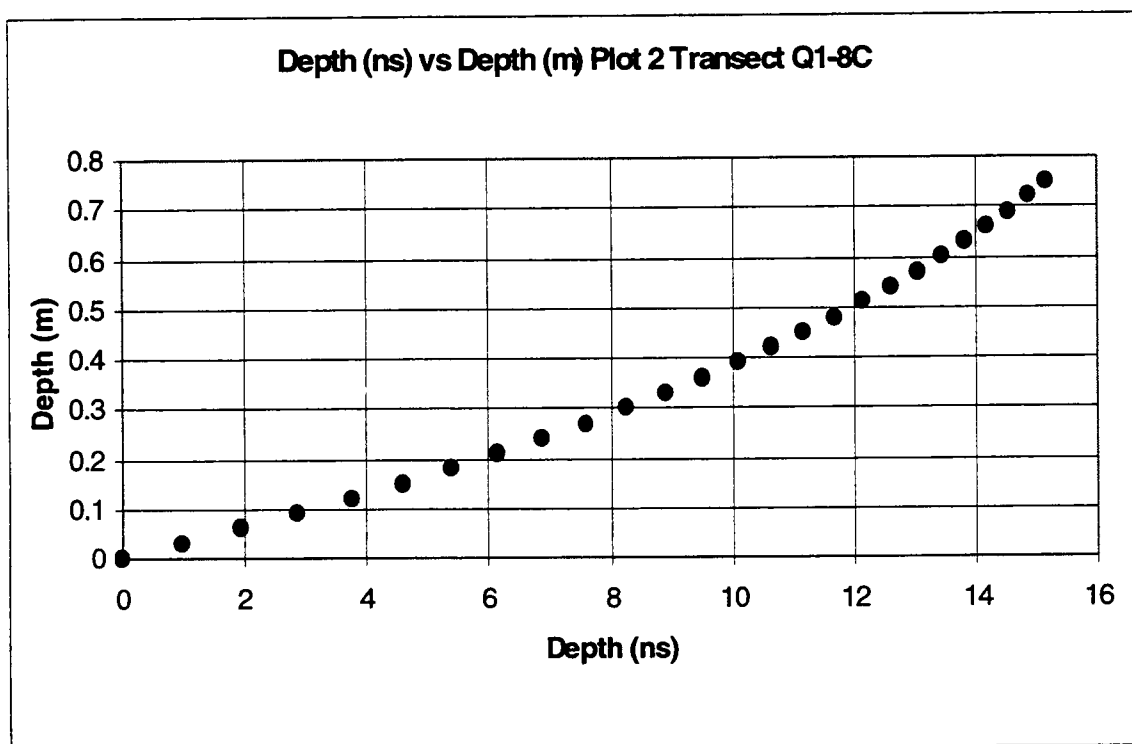
Well I.D.	Depth (ns)	Calculated Depth (m)	Ground Truth (m)	Well Information (m)	Inches	Centimeters
	8.85	0.332		0.343	13.500	34.290
	8.91	0.335		0.356	14.000	35.560
	12.5	0.571		0.483	19.000	48.260
	12.9	0.603	0.648	0.648	25.500	64.770

Plot 2 Perched Water Ground Truth Conversions 5-09-97 Transect Q1-8C					
Color Table = 1					
Color Transform = 2					
FIR LP Vertical = 66 MHz					
FIR LP Horizontal = 1023 scans					
Overall Dielectric Constant = 1.0					
FIR LP Horizontal = 1023 scans (Second Time)					
ns/ft = 2 * SQRT Dielectric Constant					
Ground Truth Information					
	Well I.D.	Depth (in)	Depth (ft)	Depth (cm)	Depth (m)
	2	13.5	1.125	34.29	0.3429
	4	19.5	1.625	49.53	0.4953
	6	25.5	2.125	64.77	0.6477
Q1-8C					
	Well I.D.	Depth (ns)	Depth (m)	Dielectric	
	2	9.14	0.3429	16.31	
	4	12	0.4953	13.48	
	6	14	0.6477	10.73	
Table Curve Information					
Iny=a+bx^(0.5)					
		Parameters	Values	Std Error	T Value
Eqn	Iny=a+bx^(0.5)	a	-3.838127211	0.037465108	-102.445381
Eqn #	33	b	0.909588801	0.010473687	86.84513954
r2	0.998668702				
DF Adj r2	0.998552937			95% Conf Lim	95% Conf Lim
Fit Std Err	0-Jan-00			-3.915468	-3.76078642



Perched Water
Q31-8C (a = 26.301 b = -1.3753)
 $2 \cdot \text{SQRT}(a \cdot \exp^{b \cdot x}) \cdot x$

Depth (m)	Depth (ns)
0	0
0.03	0.994699828
0.06	1.948779761
0.09	2.863483873
0.12	3.740022373
0.15	4.579572462
0.18	5.38327918
0.21	6.152256231
0.24	6.88758678
0.27	7.590324239
0.3	8.261493029
0.33	8.902089328
0.36	9.513081792
0.39	10.09541227
0.42	10.64999648
0.45	11.17772472
0.48	11.67946247
0.51	12.15605107
0.54	12.60830836
0.57	13.03702924
0.6	13.44298631
0.63	13.82693042
0.66	14.18959126
0.69	14.53167789
0.72	14.85387929
0.75	15.15686489



Equation $\ln y = a + b x^{(0.5)}$
 $Y = \text{EXP}(a + b * \text{SQRT}(X))$

Q1-8C
a -3.8381272
b 0.9095888
X Depth (ns)

Q1-8C	Well I.D.	Depth (ns)	Calculated Depth (m)	Ground Truth (m)	Well Information (m)	Inches	Centimeters
	1	9.02	0.331		0.330	13.000	33.020
	2	9.08	0.334	0.343	0.343	13.500	34.290
	3	9.38	0.349		0.381	15.000	38.100
	4	12.7	0.551	0.495	0.495	19.500	49.530
	5	13.1	0.579		0.572	22.500	57.150
	6	13.1	0.579	0.648	0.648	25.500	64.770
	7	14.9	0.721		0.737	29.000	73.660
	8	15.1	0.738		0.762	30.000	76.200

Plot 2 Perched Water Ground Truth Conversions 5-09-97 Transect Q1-8B

Color Table = 1

Color Transform = 2

FIR LP Vertical = 66 MHz

FIR LP Horizontal = 1023 scans

Overall Dielectric Constant = 1.0

FIR LP Horizontal = 1023 scans (Second Time)

ns/ft = 2 * SQRT Dielectric Constant

Ground Truth Information

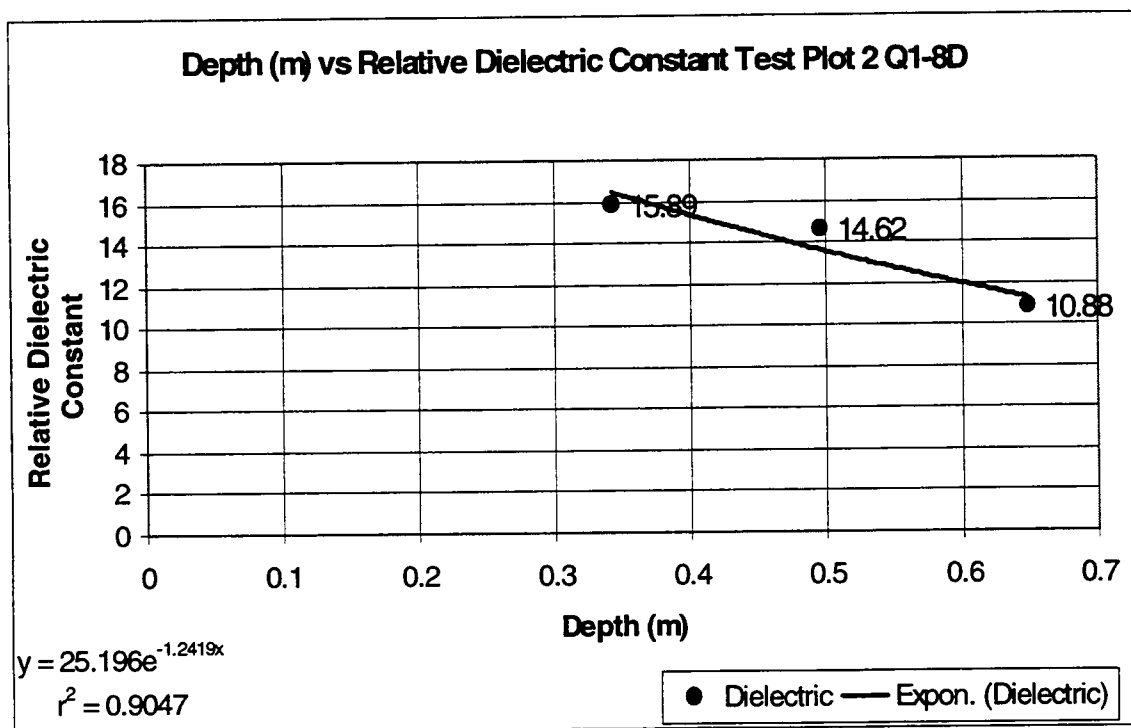
Well I.D.	Depth (in)	Depth (ft)	Depth (cm)	Depth (m)
2	13.5	1.125	34.29	0.3429
4	19.5	1.625	49.53	0.4953
6	25.5	2.125	64.77	0.6477

Q1-8B

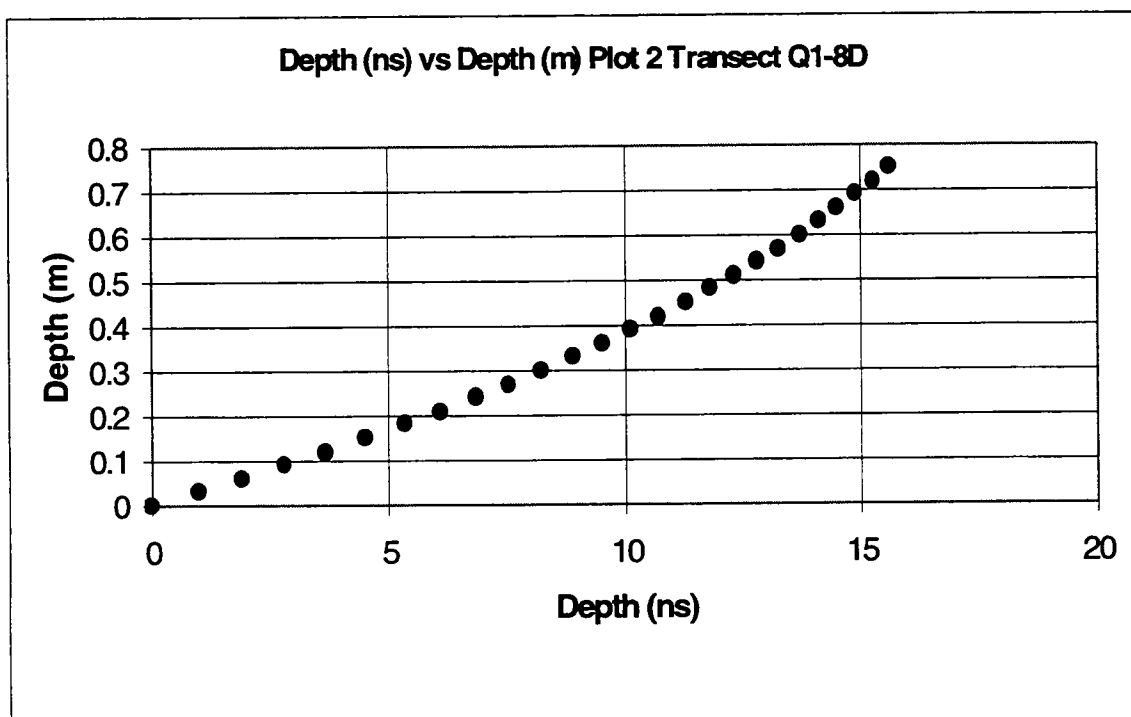
Well I.D.	Depth (ns)	Depth (m)	Dielectric
2	9.02	0.3429	15.89
4	12.5	0.4953	14.62
6	14.1	0.6477	10.88

Table Curve Information

Iny=a+bx^(0.5)					
		Parameters	Values	Std Error	T Value
Eqn	Iny=a+bx^(0.5)	a	-3.715990981	0.041463579	-89.62060364
Eqn #	33	b	0.867509611	0.011484016	75.54061064
r2	0.998241192				
DF Adj r2	0.998088252			95% Conf Lim	95% Conf Lim
Fit Std Err	0.009821386			-3.801585982	-3.63039598



Perched Water	
Q31-8B (a = 25.196 b = -1.2419)	
SQRT(a*exp^(b*x) *43.56)* x	
Depth (m)	Depth (ns)
0	0
0.03	0.975530238
0.06	1.915051582
0.09	2.819560907
0.12	3.690030556
0.15	4.527408904
0.18	5.332620918
0.21	6.106568693
0.24	6.85013198
0.27	7.56416871
0.3	8.249515494
0.33	8.906988118
0.36	9.537382029
0.39	10.14147281
0.42	10.72001663
0.45	11.27375072
0.48	11.80339379
0.51	12.30964648
0.54	12.79319176
0.57	13.25469536
0.6	13.6948062
0.63	14.1141567
0.66	14.51336329
0.69	14.89302665
0.72	15.25373221
0.75	15.5960504



Equation $\ln y = a + b x^{(0.5)}$
 $Y = \text{EXP}(a + b * \text{SQRT}(X))$

Q1-8D
a -3.715990981
b 0.867509611
X Depth (ns)

Q1-88	Well I.D.	Depth (ns)	Calculated Depth (m)	Ground Truth (m)	Well Information (m)	Inches	Centimeters
	1	8.96	0.327		0.330	13.000	33.020
	2	9.02	0.329	0.343	0.343	13.500	34.290
	3	10.6	0.410		0.381	15.000	38.100
	4	12.5	0.523	0.495	0.495	19.500	49.530
	5	13.1	0.562		0.572	22.500	57.150
	6	14.1	0.632	0.648	0.648	25.500	64.770
	7	14.5	0.662		0.737	29.000	73.660
	8	14.5	0.662		0.762	30.000	76.200

Vita

Joseph Cole Reagan was born in Atlanta, Georgia on December 1, 1972. He attended Dickson County High School and was graduated in May 1991. He entered Tennessee Technological University in August 1991 and received a Bachelor of Science degree in Agriculture with a concentration in Environmental Agriscience in May 1995. He was hired as a Graduate Research Assistant in August 1995 and initiated study toward the Master of Science degree in Agricultural Engineering Technology. Before final completion of his requirements for a Master of Science degree in Agricultural Engineering Technology, he accepted a position with Wiedeman and Singleton, Inc. as a Resident Engineer. He completed his masters in December 1997.