United States Department of Agriculture	**Natural Resources Conservation Service**	**c/o USDA Forest Service 11 Campus Boulevard Suite 200 Newtown Square, PA 19073** (610) 557-4233; FAX: (610) 557-4200

Subject: Lake Sedimentation Surveys -- Geophysical Assistance. **Date:** 8 May 2002

To: Walter W. Douglas
State Conservationist
USDA - NRCS
1835 Assembly Street, Room 950
Columbia, South Carolina 29201

Purpose:
The purpose of this survey was to determine water depths and to estimate sediment distribution and thickness within Lake Greenwood, South Carolina. This lake has experienced rapid and extensive sedimentation within its upper reaches. Lake Greenwood was competed in 1941 as a hydroelectric power generation and water supply project principally for Greenwood County, South Carolina. The lake has a full-pond surface area of about 11,400 acres. The drainage area of the lake is about 1,150 square miles.

Participants:
Neil Bartley, Program Coordinator, USDA-NRCS, Edgefield, SC
Dave Demarest, Foothills RC&D Coordinator, USDA-NRCS, Greenville, SC
Gene Dobbins, Urban Engineer, USDA-NRCS, Greenville, SC
Jim Doolittle, Research Soil Scientist, USDA-NRCS, Newtown Square, PA
Kim Kroeger, Geologist, USDA-NRCS, Raleigh, NC
Jimmy Sanders, RC&D Coordinator, USDA-NRCS, Greenwood, SC
Brian Stoddard, District Conservationist, USDA-NRCS, Greenwood, SC

Activities:
All field activities were completed during the period of 26 to 29 January 1998.

Equipment:
The radar unit used in this study was the Subsurface Interface Radar (SIR) System-2000, manufactured by Geophysical Survey Systems, Inc. Morey (1974), Doolittle (1987), and Daniels (1996) have discussed the use and operation of GPR. The SIR System-2000 consists of a digital control unit (DC-2) with keypad, VGA video screen, and connector panel. A 12-VDC battery powered the system. The 70 and 120 MHz antennas were used in this investigation. The 70 MHz antenna provided greater penetration depths than the 120 MHz antenna and was used in the deeper portions of the lake. The 120 MHz antenna was used in shallower portions of the lake because of its improved resolution.

Although GPR provides a continuous image of the subsurface, measurements were restricted to 1547 observation points. The position of each observation point was obtained with Rockwell Precision Lightweight GPS Receivers (PLGR). The receiver was operated in the autonomous and continuous modes. A mixed satellite format was used. The receiver was operated using an external power source (portable 9-volt battery). The Geodetic (latitude and longitude) coordinate system was used. Horizontal datum was the North American 1983.

The outline of Lake Greenwood was digitized by the Greenwood County GIS Department. To help summarize the results of this study, the SURFER for Windows program, developed by Golden Software, Inc., was used to construct a two-dimensional simulation of the lake. Grids were created using kriging methods with an octant search.

Background:

Sedimentation is the major cause of the reduction in reservoir storage capacity. The primary objectives of bathymetric and lake sedimentation surveys are to determine current reservoir capacity, ascertain changes in storage volume, and estimate the volume of accumulated sediments.

At the time of reservoir or lake construction, standard surveying techniques are often used to make detailed topographic maps and determine stage-storage information of lakes and reservoirs (Truman et al., 1991). With the passage of time, sedimentation alters the original lake bottom topography. To determine sedimentation rates, changes in lake-bottom topography, and stage-storage information, depth soundings are typically taken at select locations within the lake (Truman et al., 1991). This process is slow, tedious, and costly. Improved methods are needed to expedite the completion of these surveys and to provide more comprehensive coverage of lakes and reservoirs. Acoustical sounding systems (fathometer) have long been used for freshwater bathymetric surveys. However, fathometers have difficulty resolving gradational lake-bottom contacts and penetrating aquatic vegetation and layers of organic materials (Kovacs, 1991; Sellmann et al., 1992).

The use of ground-penetrating radar for bathymetric and lake sedimentation surveys has been explored by several researchers. Delaney and others (1992) found that the use of acoustical and GPR systems can provide complementary information. Sellmann and others (1992) noted that because of greater electrical than acoustical contrasts in lake bottom sediments, greater resolution and sub-bottom details are shown on GPR profiles. Ground-penetrating radar has been used for bathymetric survey of fresh water lakes (Haeni et al., 1987; Izbicki and Parker, 1991; Kovacs, 1991; Mellett, 1995; Moorman and Michel, 1997; Sellmann et al., 1992; Truman et al., 1991) and to measure stream-channel cross sections (Annan and Davis, 1977; Spicer et al., 1997) and riverbed scours at bridge piers (Gorin and Haeni, 1989). In these studies, GPR discerned the water-sediment boundary to depths as great as 10m and provided bathymetric cross-sections or contour maps. In addition, GPR was helpful in distinguishing some sub-bottom sediment type and thickness.

Powers and Haeni (1999) compared the use of continuous seismic-reflection profiling and GPR for delineating the types and thickness of sedimentary units in a small pond in eastern Massachusetts. These tools were found to provide complementary information and to detect similar interfaces. Using an estimated velocity of propagation, Haeni and others (1987) and Powers and Haeni (1999) estimated the thickness of organic deposits within portions of lake basins. In these studies, the water/organic matter and the organic matter/mineral soil interfaces were electrically contrasting and provided excellent radar reflections. However, in some portions of the lakes, the data was not interpretable because of admixtures of silts and clays. Where data were sparse, thickness was interpolated.

Survey Procedures:

The radar system was mounted in a pontoon boat and either a 70 MHz or 120 MHz antenna was towed alongside in an inflatable raft. The antenna was placed on the bottom of the raft. The proximity of the raft to the pontoon boat did create some ringing and interference to the radar signal. However, this noise did not impair the detection of the lake bottom. The boat and raft made multiple traverses across Lake Greenwood along predetermined traverse lines that were established by the project geologist. Locations of traverse lines were determined before the survey and were adjusted slightly using identifiable features on the shore. Because of very shallow water depths, the upper reaches of the lake were not surveyed with GPR. Slight variations in speed of advance were encountered because of water currents, wind conditions, and bottom depths (in areas that were too shallow or obstructed with debris). As a consequence, distances on the radar profile were variable. Observation points for both GPS and GPR were recorded simultaneously at intervals of either 10 or 15 seconds. Intervals varied with the length of traverse and speed of advance, but were constant for each traverse. In a bathymetric survey conducted by Powers and Haeni (1999) depth errors of +/- 5 feet were reported because of positioning errors.

Global Positioning System:

The estimated position error of the GPS was generally less than 6 m. In a few instances, poor satellite geometry and availability, and antenna masking (dense vegetation and high elevations bordering the lakes) accounted for slightly greater (up to 13 m) position errors. The locations of the GPS waypoints recorded on Lake Greenwood (1547 waypoints) are shown in Figure 1. The locations of these waypoints reconstruct boats' traverses and conform to the boundaries of the lakes. At each waypoint the depth of water was determined with GPR.

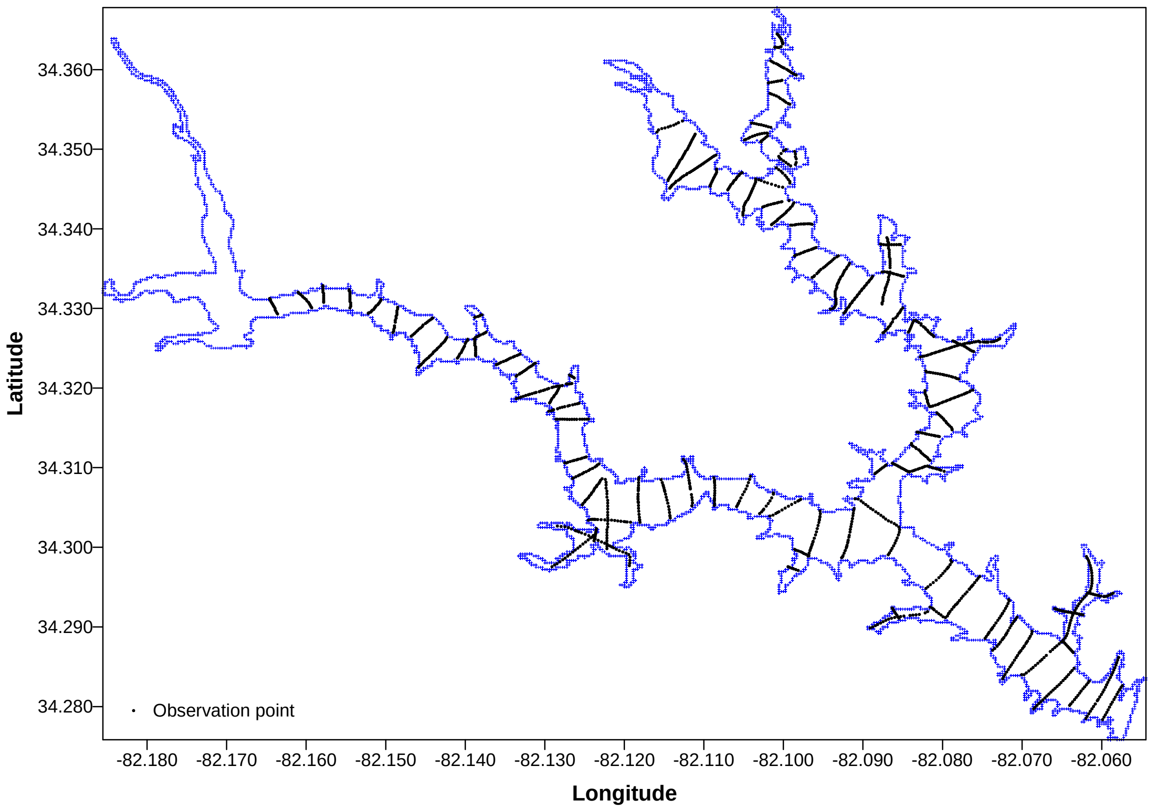

Figure 1. Outline of Lake Greenwood and the locations of transects and observation points.

Ground Penetrating Radar:

Ground-penetrating radar is an impulse radar system that is specially designed to penetrate earthen materials. Electromagnetic wave propagation is affected by contrast in electromagnetic properties (dielectric permittivity, electrical conductivity, and magnetic susceptibility) of the profiled material(s) (Daniels, 1996). Electromagnetic energy is directed into the subsurface by a transmitting antenna. When propagated waves of electromagnetic energy encounter an interface separating layers of contrasting electromagnetic properties a portion of the transmitted wave is reflected back to the antenna. The reflected energy is detected by the receiving antenna and recorded.

Ground-penetrating radar is a time scaled system. This system measures the time that it takes electromagnetic energy to travel from the antenna to an interface (e.g., lake bottom, stratigraphic layer) and back. To convert the travel time into a depth scale, either the velocity of pulse propagation or the depth to a reflector must be known. The relationships among depth (D), two-way pulse travel time (T), and velocity of propagation (V) are described in the following equation (after Morey, 1974):

$$D=V\,(T/2) \qquad [1]$$

The velocity of propagation is principally affected by the dielectric permittivity (E) of the profiled material(s) according to the equation:

$$V = C/(E)^{1/2} \qquad [2]$$

Where C is the velocity of propagation in a vacuum (0.3 m/nanosecond). Velocity is expressed in meters per nanosecond (ns). A nanosecond is one billionth of a second. The amount and physical state of water (temperature dependent) have the greatest effect on the dielectric permittivity of a material.

Interpretations of the radar records were accomplished by using a propagation velocity of 0.033 m/ns and a dielectric permittivity of 81 for water (Morey, 1974). Slight variations in velocity of propagation are known to occur because of differences in the suspended sediment concentration (Spicer and Costa, 1997).

At six calibration points on Lake Greenwood, depths to the lake bottom were measured and compared with the depths interpreted from the radar imagery and equation [1]. Depths to the lake bottom were measured with a stadia rod. At these points, the depth to the lake bottom ranged from 7.3 to 21.1 feet. The correlation coefficient (r) between measured and interpreted depths to this interface was 0.9921(see Figure 2). At the six calibration points, differences between measured and interpreted depths averaged 0.54 feet, and ranged from 0.1 to 1.4 feet.

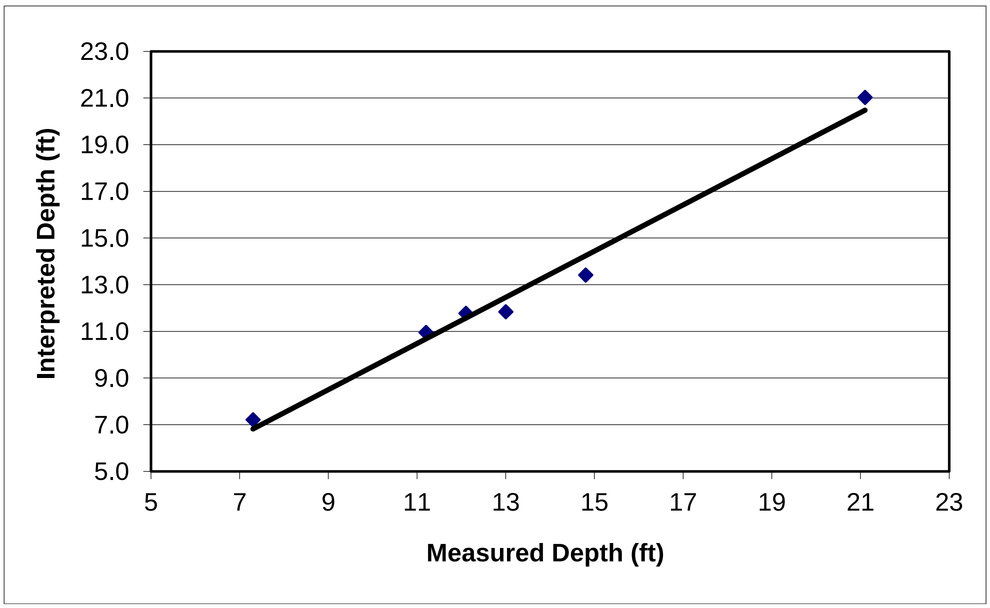

Figure 2. Relationship between measured and interpreted depths to lake bottom.

Differences between measured and interpreted depths to the lake bottom are attributed to slight spatial discrepancies between the point of stadia and radar measurements, the area scanned and the resolution of the GPR. Energy is transmitted from the radar antenna in a conical beam. The radar measures a circular footprint area beneath the antenna. This footprint area can be estimated by the formula (Kovacs, 1991):

$$2 \sin^{-1} (1/E) \qquad [3]$$

Kovacs (1991) noted that for an antenna resting on water, the beam width is approximately equal to 0.2D, where D is the water depth. Using this approximation, at the six calibration sites, the beam width scanned by GPR varied from 1.46 (water depth of 7.3 feet) to 4.22 (water depth of 21.1 feet) feet.

On radar profiles, reflections from interfaces spaced closer than one half wavelength apart are indistinguishable due to constructive and destructive interference (Daniels, 1996). Daniels (1996) used the following equation to show the relationship between velocity of propagation (v), antenna center frequency (f), and wavelength (λ):

$$\lambda = v/f \qquad [4]$$

Equation [4] shows that the propagated wavelength will decrease with decreasing propagation velocity and increasing antenna frequency. Using equation [4] and an average velocity of 0.033 m/ns results in wavelengths of about 47 cm (18 inches) at a frequency of 70 MHz and about 27 cm (11 inches) at a frequency of 120 MHz (assuming that the center frequency of the antenna is not reduced because of impedance loading with the fresh water). Layers spaced closer than 27 or 47 cm would be difficult to identify on radar profiles collected with the 120 and 70 MHz antennas, respectively.

Interpretations:

Radar profiles collected on Lake Greenwood were of good quality and interpretable. Figure 3 is a representative radar profile obtained with the 70 MHz antenna over a deeper portion of Lake Greenwood near the US Highway 221 Bridge. The radar profile appearing in Figure 3 has been compressed and reduced in size to accommodate the page. The depth scale is meters and is plotted on the left-hand side of this figure. Although the radar provides a continuous profile of the lake, measurements of water depths were restricted to observation points (white, vertical lines at the top of the radar profile). The lake bottom is apparent across this profile and varies in depth from about 2.0 to 9.6 meters. The flood plain and the former channel of the Saluda River are evident in this profile.

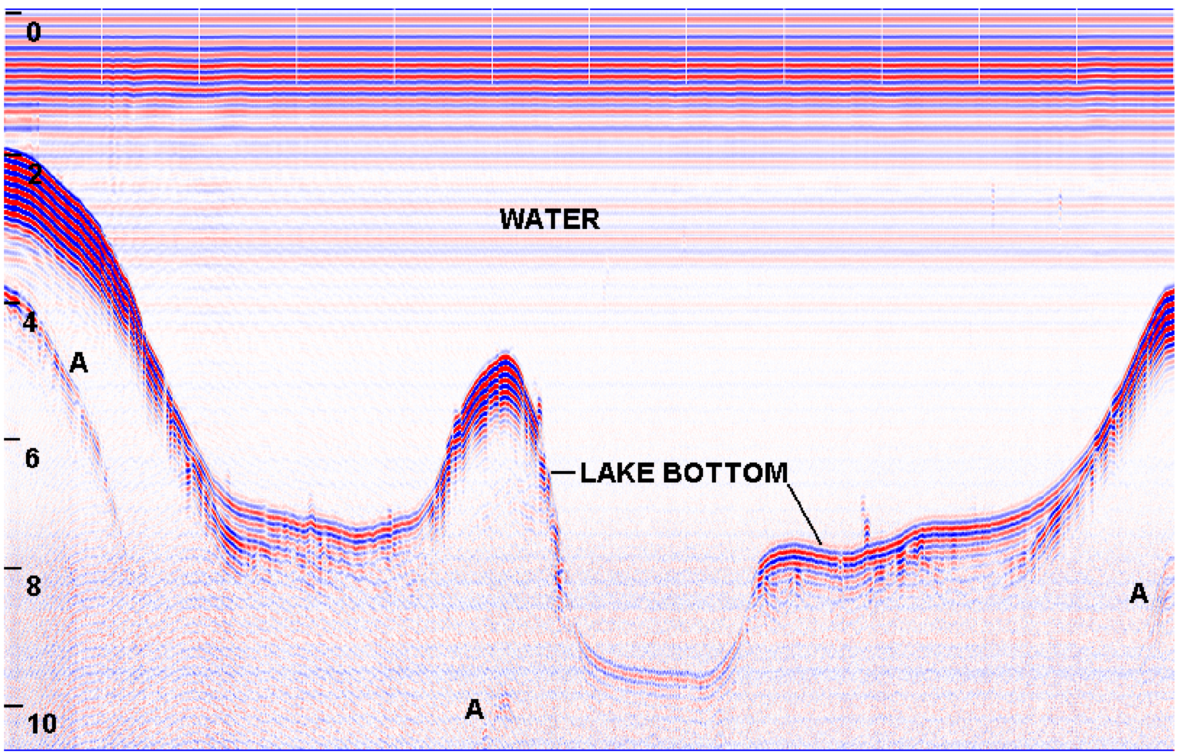

Figure 3. Representative radar profile from Lake Greenwood showing buried channel of the Saluda River.

The constant horizontal bands across the top of the radar profile are the result on antenna "ringing. Ringing is caused, in part, by an impedance mismatch between the antenna and the water (Sellmann et al., 1992). Noise, associated with the antenna's proximity to the pontoon boat, is another source of these multiple lines. Lake bottom multiples (see *A* in Figure 3) were observed on most radar profiles. They represent secondary reflections from the lake bottom. Multiples have the same shape as the lake bottom but occur at twice the travel time to the bottom reflection (Moorman, 2001). Several point reflectors are evident near the bottom of the lake. These small, hyperbolic reflectors may represent debris, rock fragments, or fish.

The lake-bottom sediments were penetrable with GPR. However, depending on the antenna used and the depth and clay content of the bottom sediments, penetration was variable. Two easily recognizable radar reflection patterns were obtained from the lake bottom: one for the steeper slopes that occurred around the margin of the lake, and one for the relatively flat-floored lake bottom. Patterns from the former portions of the lake were limited in extent (immediate edge of the lake) and contained relatively thin deposits of recent sediments. Strong, discontinuous reflections characterize the steeper slopes. Patterns from the flat-floored portions of the lake overly the former flood plains of the Saluda and Reedy rivers. These layers consist of recent lacustrine and alluvial deposits, and alluvium associated with the former flood plain of the Saluda River. Smooth, horizontal to sub-horizontal, multiple, continuous reflectors of varying signal amplitudes characterize the internal structure of the flat-floored portion of the lake.

The depth of the lake increased rapidly away from the shore. Based on reflection characteristics the extent and relative thickness of different sub-bottom sediments were recognized. In general, horizontal laminar reflectors are associated with recent sediments. In some areas, low amplitude lake/bottom reflections were assumed to represent a transitional layer of soft, fluid sediments composed of water saturated organic or organic/mineral deposits. In places, underlying these reflectors are more irregular and often-chaotic reflectors that are assumed to represent the original lake bottom. As only a limited number of borings was feasible at the time of the GPR survey, the identity of these layers could not be verified. On most radar profiles, bottom sediment layers appear discontinuous and could not be clearly identified or traced laterally across the lake with confidence. In some areas, high rates of signal attenuation limited penetration. In other areas, gradual changes in sub-bottom sediments produced weak reflections. Although lake bottom characteristics and layer could be recognized on the radar profiles, many reflections were too weakly expressed or discontinuous to be properly interpreted.

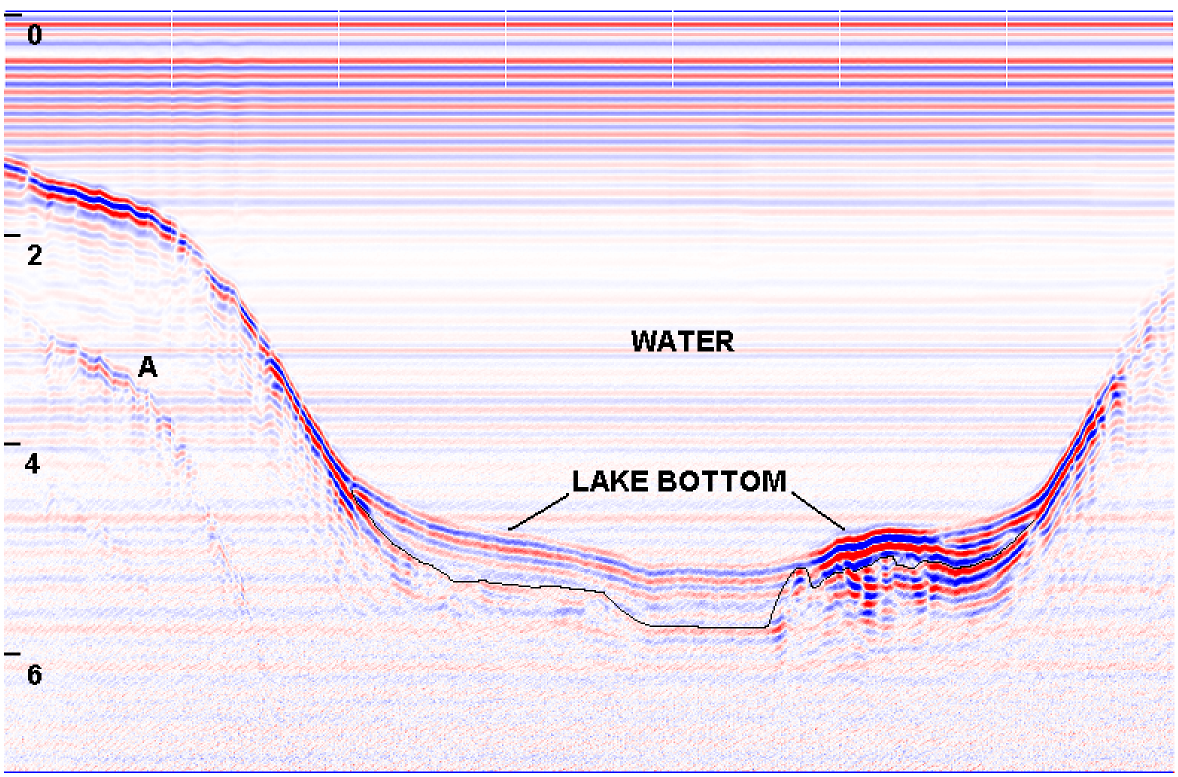

Figure 4. Representative radar profile from Lake Greenwood.

Figure 4 is a representative radar profile from an narrow arm of Lake Greenwood. This profile was collected with the 120 MHz antenna. The depth scale is meters and is plotted on the left-hand side of this figure. The lake bottom is apparent across this profile and varies in depth from about 1.4 to 5.4 meters. Lake bottom multiples (see *A*) have been labeled in the left-hand portion of this figure. An attempt was made to trace the contact between the original lake bottom and the more recently deposited, overlying sediments. A dark line has been used to interpret this interface. This interpretation is highly speculative and lacks my confidence.

Results:

1. The radar surveys of Lake Greenwood were completed in 3 days. Ninety-eight traverses were made across Lake Greenwood with GPR. Water depths were recorded at 1547 points. The coordinates of each of these points were recorded with GPS. At the time of the survey the lake level was at 438.5 feet. Based on preliminary radar data, the average depth of Lake Greenwood is 11.5 feet. Measured depths ranged from about 2.8 to 32.4 feet. One half of the radar observation points had depths between about 7.0 and 15.1 feet.

2. GPR is an excellent tool for bathymetric surveys of freshwater lakes and reservoirs. The lake bottom was clearly identifiable on all radar profiles. The depth of the water was estimated with confidence at all observation points. A high correlation (r= 0.99) was found to exist between measured and interpreted depth to the lake bottom

3. Although the lake-bottom sediments were penetrable with GPR, depths of penetration varied with antennas, water thickness, and the clay and silt contents of the bottom sediments. Not only was the depth of penetration variable, but also interpretations of the original bottom were unreliable. Reflections from bottom sediments often consisted of smooth, parallel lines of varying signal amplitudes. The bottom sediment layers produced multiple reflections that were discontinuous and could not be confidently resolved or traced laterally across the lake. GPR was unsuited to profiling and estimating the thickness of recent sediments within Lake Greenwood.

4. GPR is highly suited to bathymetric surveys within the Piedmont. However, because of restricted penetration and the absence of clearly identifiable and distinguishable interfaces, its use for lake sedimentation surveys is considered inappropriate unless data on the original bottom topography is available.

5. All radar profiles and a disc containing spreadsheets of the GPS and GPR data have been forwarded to Kim Kroeger. Kim will use computer aided drafting (CAD) software to manage and manipulate the data. Kim will produce the final products of this survey.

It was my pleasure to work in South Carolina and with members of your fine staff.

With kind regards,

Jim Doolittle
Research Soil Scientist

cc:
H. Adkin, State Conservation Engineer, USDA-NRCS, 1835 Assembly Street, Room 950, Columbia, SC 29201
B. Ahrens, Director, USDA-NRCS, National Soil Survey Center, Federal Building, Room 152, 100 Centennial Mall North, Lincoln, NE 68508-3866
D. Demarest, Foothills RC&D Coordinator, USDA-NRCS, 301 University Ridge, Suite 4900, Greenville, SC 29601
B. Hudson, Director of Soils Survey Division, USDA-NRCS, Room 4250 South Building, 14^{th} & Independence Ave. SW, Washington, DC 20250
K. Kroeger, Geologist, USDA-NRCS, 4405 Bland Road, Suite 205, Raleigh, NC 27609
C. Olson, National Leader, Soil Survey Investigations, USDA- NRCS, National Soil Survey Center, Federal Building, Room 152, 100 Centennial Mall North, Lincoln, NE 68508-3866.
J. Sanders, RC&D Coordinator, USDA-NRCS, PO Box 3127, Greenwood, SC 29648

References

Annan, A. P. and J. L. Davis. 1977. Impulse radar applied to ice thickness measurements and freshwater bathymetry. 63-65 pp. IN: Report of Activities, Part B. Geol. Survey of Canada. Paper 77-1B. Ottawa, Canada.

Daniels, D. J. 1996. Surface-Penetrating Radar. The Institute of Electrical Engineers, London, United Kingdom.

Delaney, A. J., P. V. Sellmann, and S. A. Arcone. 1992. Sub-bottom profiling: a comparison of short-pulse radar and acoustic data. 149-157 pp. IN: IN: P. Hanninen and S. Autio (ed.) Fourth International Conference on Ground-Penetrating Radar. 7 to 12 June 1992. Rovaniemi, Finland. Geological Survey of Finland, Special Paper 16.

Doolittle, J. A. 1987. Using ground-penetrating radar to increase the quality and efficiency of soil surveys. pp. 11-32. In: Reybold, W. U. and G. W. Peterson (eds.) Soil Survey Techniques, Soil Science Society of America. Special Publication No. 20.

Gorin, S. R., and F. P. Haeni. 1989. Use of surface-geophysical methods to assess riverbed scour at bridge piers. US Geological Survey Water-Resources Investigation Report 88-4212. Hartford, Connecticut. 33 p.

Haeni, F. P., McKeegan, D. K., and D. R. Capron. 1987. Ground-penetrating radar study of the thickness and extent of sediments beneath Silver Lake, Berlin and Meriden, Connecticut. US Geological Survey Water-Resources Investigation Report 85-4108. Hartford, Connecticut. 19 p.

Izbicki, J. A. and G. W. Parker. 1991. Water depth and thickness of sediment in Reservoirs 1 and 2, Framingham and Ashland, Massachusetts. US Geological Survey Open-File Report 91-508. 18 p.

Kovacs, A. 1991. Impulse radar bathymetric profiling in weed-infested fresh water. CRREL Report 91-10. U. S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Hanover New Hampshire. 19 p.

Mellett, J. S. 1995. Profiling of ponds and bogs using ground-penetrating radar. Journal of Palelimnology. 14:233-240.

Moorman, B. J. 2001. Ground-penetrating radar applications in paleolimnology. 1-25 pp. IN: Last, W.M. and J. P. Smol (eds.). Tracking Environmental Change using Lake Sediments: Physical and Chemical Techniques. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Moorman, B. J. and F. A. Michel. 1997. Bathymetric mapping and sub-bottom profiling through lake ice with ground-penetrating radar. Journal of Palelimnology 18:61-73.

Morey, R. M. 1974. Continuous subsurface profiling by impulse radar. pp. 212-232. IN: Proceedings, ASCE Engineering Foundation Conference on Subsurface Exploration for Underground Excavations and Heavy Construction, held at Henniker, New Hampshire. Aug. 11-16, 1974.

Powers, C. J., and F. P. Haeni. 1999. Integrated use of continuous seismic-reflection profiling and ground-penetrating radar methods at John's Pond, Cape Cod, Massachusetts. 359-688. IN: Powers, M. H., L. Cramer, and R. S. Bell (eds.). Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems. Annual meeting of the Environmental and Engineering Geophysical Society. March 14-18, 1999, Oakland, CA.

Sellmann, P. V., A. J. Delaney, and S. A. Arcone. 1992. Sub-bottom surveying in lakes with ground-penetrating radar. CRREL Report 92-8. U. S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire. 18 p.

Spicer, K. R. , J. E. Costa, and G. Placzek. 1997. Measuring flood discharge in unstable stream channels using ground-penetrating radar. Geology. 25(5): 423-426.

Truman, C. C., L. E. Asmussen, and H. D. Allison. 1991. Ground-penetrating radar: A tool for mapping reservoirs and lakes. Journal of Soil and Water Conservation. 46(5):370-373.