Bathymetry and Sediment Accumulation of Walker Lake, PA Using Two GPR Antennas in a New Integrated Method

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ABSTRACT

Siltation within all man-made reservoirs can be a major problem because of a lower potential water storage. Exploring a lake’s bathymetry with electromagnetic techniques is one way to identify the magnitude of sediment accumulation in these reservoirs. In this study, the bathymetry and sediment accumulation of Walker Lake, Pennsylvania were explored with ground penetrating radar (GPR) using either a 400 or 100 MHz antenna, depending on the depth of the lake. The assembled apparatus herein included two GPR antennas placed in an inflatable boat towed by another boat powered by an electrical trolling motor. A total of eighteen crossings were performed along the entire length of the lake and a new integrated method using multiple processing software was applied to generate three-dimensional and contoured surfaces of bathymetry, sediment accumulation, and the original 1971 basin topography prior to the construction of Walker Lake Dam. The bathymetry, volume of sediment, and its accumulation rate were estimated. The lake depth was found to vary between a few centimeters near the inlet to 9 m nearer the dam. Deposition of sediment takes place mainly near the inlet to the lake and along the old channel of Middle Creek. The sedimentation gradually decreases toward the dam, ranging between 0 and 1.85 m in terms of bulk sediment volume.

Introduction

Siltation is a major issue in most lakes and water reservoirs and may cause clogging, increased lake turbidity, or a reduced factor of safety for flood water retention. The occurrence of siltation reduces the designed lake’s volume by making it shallower and therefore less water can be stored. In the Chesapeake Bay, significant nutrient pollution from siltation has also been observed (Howarth et al., 2002), causing eutrophication and rapid sediment accumulation caused by the sediment transport from the Susquehanna River. Dredging to remove the sediment, however, can be expensive and in many cases environmentally damaging by stirring and re-exposing the buried nutrients (Pimentel et al., 1995). It is much more cost effective to address the transport problems at their sources along the upstream tributaries and related water impoundments. Therefore, investigating the conditions of sediment accumulation on upstream lakes and reservoirs near their origins is of great importance.

As sediments enter lakes and dammed reservoirs from different waterways, they deposit as water decelerates giving rise to siltation. Sediments that extend beyond the confluence point are usually finer in texture and can cover an entire water impoundment. Assessments of siltation and its rates in lakes and reservoirs can be obtained through several methods, including several indirect methods: measurement of suspended sediment flux, sediment traps, and runoff/sediment yield. More direct methods involve bathymetric surveys or sediment coring. Depth sonar has been used successfully to measure bathymetry, yet is incapable of finding the thickness of sediment below the bottom of the lake in a single survey. A depth sonar can provide information of sediment thickness if the surveyed bathymetry is compared to the topography at the time of the construction of the dam. This is usually done 10 years after the construction of the dam (Brunner et al., 2009). In other studies, measuring the bathymetry before and after storm events to quantify the magnitude
of bottom sediment erosion, deposition, and redistribution processes have been successful (Lin et al., 2009).

Simultaneous bathymetric and sub-bottom surveying using GPR techniques can rapidly reveal sediment thickness without referring to previously known topography. The measurements can be especially useful when detailed topographic information is not available during the time of the survey. This study aims to use a GPR survey and integrated software tools to measure the bathymetry and sub-bottom layers of a small reservoir known as Walker Lake located on Middle Creek; Middle Creek is one tributary of the Susquehanna River.

The selection of specific frequencies of GPR antennas to accurately survey the bathymetry and sediment accumulation depends on the depth of the lake, the type of sediment, accumulation depth, and other conditions relating to the quality of water. A literature review reveals that most bathymetry surveys performed with a GPR have been conducted with one antenna or a combination of one antenna and other techniques (Delaney et al., 1992; Moorman and Michel, 1997; Lin et al., 2009; Sambuelli et al., 2009; Sambuelli and Silvia, 2012). The technique developed in this study includes two antennas, 100 MHz and 400 MHz, based on Walker Lake’s wide range of water depths. The antennas were placed on a small inflatable boat towed by a 14-ft (4.26-m) flat-bottom Jon boat. Two people performed the survey; one person navigates the boat and keeps track of the direction and orientation of each transect across the lake, while the other person operates the GPR system. The technique then combines a number of different software to post-process the data, with the goal of generating a 3-D bathymetry surface and volume of sediment since the construction of the dam, approximately 43 years ago.

Site Location and Setting

Walker Lake is located in a rural area near Troxelville, Pennsylvania in Adams Township, Snyder County. The lake is owned by the Pennsylvania Fish and Boat Commission (PFBC) and it is located on the North Branch Middle Creek, a tributary to Middle Creek within the Susquehanna River basin. The North Branch Middle Creek was impounded in 1970 to create a 239 acres (1 km²) lake, which drains a 19 mi² (50 km²) watershed consisting primarily of forested (57%) and agricultural (39%) land. Walker Lake has a maximum depth of 9.75 m, an average depth of 4.2 m, and an overall volume of 4 million m³ (Water Quality Standards Review UAA-Lake Redesignation Evaluation, 2005). The lake has three small feeding stream inlets including Middle Creek, Moyers Mill Run and a small unnamed stream (Fig. 1).

Geophysical Tools and Methods

Geophysical surveys are useful for many applications, from investigating rock composition and stratigraphy, to exploring objects beneath the ground surface. Geophysical methods are well established and are successfully used in many applications (Conyers, 2004). Common near-surface geophysical methods to explore the subsurface include GPR (Huisman et al., 2001), electrical resistivity (Loke et al., 2013), seismic refraction (Orlando and Pelliccioni, 2010), and other non-invasive techniques. Sonar, sub-bottom sonar, and GPR are three geophysical methods used in the exploration of bathymetry and its sub-bottom outlining (Sambuelli et al., 2011). Sonar provides an inexpensive means to map the bathymetry, but cannot give a direct reading of sediment thickness and is limited because it requires direct contact with water. The sub-bottom sonar, which uses a low frequency seismic reflection, can image the upper sediment accumulation, yet there are several limitations including attenuation caused by microbubbles from decaying material in the sediments (Lin et al., 2009). GPR can be operated without direct contact with water surveying and compliments sonar data. It is often used independently for mapping lake bathymetry and is a well-established technique for lakesediment profiling (Mellet, 1995). It provides fully digital data which can be processed and used more easily. Modern GPR units also have become increasingly light-weight and new developments have allowed for Windows based operation, making them easier to use (Moorman, 2001).

Electromagnetic methods, including GPR, are sensitive to variations in electrical properties of subsurface materials. GPR relies on electromagnetic wave propagation, which is initiated at the transmitting antenna, reflects off the subsurface interfaces, and returns back to the receiving antenna (Burger et al., 2006). The GPR system records the two-way travel time (TWTT) of these waves traveling from the antenna to the targeted interface and back. The velocity at which these waves travel within a material is based on the dielectric permittivity (εr). Air, for instance, has a dielectric permittivity of 1 and therefore wave propagation occurs at the speed of light, c = 3×10⁸ m/s. A typical dielectric permittivity of freshwater is around 80. By knowing the dielectric permittivity and the TWTT, the depth of the measured formation can be obtained. The propagation of electromagnetic energy can quickly dissipate and be absorbed in salty or even slightly brackish water because of its high electrical conductivity. To help calibrate the wave velocity for the Walker Lake project, a series of physical water properties were measured using a YSI 556 multimeter. During the survey period, the average
Figure 1. Location of Walker Lake in Snyder County, Pennsylvania.

Figure 2. A GPR profile across an area near the center of Walker Lake with 23x vertical exaggeration.
temperature was 19°C, electrical conductivity was 95 μS/cm, and total dissolved solids were 74 mg/l. Different relative dielectric values were tested by comparing the depth of the lake measured by a weighted line or a survey rod to the velocity measured by the GPR. The relative dielectric permittivity was selected as 80 after trying different values between 75 and 81. Most dielectric permittivity values of freshwater reported in the literature vary between these two values.

GPR data can be processed to generate a 3-D image of the bottom of the lake by collecting data along transects within a gridded area or guided by a GPS. Each transect consists of thousands of reflection traces from subsurface features, and a series of these traces produce a two-dimensional (2-D) cross-section image. By spatially interpolating and connecting these two-dimensional cross-section images, a 3-D block diagram can be generated. An example of a 2-D radargram acquired during this study (transect 7) is shown in Fig. 2.

The maximum depth in which the electromagnetic waves penetrate a material depends on the electrical conductivity, homogeneity, magnetic properties and the frequency output of the antenna. For a given conductivity, lower frequency antennas can penetrate deeper into the subsurface, but lack in resolution. Higher frequency antennas have higher resolution, but have a shallower depth of investigation (Smith and Jol, 1992).

Methodology

Data Collection

Because the lake depths vary between a few centimeters to over 9 m, 100 MHz and 400 MHz antennas were used for the survey. The 400 MHz antenna provides four times the resolution of a 100 MHz antenna, which is advantageous in shallow water (Smith and Jol, 1992; Spicer et al., 1997; Schwamborn et al., 2002; Sambuelli et al., 2009). High resolution profiles are advantageous because they can easily allow for the identification of the top and bottom interfaces of sediment deposited in the lake. Lower frequency antennas with relatively lower resolution provide results with higher uncertainty.

The SIR 3000 GPR controlling system from Geophysical Survey Systems, Inc (GSSI) was used to collect and record data from the two antennas. The GPR antennas were placed in an inflatable boat, which was towed behind a Jon boat powered by a 55 lbs. thrust electrical trolling motor. The bottom of the inflatable boat has a thin plastic layer of non-radar inhibiting material separating the antenna from the water surface. Figure 3 shows the equipment setup employed in this study with the 100-MHz antenna placed in the inflatable boat.

Data were collected along 18 transects laid perpendicular to the main axis of the lake (Fig. 1).
assumed to be distributed evenly along the distance of the transect.

Data Processing

Figure 4 shows the flow chart of data processing followed in this study. Radargrams were processed by RADAN 7 using standard signal processing tools built into the software. For example, bathymetric and sub-bottom contour lines were determined using the Interactive Interface tool. Data points for the depth of bathymetry and sub-bottom layering were then exported as ASCII files for additional processing. GPR Viewer software was separately used to process the radargrams for visualization purposes only (Fig. 5; Lucius and Powers, 2002). Radargrams 1 to 10 in Fig. 5 were obtained using the 400-MHz antenna, while 11 to 18 were obtained with the 100-MHz antenna. Bathymetry and sublayer profiles obtained with the 400-MHz antenna were detectable down to a depth of 4 m, after which attenuation made interpretation difficult. The 100-MHz antenna was needed to collect transects where the lake depth exceeded 4 m.

Bathymetry and sub-bottom layering data were processed using Statistical Analysis System (SAS 9.1.3) and MATLAB to generate surface and 3-D contour images. SAS was used to linearly interpolate along each transect at a 1-m spacing and between transects. To calculate the thickness of sediment deposition, the propagation velocity of the electromagnetic wave in these sediments must be identified. The dielectric permittivity of deposited sediments depends on many factors, including the volumetric ratio of solids to water. Given that deposition occurred within the last 43 years and the material is not yet consolidated, the depth of sedimentation was measured for several samples. A hand corer was used to take samples of sediments in three shallow submerged areas near the inlet of the lake where wading was possible. The sampled sediments were mostly soft material comprised mainly of fine silty material.

Figure 6 shows how the propagation velocity of the radar wavelet within the deposited material was calibrated. Several propagation velocity values given in the literature were tested to determine that 0.06 m/ns is the best estimate for the type of material settled in Walker Lake. The three core samples show thicknesses of deposited material matching the calculated depths when using a velocity of 0.06 m/ns. This velocity value is estimated to have an uncertainty of less than 15% (Moorman and Michel, 1997).

Two aerial photographs showing the lake area before and after the construction of the dam (Fig. 7) were used to project Walker Lake boundaries and locate Middle Creek. The trajectory of Middle Creek was
Figure 5. Flow chart showing the steps taken in the processing of the GPR data.
Figure 5. Continued.
extracted from a 1957 aerial photograph (Fig. 7(A)) taken before the construction of Walker Lake Dam. The extracted course of Middle Creek was projected on a second aerial photograph taken in 1971 (Fig. 7(B)), after the water impoundment. The goal of these projections was to verify the results of the GPR survey and make sure the channel on the aerial photograph matches the pathway of Middle Creek on the 3-D bathymetry generated by the radar data. Both the aerial photos and the generated 3-D contours show the same trajectory of Middle Creek beneath the water.

Results and Discussion

Figure 8 shows the final 3-D contour map of bathymetry of Walker Lake. The radar data confirms that the depth of the lake ranges between a few centimeters at its inlet to a maximum of 9 m near the dam. Several other features can be seen in this figure. The depth of Walker Lake increases towards the dam, the general pathway of Middle Creek channel now quasi-filled with sediments matching the 1957 aerial photograph shown in Fig. 7, and the thickness of the deposited material slightly decreases toward the dam. The survey also revealed a visible reflection for the bathymetry and the sub-bottom interface corresponding to the pre-1971 topography. The sediment accumulation was then found based on the analysis of TWTT of the radar wave from the bathymetry and the old topography and the velocity of propagation in sediments. This relationship is expressed as:

\[
\text{Sediment thickness} = V_{\text{sed}} \times \left( \frac{TWTT_T - TWTT_B}{2} \right)
\]

where \( V_{\text{sed}} \) is the propagation velocity of the wavelet within the material deposited in the bottom of the lake, \( TWTT_B \) and \( TWTT_T \) are, respectively, the two-way travel time of the wavelet from the bottom of the lake and the sub-layer corresponding to the topography of the lake.

All sediment profiles were combined and interpolated using a 3-D coordinate array generated by MATLAB meshgrid to create a 3-D surface plot (Figs. 8 and 9). The bottom sediment layer is thick because it is mainly composed of supersaturated sediment with organic materials. The bulk volume can be calculated using several techniques (e.g., Rausch and Heinemann, 1984; Foster et al., 1990a,b). In this study, the focus was to use a GPR technique to quickly map the bathymetry and sub-bottom profiles to provide an estimate of sediment deposition and its accumulation rate. An analysis of three core samples collected for the calibration of sediment thickness to GPR measurements revealed that sediment in the lake is predominately composed of fine material with a small fraction of coarse sand and organic materials. Sand is not a significant constituent in the three samples.
The survey clearly showed that the lake depth increases and the sedimentation decreases from the inlet to the dam. The estimated sediment depth ranged between 0 and 1.85 m ± 0.15 m. The survey also showed that the old Middle Creek channel contains the thickest accumulation of sediment. However, the bulk of the sediment, in terms of volume, lies outside the channel with the exception of two transects in the middle of the lake, which corresponds to a relatively flat area with a large number of small channels. The area in the middle of the lake can be explained by the existence of a lowland covered with herbaceous plants, a typical vegetation of marshlands, visible in the 1957 aerial photograph. In fact, not far upstream of Walker Lake, several marshlands along the stream path can be seen today.

A rough estimate of total sediment accumulation can be calculated by multiplying the average thickness of sediment accumulation by the surficial area of the lake. The total estimated sediment deposit was found to be $3.9 \times 10^5$ m$^3$ accumulated over a period of 43 years, which gives an average of 9,512 m$^3$/year. Note that 9,512 m$^3$/year is a bulk sediment volume rate, not the sediment mass. We expect the average annual water storage loss to be lower than the average annual sediment accumulation because of the supersaturated nature of the accumulated sediment and its lack of compaction.

**Conclusions**

This study aimed to outline a method of exploration of sediment accumulation in a body of water without referring to prior records. The approach taken combines a GPR unit with two different frequency antennas and made use of basic computer software tools.

**Figure 7.** A) 1957 aerial photograph showing the study area prior to the construction of Middle Creek Dam. The photograph was used to identify the pathway of Middle Creek in the 3-D bathymetry and topography elevation surfaces generated by the data. B) 1971 aerial photograph taken soon after the construction of the dam.

**Figure 8.** Bathymetry map of Walker Lake.
to determine the bathymetry and sediment accumulation in a lake. Walker Lake was selected as the experimental site. A total of 18 GPR survey transects were collected using 400- and 100-MHz GPR antennas, and contours of the bathymetry and sediment accumulation were constructed. Results showed that sediment deposition has settled along the old channel of Middle Creek and it is the location of the thickest deposit, yet the bulk volume lies outside this channel. The estimated total sediment deposit is $3.9 \times 10^5$ m$^3$ accumulated over a period of 43 years. Sediment depth ranges between 0 and 1.85 ± 0.15 m. The rate of sediment accumulation is estimated to be 9,512 m$^3$ per year. The amount of sediment deposited over 43 years represents 9.5% of the total volume of the lake in bulk volume, yet it is not to be mistaken with the annual water storage loss because the sediment layer is not fully compacted.

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