Measuring flood discharge in unstable stream channels using ground-penetrating radar

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ABSTRACT

Field experiments were conducted to test the ability of ground-penetrating radar (GPR) to measure stream-channel cross sections at high flows without the necessity of placing instruments in the water. Experiments were conducted at four U.S. Geological Survey gaging stations in southwest Washington State. With the GPR antenna suspended above the water surface from a bridge or cableway, traverses were made across stream channels to collect radar profile plots of the streambed. Subsequent measurements of water depth were made using conventional depth-measuring equipment (weight and tape) and were used to calculate radar signal velocities. Other streamflow-parameter data were collected to examine their relation to radar signal velocity and to clarity of streambed definition. These initial tests indicate that GPR is capable of producing a reasonably accurate (±20%) stream-channel profile and discharge far more quickly than conventional stream-gaging procedures, while avoiding the problems and hazards associated with placing instruments in the water.

INTRODUCTION

Accurate and timely determination of riverbed geometry is essential for discharge and sedimentation studies involving unstable river channels. Knowledge of stream-channel cross-sectional area is a critical component of any direct estimate of water discharge at flood stage, and, by extension, of any calculation of suspended sediment discharge or bedload transport rate for the same peak flow. Sequential profiles of channel geometry can help define the active zone of bedload transport (to assist in the design of a sampling program), as well as aid in the indirect computation of bedload transport rates by developing a relation between bedform volume and celerity, and bedload discharge (Mahmood and Mehrdad, 1991). Typically, however, the conditions that result in the greatest movement of sediment and the greatest variability in channel geometry are also those that most challenge standard measuring techniques. Rivers at flood stage are dangerous to gage because of high velocities and drift (logs, stumps, debris), and traditional depth-measuring equipment is increasingly subject to error and/or failure as stream depth, velocity, and bed instability increase (Sauer and Meyer, 1992). A technique that allows noncontact monitoring of streambed changes during high flow conditions is needed to avoid such problems, and to provide a safe way to acquire flow data that would otherwise be impossible to obtain.

One technology that may help improve the acquisition of channel-geometry data during high flow periods is ground-penetrating radar (GPR). Ground-penetrating radar is a geophysical technique that produces continuous high-resolution profiles of the subsurface by measuring the travel time of an electromagnetic pulse between a transmitter, a reflective boundary, and a receiver. The velocity of an electromagnetic pulse varies with the dielectric of the penetrated material (Davis and Annan, 1989). It is therefore necessary either to calibrate signal travel time to a known distance traveled in order to infer distance from the recorded travel time, or to use a known velocity through a material to calibrate the instrument.

Ground-penetrating radar has been used extensively and successfully to investigate surficial deposits (Smith and Jol, 1992), but much less so in surface-water hydrology. Applications of GPR in hydrogeologic studies have shown that GPR can discern water-sediment boundaries. Ground-penetrating radar studies on lakes and rivers have shown that when a low-frequency (100 MHz) antenna is towed across relatively low conductivity (400 S/cm) water, GPR can be used to map water depth up to about 10 m with resolution on the order of 10 cm. GPR has been used to detect the water-streambed interface on a river and a lake in Connecticut (Beres and Haeni, 1991), and to profile a lake bed in Arizona (Sensors and Software, 1994). These studies, and the fact that a radar pulse can travel through both air and water (Davis and Annan, 1989), suggest that GPR can be used to obtain estimates of water depth in streams and rivers when conditions make conventional stream gaging difficult or dangerous. The following report is a description of field tests conducted to assess this possibility.

OBJECTIVES AND METHODS

The purpose of the tests described here is to evaluate, under field conditions, the suitability of GPR for the measurement of stream-channel cross-section geometry. When combined with mean velocity estimates from surface-velocity measurements, flood discharge can be computed. Two basic questions were posed. (1) Can ground-penetrating radar profile a streambed when the radar antenna is suspended above the stream surface? (2) Is the radar-signal velocity sufficiently reliable to provide reasonable confidence in the accuracy of depth estimates based on signal travel time? (In other words, can worthwhile estimates of channel geometry result from GPR profiles?)

A GSSI system-10 ground-penetrating radar unit, with thermal printer, magnetic tape recorder, and 60–300 MHz transceiving antennas, was used in this study. Field tests were conducted at four sites on rivers draining Mount St. Helens in southwestern Washington: Cowlitz River at Castle Rock (bridge site); Toutle River at Tower Road (cableway site); North Fork Toutle River at Kid Valley (cableway site); and Muddy River below Clear Creek (cableway site). Initial tests were made to determine appropriate radar signal-processing settings (gain and filters), data-collection parameters (data samples per scan, scans per second, and recorded time range), and optimal antenna frequency.

The 100 MHz antenna represented the best compromise between resolution and penetration. With resolution defined as one-third the radar wavelength (Beres and Haeni, 1991), the 300 MHz antenna (approximate wavelength in water, 10 cm) theoretically provides three times the resolution of the 100 MHz antenna (approximate wavelength in water, 34 cm). However, the shorter wavelength of the 300 MHz antenna also limits penetration. The 60 MHz antenna signal will penetrate greater depths than the 100 MHz or

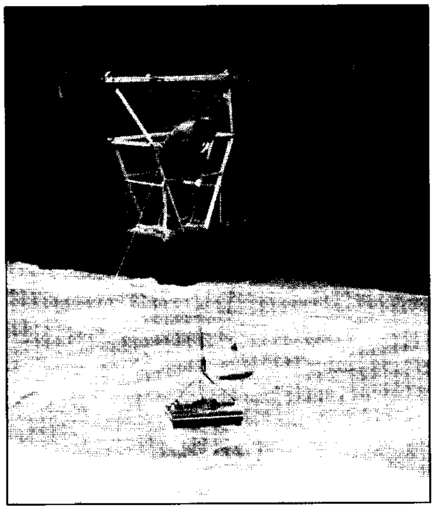

Figure 1. Photograph of a ground-penetrating radar (GPR) antenna (100 MHz), along with a 100 lb (45.36 kg) sounding weight, being used from U.S. Geological Survey cableway on Muddy River, southwest Washington, during 20 yr flood discharge.

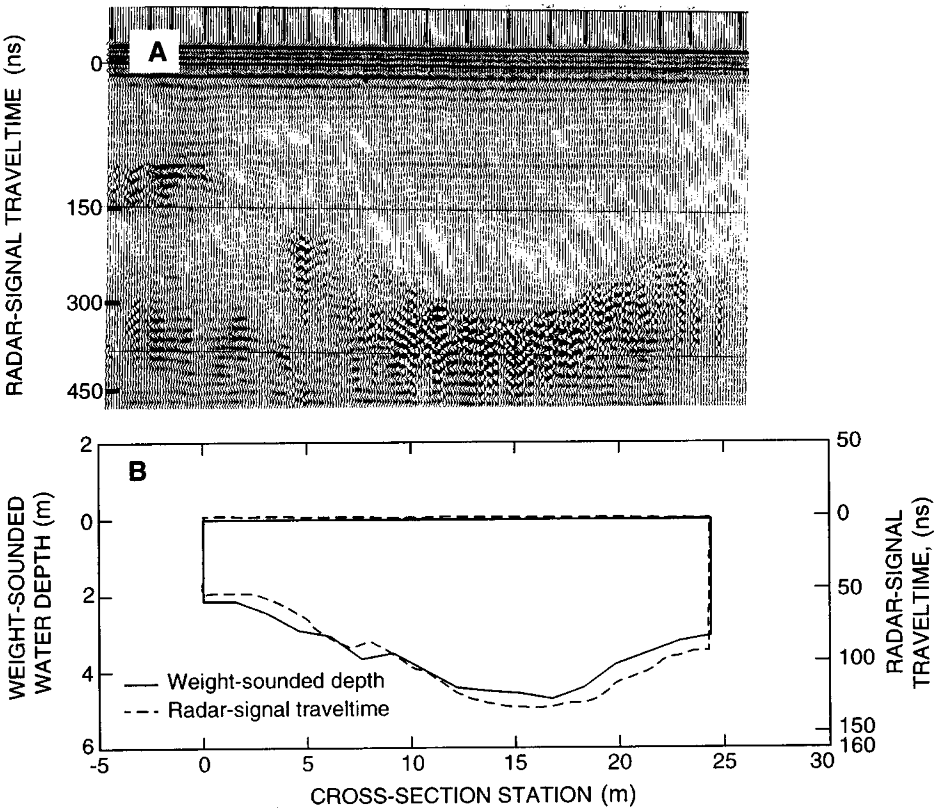

Figure 2. A: Unprocessed ground-penetrating radar (GPR) plot of stream channel at Muddy River gaging station. Locations of lead-weight depth-soundings marked by the changes in the line defining the sounding cross section. B: Shape comparison of ground-penetrating radar (GPR)–extracted cross-section plot and weight-sounded cross-section plot.

300 MHz antennae signals, but the longer wavelength results in reduced resolution.

Radar cross-section profiles were made by suspending the radar antenna (the 100 MHz transceiver housed in a 0.30 m × 0.61 m × 1.2 m fiberglass box) over the stream (Fig. 1). The antenna was first positioned near the center of the stream channel, ~0.5 m above the water surface, and radar signal gains were set to achieve optimal recognition of the water-streambed boundary. The antenna was then repositioned at the edge of the stream and towed from bank to bank at a rate of ~0.15 m/s. Radar data were output to the thermal printer and magnetic tape. Cableway and/or bridge stationing was marked in the GPR data file to indicate antenna location relative to stream cross-section position. To assess radar signal consistency, subsequent lead-weight depth soundings were collected at the cross-section stationing marked by the changes in slope of the solid line in Figure 2B. Twenty-five soundings were used to define the cross-section geometry (Fig. 2A) and to enable calculation of radar signal velocity at those points.

Stream water conductivity, suspended sediment concentration, bed material, and water temperature were collected at selected sites to examine their effects on radar signal velocity and clarity of boundary reflectivity (how clearly the radar plot shows the water-streambed boundary).

RESULTS

Results indicate that GPR can provide a good image of a stream-channel cross section when the radar antenna is suspended above the water surface. Construction of a stream-channel cross-section plot from an unprocessed radar plot requires visual definition of both water-streambed and air-water interfaces. Unprocessed radar plots show the water-streambed boundary as an intersection of a higher-amplitude, more chaotic section (representing underlying sediments) overlain by a transparent, more uniform section (representing the water column). Less distinctly shown, due to the radar's greater wavelength in air (and thus lesser resolution), is the air-water boundary. Traverses in which the antenna height above water varied with cableway sag show a curved band visible near the top of radar plots. This band, which represents the water surface, is curved because the varying antenna height above the water results in varying signal travel time. Figure 2 shows an example of an unprocessed radar plot, and a comparison of the cross-section plot derived from the radar plot with a cross-section plot obtained by directly measuring depth with a tape and lead weight. At all sites, under a variety of field conditions, it was possible to determine basic channel shape from unprocessed radar plots.

To determine the consistency of this methodology, radar-signal travel time between the water surface and bed sediments was plotted against directly measured water depth for the four sites (Fig. 3). Linear regression produced coefficient of determination (*r*) values of >0.84 for all four sites (>0.94 for three of the sites), while the all-sites composite *r* value was 0.97, indicating that most of the variation in radar-signal travel time was a result of the depth of water traversed. Remaining variation in travel time is probably influenced by suspended-sediment concentration. Stream-parameter data collected during these tests (Table 1), however, show no strong relation between signal

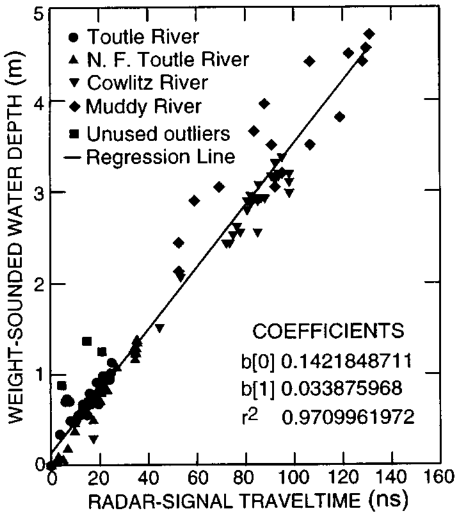

Figure 3. Linear regression of radar signal travel time versus weight-sounded water depth at four different rivers in southwest Washington.

TABLE 1. STREAMFLOW PARAMETERS MEASURED DURING GROUND-PENETRATING RADAR SURVEYS

Site	Date	Computed flow (m^3/s)	Conductivity (μ s/cm)	Suspended sediment concentration (mg/l)	Water temperature (°C)	Bed material	Remarks
Cowlitz River at Castle Rock	April 21, 1994	231	est. 100	--	--	sand, gravel	Low flow
Cowlitz River at Castle Rock	January 10, 1995	487	--	--	--	sand, gravel	Medium flow
Cowlitz River at Castle Rock	January 26, 1995	240	92	184	6.5	sand, gravel	Low flow
North Fork Toutle River at Kid Valley	April 19, 1994	44	--	47	--	gravel, cobble	Medium flow
North Fork Toutle River at Kid Valley	January 12, 1995	51 (estimate)	262	324	--	gravel, cobble	Medium flow
Muddy River below Clear Creek	January 31, 1995	326	26	10,000	--	sand, gravel, cobble	High flow
Muddy River below Clear Creek	February 1, 1995	249	32	4,060	6	sand, gravel, cobble	High flow
Muddy River below Clear Creek	February 24, 1995	52	--	100	--	gravel, cobble	Medium flow
Toutle River at Tower Road	January 24, 1995	60	210	222	7	gravel, cobble	Medium flow

Note: -- is no data.

velocity and suspended-sediment concentration, although data in Figure 3 suggest that electromagnetic wave propagation velocity is higher for flood flows containing high suspended-sediment loads. Other possible sources of signal velocity variation may include height of the antenna above the water surface, angle of the riverbed relative to the radar antenna, and inaccurate interpretation of the radar record.

The greatest differences between GPR-estimated depths and directly measured depths consistently occur near stream edges, in the part of the cross section where antenna height above water variation and riverbed angles were greatest. More testing is required to determine the causes of the unexplained variation in signal travel time.

Three methods were used to evaluate the usefulness of GPR-based cross-section plots: comparison of water depths and stream-channel cross-sectional areas obtained by GPR and computed by conventional measurement methods; comparisons of GPR-based discharge estimates with a stage-discharge rating curve; and comparison of two sequential profiles.

On the basis of the signal travel-time data shown in Figure 3, a single value (0.04 m/ns) was selected as the most representative signal velocity in impure fresh water. This value was then used to calculate depths at those points in the radar plot corresponding to the points where direct measurements of depth were obtained. Using 0.04 m/ns as a conversion factor, 80% of the GPR-based depth estimates fell within 20% of the weight-measured depth. Cross-sectional area was then calculated using the U.S. Geological Survey standard midpoint method (Rantz et al., 1982). These comparisons show that when a single signal velocity is used, areas computed from GPR plots differ by ±18% from areas computed by direct measuring techniques. Better results are achieved when signal velocities based on calibrations specific to each cross section are used to calculate areas. When this approach is used, areas computed from direct depth measurements and GPR plots differed by <10%.

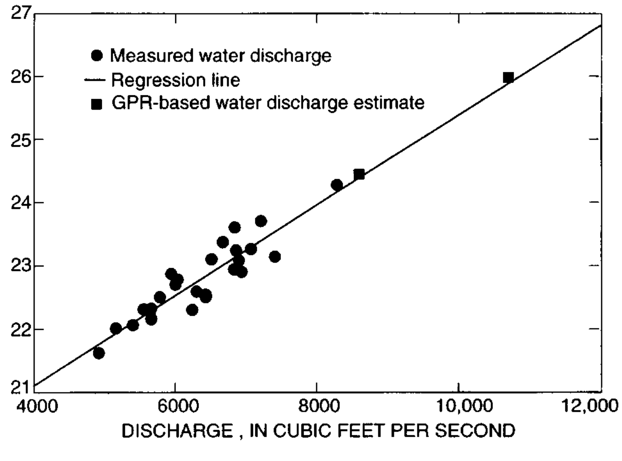

Figure 4. Flood rating curve containing linear regression through all discharge measurements above 4900 ft^3/s (140 m^3/s), and ground-penetrating radar-based discharge estimates for U.S. Geological Survey gaging station on Muddy River below Clear Creek, Washington. (1 ft^3/s = 0.0283 m^3/s.)

GPR-based discharge estimates were also compared against a stage-discharge rating curve. GPR data were collected at Muddy River during a flood peak on January 31 and February 1, 1995. Surface velocities were estimated by timing drift. Cross-sectional area was estimated from the GPR plot using 0.13 ft/ns to convert to units of square feet. (English units were used for this comparison to agree with units used for previous discharge measurements.) Mean water velocity was estimated by applying a coefficient of 0.80 (estimated from previously collected discharge measurement data) to the timed surface velocities. The two estimated discharges were then com-

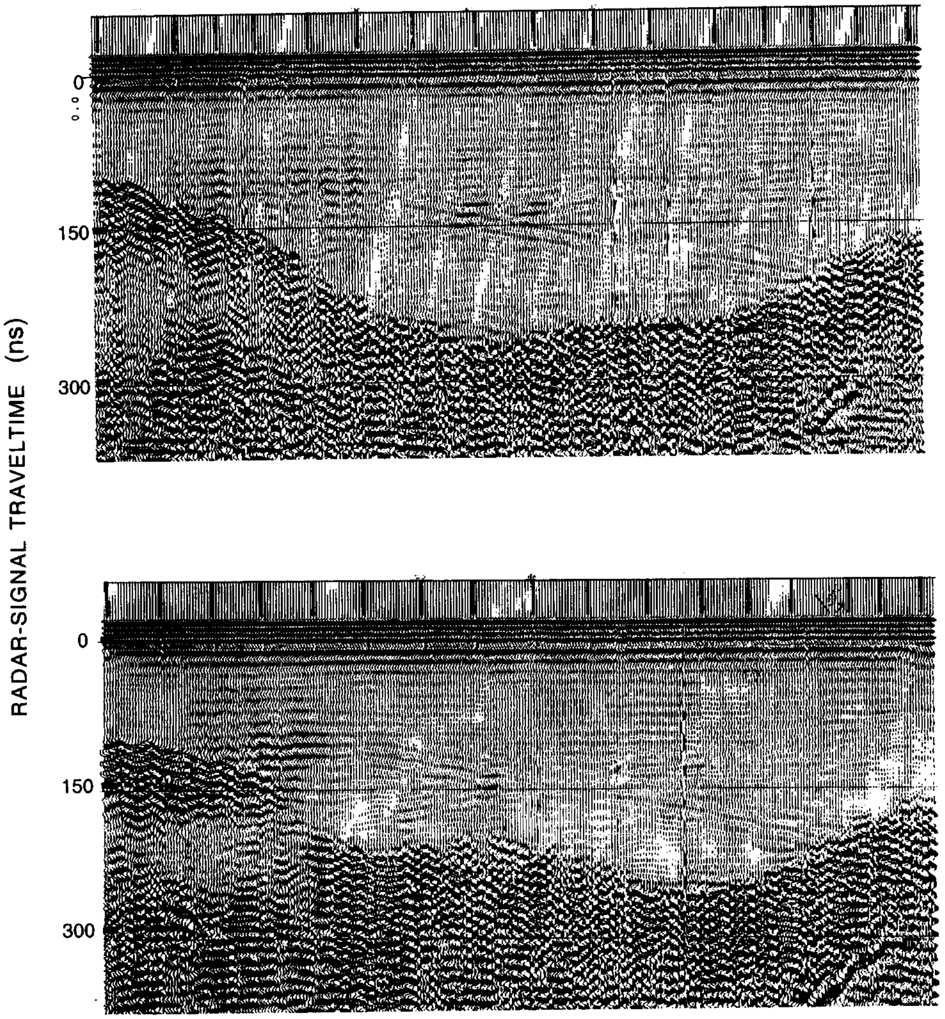

Figure 5. Sequential ground-penetrating radar (GPR) cross-section profiles at Muddy River on February 1, 1995, showing rapid change in channel geometry. Crisscrossing reflections within the water column at ~150 ns are interpreted to be interference reflections from the channel banks.

pared with a regression line based on all measured discharges above 140 m^3/s. As shown in Fig. 4, the two GPR-based discharge estimates fall close to the regression line. Although this portion of the rating is not defined by direct measurements, the vertical bedrock walls of the channel support extension of the regression line in the manner shown. Determination of mean stream velocity, radar signal velocity, and appropriate rating extension all represent sources of error. Nevertheless, these results indicate that GPR radar plots can provide useful information about channel geometry and discharge at high flow.

Two radar cross-section plots obtained five minutes apart during high flow at Muddy River demonstrate the ability of GPR to improve knowledge of channel geometry in unstable-bed conditions (Fig. 5). These two images record a significant change in channel geometry within a five minute time span as a gravel bedform passed under the cableway. This interpretation is supported by studies that documented these gravel waves in another stream draining Mount St. Helens, Washington (Dinehart, 1989). These investigations show that GPR can provide useful water- channel-geometry information not obtainable by conventional methods.

CONCLUSIONS

GPR is a viable technology for mapping stream-channel cross-section geometry at high flow and computing discharge, particularly under conditions in which conventional methods are either unsafe or inadequate. Radar plots collected in the field under a variety of conditions show, to varying degrees, the water-streambed interface, as well as the water-air interface. It appears possible to estimate channel cross-sectional area to within ±20% or better. Data suggest that if sufficient effort is made to calibrate the radar signal to a specific site and time, channel cross-sectional area estimates within ±10% are possible. These tests have shown that currently available GPR units can be used successfully from cableways and bridges. The light weight of the radar antenna and the rapid data-acquisition ability of the GPR equipment increases the safety and speed of cross-section measurement in hazardous flows. Because the radar antenna weighs only 11 kg and does not contact the stream, risk of injury to personnel and equipment is lessened. GPR has the additional advantage of producing a continuous profile of the channel cross section, which is a more accurate representation of the shape of a channel than obtained by conventional point samples made with lead weights. It is possible to acquire direct measurements of channel geometry and discharge during high flows with GPR that heretofore could not be accomplished.

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