A Proposed Radar-Based Streamflow Measurement System For The San Joaquin River At Vernalis, California

By Robert R. Mason, Jr., P.E.[1], John E. Costa[1], Ralph T. Cheng[1], Kurt R. Spicer[1], F. Peter Haeni[1], Nick B. Melcher[1], William J. Plant[2], William C. Keller[2], and Ken Hayes[2]

Abstract

Accurate measurement of flow in the San Joaquin River at Vernalis, California, is vital to a wide range of Federal and State agencies, environmental interests, and water contractors. The USGS (U.S. Geological Survey) uses conventional stage-discharge rating techniques to gage flows at Vernalis. These techniques, however, are poorly suited to the gaging of extremely unstable alluvial channels due to the frequent migration of bed forms and the scour and fill of the channel. The channel at Vernalis has scoured and filled as much as 20 feet in some sections since the flood of January 1997. These processes alter the relation between river stage and flow, diminish the accuracy and reliability of the resulting flow records, and hamper the real-time management of the water resource. Similar conditions exists at other gaging stations throughout the United States.

In response to the need for more accurate measurement methods, the USGS has undertaken a technology demonstration project to develop and deploy a radar-based streamflow measuring system at Vernalis. Ultimately, the radar systems may be used to make continuous, near-real-time flow measurements during high and medium flows. The proposed flow-measurement system consists of ground-penetrating radar (GPR) for mapping channel geometries, a micro-wave radar system for measuring surface velocities, and supporting infrastructure. This paper discusses efforts to develop and test this system.

Introduction

Accurate measurement of flow in the San Joaquin River at Vernalis, California, is vital to a wide range of Federal and State agencies, environmental interests, and water contractors. Streamflow data are used in managing reservoir releases, preparing river and estuary flow forecasts, and scheduling water withdrawals for the Delta-Mendota and California State Water Project canals for delivery to users in central and southern California. In addition, from April 15 to May 15, the gage at Vernalis serves as the principal point of control for the Vernalis Adaptive Management Program (VAMP). The VAMP is an effort by the U.S. Bureau of Reclamation, the California Department of Water Resources, and water contractors to improve the survivability of outward migrating juvenile Chinook salmon by temporarily increasing releases from upstream water-supply reservoirs, constructing flow and fish barriers on some downstream distributaries, and reducing pumping operations at the Delta-Mendota and California State Water Project intakes. During the VAMP, the need for accurate, near-

[1] U.S. Geological Survey.

[2] Applied Physics Laboratory, University of Washington

real-time flow data increases and the Vernalis streamflow records come under close scrunity. Conventional streamgaging techniques rely on periodic physical measurements of water velocities and channel widths and depths to measure flow, and stage-discharge relations (ratings) to relate the measured flow to stream stage. Continuous, real-time flow records are developed by applying these ratings, along with periodic corrections, to stage readings. The stage-discharge process is reliable and accurate for streams with stable hydraulic controls (weirs, flumes, rock ledges, gravel bars, and waterfalls). In the absence of such stabilizing features, however, channel geometry, bed slope, and roughness control the flow, and changes to either geometry or roughness may result in significant changes in the rating or "shifts."

The range and timing of shifts caused by channel scour and fill are difficult to determine, particularly if the streambed is soft and erodible as is the case at Vernalis. At Vernalis bedforms change and migrate, altering channel geometries and roughness and shifting the rating unpredictably. Even with frequent flow measurements, it is difficult to know the range of stage or period of time for which a measured shift should be applied. These uncertainties lead to conservative shift estimates: shifts are applied only when they are relatively large or when shifting patterns are well documented by a series of consecutive measurements over days or weeks.

There are technologies that could replace or supplement conventional streamgaging methods. For example, ultrasonic velocity meters (UVMs) and side-looking acoustic Doppler current profilers (SL-ADCPs) have been considered for use at Vernalis. But, both technologies are predicated on the presence of a stable channel, which does not exist at Vernalis. Without accurate channel geometry data, UVM or SL-ADCP data would be as problematic as conventionally acquired data.

Radar-Based Streamflow Measurement

While there are significant technical hurdles that must be overcome in order to provide continuous, real-time flow data, USGS Hydro 21 (a nationwide USGS research group chartered to identify and develop innovations in hydrometric measurement techniques) has been experimenting with adaptation of ground-penetrating radars (Spicer and others, 1997) and microwave Doppler-shift radars to the measurement of streamflow (Costa and others, 2000).

In 1999, radar-based systems were successfully deployed by the USGS for experimental measurements of streamflow at the Skagit River in Washington. The radar systems reproduced traditional current-meter measurement results to within one percent (Costa and others, 2000). Variations of the systems have now been tested by the USGS on the Shenandoah River in Virginia in March 2000, and on the Delta-Mendota Canal and American River in California in June 2000.

These technologies have significant potential for application to unstable alluvial channels such as that at Vernalis. They could also be used in conjunction with UVMs or SL-ADCPs to make those technologies more robust for applications on shifting alluvial channels. In order to further develop the technology, the USGS has undertaken a demonstration project at

Vernalis. The objective of the project is to develop a system for periodic noncontact flow measurements at Vernalis. Ultimately, the radars may be used for continuous, near-real-time flow measurements during high and medium flows. Components of the proposed system were deployed at Vernalis from April 14 to May 17, 2002. This paper provides an update on this work and presents some prelininary results.

System Components

The Vernalis flow-measurement system consists of a GPR for mapping channel geometries, a microwave radar system for measuring water-surface velocities, and supporting infrastructure. The infasture consists of a bank-operated cableway located about 1,200 feet downstream of the existing Vernalis gage and a temporary gagehouse (figure 1) that was built around, and now encloses, the cableway support on the left bank. The cableway was used to position the GPR and ADCP and other equipment for collecting ground-truth data (figure 2). The channel beneath the cableway is approximately 225 feet wide. During the experiment, flow depths ranged from 8.5 feet near the left bank to 4 to 6 feet for most of the measurement cross section.

Due to site access restrictions, permanent electrical service was not installed. Consequently, the radar systems could only be run on an entermitent basis with electrical generators until May 7 when tempoary service was provided. After May 7 the microwave radar was allowed to operate continuously. However, on several days, high temperatures affected the radar processing unit, resulting in some periods of lost record.

Figure 1. --Vernalis experimental streamgage. Note microwave transceiver (installation is

in progress) at upper center left and ground-penetrating radar attached to cableway just to right of shelter.

Surface-Velocity Radar

The surface-velocity microwave radar is an X-band pulsed Doppler radar developed at the University of Washington. The radar emits bursts of 9.36 GHz microwaves across the water surface from one riverbank. The system measures the time elapsed between the transmission of the microwave and the return of the reflected signal in order to estimate the location of the signal reflectors and compares the frequency of the returning Bragg scatter to that of the original transmission. Bragg scatter reflected from waves moving toward or away from the radar is shifted slightly in frequency. The magnitude of this frequency shift is directly proportional to the relative velocity of the reflector and thus the water. Frequency shift data are collected and averaged over a 30.5-second interval.

To resolve the velocity vectors into net downstream components, two microwave transmitters are used, one emitting a signal 23 degrees upstream, and another emitting a signal 23 degrees downstream of the measurement section. The radar data are collected and grouped into 35 bins, each approximately 12 feet wide. (Velocity data are also sensed, but not used for 10 bins that extend beyond the bank on either side of the channel.) Due to the antenna configuration, the bins vary in length from 34 feet nearest the left bank to 226 feet on the right bank. Thus, the radar data represent average velocities over varying lengths of the river rather than point velocities at the measurement section. This has important implications for the interpretation and checking of the velocity data and for flow measurement computations.

The microwave radar was installed and tested on February 24 and 25 (figure 1). Following testing the equipment was removed, recalibrated, and reinstalled on April 14. The radar was activated during daylight hours from April 15 to April 18. Thereafter, it was used to make near-continuous measurements of surface velocities on April 24, May 1, and May 7 through May 17.

To evaluate the radar data and develop surface-velocity versus mean-velocity ratings for the measurement section, intensive surveys of velocity profiles were conducted. Velocity profiles were measured using various ADCPs (an RDI 600 kHz Workhorse, an RDI 1200 kHz Workhorse with a ZedHed transducer, and an RDI 1200 kHz Rio Grande with a ZedHed and radio modem) a 10 kHz Acoustic Doppler Velocity (ADV) meter (SonTek/Yslan 10 mHz Hydra model), a conventional Price pygmy current meter, and a "BoogieDopp" manufactured by Nortek, which is an experimental three-beam Doppler system that includes a 2 mHz forward-mounted transducer. Different instruments were tested to identify an instrument that could collect accurate near-surface velocities and function in the relatively shallow waters at Vernalis. Typically, two or more pieces of equipment were paired (figure 2) and deployed by small boats or boogie boards positioned using the bank-operated cableway (figure 3) at 20 fixed measurement locations beneath the cableway. Using these instruments, velocity data were logged at each measurement location for 2 minutes in order to average out velocity surges. In addition to the velocity measurements, additional flow measurements were made using the ADCPs and conventional current meters.

Figure 2. –(A) Coupled deployment and positioning of BoogieDopp (white vessel), ADCP (aluminum skid boat), and current meter (attached to bow of skid boat) via cableway; and, (B) towing of GPR across channel.

Analysis of the velocity data is just beginning, but the results are promising. Example comparisons of surface-velocity data collected with the microwave radar for various recording periods on April 16 and May 16 and near-surface velocity data collected with the ADCP and BoogieDopp are shown in figures 3a and 3b. The discharge for these measurement periods was nearly constant. Overall, the April 16 radar data are very consistent (figure 3a). Surface-velocity data recorded at 10:29, 10:45 and 11:00 are generally within 0.25 feet per second (f/s) of one another. Data collected at 11:15 indicate a different pattern but may have been affected by ADCP measurements underway at the time. (The ADCP boat was positioned near section 190 at 11:15.) The surface velocities appear to be less than the near-surface velocities, but the magnitude of the bias does not exceed the differences between the ADCP (collected at 35 cm below the water surface) and BoogieDopp data (collected at 18 cm below the water surface). This bias may be due to varying depths for which the velocity data were collected, but is more likely the result of the longitudinal separation of measurement locations. Due to the angle between the transceivers and the width of the channel, the radar data represent average velocities over lengths of the river of from 21 to as much as 113 feet either side of the cableway. The ADCP and BoogieDopp data represent point velocity estimates for the measurement section below the cableway.

The May 16 data (figure 3b) indicate similar patterns. The radar surface velocity data are consistent for the recording periods, but appear to underreport the ADCP and BoogieDopp near-surface velocities. Measurement bias is also more significant near the right bank (generally to the right of section 200). As described previously, the measurement bins nearest the right bank are substantially longer than those on the left bank. Thus the differences in reported velocities could be related to differences in measurement locations.

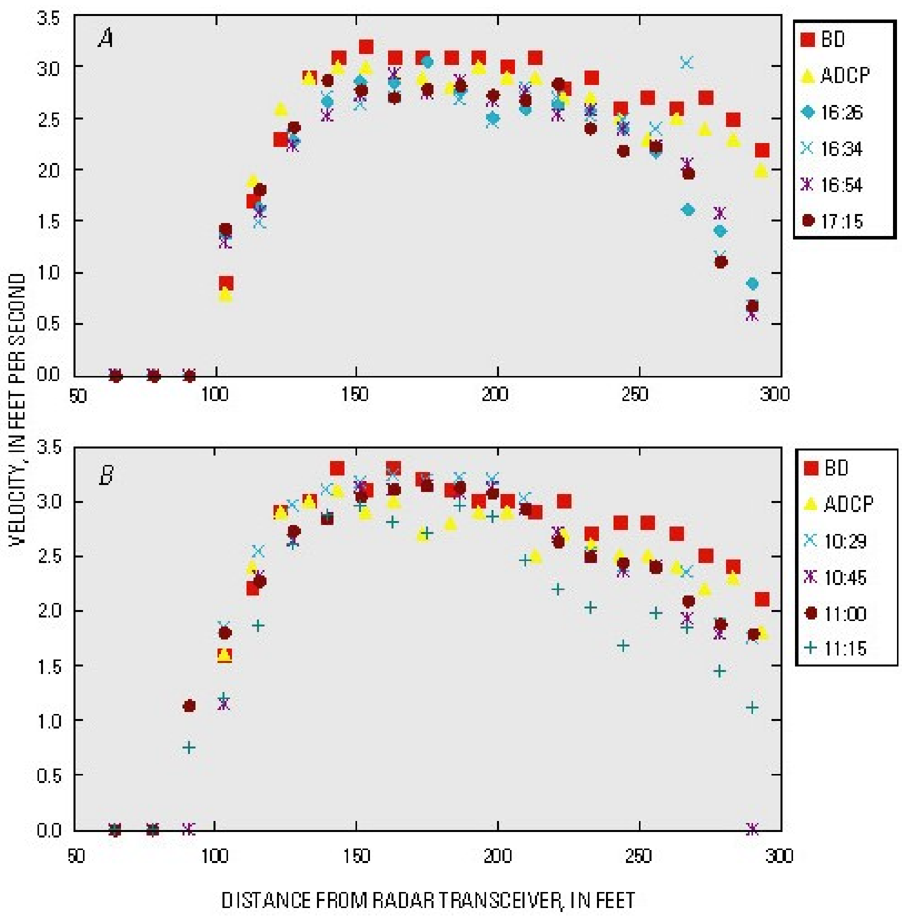

Figure 3. –Near-surface velocity data collected with BoogieDopp (BD) and Acoustic Doppler Current Profiler (ADCP) and surface-velocity data collected with microwave radar for selected recording periods on April 16 (A) and May 16 (B).

Ground-Penetrating Radar

Ground-penetrating radars (GPR) emit radar waves that pass through or are reflected by soil and water to varying degrees. The strength or intensity of the reflected signal is primarily a function of the electromagnetic impedance of the soil or water. The GPR measures the elapsed time between the emission of a radar signal and the arrival of its reflection to estimate the depth to signal reflectors. It then maps the intensity of reflected signals against depth to produce a radar image of the soil or water column. For the Vernalis experiment a Mala Geoscience Ramac X3M GPR system with a 100 MHz shielded antenna was used. This was a pre-production model and among the first of its kind released for field use. A dielectric constant of 0.11 ft/ns was assumed to convert the raw GPR data in to channel depth estimates.

The accuracy of GPR measurements are adversely affected by high conductivity. Water conductivity of about 1000 mS/cm (microsiemens per centimeter) will absorb all radar energy and not produce reflections. During dry periods the waters of the San Joaquin River consist largely of irrigation returns and conductivities are high (greater than 500 mS/cm) for most of the typical year. The radar experiments were conducted during the VAMP when the conductivities were expected to be lower due to flood flows and snowmelt. However, in 2002, mean flows for April and May were about half of their normal flows and the conductivity during the experiment ranged from a high of 850 to a low of about 260 mS/cm., degrading GPR performance.

For the Vernalis experiment, the GPR was suspended from the bank-operated cableway (figure 1) and transported across the channel 2 to 4 feet above the water surface (figure 2). A shaft encoder attached to the suspension hoist tracked the horizontal position of the GPR. An example of the GPR data following post-processing is shown in figure 4. Channel depths for distances corresponding to the microwave radar bins are indicated with red cross marks.

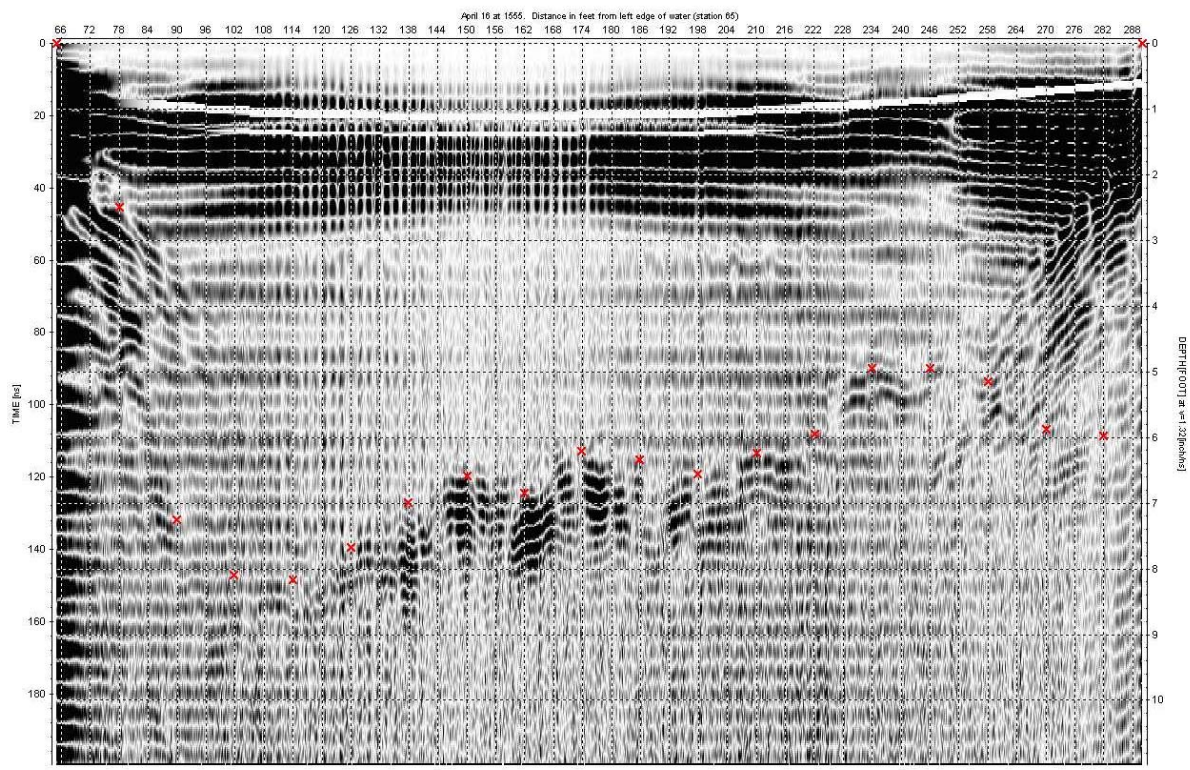

Figure 4. –Example of ground-penetrating radar (GPR) output.

Conclusions

Final data analysis is incomplete, but preliminary results indicate the surface-velocity patterns and magnitudes collected by the pulsed Doppler radar system are very similar to surface-velocity patterns and values derived from extrapolation of acoustic instrument results . GPR-derived channel cross-sections were difficult to derive in the high-conductivity waters of the

San Joaquin River near Vernalis, Ca. Preliminary results indicate GPR-derived cross-sections were very similar to depths measured with a fathometer. Data from this experiment continues to be analyzed, but plans for an additional round of experiments next year include more frequent GPR measurments and near-continuous surface-velocity data collection for at least a week during the times when the channel is most unstable.

Acknowledgements

The authors wish to thank Bill Brazelton, Joe Grant, Joe Cruz, Mike Galvez, Neil Ganju, and Kevin Wright of the USGS California District; and Jeff Gartner of the USGS National Research Program for their assistance in the collection and interpretation of the field data. This project was funded through a CALFED contract administered by the U.S. Environmental Protection Agency and the USGS National Streamflow Information Program through the USGS Hydro 21.

References

Costa, J.E., Spicer, K.R., Cheng, R.T., Haeni, Peter, Melcher, N.B., and Thurman, E.M., 2000, "Measuring stream discharge by non-contact methods: A proof-of-concept experiment": Geophysical Research Letters, Vol. 27, No. 4, Feb. 2000, pp. 553-556.

Spicer, K.R., Costa, J.E., and Placzek, G., 1997, Measuring flood discharge in unstable stream channels using ground-penetrating radar: Geology, v. 25, no. 5, p. 423-426.