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INVESTIGATING TECHNOLOGIES TO MONITOR OPEN-CHANNEL DISCHARGE BY DIRECT MEASUREMENT OF CROSS-SECTIONAL AREA AND VELOCITY OF FLOW.

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ABSTRACT

The U.S. Geological Survey is investigating technologies that may enable the direct, continuous, noncontact measurement of open-channel discharge. Measurement of open-channel discharge could be achieved by monitoring bottom and surface elevation and flow velocity of open channels. These parameters have been individually measured using particle-image velocimetry, lasers, radar, and acoustics in related applications. The U.S. Geological Survey is planning research to analyze and refine the use of these technologies for direct measurement of open-channel discharge. Direct measurement of discharge may reduce streamflow-gaging costs, improve accuracy, and reduce hazards associated with the traditional streamflow-gaging methods.

KEYWORDS

Stream gages
Discharge measurement
Average velocity
Surface velocity
Radar
Lasers
Particle-image velocimetry
Acoustics

INTRODUCTION

The U.S. Geological Survey (USGS) operates a network of about 7,000 streamflow-gaging stations that monitor open-channel discharge at selected locations throughout the United States (Wahl and others, 1995). The traditional method for determining open-channel discharge for these gaging stations was developed during the 19th century and has been refined to its present state in the past 100 years. The general equation for discharge at a selected cross section is (Rouse, 1946):

(1) ,

where

Q = discharge,

ν = velocity, and

A = cross-sectional area.

Open-channel discharge at gaging stations is determined by monitoring water-surface elevation (stage) and defining a relation between the stage and discharge (Rantz and others, 1982a,b).

Typically, water-surface elevation (stage) at a streamflow-gaging station is monitored using one or more of a variety of stage-sensing stilling wells or devices. A stage-discharge relation is defined by making periodic direct measurements of discharge at various stages. Then, discharge is computed by using the record of stage and the defined relation between stage and discharge. Adjustments to the stage-discharge relation caused by changing channel conditions are made by applying corrections defined by the periodic-discharge measurements (Rantz and others, 1982a, b). This method of indirectly computing a continuous record of discharge is well documented and broadly accepted by water users and managers. Discharge data collected under "good" conditions are considered to be accurate within ±10 percent of the true value (Novak, 1985).

Despite its accuracy and near universal acceptance and use, the present method of computing discharge has significant shortcomings. The extensive labor and travel required to service gaging stations and to make current-meter measurements of discharge are significant parts of the cost in compiling discharge data. Most of the equipment used to monitor stage requires direct contact with the channel and water, which exposes the equipment to a variety of hazards such as sediment deposition, flood damage, and vandalism. Using stage as an index of discharge requires current-meter measurements throughout the full range of stage to adequately define the stage-discharge relation and requires the use of expensive measuring equipment. Making current-meter measurements under some conditions may expose personnel to hazardous situations. Streamflow data may be needed at locations on a channel where the stage-discharge relation is unstable; significant uncertainty may exist in discharge data computed during the intervals between current-meter measurements. Many of these shortcomings could be reduced or resolved if a method could be devised to directly measure discharge.

DISCUSSION OF POTENTIAL TECHNOLOGIES

In 1996, the USGS established a committee, Hydro 21, to identify and evaluate technologies that might be used to more cost-effectively and safely monitor open-channel discharge. The committee comprises personnel of the USGS that have expertise on river measurements, hydraulics, and field instrumentation. The committee was charged with reviewing the literature, gathering information about new surface-water methods and technologies, and assessing their potential for measuring and (or) monitoring discharge.

After reviewing the present process, proposed methods, and relevant technologies, the Hydro 21 Committee determined that the desired method for monitoring open-channel discharge would be the direct measurement of open-channel cross-sectional area and mean velocity from a noncontact sensor mounted on the channel bank. Monitoring cross-sectional area would require monitoring channel bottom, channel surface, and river width. Open-channel width would be determined by the locations of points of intersection of channel bottom and channel surface. Surface velocity could be used as a reliable indicator of mean velocity for typical open-channel cross sections. After an extensive evaluation, the committee determined that opportunities for measuring velocity or cross-sectional area exist using particle-image velocimetry (PIV), lasers, radar, and acoustics.

PARTICLE-IMAGE VELOCIMETRY

Particle-image velocimetry (PIV) uses successive images to track the motions of particles in suspension or certain features of the water surface (Raffel and others, 1998). The motion of the particles or features are assumed to be the water velocity. Discrete particle displacements can be computed from cross-correlation between successive images taken over a known lapsed time. The displacement divided by the lapsed time is the velocity. The Iowa Institute of Hydraulic Research made successful experiments in monitoring surface-water velocity of a small creek by this method (Anton Kruger, Iowa Institute of Hydraulic Research, written commun., 1998) and made measurements of mean velocity in a laboratory using water-contact sensors (Muste and Patel, 1997). The feasibility of identifying sufficient particles to determine a representative velocity by this method is largely untested, and the method may only be suitable for monitoring surface velocity.

LASERS

Lasers are being used by the U.S. Navy and other researchers for mapping the elevation of the ocean bottom. Lasers can be designed to reflect off the water surface to determine stage and penetrate to the channel bottom to determine channel-bottom elevation. This capability could be used to monitor cross-sectional area. Additionally, laser doppler may be suitable for measuring mean open-channel velocity. Research is needed to determine the effects and limits of suspended sediment on signal penetration, what incident angles are feasible for the sensor, and whether needed data can be collected using lasers that are optically safe.

RADAR

Radar technology has been used to measure stage, channel-bottom elevation, and flow velocity in specific applications. A number of commercially available instruments use radar to monitor stage. Successful experiments have been made by the USGS using low-frequency radar to measure channel-bottom elevation during a discharge measurement (Spicer and others, 1997). Radar equipment has been used by oceanographers to monitor ocean surface velocities from a fixed point on shore. The Japanese are using radar to monitor flow velocity across a river. Research is needed to determine the optimal radar frequencies, feasible incident angles, and the effects of electrical conductivity on signal dispersion.

ACOUSTICS

Acoustics have been used to measure cross-sectional area and velocity for many applications. This technology could be used to monitor channel discharge; however, all known applications require a sensor with direct channel contact. Consequently, acoustics would only be considered for conditions for which noncontact methods were unworkable.

A summary of some identified technologies and their potential for use in measuring the needed parameters is shown in table 1. Note that for each of the needed parameters, at least one successful field application has been demonstrated.

RESEARCH METHODS

Research to determine the optimal method for direct measurement of cross-sectional area and velocity will be done in three steps. The first step will determine the optimal wavelengths and conditions for each parameter by reviewing test results of experiments for similar conditions and through numerical analysis of various wavelengths under various flow and channel conditions. These analyses should provide preliminary information on depth limits and the effects of electrical conductivity and sediment concentration. The numerical analysis should establish the limits and conditions of each of the various methods and provide data for a more refined field test. Upon completion of these analyses, specific technologies will be selected for further testing.

The second step will be controlled laboratory tests to determine the actual performance of the selected technologies under controlled conditions for all three parameters. This step will provide measurements of the accuracy of the methods and the suitability under various conditions. If these tests indicate that one technology or a combination of technologies can measure all three parameters within acceptable accuracy bounds, a field test will be organized.

The third step will be the development and testing of field equipment for the selected technologies. The equipment will be developed in a modular form to permit easy field modification and adaptation to various conditions. The field tests will be done at a USGS gaging station that has a stable stage-discharge relation and conditions that allow accurate discharge measurements in order for test results to be compared to accurate baseline data. For the first test, the selected site will represent typical conditions of river geometry, river velocity, channel stability, and water chemistry, and a range of conditions at a streamflow-gaging station on a natural watershed. If the initial test is successful, subsequent tests can be done under various physical and environmental conditions to determine the limits of the method.

BENEFITS

The direct measurement of stage, channel-bottom elevation, and flow velocity to monitor open-channel discharge will have significant advantages over the traditional method, which principally depend on the relation between stage and discharge. In the traditional method, uncertainty in the stage-discharge relation is minimized using current-meter discharge measurements. During the 4- to 6-week interval between current-meter discharge measurements, uncertainty increases with time until the relation is validated or corrected by another discharge measurement. This uncertainty will no longer be a factor if cross-sectional area and flow velocity are measured continuously. As the methods and equipment for direct measurement are perfected, the frequency of visits to the gaging station and the overall costs to collect open-channel discharge data likely will be reduced. Current-meter discharge measurements could be reduced or eliminated, which would lessen exposure of personnel to hazardous conditions. The accuracy of discharge data will not be as dependent on site conditions, a stable channel, and a stable stage-discharge relations as is the traditional method. As a result, the collection of accurate discharge data will be possible under conditions presently considered unsuitable.

If noncontact-equipment sensors can be designed, problems associated with exposure to the environmental hazards and vandalism will be reduced significantly because the sensor can be protected in the gaging-station structure. As this method is refined, the projected reduction in costs and service could result in a reduction in overall data-acquisition costs.

SUMMARY

A critical need exists for more discharge data at more river locations throughout the world. The traditional method for monitoring open-channel discharge uses stage as an indicator of discharge. This method has been used throughout the world for over 100 years and can produce a reliable record of discharge if site conditions are favorable. The method is labor intensive because it requires frequent direct measurements of discharge to define the stage-discharge relation for a river. The use of new technologies may make the direct measurement of the open-channel cross-sectional area and mean velocity of flow feasible. A continuous record of surface-water discharge could be produced by continuously monitoring these parameters. The U.S. Geological Survey is researching the suitability of selected technologies for this application. The combination of reduced streamflow-gaging costs and more flexible site requirements should facilitate an increase in the number of gaged sites and improved streamflow-gaging networks.

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Table 1. Comparison of potential technologies

[1, tested (see example application); 2, possible; 3, not possible]

Technique	Stage	River bottom	Mean velo-city	Sur-face velo-city	Example application	Problems
High-frequency radar	1	3	3	1	Tokyo University	Need waves or surface roughness to return signal
Low-frequency radar	2	1	2	3	Japan/Spicer and others (1997)	High conductivity will attenuate signal. Limited distance
Lasers	2	1	2	2	Naval Research	High-sediment concentration may affect penetration in water. Limited distance

Particle-image velocimetry (PIV)	2	3	3	1	Iowa Institute of Hydraulic Research	Need tracer/night use
Acoustics	1	1	2	2	Acoustic-velocity meter/acoustic doppler current profile	Water contact