Prepared in cooperation with Arizona Department of Transportation

Reach-Scale Monitoring and Modeling of Rivers— Expanding Hydraulic Data Collection Beyond the Cross Section

For over 125 years, the U.S. Geological Survey streamgage network has provided important hydrologic information about rivers and streams throughout the Nation. Traditional streamgage methods provide reliable stage and streamflow data but typically only monitor stage at a single location in a river and require frequent calibration streamflow measurements. Direct measurements are not always feasible, therefore improved sensors and methods are being deployed at gages to better document streamflow conditions between measurements. The technology and techniques of reach-scale monitoring allow the U.S. Geological Survey to collect more data across the full range of streamflow without requiring that a hydrographer be present. The U.S. Geological Survey Arizona Water Science Center's reach-scale monitoring program will enhance the Arizona streamgage network with more accurate streamflow measurements and provide more extensive streamflow records and geomorphological datasets for our agency partners and the public. Reach-scale monitoring installations and techniques are applicable to streams of the western United States and likely throughout the Nation.

Why Look Beyond the Cross Section?

Floods in the United States are extremely dangerous, costly, and routinely threaten life, property, and infrastructure. The U.S. Geological Survey (USGS) streamgage network quantifies the Nation's water supply, provides data for flood warning and forecasting, informs critical infrastructure decisions, and delivers valuable hydrologic information to better understand the responses of rivers and streams to changes in their watersheds. However, traditional streamgages typically only monitor stage at a single location in a river and require frequent calibration streamflow measurements by hydrographers to maintain accuracy. Direct streamflow measurements can prove difficult or impossible, especially in the arid southwest, where streamflow can be infrequent and flashy, sites may be remote or inaccessible during high streamflow, infrastructure from which to measure floods is limited, and conditions may pose hazards to field personnel.

Traditional Monitoring

Methods used at traditional USGS streamgages provide reliable stage and streamflow data continuously and in near real time and are the foundation upon which the reach-scale monitoring network is built.

(Right) U.S. Geological Survey (USGS) photograph of USGS scientist installing rapid deployment gage. (Below) Flash flood of New River near Phoenix, Ariz. on Interstate 17. Photograph courtesy of the Arizona Department of Transportation.

Streamgaging

Traditional streamflow records are based on river stage measured at a single location along a stream where the stage is recorded and streamflow is derived every 15 minutes, which is then transmitted via satellite to National Water Information System Web Interface (http://waterdata.usgs.gov/nwis). Streamflow is calculated through the relation between the measured stage (water level height above an arbitrary point) and discharge (average water velocity multiplied by stream cross-sectional area), which is typically developed by repeated direct measurements of streamflow at many different stages by a hydrographer.

The most commonly used method for direct streamflow measurement requires the hydrographer to measure the width, depth, and velocity of water within a cross section near the streamgage. The streamflow measurement is then associated with the stage value recorded by the streamgage at the time of the measurement. Once enough stage-versus-streamflow points have been plotted over the entire range of measured stages, a rating curve can be fitted to the points to then accurately compute streamflow from any stage within the range of stages for which streamflow has been measured. Additional measurements, particularly during high streamflow, help refine the rating at the streamgage and help document any changes to the stage-streamflow relation caused by geometric changes in the hydraulically controlling river channel cross section or its roughness.

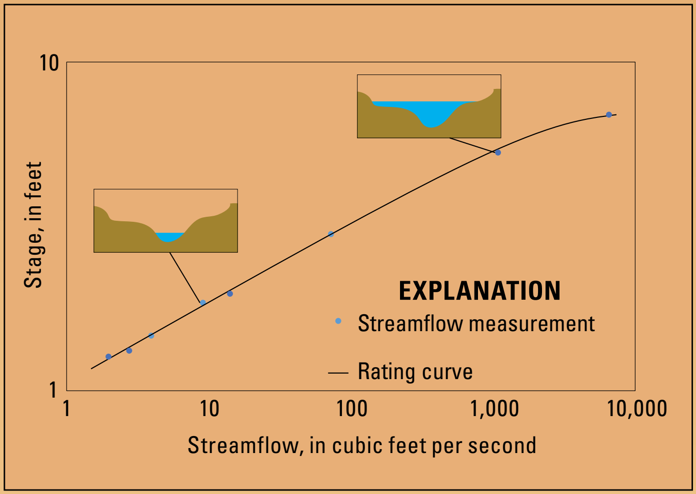


Diagram of streamgage rating and illustrations of corresponding river stages.

U.S. Geological Survey (USGS) photographs of USGS scientists conducting streamflow measurements by (below left) cableway on the Gila River near Virden, New Mexico and (below right) by wading measurements on the Gila River near Clifton, Arizona.

Indirect Measurement of Peak Streamflow

Indirect measurements of peak streamflow are conducted after a high streamflow event, because direct measurements are not often possible during the event. This is common in the southwest, because many streamgages are located in remote areas, many sites are inaccessible during high streamflow, and high streamflow events during the summer thunderstorm season often occur with little predictability.

Indirect measurements of streamflow require surveys of the river reach after the flood has occurred. The high-water marks left by the flood are surveyed longitudinally along the stream bank and provide estimates of the water surface depth and slope that occurred during the high streamflow event. Cross-sectional surveys provide the cross-sectional areas of the flood. These data are then used to calculate the peak streamflow of the flood using hydraulic modeling techniques. The limitations of this technique are that only one value (the peak) is obtained to calibrate the stage-streamflow relation, high-water marks can be difficult to locate and can degrade soon after the event, and a suitable reach is needed for accurate results.

Photograph of high-water mud line (white line) beside Moenkopi Wash near Moenkopi, Ariz. U.S. Geological Survey photograph by Jon Mason.

What is Reach-Scale Monitoring?

Reach-scale monitoring employs recent advances in techniques and technology to develop a better understanding of the hydraulics of a river reach. At a reach-scale monitoring installation, compact pressure transducers, video cameras, velocity radars, tilt sensors, light detection and ranging (lidar) scanners, and small unmanned aircraft systems (sUAS), in conjunction with traditional monitoring methods, account for more hydrologic parameters over larger areas of a stream compared to a traditional streamgage.

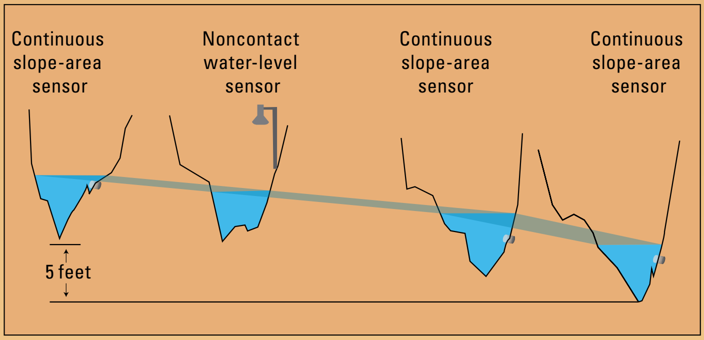
Reach-scale monitoring gages consist of an array of sensors deployed throughout the river reach to remotely and continuously measure river stage and velocity. Complete topographic models of the river reach are obtained with GPS, lidar, or photogrammetric surveys. With channel geometry data in hand, velocity data can be collected during streamflow events using radar sensors, video cameras, and image velocimetry technology to compute streamflow. These robust datasets provide measurements in previously unmeasurable conditions and during every streamflow event, potentially improving traditional streamgage accuracy. Reach-scale monitoring gages provide data necessary to monitor changes in channel geometry over time and collect parameters needed to build an accurate hydraulic model—that is, a numerical streamflow simulation that represents the direction and magnitude of streamflow in the river channel.

Reach-scale monitoring methods allow the USGS to collect more data across the full range of streamflow and can generally do so without requiring that a hydrographer be present. The new methods subsequently discussed provide more accurate, safer, and efficient ways to measure streamflow.

U.S. Geological Survey photograph of Brandon Forbes and Jeff Cordova surveying cross sections at Sycamore Creek, Ariz.

Water Surface Profiling Gages

Water-surface profiling sensors are at the heart of the reach-scale monitoring network. Compact submersible pressure transducers are installed in rugged, low-profile mounts at three or more cross sections within a reach and measure the elevation of the water surface at regular intervals, typically every 5 minutes. These sensors provide stage hydrographs of the entire event from multiple locations along the reach. The hydrographs can then be used to compute streamflow, water surface slope, velocity, cross-sectional area, and other hydraulic parameters using streamflow modeling methods, such as the continuous slope-area (CSA) method Smith and others, (2010).



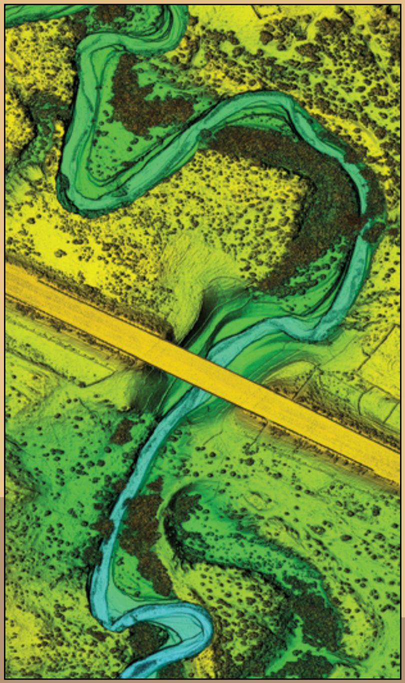
(Above) U.S. Geological Survey photograph of a continuous slope-area sensor. (Left) Stage hydrograph produced from continuous slope-area and noncontact water-level sensors.

Three-Dimensional Land Surface Models

Three-dimensional land surface models are derived from terrain data using new surveying techniques and are the foundation for the new generation of hydraulic models. Terrain data include measurements of the river channel shape along a reach and adjacent floodplain that can be inundated during a flood.

Terrain data may be obtained from ground-based lidar scanning equipment and (or) high definition, overlapping, photographic data collected via sUAS, which are post-processed using photogrammetric software. In particular, sUAS-based data collection makes land surface data available on a much larger scale and at a much lower cost than is possible using traditional surveying methods. Ground-based lidar provides additional data for areas where sUAS scans do not reach (for example, under bridges or under tree canopy). Subsequent lidar scans and sUAS flights can be compared to baseline data to measure changes in the riverbanks and bed following streamflow events. Land surface models can also be used to model hydraulic parameters (for example, streamflow, stream depth, stream velocity, stream power, and shear stress) and further calibrate the streamgage to a wider range of streamflow.

(Below) U.S. Geological Survey (USGS) photograph of USGS scientist using one of the many types of unmanned aerial vehicles that help produce (right) three-dimensional models showing areas where flooding may affect infrastructure.



Noncontact Velocity Radar Sensor

Newly developed velocity sensors, when deployed in conjunction with a permanent streamgage, can continuously measure surface velocity of flows. Surface-velocity radars use the Doppler shift of a radar signal reflected back from the stream surface to measure the surface velocity during periods of streamflow without coming in direct contact with the water column. The average velocity through the water column is then calculated by multiplying the surface velocity by a coefficient that typically ranges from 0.84 to 0.90, depending upon the shape of the vertical-velocity curve and the proximity of the channel banks (Koenig and Fulton, 2019). A velocity radar typically measures a relatively small area of the channel surface and is installed over an area of the river channel where the highest velocities are expected. The ability to constantly measure stream velocity ensures a more robust dataset that can improve streamgage records and provides calibration data for velocity mapping techniques and streamflow modeling.

Video for Surface Velocity Measurements

Image velocimetry through videography and large-scale particle image velocimetry (LSPIV) techniques can be used to calculate surface velocity and therefore streamflow. LSPIV software splits streamflow video into its component still frames and compares the individual images, identifying surface features moving through the images of streamflow, such as waves and debris. Unaided, the software can only detect the presence of movement; it cannot directly quantify the absolute distance a particle has moved. However, combined with predetermined, measured, channel geometry, the software can orthorectify the video to determine how far the particle has traveled between images and thus more accurately estimate surface velocity.

Like the noncontact radar velocity sensors, video cameras used for particle tracking can be mounted on structures away from the flowing water or hovered overhead using sUAS, which greatly improves personnel and equipment safety during a major flood. A clear advantage of particle tracking videography is that cameras can collect wide views of the flowing water—a much wider footprint compared to the noncontact radar velocity sensor—and typically provide a robust measurement of velocity during the streamflow event. In addition to data for LSPIV analysis, the recorded videos provide visual documentation of the hydraulics in the reach.

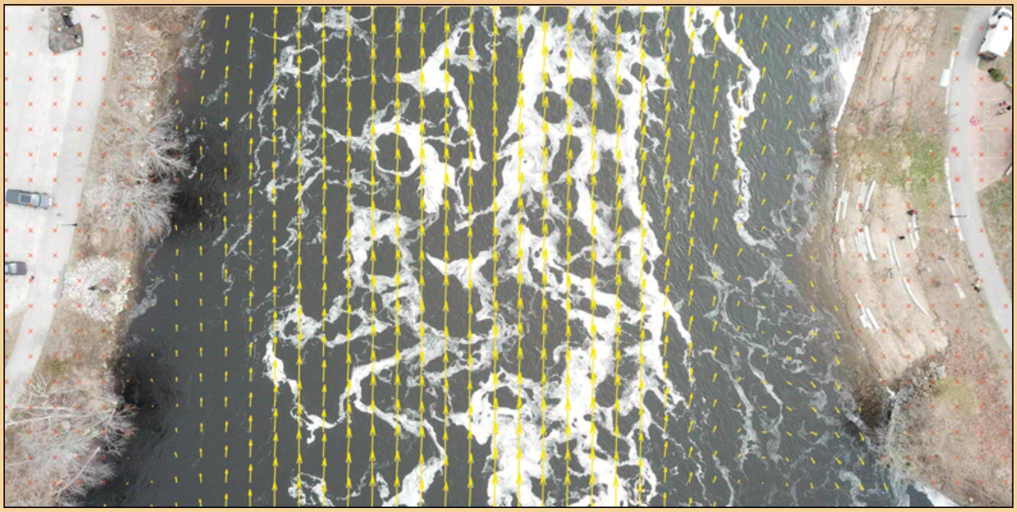
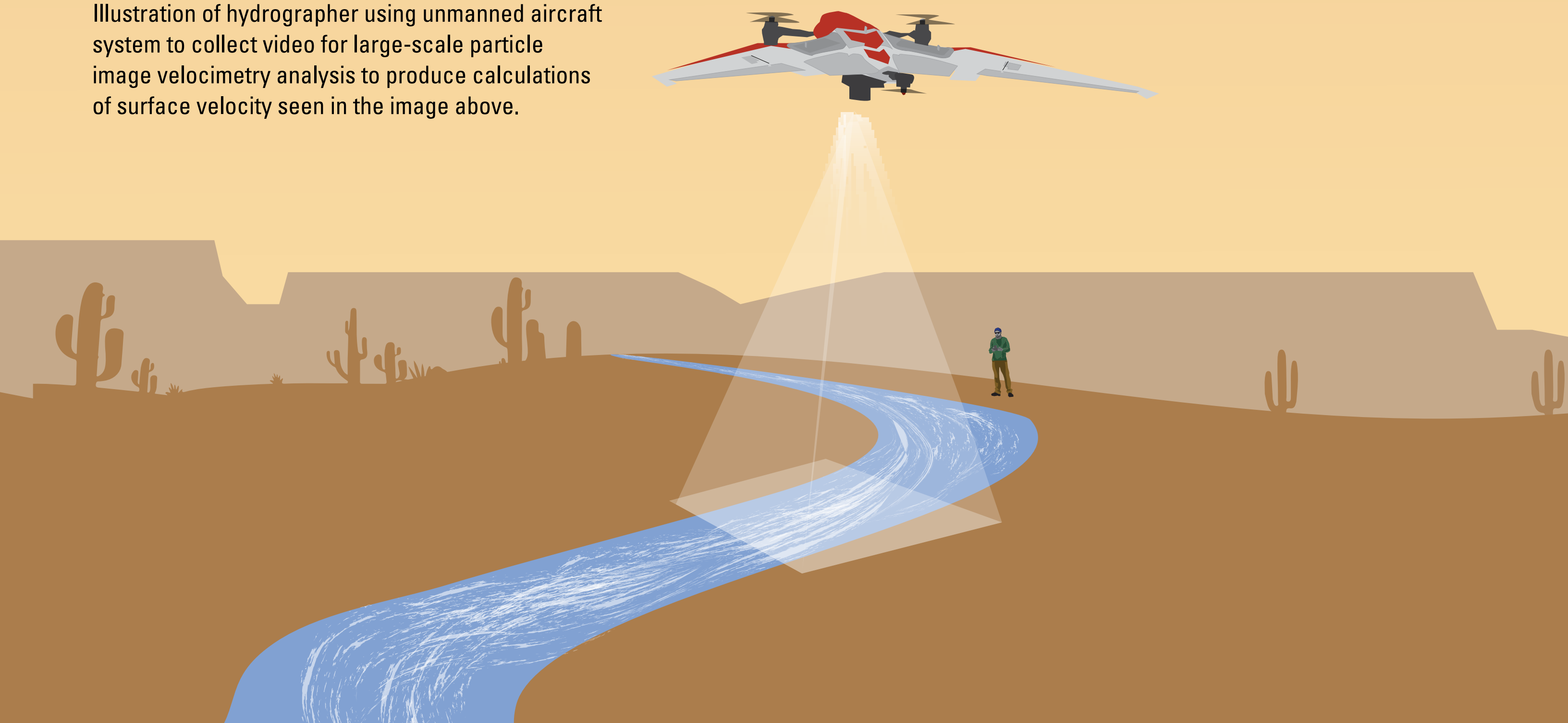


Illustration of hydrographer using unmanned aircraft system to collect video for large-scale particle image velocimetry analysis to produce calculations of surface velocity seen in the image above.



Data Packages for Advanced Streamflow Modeling

The packages of hydraulic information that a reach-scale monitoring installation collects are necessary to calibrate hydraulic streamflow models (the computer simulation used to represent the direction and magnitude of streamflow vectors in the river channel). Hydraulic modeling requires many assumptions to be made when designing the numerical simulation, which creates a theoretical representation of how floods move through a river channel. Some of these assumptions are Manning's roughness coefficients, how roughness varies with depth, drag coefficients, interpretations of channel geometry, streambed stability, and subsurface losses in the river reach. These decisions are made using available data and often require the modeler to use their best hydraulic judgement to determine the most appropriate value for a parameter. These decisions rely on research and the experience of the modeler, and these assumptions introduce uncertainty into the model results.

Reach-scale monitoring data allow modelers to use accurate representations of the channel and hydraulic parameters when making modeling decisions. Replacing modeling assumptions with reach-scale monitoring data allow modelers to evaluate the usefulness, accuracy, and limitations of the modeling software. Once the models are calibrated with data collected by the reach-scale monitoring gage, they can be used to simulate more complex hydraulic parameters, such as channel roughness or drag coefficients, stream power, flow angle of attack, bed scour, and bridge-pier scour. Such information will ultimately result in more accurate streamgages, more efficiently designed infrastructure, and ultimately, the safety of the public at large. As more packages of reach-scale monitoring data are collected, we will continue to learn how to use these complex models to answer some of the difficult hydrologic questions we face.

Photograph showing large boulders and sediments impeding traffic on U.S. Route 89A between Marble Canyon and Jacob Lake, Ariz. after heavy rainfall on August 9, 2015. Photograph courtesy of Arizona Department of Transportation.

Transportation and Reach-Scale Monitoring

The Arizona Water Science Center (AZWSC) is working with the Arizona Department of Transportation (ADOT) to demonstrate the value of data collected at reach-scale monitoring gages to the transportation sector. Reach-scale monitoring provides data on flood magnitude and changes in cross-sectional area that can be used to refine the accuracy of hydrologic models and increase understanding of how channel conditions affect infrastructure. Such comprehensive hydrologic data was generally unavailable in the past for making infrastructure maintenance and design decisions.

The partnership between AZWSC and ADOT has allowed for rapid installation of sensors to monitor water level and velocity, as well as timely surveys of channel and bank topography to inform bank stabilization projects and bridge and culvert design. Importantly, velocity and water level data can be used to determine when bridges and roadways should be closed to ensure the safety of the traveling public. Local and national transportation departments will likewise benefit from the increase in hydraulic data obtained from reach-scale monitoring gages and from the opportunity the data provide to more efficiently and effectively manage and maintain infrastructure to ensure public safety.

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