Prepared in Cooperation with the Flood Control District of Maricopa County

Continuous Slope-Area Discharge Records in Maricopa County, Arizona, 2004–2012

Scientific Investigations Report 2015–5172

U.S. Department of the Interior
U.S. Geological Survey

COVER

Photographs show Vekol Wash near Stanfield, Arizona, in flood (top) and at zero flow (bottom). Photographs by John W. Heaton.

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SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

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Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

Acknowledgments

The installation and maintenance of the continuous slope-area streamgages in Maricopa County, Arizona, and the writing of this report were funded by the Flood Control District of Maricopa County (FCDMC). Steve Waters and Dave Gardner of the FCDMC have enabled the development of streamgage methods and the ability to obtain discharge records in ephemeral channels in the arid southwest through their support of U.S. Geological Survey projects and streamgages.

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Abstract

Continuous slope-area (CSA) streamgages have been developed and implemented by the U.S. Geological Survey (USGS) to enable the recording of discharge hydrographs in areas where direct discharge measurements cannot be made. The flashy nature of streamflow in parts of the arid Southwest and remote location of many sites make discharge measurements difficult or impossible to obtain. Consequently, available discharge measurements may be insufficient to develop accurate rating curves, which relate discharge to continuously recorded stage measured at standard streamgages. Nine CSA streamgages have been installed in Maricopa County, Arizona, since 2004 in cooperation with the Flood Control District of Maricopa County. This report presents the data and analysis of computed discharges from those streamgages, along with descriptions of the streamgage site and stream properties.

Analyses of sources of errors and the impact stage data errors have on calculated discharge time series are considered, along with issues in data reduction. Steeper, longer stream reaches are generally less sensitive to measurement error. Other issues considered are pressure transducer drawdown, capture of flood peaks with discrete stage data, selection of stage record for development of rating curves, and minimum stages for the calculation of discharge.

Introduction

Surface water is a major component of the water supply in Arizona. Fifty-eight percent of consumptive water use in the state is derived from surface water. Sixty-three percent of agricultural consumptive water use is from surface water (Saeid Tadayon, U.S. Geological Survey, oral commun., 2013). Flooding in Maricopa County, Arizona, is a significant hazard, made more dangerous by the flashy nature of runoff, particularly during summer months. Quantifying the properties of surface-water flow is critical for designing structures, formulating streamflow statistics, tracking water supply, and warning of flood hazards.

Standard U.S. Geological Survey (USGS) streamgages can provide accurate records of streamflow by tracking stage and using a relation between stage and discharge to determine the discharge record. The stage-discharge relation, known as a rating curve, relies on discrete measurements of discharge, which are often direct measurements of flow velocity and depth across the channel from which discharge can be calculated. With discharge determined at known stages over a range of flow, lines can be fitted to form the rating curve (Rantz and others, 1982).

Discharge measurements can be made difficult or impossible by the remoteness or inaccessibility of streamgages and the rapid rise and fall of hydrographs. In such circumstances, a method is needed to estimate discharge hydrographs with reasonable accuracy without direct measurements. The USGS has long estimated peak discharges in the absence of direct measurements by using calculations based on cross-section surveys, surveys of markers of the peak water surface, and estimates of channel roughness. This indirect method of estimating peak discharge, known as the slope-area method, relies on cross-sectional areas and water-surface slopes derived from the reach surveys (Benson and Dalrymple, 1967; Dalrymple and Benson, 1967). The USGS Arizona Water Science Center has extended the slope-area method of determining peak discharge to include time-varying hydrographs using the continuous slope-area (CSA) method (Smith and others, 2010). The CSA method has been implemented for several purposes, including (1) to measure discharge in the aftermath of wildfires in streams with especially high flooding potential and (2) to provide discharge records from which streamflow infiltration into the bed can be derived (Stewart and others, 2012). In Arizona, CSA streamgages have been installed in channels that are usually dry, but the method has also been used to acquire complete hydrographs in perennial streams (Brown and Metcalfe, 2014).

The CSA method has been implemented in nine reaches in Maricopa County (fig. 1). The CSA streamgages were installed in cooperation with the Flood Control District of Maricopa County (FCDMC). The FCDMC is tasked with providing real-time flood warning information to residents in Maricopa County, Ariz. The FCDMC maintains approximately 120 streamgages on natural streams in Maricopa County and in surrounding counties where drainages affect Maricopa County. The FCDMC maintains real-time water-level sensors at each site, as well as streamflow rating curves. The data allow hydrologists, meteorologists, and other decision makers to issue warnings about current and future runoff and flood conditions.

Maricopa County covers about a 9,100-square-mile area and is the fourth most populated county in the United States. The FCDMC ALERT (Automated Local Evaluation in Real Time) streamgages are located in most of the county and beyond. Travel distances between ALERT streamgages are long, so site visits are very time consuming. A high number of ALERT streamgages and a limited staff factor into the inability to collect data from simultaneous runoff events. Direct measurements of discharge are very difficult to obtain, and even indirect measurements are difficult to obtain, owing to limited resources of staff, time, and equipment. The CSA streamgages help the FCDMC with their flood warning responsibilities by providing discharge data in addition to stage data.

The CSA streamgages will improve the USGS streamflow data in two ways: (1) as a means of obtaining data for indirect measurements near remote standard USGS streamgages and (2) as an alternative for the crest-stage gage program. Many USGS standard streamgages rely on indirect measurements to define the upper end of the rating curves; CSA streamgages will help improve the accuracy of the streamgage rating by making multiple slope-area measurements throughout flow events.

In Maricopa County and throughout Arizona, many of the counties have installed ALERT networks to provide flood-warning data to emergency managers. By installing a CSA streamgage near a county ALERT gage, the USGS would be able to publish peak flow and unit value data that could

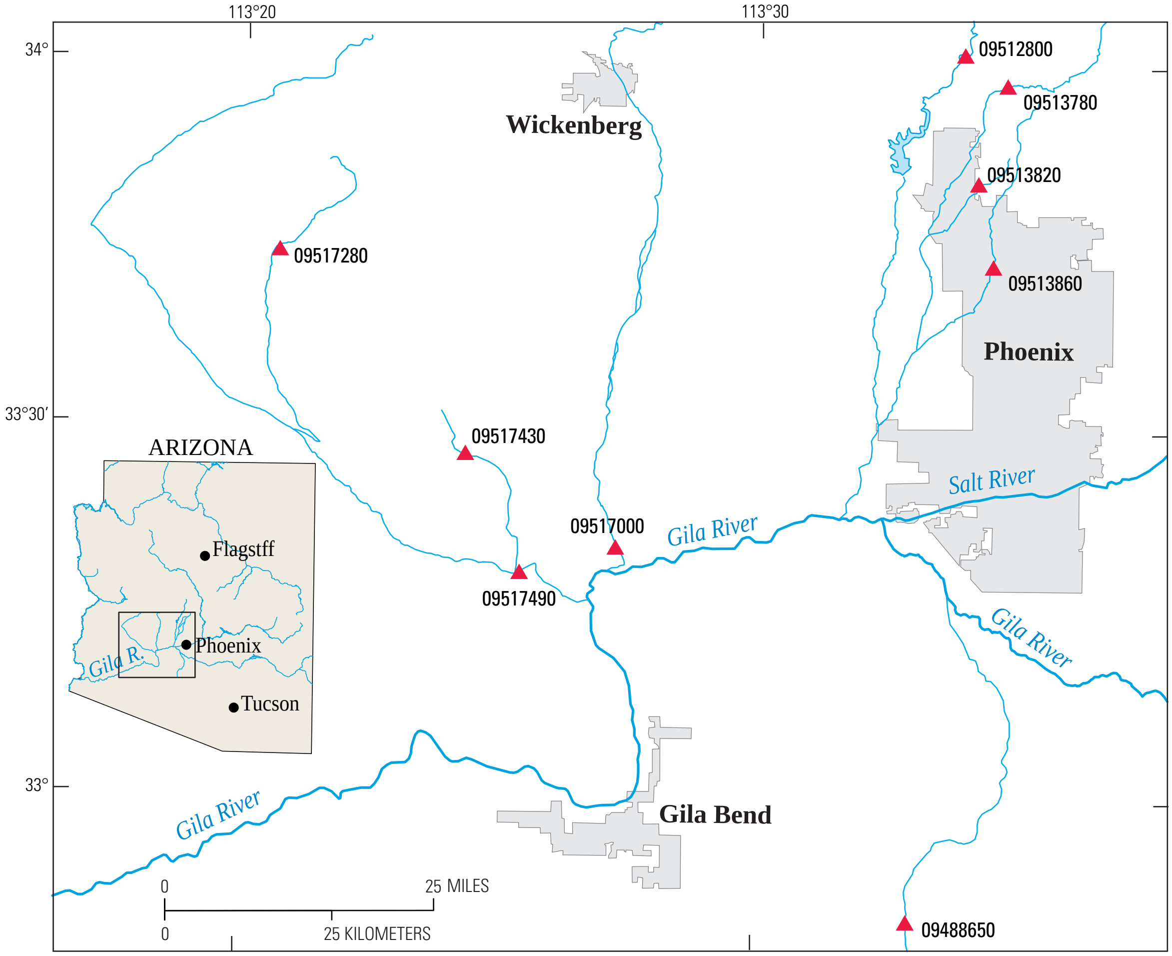

Figure 1. Map showing the locations of the continuous slope-area reaches in Maricopa County, Arizona.

EXPLANATION

Agua Fria near Rock Springs (09512800)
Centennial Wash at Southern Pacific Railroad Bridge near Arlington (09517490)
Deadman Wash near New River (09513820)
Delaney Wash near Tonopah (09517430)
Hassayampa River near Arlington (09517000)
New River near Rock Springs (09513780)
Skunk Creek near Phoenix (09513860)
Tiger Wash near Aguila (09517280)
Vekol Wash near Stanfield (09488650)

be used by the county to develop a verified rating curve. In addition to improving the quality of flood-warning data, it would allow the National Weather Service to use the county ALERT gage as a forecast point to issue flood warnings.

The Continuous Slope-Area Method for Computing Discharge

The continuous slope-area (CSA) method was developed by the USGS Arizona Water Science Center to address a problem common with stream gaging in Arizona—the streamgage sites are often not accessible for measurements when rivers flow. Typical streamgages rely on discrete direct measurements of discharge to build rating curves that relate stage to discharge. Stage is recorded continuously, typically at 15-minute intervals, and the discharge record is computed by relating stage to discharge with the rating curve. In the absence of measurements, computational methods involving channel properties and stage information must be used to estimate discharge. The CSA method is an extension of standard USGS methods of determining peak discharge after a flow event if no standard discrete direct measurements were made.

The CSA method was initially developed on the Babocamari River, a tributary to the San Pedro River in southeastern Arizona (Smith and others, 2010). The streamgage was installed in 2002, and it operated for 8 years before the description of the installation and results were published. Six significant flows occurred during that time, ending with a 25-year (0.04 annual exceedance probability) flow on July 27, 2006, which modified the channel by transporting cobbles and removing vegetation. The Babocamari River installation provided a good opportunity to evaluate installation methods and the suitability of equipment for the CSA streamgage over a range of flows.

Indirect Methods of Computing Peak Discharge

The USGS estimates peak discharges after significant flows where or when no discrete direct measurements were possible using what are known within the USGS as indirect measurement techniques. In channel flows, as distinct from flow through or over structures such as culverts or weirs, these indirect measurements are known as slope-area calculations because of the survey-derived information that goes into them. With a slope-area indirect measurement, channel cross sections, typically three or more, are surveyed; the water-surface profile is surveyed from evidence along the channel banks; and the channel roughness is estimated. The water-surface profile provides both the cross-sectional area during the flow of interest as well as the water-surface slope between cross sections. The basic equation used to compute discharge is the Manning equation:

$$Q = \frac{1.49Ar^{2/3}Sf^{\,1/2}}{\mathrm{n}} \qquad (1)$$

where Q is discharge, n is Manning roughness, R is the hydraulic radius ($=A/P$ where A is the cross-sectional area and P is the wetted perimeter), S_f is the friction slope, and 1.49 is a constant used when the values are in U.S. customary units (in metric units, 1 is substituted for 1.49; the Manning equation is not dimensionally consistent).

The procedure for making indirect slope-area measurements of discharge has been documented in detail by Dalrymple and Benson (1967). Some key recommendations include selection of reaches that are straight with little expansion and preferably a mild constriction, reaches sufficiently long and steep to allow for accurate slope determination, and reaches where flow is within the channel banks. In peak discharge calculations for the southwest United States, water-surface elevation corresponding to peak discharge is typically derived from debris lines along the channel banks. Sediment or vegetal debris can leave lines along the banks that mark the high water elevation. Reaches that conform to optimal standards for peak discharge calculations can be difficult or impossible to find, and debris lines can be diffuse or confounded by multiple levels generated on the receding limb or by flows that occur between the peak discharge and field work. Such conditions degrade the accuracy of the calculated discharge and lower the accuracy rating applied by the analyst making the calculation.

The Slope-Area Computation (SAC) program (Fulford, 1994) is used to compute the discharge using a standard input file. A graphical user interface (Bradley, 2012) is also available that greatly eases data reduction tasks by preparing the input file for SAC directly from survey data, running SAC, and generating graphs of output.

Use of three or more cross sections is usually considered essential for achieving reasonably accurate results. In addition to accounting for variations in channel shape, multiple cross sections provide information necessary for evaluating the suitability of the computational reach. The SAC program that is used for calculating discharge does so for a range of possible combinations of cross sections and uses the results to flag potential sources of error.

Extension of Slope-Area Indirect Methods of Computing Peak Discharge to Time-Varying Discharge

Indirect slope-area methods allow for calculation of peak discharge, but because they rely on peak water-surface profiles estimated from debris lines, they cannot be used to obtain discharges during the rest of the hydrograph. The initial installation of a CSA streamgage (Smith and others, 2010) was inspired by the availability of low-cost pressure transducers (PTs) that record stage. The PTs installed in the channel provide the stage data over a range of discharges during an event, which can be used to calculate discharge with equation 1. Pressure transducers can also help accurately determine water-surface elevations in reaches with poorly defined high-water marks. These PTs can be programmed to record stage at regular intervals (typically 5-minute intervals over 2–3 months). In contrast to traditional indirect peak-flow calculations, CSA applications require the choice of reaches prior to flows. The guidelines provided by Dalrymple and Benson (1967) for selecting suitable reaches for peak-flow calculations apply to CSA reaches as well.

The PTs have been mounted in channels on channel iron set in concrete in the channel bed (Smith and others, 2010) and in pipe hammered into sand-bedded channels (Stewart and others, 2012). Mounting PTs on T-posts hammered into the channel can be a low-impact alternative that makes installation in sensitive areas more palatable to landowners or land agencies but will be more vulnerable to damage or loss. In bedrock channels, PTs housed in pipes can be directly bolted to the channel bed. The PTs used by the Arizona Water Science Center have been unvented to ease installation and eliminate fouling on vent lines by debris or sediment, although data from unvented PTs require corrections for barometric pressure.

Error Sources and Data Reduction Considerations

Error Sources

Because of the simplicity of the computational component of the CSA, testing for sensitivity to measurement errors or Manning's *n* is a straightforward process. Measurement errors refer to the accuracy of stage magnitude and timing. Stages, timing, or roughness can be systematically varied and compared to the variations in computed discharge for specific applications. A general understanding of the behavior of the equations and their sensitivity to computational inputs, however, can be facilitated by looking at simplified versions of the equation and comparing a true value for discharge to one degraded by real-world judgments, such as selection of *n*, and limitations on measurement accuracy.

Steady Flow Assumption

The equations solved in SAC to determine discharge are for steady flow. At peak discharge, the time derivative in the governing flow equations is zero, so the use of steady-flow equations to calculate peak discharge is appropriate and contributes no error to the calculated discharge. With discharge that is varying over time, as with CSA applications, the time derivative is not zero, and neglecting it contributes some error to the calculated discharge. Smith and others (2010) considered the magnitude of this error by first nondimensionalizing the momentum equation:

$$\frac{\partial u}{\partial t} + u\,\frac{\partial u}{\partial x} + g\left(\frac{\partial e}{\partial x} - S\right) + \frac{u_*^2}{R_h} = 0 \qquad (2)$$

where x is the streamwise dimension, g is gravity, de/dx is the additional water-surface slope in a varying flow field, S is the steady-flow water-surface slope, u_* is the shear velocity, and R_h is the hydraulic radius, and then examining the magnitude of the time derivative. The error introduced by neglecting the time derivative is inversely proportional to the channel slope. The error is small in steep slopes but can be significant as the slope gets milder. Channel slopes in Arizona are generally sufficiently steep that the error is typically no more than a few percent. Other sources of error in CSA applications are considered in the following sections.

Range of Useful Data

The CSA streamgage requires the cross sections to be continuously hydraulically connected before reliable calculations of discharge can be made. At low flows, the water-surface slope between cross sections derived from PT data may not represent a continuous water surface, even if the PTs are inundated, if they have been installed low in the channel. As the flow rises, a smooth slope between cross sections develops that, with the addition of the velocity heads at each end of the reach, represents the hydraulic head loss

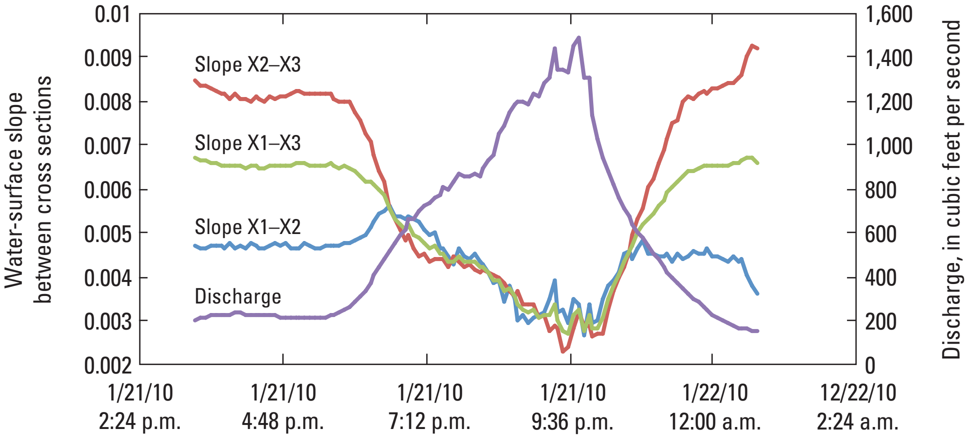

Figure 2. Graph showing water-surface slopes and discharge at the Deadman Wash, Arizona, continuous slope-area streamgage during the January 21–22, 2010, flow.

through the reach. Prior to and following a flow at Deadman Wash (fig. 2), the slope derived from PT stages is only a function of the surveyed elevations of the instruments. As the stage rises, the slopes begin to converge, and at around 600 cubic feet per second (ft^3/s), the slope is consistent through the reach. The slope steadily declines as the stage rises, then increases again as the stage falls. At around 600 ft^3/s, the slopes again decouple and return to their preflow values. In this case, reliable discharge could be computed above 600 ft^3/s. Plotting the slope between cross sections can be useful for identifying the lowest flow that should be calculated with the CSA streamgage.

Roughness

Channel roughness is represented by n in the Manning equation (equation 1). If a reach is well-suited for slope-area computations of discharge, discharge will be inversely and linearly proportional to n. Consequently, n selection is an important component of slope-area calculations of discharge and a potential source for error. Various methods have been developed for determining n (for example, Phillips, 1998), but selection typically depends on the experience and judgment of the analyst, aided by guides such as those provided by Chow (1959) and Arcement and Schneider (1989). Selection of n for Maricopa County reaches benefits from publications that are specifically focused on Arizona (Phillips and Ingersoll, 1998; Thomsen and Hjalmarson, 1991; and Aldridge and Garrett, 1973).

The channels in the study area are sand or gravel bedded and are not marked by high relative roughness owing to bed material. The data of Phillips and Ingersoll (1998) do not show consistent evidence of roughness varying with discharge, but their data typically cover narrow ranges of discharge. Channels in the study area do have potential sources of high relative roughness from vegetation that grows in the channel, along the banks, and in the flood plain. Accounting for vegetation roughness is complicated by difficulty in quantifying its density and estimating how it will respond to streamflow. Vegetation roughness can be reduced at higher flows as a result of bending or scouring out or by hydraulic lubrication at higher discharges, as occurs with coarse bed material. Phillips and Tadayon (2006) estimated the effects of vegetation density on channel flow capacity, and their results and recommendations can be used as a guide in selecting a roughness value. Accuracy of computed discharges would benefit from further development of Phillips' pioneering work on channel roughness in the region.

Phillips and Ingersoll (1998) provide verified n values primarily in Maricopa County. They calculated discharge from direct velocity and stage measurements during significant flows. They then made indirect slope-area measurements of discharge in the same reaches and adjusted n to match the discharge determined with direct methods. These verified n values are most accurate and reliable for channel roughness and should be used in the same or similar streams whenever possible.

Thomsen and Hjalmarson (1991) and Aldridge and Garret (1973) assembled picture books of streams in Arizona. Thomsen and Hjalmarson focused on photographs of specific reaches in Maricopa County, whereas Aldridge and Garret included photographs showing a wide range of channel roughness, organized by streams with decreasing roughness throughout Arizona.

In addition to photos, Aldridge and Garret included channel dimensions and slope. Most of the n values in this publication were based on the authors' experience and judgment; a few reaches have verified n values. The report provides a comprehensive, consistent, and coherent guide to channel roughness. Channels of various roughnesses can be directly compared to one another and to field sites to help determine reasonable roughness values. The guide thus facilitates documentation of roughness values used in calculations, as users can reference specific examples in the guide that match field sites. Users of the guide are free to modify values in their applications based on their own judgment and experience.

With direct measurements of discharge, CSA streamgages can be used to determine n over a range of flows if the streamgage site is accessible during events. The value of n can be adjusted in the calculation of discharge using CSA data until the discharge matches the measured value. In typical n verification studies, n is calculated for the peak discharge. With continuous recording of stage data during an event, a value for n can be determined for discharges measured at any point in the hydrograph with the CSA stage data recorded at the same time. Soong and others (2012) determined n over a range of discharges in Illinois streams with measured discharges and observation of water-surface elevations on staff gages. An n value of 0.031 was determined for the New River near Rock Springs site on January 23, 2010, at 11:55 a.m. from a discharge measurement taken at that time.

Effect of Time Step

The time step used in the PTs will determine the resolution of the hydrograph. A standard time step for USGS gaging stations is 15 minutes. The original CSA installation (Smith and others, 2010) used 5-minute time steps. Stewart and others (2012) employed a variable time step by programming their data recorders to respond to changes in stage.

The effect of the time step on the hydrograph resolution is entirely dependent on the rate at which the flow rises or falls and the duration of the peak. Because the time derivative in the momentum equation is neglected in the SAC calculation, each calculation of discharge over the course of a hydrograph is independent of every other calculated discharge; coarse time steps do not introduce discretization error. Smith and others (2010) showed that the use of the steady-flow equations introduces little error in the calculated discharge in Arizona but can introduce significant error for rapidly varying flow in very low-gradient streams. Stream gradients are sufficiently steep in the Maricopa County CSA installations, so error induced by steady-flow calculations is small.

In flashy systems, however, a coarse time step could reduce the chances of capturing the peak discharge because the peak may occur between stage recordings. Higher wave speeds at higher discharges steepen discharge waves as they move downstream, but sharp transitions in discharge are smoothed by diffusion of the wave. Both effects are explicitly represented in the diffusion wave equation (Lighthill and Whitham, 1955):

$$\frac{\partial u}{\partial t} + c\,\frac{\partial h}{\partial x} = u\,\frac{\partial^2 h}{\partial x^2} \qquad (3)$$

where u represents velocity, h is depth, and c represents the wave speed ($c = \frac{dQ}{dA}$, which can be related to the stage-discharge relation by $c = \frac{dQ}{dh}\frac{dh}{dA}$). The second order term on the right side of equation 3 represents the tendency for sharp transitions to be smoothed. Consequently, even flashy flows with rapid rises and declines typically have rounded peaks. Examination of the stage records from the Maricopa County CSA streamgages indicates that the 5-minute recording time interval typically defines the transition from rising to falling discharge with sufficient resolution. The stage record at the upstream cross section at Tiger Wash during a high flow on July 14, 2012, near the peak, for example, shows some fluctuations, but the overall shape of the peak of the wave is resolved by the 5-minute time interval (fig. 3).

Differences Between High-Water Marks and Pressure Transducer Peaks

A discrepancy between the high-water marks (HWM), crest-stage gage (CSG), and PT peaks was observed in some cases, with the HWM typically higher than the CSG, which was in turn higher than the PT peak recorded by the CSA streamgage. The higher HWM could be a result of wave action or other near-bank instabilities. Drawdown has also been observed to reduce the recorded stage at streamgages, however. Because the HWMs tended to be well defined and apparently unaffected by near-bank irregularities, the discrepancies observed in these CSA streamgages were generally judged to be the result of drawdown.

Drawdown can be addressed in several ways if HWMs are available for corrections. The difference between the peak PT stage and the HWM can be added as (1) a constant, (2) a correction that varies linearly between the peak difference and a difference at a lower stage, or (3) a physically based correction related to the square of the velocity. Implementation of a constant or a linear variation as a function of stage is straightforward and does not require any additional application of the CSA computation. Use of the velocity in a correction factor would require iteration.

Pressure variations that result from flow past the PT orifice can modify the recorded stages. According to the Bernoulli equation, stagnation pressure (the location where velocity goes to zero along a streamline) is proportional to the square of the velocity. A reasonable assumption regarding the variation in drawdown as discharge changes, then, is that it is proportional to the square of the velocity. The precise effect for a given installation depends on the installation details, but an approximate correction can be made by relating the ratio of the stage differences to the ratio of the differences in velocity squared. A correction for drawdown can be estimated from the difference between the PT reading and an assumed correct value with

$$h_n = h_o + (h_{hwm} - h_p)(u_t/u_p)^2 \qquad (4)$$

where h_n indicates corrected water-surface elevation, h_o indicates uncorrected elevation, h_{hwm} indicates high-water mark elevation, h_p indicates peak value from the streamgage, u_t indicates the velocity at time t, and u_p indicates peak velocity.

Implementation of equation 4 would require iteration, however, and complicate the calculation of the discharge record. The velocity used is the cross-sectionally averaged velocity ($u = Q/A$) and would have to be calculated first with the uncorrected PTs to obtain an initial velocity time series.

A simpler approach would relate the correction to stage. According to the Manning equation, $u \sim h^{2/3}$ in a very wide, flat channel, and so $u^2 \sim h^{4/3}$. Velocity is nonlinearly proportional to depth, but weakly so in this simple case. The relation is

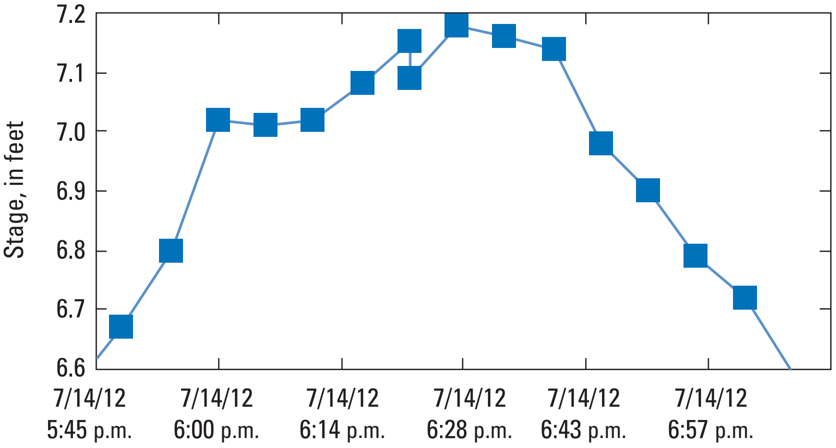

Figure 3. Graph showing stage record at the upstream cross section in the Tiger Wash, Arizona, continuous slope-area reach during the July 14, 2012, streamflow.

more complicated in natural rivers, but approximating the variation in the stage correction linearly as a function of distance above the channel bed rather than iterating on u^2 generally introduces a relatively small error. Consequently, the PT stage can be corrected with

$$h_n = h_o + (h_{hwm} - h_p)(h_t - h_b)/(h_p - h_b) \qquad (5)$$

where h_b indicates bed elevation and the other variables are as defined above.

Use of h_b as the lower boundary introduces another approximation. At the stages where the PT is inundated or where the CSA method becomes useful, the velocity in the channel is greater than zero. Near the bank, where the PT is typically located, however, the velocity is small because the PT is inundated (near the datum level), so the assumption of zero velocity is adequate.

Differences between HWMs and the peak stage recorded by the PT at Tiger Wash indicated drawdown during a flow on July 14, 2012. Discharge was computed (fig. 4) using no stage correction and the four correction methods discussed above (constant, linear, function of u^2, and function of $h^{4/3}$). Because it is based most directly on the flow physics, the correction based on u^2 is taken as likely to be the closest to reality. The calculation with no correction shows a poor fit over the range of flows. The constant correction fits the peak well, but agreement diverges at lower flows. The correction that uses $h^{4/3}$ in place of u^2 shows close agreement on the rising limb but diverges on the falling limb. The linear approximation shows reasonable agreement and is straightforward to implement, and it is used in this report where drawdown was indicated by differences between HWMs and PT peaks.

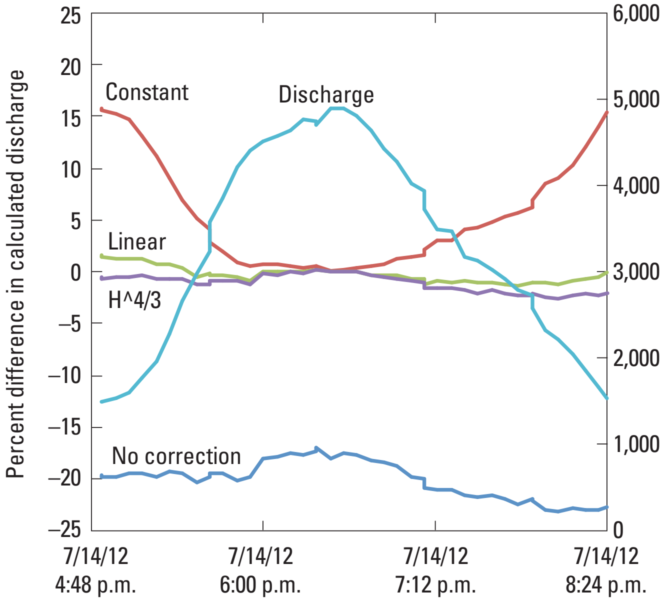

Figure 4. Graph showing continuous slope-area streamgage discharge record at the Tiger Wash, Arizona, streamgage. The discharge shown was computed using a drawdown correction based on u^2, where u is velocity, and is used as a reference for the differences in discharge calculated with other corrections for drawdown.

Formulation of Stage-Discharge Relations with Continuous Slope-Area Data

Unlike standard USGS streamgages, CSA streamgages do not require stage-discharge relations based on direct measurements to determine discharge records. Instead, the discharge is calculated directly from the stage data recorded with the PTs. Stage-discharge relations can be useful in some cases, however, such as during the malfunction of some PTs, or if all but one PT is removed from a stable channel. Stage-discharge relations developed from CSA data can also be used at sites, such as crest-stage gages or ALERT gages, where a stage record has been recorded to calculate past discharge records.

Stage-discharge relations can be complex, but simple yet accurate stage-discharge relations can be developed for some channels by plotting the calculated discharge against a recorded stage (usually the most upstream PT, as explained in the next section) and fitting a power function. U.S. Geological Survey hydrographers have the option of dividing the stage-discharge relation into more than one segment (up to three) and adjusting the shape and fit of the stage-discharge relation by adding a constant offset to the stage. A similar procedure limited to a single segment can be followed in a spreadsheet to achieve the best fit. This process was used to formulate the stage-discharge relations in the appendixes. The single-segment rating was found to be a good fit to the data in these cases.

Selection of Continuous Slope-Area Stage Record for Stage-Discharge Relations

The stage record from each PT can have some variability as a result of turbulent fluctuations, surface waves, or channel changes. This variability can cause scatter in stage-discharge relations by altering the local stage and by affecting the reach slope calculated from stage data and used in the slope-area computation of discharge. Examples from field data generally show that the upstream PT provides a tighter stage-discharge relation than the downstream PT (fig. 5), an effect that is due at least in part to the fluctuations in the stage record at the upstream and downstream PTs, resulting in opposite effects on the calculated water-surface slope.

If the stage at the upstream end fluctuates upward, then the computed water-surface slope will increase and the computed discharge will increase. At the downstream end, however, an upward fluctuation in the stage will lead to a lower computed water-surface slope and, consequently, a lower computed discharge. The higher computed discharge at the upstream end is trending in the same direction as the stage (both are increasing), whereas at the downstream end, they are moving in opposite directions (fig. 6). As a result, the downstream PT will produce more scatter in the stage-discharge relation.

The difference between using the upstream or downstream PTs for the stage record in developing a stage-discharge relation can be illustrated with a simple model of a flume-like reach and the Manning equation (equation 1). The dimensions of the modeled reach are similar to the Agua Fria reach, with a width of 100 feet (ft), an average slope of 0.002, and a Manning roughness of 0.035. The stage at the upstream and downstream ends were perturbed with a value determined with a random Gaussian distribution with a mean of 0 and a standard deviation of 0.1 ft calculated independently at the upstream and downstream locations. Discharge was then computed over a hypothetical flow event represented by a sine wave (fig. 7). The stage-discharge relation using the upstream stage record shows significantly less scatter than the stage-discharge relation using the downstream PT (fig. 8). If a good record is obtained from the upstream PT, use of that stage record will generally provide a smoother stage-discharge relation than use of the stage record from a PT farther downstream.

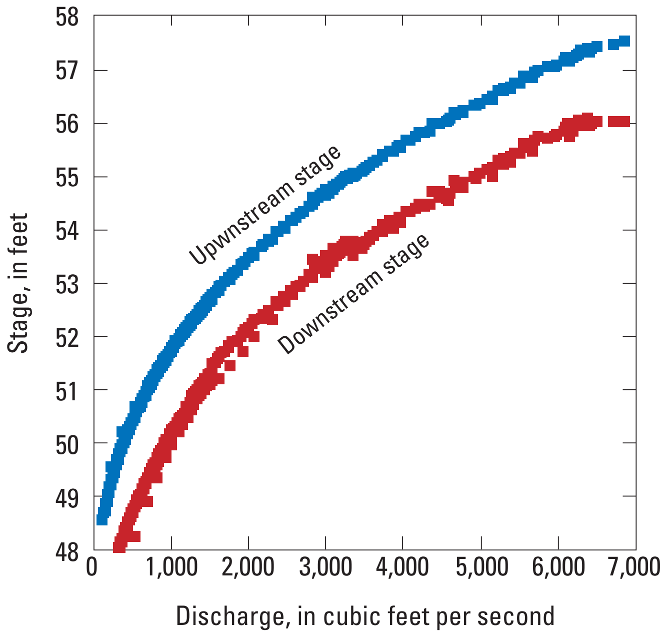

Figure 5. Plots showing stages and computed discharges at the Centennial Wash at Southern Pacific Railroad Bridge near Arlington, Arizona, continuous slope-area streamgage during the January 21, 2010, streamflow.

The Effect of Timing Errors on Computed Discharge

If the clocks in the pressure transducers are not perfectly synchronized, then the recorded stages will be shifted in time and will degrade the accuracy of the computed discharges. If the clock in a downstream pressure transducer is ahead of the clock in an upstream pressure transducer, for example, the downstream stage gage will show a lower stage on the rising limb, and consequently, the computed slope on the rising limb would be steeper than actually occurred.

The manufacturers of the PTs used in the Maricopa County CSA installations indicate that the clocks have an accuracy of about ±1 to ±2 minutes per year. The PT clocks in the Maricopa County installations were reset about every six months even if no flow occurred, and no significant drifts in the clocks were observed when downloading the data contained in this report.

If a difference in the clock settings is observed when the data are downloaded, applying an offset to the drifting clocks to bring them into synchronicity would be a reasonable and straightforward remedy. If significant time has passed between the event and downloading the data, and assuming the clocks were synchronized previously, a correction could be linearly interpolated over time. Plotting the stage hydrographs together can also be useful for determining a time correction. The travel time of a wave through a reach is typically no more than a few minutes, so the time of one stage plot with respect to another can be offset until they line up. The time correction would be equal to the offset.

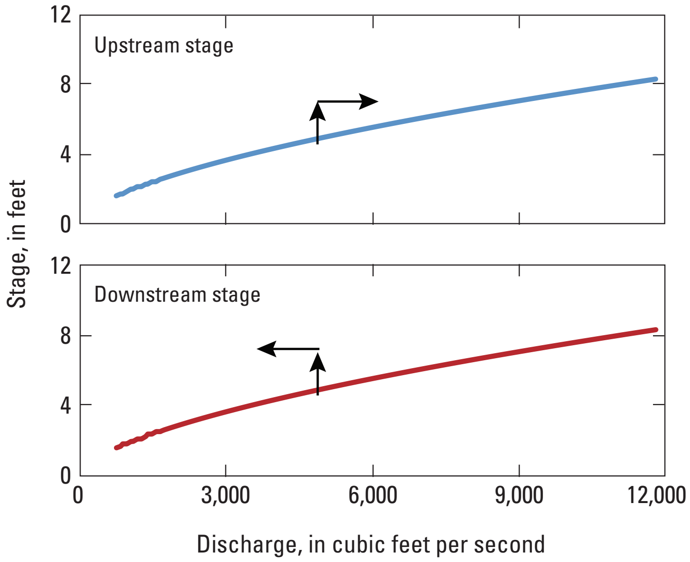

Figure 6. Graphs showing the difference between using the upstream pressure transducer and the downstream pressure transducer in developing rating curves. An upward fluctuation in stage increases the slope used to compute discharge. This increases the computed discharge and tends to move the stage-discharge pair towards the rating line (top). With an upward fluctuation in stage at the downstream gage, the opposite occurs. The slope used to compute discharge is lower, leading to a lower computed discharge. The stage-discharge pair moves away from the rating line (bottom).

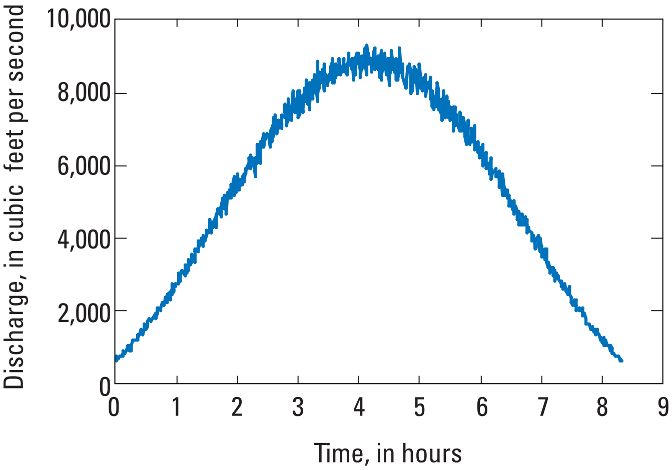

Figure 7. Hydrograph computed with hypothetical stages with random fluctuations. Mean = 0; standard variation = 0.1 ft.

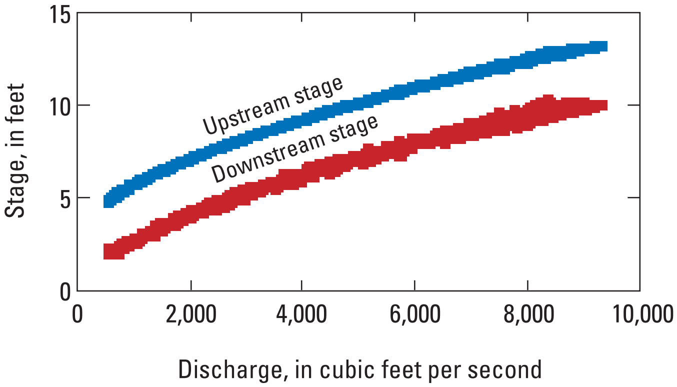

Figure 8. Stage-discharge plots using values from the hydrograph in figure 7. The plot using the upstream stage pressure transducer (blue) shows less scatter than with the downstream pressure transducer (red).

The effect of asynchronicity in the pressure transducer clocks can be illustrated by applying a time offset to the stage records in the case considered in the previous section (fig. 9). A positive offset at the upstream PT leads to large percentage errors at low flows; the error goes to zero at the peak. If the hydrograph computed with the timing offset is shifted in time to line up better with the error-free hydrograph, however, the percentage errors are much smaller. The magnitude and distribution in the error in computed discharges will vary with the shape of the hydrograph and the characteristics of the gaged reach. The sensitivity of computed discharges to timing errors can be evaluated at particular CSA streamgages by adding timing offsets to the stage data and computing the resulting discharges.

Continuous Slope-Area Streamgages in Maricopa County

CSA streamgages have been installed in nine reaches in Maricopa County (fig. 1). Six of the reaches are ephemeral, two have periods of low base flow, and one has continuous agricultural return flow. The reaches are distributed throughout the county and range from potentially unstable sandy beds to relatively stable gravel-bedded streams.

Several streamgage sites covered in this report were considered in previous USGS publications that evaluated channel change and potential errors in rating curves. Channel changes in the Agua Fria River near Rock Springs, Ariz.; Hassayampa River near Arlington, Ariz.; New River near New River, Ariz.; and Tiger Wash near Aguila, Ariz., streamgages were presented by Capesius and Lehman (2002). Tillery and others (2001) described potential errors in stage-discharge

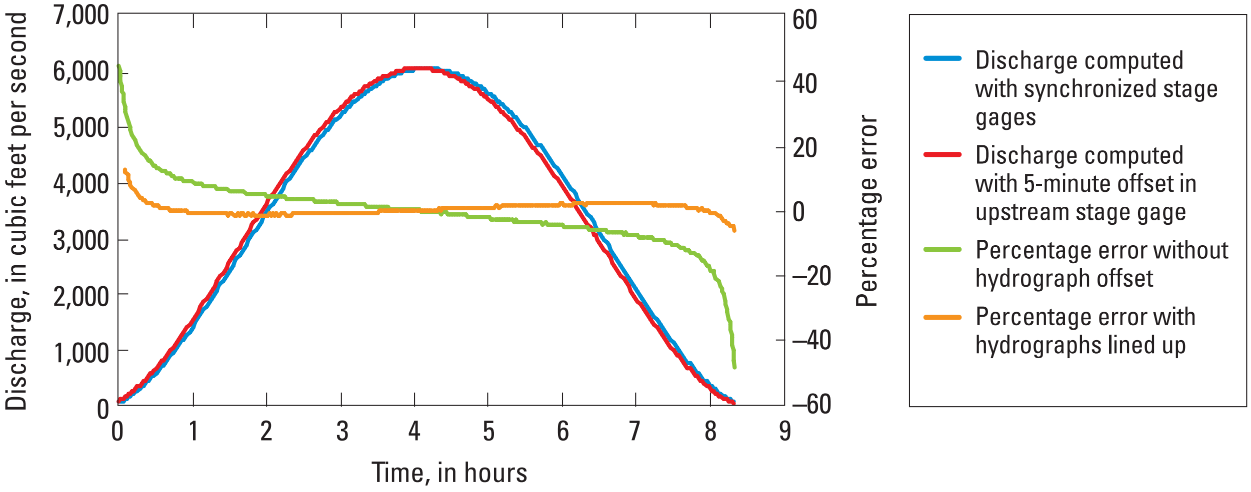

Figure 9. Hydrograph computed with and without 5-minute clock error in the upstream pressure transducer. The percentage errors are the difference between the two hydrographs with no adjustment to the second hydrograph, and with the second hydrograph offset by five minutes to better match the error-free hydrograph.

relations in the New River near Rock Springs, Ariz.; Hassayampa River near Arlington, Ariz.; Centennial Wash at Southern Pacific Railroad Bridge near Arlington, Ariz.; and Tiger Wash near Aguila, Ariz., streamgages.

The CSA sites were originally established in cooperation with the FCDMC as channel-change monitoring sites. The CSA streamgages were added starting in 2004 to provide discharge records to associate with measured channel change. Six of the CSA streamgages are located within 0.25 miles (mi) of a standard USGS streamgage. Two of the CSA streamgages were established at existing USGS crest-stage gages, and one is located independently of other USGS streamgages.

In the reach descriptions below, descriptions of the channel properties were derived from the Station Descriptions and Station Analyses (Rantz and others, 1982) for the full gaging stations where they exist, with appropriate modifications for the CSA site if it was not colocated with the streamgage. Basin properties were determined with StreamStats (Ries and others, 2008), an interactive online program developed by the USGS and implemented for Arizona (Paretti and others, 2014). The streamflow statistics region is an area covered by a set of recurrence interval relations (Paretti and others, 2014).

Cross-section surveys are routinely obtained after significant flows that may have altered the channel. None of the repeated surveys, however, showed significant channel change. Some reworking of the bed, such as would result from sand or gravel bar migration, is evident, but overall channel cross sections were stable. With one exception, the highest discharges had an annual exceedance probability of more than 0.08 (less than an exceedance interval of 12 years). The exception was an annual exceedance probability of more than 0.04 (less than an annual exceedance interval of 26 years) at Vekol Wash.

General descriptions of the CSA streamgages are provided below, including reach and basin properties and location. Peak discharges and their recurrence intervals are summarized in tables. Cross sections shown in the photographs are numbered upstream to downstream. The locations are for the left bank of the downstream cross section as shown in Google Earth. Measured stage, computed discharges, and cross-section surveys are contained in the appendixes.

Appendixes

Each CSA streamgage corresponds to an appendix posted online with this report. The appendixes consist of Excel spreadsheets and contain the stage data referenced to the appropriate datum for each flow event, a plot of each computed hydrograph, and a plot showing a stage-discharge relation for each hydrograph. Surveys of each cross section are plotted together. The stage-discharge relations are simplified versions of standard USGS relations because only one offset is used to develop a good fit on a log-log plot. If high-water marks were used to correct the stage record, the corrected and uncorrected stages are included.

Stage-discharge relations were formulated by fitting a power curve of the stage as a function of discharge. The stage from the upstream cross section was used, and an offset was added to achieve the best fit, as represented by R^2, as determined in Excel 2010. In most cases, the single power curve represents the stage-discharge relation well. In a few cases where hysteresis is evident, the fitted line is between the rising and falling limb discharges. In a few other cases, the stage-discharge relation would benefit from multiple segments representing distinct hydraulic conditions, as is usual practice in USGS rating curve development.

Agua Fria near Rock Springs, Arizona

Station number: 09512800
CSA installed: June 23, 2006
Reach location: lat 34°01’09” N., long 112°09’37” W.
Reach length: 1,467 ft
Basin characteristics:
Drainage area: 1,100 square miles (mi^2)
Mean basin elevation: 4,550 ft above sea level (asl)
Mean annual precipitation: 19.4 inches (in.)
Streamflow statistics region: 2
Drainage area: 110 mi^2

Channel description:

The main channel is composed of cobbles with sand in patches. The reach has wide, low terraces on river left in the upstream section and river right in the downstream section. Surface sediment is a medium sand in the terraces. Vegetation is sparse in the main channel, but dense, mature vegetation, including mesquite trees, occupy the terraces. The reach bends to the right going upstream to downstream. The reach has pools and riffles at low flows, but at higher flows where the CSA streamgage is effective, the control appears to be the channel.

Table 1. Agua Fria near Rock Sprtings, Arizona, peak stramflow statistics.

Annual exceedance probability, in years^{-1}	0.2	0.1	0.04	0.02	0.01	0.005	0.002
Recurrance interval, in years	5	10	25	50	100	200	500
Discharge, in cubic feet per second	8,025	15,270	39,147	57,083	79,246	107,823	168,768

Table 2. Peak discharges recorded by continuous slope-area streamgage in Agua Fria near Rock Springs, Arizona.

Date	Discharge, in cubic feet per second	Annual exceedance probability, in years-1	Recurrence interval, in years
July 29, 2006	2,033	0.49	2.06
December 1, 2007	2,559	0.44	2.29
December 7, 2007	2,769	0.42	2.38
January 7, 2008	4,376	0.33	3.07
January 27, 2008	14,648	0.11	9.39
December 26, 2008	3,559	0.37	2.71
July 14, 2012	2,221	0.47	2.14

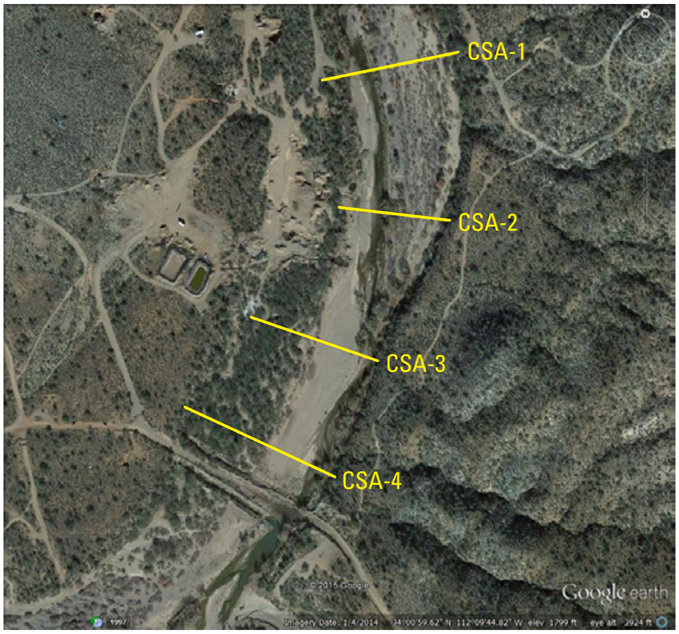

Figure 10. Aerial view of the Agua Fria near Rock Springs, Arizona, continuous slope-area (CSA) reach. The cross sections are shown in yellow. Flow is from top to bottom. The image is from Google Earth and was taken January 4, 2014.

Figure 11. Overview of the Agua Fria near Rock Springs, Arizona, continuous slope-area reach, February 4, 2010.

Figure 12. Cross section 1 in the Agua Fria near Rock Springs, Arizona, continuous slope-area reach, February 4, 2010.

Figure 13. Cross section 2 in the Agua Fria near Rock Springs, Arizona, continuous slope-area reach, February 4, 2010.

Figure 14. Cross section 3 in the Agua Fria near Rock Springs, Arizona, continuous slope-area reach, February 4, 2010.

Figure 15. Cross section 4 in the Agua Fria near Rock Springs, Arizona, continuous slope-area reach, February 4, 2010.

Centennial Wash at Southern Pacific Railroad Bridge near Arlington, Arizona

Station number: 09517490
CSA installed: November 10, 2004
Reach location: lat 33°18’17” N., long 112°52’35” W.
Reach length: 813 ft
Basin characteristics:
Drainage area: 1,690 mi^2
Mean basin elevation: 1,860 ft asl
Mean annual precipitation: 8.9 in.
Streamflow statistics region: 2

Channel description:

Centennial Wash is a wide, flat, low-relief channel bounded by well-defined banks about 10–15 ft high. Vegetation is sparse in the main channel but more dense along the channel sides. High flows can scour out vegetation in the main part of the channel. Bed material ranges from fine sand to pebbles.

Remarks:

A discharge measurement of 393 ft^3/s was used to calibrate lower *n* at that discharge. The *nd* parameter was used in SAC to vary *n* with hydraulic depth. Only two stage PTs operated during the November 28, 2008, flow.

Table 3. Centennial Wash at Southern Pacific Railroad Bridge near Arlington, Arizona peak streamflow statistics.

Annual exceedance probability, in years^{-1}	0.2	0.1	0.04	0.02	0.01	0.005	0.002
Recurrance interval, in years	5	10	25	50	100	200	500
Discharge, in cubic feet per second	7,418	12,144	22,040	32,899	45,937	58,146	85,489

Table 4. Peak discharges recorded by continuous slope-area streamgage in Centennial Wash at Southern Pacific Railroad Bridge near Arlington, Arizona.

Date	Discharge, in cubic feet per second	Annual exceedance probability, in years-1	Recurrence interval, in years
November 12, 2004	925	>0.5	<2
August 10, 2006	948	>0.5	<2
July 26, 2007	1,510	>0.5	<2
August 26, 2008	696	>0.5	<2
November 28, 2008	1,100	>0.5	<2
January 21, 2010	6,866	0.26	3.8
July 6, 2011	4,991	0.31	3.2
August 24, 2012	7,460	0.2	5.0

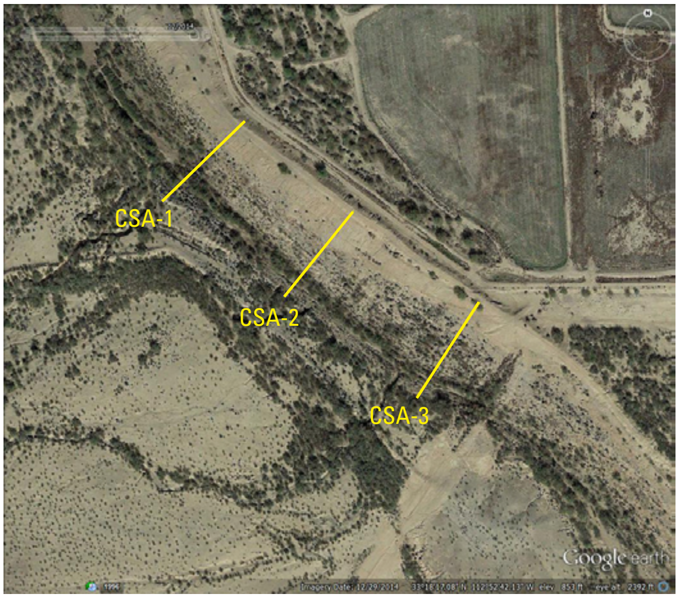

Figure 16. Aerial view of the Centennial Wash at Southern Pacific Railroad Bridge near Arlington, Arizona, continuous slope-area (CSA) reach. Cross sections are shown in yellow. Flow is from upper left to lower right. The image is from Google Earth and was taken December 29, 2014.

Figure 17. Cross section 1 in the Centennial Wash at Southern Pacific Railroad Bridge near Arlington, Arizona, July 1, 2009.

Figure 18. Cross section 2 in the Centennial Wash at Southern Pacific Railroad Bridge near Arlington, Arizona, July 1, 2009.

Figure 19. Cross section 3 in the Centennial Wash at Southern Pacific Railroad Bridge near Arlington, Arizona, July 1, 2009.

Deadman Wash near New River, Arizona

Station number: 09513820
CSA installed: August 13, 2004
Reach location: lat 33°50’12” N., long 112°08’45” W.
Reach length: 426 ft
Basin characteristics:
Drainage area: 13.8 mi^2
Mean basin elevation: 1,950 ft asl
Mean annual precipitation: 12.9 in.
Streamflow statistics region: 2

Channel description:

Bed material in Deadman Wash is poorly sorted and ranges up to small boulders in size. The bed is irregularly shaped with pools and riffles at low flow. Vegetation in the main channel is primarily low grasses, but large mature vegetation contributes significantly to roughness along the channel banks.

Remarks:

Crest-stage gage only used at this station.

Table 5. Deadman Wash near New River, Arizona, peak streamflow statistics.

Annual exceedance probability, in years^{-1}	0.2	0.1	0.04	0.02	0.01	0.005	0.002
Recurrance interval, in years	5	10	25	50	100	200	500
Discharge, in cubic feet per second	1,365	2,123	3,030	4,331	5,813	7,758	11,072

Table 6. Peak discharges recorded by continuous slope-area streamgage in Deadman Wash near New River, Arizona.

Date	Discharge, in cubic feet per second	Annual exceedance probability, in years-1	Recurrence interval, in years
December 1, 2007	692	0.42	2.4
January 27, 2008	361	>0.5	<2
January 21, 2010	1,489	0.18	5.5

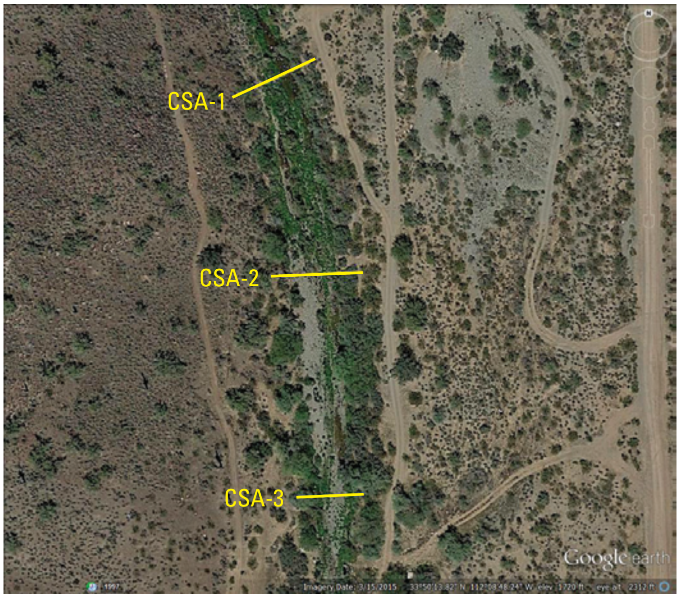

Figure 20. Aerial view of the Deadman Wash near New River, Arizona, continuous slope-area (CSA) reach. Cross sections are shown in yellow. Flow is from top to bottom. Image is from Google Earth and was taken March 15, 2015.

Figure 21. Overview of Deadman Wash near New River, Arizona, continuous slope-area reach, February 17, 2010.

Figure 22. Cross section 1 in the Deadman Wash near New River, Arizona, continuous slope-area reach, February 17, 2010.

Figure 23. Cross section 2 in the Deadman Wash near New River, Arizona, continuous slope-area reach, February 17, 2010.

Figure 24. Cross section 3 in the Deadman Wash near New River, Arizona, continuous slope-area reach, February 17, 2010.

Delaney Wash near Tonopah, Arizona

Station number: 09517430
CSA installed: May 24, 2012
Reach location: lat 33°28’08” N., long 112°58’02” W.
Reach length: 466 ft
Basin characteristics:
Drainage area: 49.9 mi^2
Mean basin elevation: 1,710 ft asl
Mean annual precipitation: 8.7 in.
Streamflow statistics region: 2

Channel description:

The channel bed consists of poorly sorted, loose sediment ranging from coarse sand to pebbles. The channel bed was flat at the time of streamgage installation, with no apparent bedforms or scour depressions. The banks are generally steep, consist of cohesive material, and are lined with dense bushes that grow on the banks or hang over the banks. The streamgage reach is slightly curved. The hydraulic control in the reach is the channel. The FCDMC operates an ALERT gage at the site. This site is also being used to test telemetry of CSA data to the FCDMC offices for real-time CSA discharge data.

Remarks:

The Delany Wash reach is the first CSA streamgage to incorporate telemetry. The telemetry system was designed and installed by the Flood Control District of Maricopa County. The USGS has supplied a version of the analysis software that is compatible with the FCDMC system, and the site will be used to test and develop real-time reporting of discharges at CSA streamgages.

Table 7. Peak streamflow statistics in Delaney Wash, Arizona.

Annual exceedance probability, in years^{-1}	0.2	0.1	0.04	0.02	0.01	0.005	0.002
Recurrance interval, in years	5	10	25	50	100	200	500
Discharge, in cubic feet per second	1,408	2,356	3,847	5,605	7,610	9,755	13,681

Table 8. Peak discharges recorded by continuous slope-area streamgage in Delaney Wash, Arizona.

Date	Discharge, in cubic feet per second	Annual exceedance probability, in years-1	Recurrence interval, in years
August 22, 2012	314	>0.5	<2

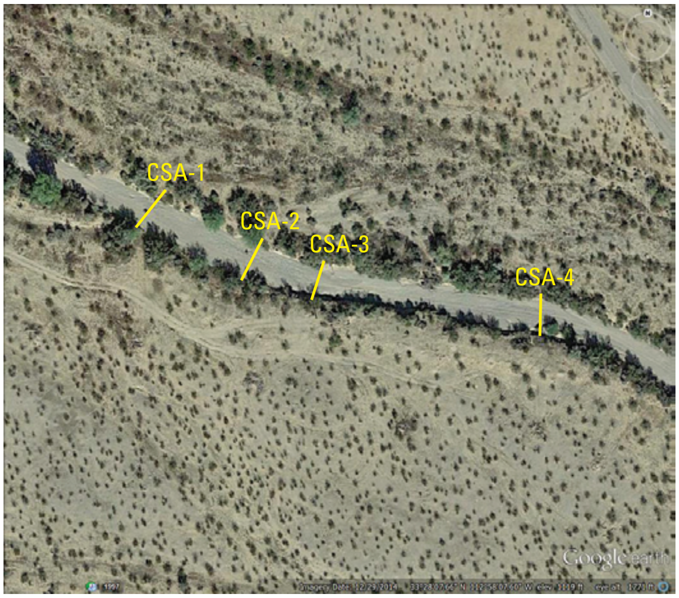

Figure 25. Aerial view of the Delaney Wash, Arizona, continuous slope-area (CSA) reach. The cross sections are shown in yellow. Flow is from left to right. Image is from Google Earth and was taken December 29, 2014.

Figure 26. Overview of the Delaney Wash, Arizona, continuous slope-area reach.

Figure 27. Looking downstream in the Delaney Wash, Arizona, continuous slope-area reach upstream of cross section 3. The USGS crest-stage gage and stage pressure transducer are on the left bank, and the Flood Control District of Maricopa County stage sensor is on the right bank.

Hassayampa River near Arlington, Arizona

Station number: 09517000
CSA installed: July 11, 2007
Reach location: lat 33°20'30" N., long 112°43'03" W.
Reach length: 855 ft
Basin characteristics:
Drainage area: 1,420 mi^2
Mean basin elevation: 2,900 ft asl
Mean annual precipitation: 14.0 in.
Streamflow statistics region: 2

Channel description:

The Hassayampa River near Arlington consists of a deep, narrow, and well-defined low-flow channel and an overbank channel that is constrained by well-defined banks about 10 ft high. The low-flow channel has dense, mature vegetation growing along its entire length. The overbank area is flat, with grasses and sparse, bushy vegetation. Surface sediment is primarily medium sand.

Remarks:

Flows on January 28, 2008, and August 29, 2008, were not recorded by the CSA streamgage. The flow on January 26, 2010, significantly altered the channel and buried the PTs. The channel was regraded with heavy machinery before it could be resurveyed. Cross sections surveyed on July 8, 2009, were used to compute discharge.

Table 9. Hassayampa River near Arlington, Arizona, peak streamflow statistics.

Annual exceedance probability, in years^{-1}	0.2	0.1	0.04	0.02	0.01	0.005	0.002
Recurrance interval, in years	5	10	25	50	100	200	500
Discharge, in cubic feet per second	9,978	16,499	32,003	47,148	65,651	86,653	132,274

Table 10. Peak discharges recorded by continuous slope-area streamgage in Hassayampa River near Arlington, Arizona.

Date	Discharge, in cubic feet per second	Annual exceedance probability, in years-1	Recurrence interval, in years
January 22, 2010	6,025	0.33	3.0

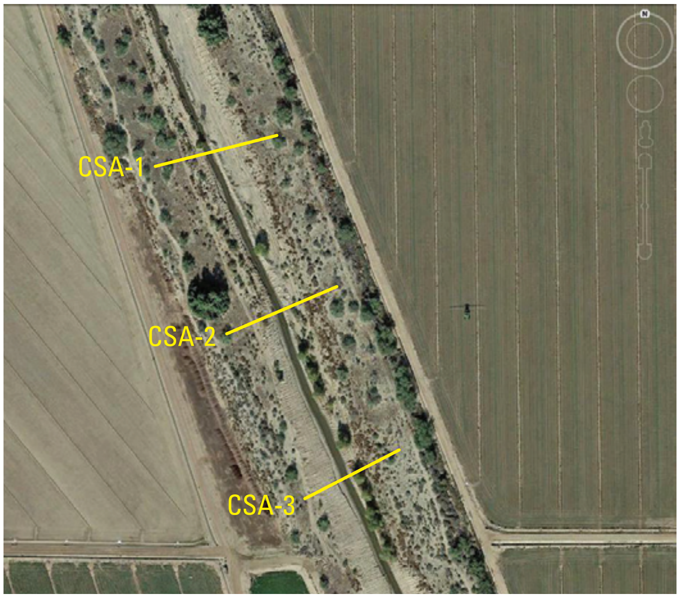

Figure 28. Aerial view of the Hassayampa River near Arlington, Arizona, continuous slope-area (CSA) reach. Cross sections are shown in yellow. Flow is from upper left to lower right. Image is from Google Earth and was taken December 29, 2014.

Figure 29. Cross section 1 in the Hassayampa River near Arlington, Arizona, continuous slope-area reach, July 9, 2009.

Figure 30. Cross section 2 in the Hassayampa River near Arlington, Arizona, continuous slope-area reach, July 9, 2009.

Figure 31. Cross section 3 in the Hassayampa River near Arlington, Arizona, continuous slope-area reach, July 9, 2009.

New River near Rock Springs, Arizona

Station number: 09513780
CSA installed: June 23, 2006
Reach location: lat 33°58’30” N., long 112°05’43” W.
Reach length: 650 ft
Basin characteristics:
Drainage area: 68.2 mi^2
Mean basin elevation: 3,970 ft asl
Mean annual precipitation: 20.8 in.
Streamflow statistics region: 2

Channel description:

The New River near Rock Springs reach is confined between well-defined hillslopes. The bed consists of bouldery gravel with patches of medium sand. No vegetation grows in the main channel. The banks are lined with mature vegetation or consist of steep bedrock.

Remarks:

A Manning *n* of 0.031 was calculated using direct discharge measurement on December 23, 2010, at 11:55 a.m. Only two PTs were operating during the flows on December 1, 2007, December 7, 2008, and December 27, 2008.

Table 11. New River near Rock Springs, Arizona, peak streamflow statistics.

Annual exceedance probability, in $years^{-1}$	0.2	0.1	0.04	0.02	0.01	0.005	0.002
Recurrance interval, in years	5	10	25	50	100	200	500
Discharge, in cubic feet per second	3,006	5,305	10,717	15,299	20,767	28,752	43,669

Table 12. Peak discharges recorded by continuous slope-area streamgage in New River near Rock Springs, Arizona.

Date	Discharge, in cubic feet per second	Annual exceedance probability, in years-1	Recurrence interval, in years
July 30, 2006	990	0.47	2.2
August 24, 2006	1,891	0.31	3.2
September 7, 2006	1,642	0.34	2.9
December 1, 2007	4,607	0.12	8.0
December 7, 2007	1,804	0.32	3.1
January 7, 2008	1,703	0.34	3.0
January 27, 2008	4,959	0.11	8.9
December 25, 2008	2,969	0.20	4.9

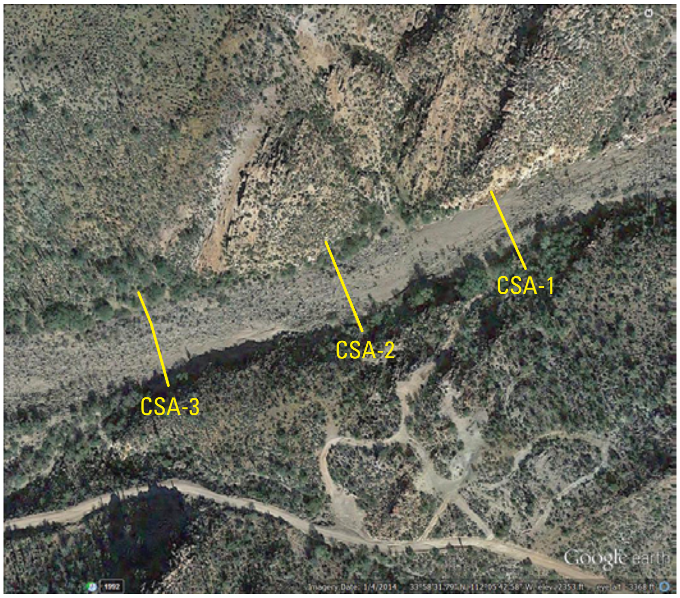

Figure 32. Aerial view of the New River near Rock Springs, Arizona, continuous slope-area (CSA) reach. Cross sections are shown in yellow. Flow is from right to left. Image is from Google Earth and was taken January 4, 2014.

Figure 33. Overview of the New River near Rock Springs, Arizona, continuous slope-area reach, February 9, 2010.

Figure 35. Cross section 2 in the New River near Rock Springs, Arizona, continuous slope-area reach, February 9, 2010.

Figure 34. Cross section 1 in the New River Rock Springs, Arizona, continuous slope-area reach, February 9, 2010.

Figure 36. Cross section 3 in the New River near Rock Springs, Arizona, continuous slope-area reach, February 9, 2010.

Skunk Creek near Phoenix, Arizona

Station number: 09513860
CSA installed: August 13, 2004
Reach location: lat 33°43’57” N., long 112°06’57” W.
Reach length: 512 ft
Basin characteristics:
Drainage area: 65 mi^2
Mean basin elevation: 2,240 ft asl
Mean annual precipitation: 13.9 in.
Streamflow statistics region: 2

Channel description:

Skunk Creek is a wide, flat, poorly defined channel. Sparse vegetation grows over the entire channel. Bed sediment is variable, consisting of patches of pebbles and sand. During the September 9, 2006, flow, only two PTs were operating.

Remarks:

Flow occurred on August 23, 2012, but was too low for CSA streamgages to detect.

Table 13. Skunk Creek near Phoenix, Arizona, peak streamflow statistics.

Annual exceedance probability, in years^{-1}	0.2	0.1	0.04	0.02	0.01	0.005	0.002
Recurrance interval, in years	5	10	25	50	100	200	500
Discharge, in cubic feet per second	2,916	4,544	6,989	10,079	13,693	18,286	26,799

Table 14. Peak discharges recorded by continuous slope-area streamgage in Skunk Creek near Phoenix, Arizona.

Date	Discharge, in cubic feet per second	Annual exceedance probability, in years-1	Recurrence interval, in years
January 26, 2005	547	>0.5	<2
February 12, 2005	490	>0.5	<2
February 17, 2005	437	>0.5	<2
September 9, 2006	774	>0.5	<2
December 1, 2007	2,093	0.30	3.3
January 20, 2010	5,053	0.09	11.74
July 21, 2012	769	>0.5	<2

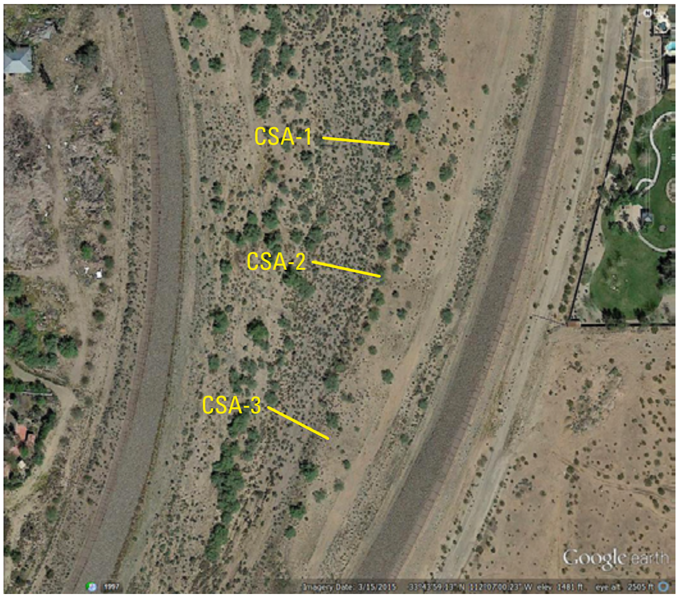

Figure 37. Aerial view of the Skunk Creek near Phoenix, Arizona, continuous slope-area (CSA) reach. Cross sections are shown in yellow. Flow is from top to bottom. Image is from Google Earth and was taken March 15, 2015.

Figure 38. Cross section 1 in the Skunk Creek near Phoenix, Arizona, continuous slope-area reach, July 27, 2012.

Figure 39. Cross section 2 in the Skunk Creek near Phoenix, Arizona, continuous slope-area reach, July 27, 2012.

Figure 40. Cross section 3 in the Skunk Creek near Phoenix, Arizona, continuous slope-area reach, July 27, 2012.

Tiger Wash near Aguila, Arizona

Station number: 09517280
CSA installed: June 22, 2006
Reach location: lat 33°44’27” N., long 113°16’47” W.
Reach length: 537 ft
Basin characteristics:
Drainage area: 84.7 mi^2
Mean basin elevation: 2,570 ft asl
Mean annual precipitation: 10.6 in.
Streamflow statistics region: 2

Channel description:

The main conveyance in Tiger Wash is a wide, flat main channel with a steep rock wall along river left, and a flat, mildly sloping right bank. The main channel sediment is patchy sand and pebbly gravel. Vegetation in the channel has been sparse, but dense mature vegetation lines the banks and extends overbank along river right.

Remarks:

Comparisons of CSA peaks and CSG peaks indicate drawdown occurred in CSA streamgages during the July 14, 2012, event. Correction as described above applied to CSA stage records.

Table 15. Tiger Wash near Aguila, Arizona, peak streamflow statistics.

Annual exceedance probability, in years^{-1}	0.2	0.1	0.04	0.02	0.01	0.005	0.002
Recurrance interval, in years	5	10	25	50	100	200	500
Discharge, in cubic feet per second	1,806	3,203	6,067	8,826	12,026	15,657	22,489

Table 16. Peak discharges recorded by continuous slope-area streamgage in Tiger Wash near Aguila, Arizona.

Date	Discharge, in cubic feet per second	Annual exceedance probability, in years-1	Recurrence interval, in years
July 25, 2006	348	>0.5	<2
July 22, 2007	1,523	0.24	4.1
November 27, 2008	1,017	0.35	2.9
September 5, 2009	2,571	0.14	7.2
July 13, 2012	3,039	0.11	9.2

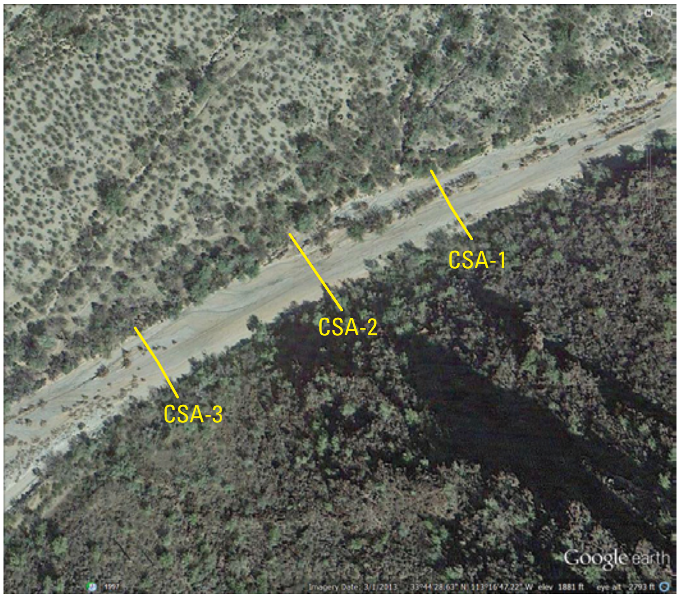

Figure 41. Aerial view of the Tiger Wash near Aguila, Arizona, continuous slope-area (CSA) reach. Cross sections are shown in yellow. Flow is from right to left. Image is from Google Earth and was taken March 1, 2013.

Figure 42. Continuous slope-area reach in Tiger Wash near Aguila, Arizona, September 10, 2009. View is looking downstream.

Figure 44. Cross section 2 in the Tiger Wash near Aguila, Arizona, continuous slope-area reach, September 10, 2009.

Figure 43. Cross section 1 in the Tiger Wash near Aguila, Arizona, continuous slope-area reach, September 10, 2009.

Figure 45. Cross section 3 in the Tiger Wash near Aguila, Arizona, continuous slope-area reach, September 10, 2009.

Vekol Wash near Stanfield, Arizona

Station number: 09488650
CSA installed: July 29, 2004
Reach location: lat 32°50’45” N., long 112°15’04” W.
Reach length: 1,050 ft
Basin characteristics:
Drainage area: 148 mi^2
Mean basin elevation: 2,260 ft asl
Mean annual precipitation: 10.0 in.
Streamflow statistics region: 2

Channel description:

The channel bed is primarily unconsolidated, angular pebbles and pea-gravel with sand in the interstices. No vegetation grows in the channel bottom but lines the banks the entire reach. The channel bottom is flat and is used by off road vehicles. The channel bends mildly to the right. There are no apparent section controls, and the channel appears to be the control. The overbank area has a very low slope.

Remarks:

Crest-stage gage only used at this station.

Table 17. Vekol Wash near Stanfield, Arizona, peak streamflow statistics.

Annual exceedance probability, in years^{-1}	0.2	0.1	0.04	0.02	0.01	0.005	0.002
Recurrance interval, in years	5	10	25	50	100	200	500
Discharge, in cubic feet per second	3,558	5,287	8,606	11,477	14,843	18,802	25,062

Table 18. Peak discharges recorded by continuous slope-area streamgage in Vekol Wash near Stanfield, Arizona.

Date	Discharge, in cubic feet per second	Annual exceedance probability, in years-1	Recurrence interval, in years
July 23, 2005	1,748	0.26	3.9
August 10, 2005	2,488	0.32	3.1
July 24, 2007	1,410	>0.5	<2
May 22, 2008	2,215	0.36	2.7
July 3, 2009	3,875	0.18	5.6
August 27, 2010	8,903	0.04	26.6

Figure 46. Aerial view of the Vekol Wash near Stanfield, Arizona, continuous slope-area (CSA) reach. Cross sections are shown in yellow. Flow is from bottom to top. Image is from Google Earth and was taken August 29, 2014.

Figure 47. Cross section 1 in the Vekol Wash near Stanfield, Arizona, continuous slope-area reach, July 26, 2005.

Figure 48. Cross section 2 in the Vekol Wash near Stanfield, Arizona, continuous slope-area reach, July 26, 2005.

Figure 49. Cross section 3 in the Vekol Wash near Stanfield, Arizona, continuous slope-area reach, July 26, 2005.

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