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Annual and Approximately Quarterly Series Peak Streamflow Derived From Interpretations of Indirect Measurements for a Crest-Stage Gage Network in Texas Through Water Year 2015

Scientific Investigations Report 2018–5107

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

Cover, U.S. Geological Survey crest-stage gage 07307550 Wind River tributary at Farm to Market 656 near Northfield, Texas, looking downstream, May 24, 2014 (photograph by W.H. Asquith).

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RYAN K. ZINKE, Secretary

U.S. Geological Survey
James F. Reilly II, Director

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square inch (in^2)	6.452	square centimeter (cm^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
mile per hour (mi/h)	1.609	kilometer per hour (km/h)

Datum

For the crest-stage gage network, the vertical datum is local and not referenced to any geoid datums of the Earth such as the North American Vertical Datum of 1988 (NAVD 88) because such a vertical reference does not add pertinent information to computations or interpretations. For some of the reactivated stations, there is a datum in the U.S. Geological Survey National Water Information System peak-streamflow database (U.S. Geological Survey, 2018a), but the stored value presumably exists prior to NAVD 88.

Symbols and Descriptions

d_c	maximum depth in critical-flow section; units of feet
d_i	depth in ith section; units of feet
g	gravitational constant (acceleration); units of feet per square second
h_i	static or piezometric head above an arbitrary datum of section i; units of feet
h_c	$d_c + z$ for type 1 culvert flow; units of feet
h_f	energy loss attributable to boundary friction in the reach
h_{vi}	velocity head at a section at the ith cross section, $h_{vi} = \alpha_i V^2/(2g)$; units of feet
Δh	difference in water-surface elevations at the two sections
$hf_{i\text{–}j}$	head loss attributable to friction between the ith and jth section; units of feet
i and j	a counter used to indicate cross section number
k and $k_{i\text{–}j}$	a coefficient for expansion energy losses between cross sections 1 and 2 or between cross sections i and j
n^2	the square of Manning's roughness coefficient; units of one-sixth foot (fig. 2, submerged outlet calculation)
n	a counter used to indicate nth cross section number (same as number of cross sections, fig. 3) and not Manning's roughness coefficient referred to as Manning's n value (see also K_i in this list, fig. 3)
z	elevation of a section above an arbitrary datum; units of feet
A_0	area of culvert barrel; units of square feet
A_c	area of section of flow at critical depth; units of square feet
A_i	cross-sectional area of ith cross section of the channel reach; units of square feet
C	coefficient of discharge based on various culvert properties
D	maximum inside vertical dimension of culvert barrel, the inside diameter of a circular section, or for corrugated metal pipes, D measured as the minimum inside diameter; units of feet
K_i	conveyance of the ith cross section, $K = 1.486/n\,A\,R^{2/3}$ based on the dimensionless Manning's roughness coefficient (Manning's n value) that is abbreviated as n in this definition but is not the counter n described elsewhere in this list, cross-section area (A), and hydraulic radius (R); units of cubic feet per second
L	length of culvert barrel; units of feet (fig. 2)
L and $L_{i\text{–}j}$	length in direction of streamflow of channel reach or length of section i to section j; units of feet (fig. 3)
L_w	distance from approach section to culvert entrance or upstream side of contraction; units of feet
Q	peak streamflow; units of cubic feet per second
R_o	hydraulic radius of a culvert barrel computed as cross-section area divided by wetted perimeter of full culvert barrel; units of feet
S_c	critical slope for open channel flow; dimensionless (feet per feet)
S_0	bed slope of culvert barrel; dimensionless (feet per feet)
V_i	mean velocity of streamflow in the ith section; units of feet per second
α	velocity-head coefficient; dimensionless
α_i	velocity-head coefficient at the ith section; dimensionless
$<$	relational operator: less than
$\leq$	relational operator: equal to or less than
$>$	relational operator: greater than
$\geq$	relational operator: equal to or greater than
S and T	two terms used to simplify algebra

Annual and Approximately Quarterly Series Peak Streamflow Derived From Interpretations of Indirect Measurements for a Crest-Stage Gage Network in Texas Through Water Year 2015

By William H. Asquith, Glenn R. Harwell, and Karl E. Winters

Abstract

In 2006, the U.S. Geological Survey (USGS), in cooperation with the Texas Department of Transportation, began collecting annual and approximately quarterly series peak-streamflow data at streamflow-gaging stations in small- to medium-sized watersheds in central and western Texas as part of a crest-stage gage (CSG) network, along with selected flood-hydrograph data at a subset of these stations. CSGs record the peak stage during storm events, which is the maximum gage height (elevation of water surface above a local vertical datum), at each CSG station. Established and widely used indirect methods of peak streamflow estimation and interpretation, such as culvert-flow, slope-area, and flow-over-road methods, are used in conjunction with peak gage height data to create the database of peak streamflow described herein. The CSG network is focused on hydrology of small- to medium-sized watersheds in central and western Texas because additional streamflow data for this semiarid to arid study area will eventually provide for more statistical information and presumably reduced uncertainty in regional regression equations or other regionalized statistical methods for peak-streamflow frequency estimation at ungaged locations. The database of annual and approximately quarterly peak streamflow is published through USGS ScienceBase and described in this report.

Introduction

Estimates of annual peak-streamflow frequency are needed for flood-plain management, assessment of flood risk (Kite, 1988; National Research Council, 2000), and design of structures, such as roads, bridges, culverts, and other water-conveyance structures. Annual peak (annual maximum instantaneous peak streamflow) data can form the basis of statistical methods for such frequency estimates (Interagency Advisory Committee on Water Data, 1982; Stedinger and others, 1993; Veilleux and others, 2014). In addition to annual peak streamflows, estimates of peak streamflow on a more frequent basis such as quarterly peak streamflow (if nonzero) are also useful for flood-plain management, assessment of flood risk, and other statistical assessments.

Regional regression equations for Texas have been developed and are used extensively to estimate annual peak-streamflow frequency of various annual exceedance probabilities for ungaged sites in natural (unregulated and rural or otherwise nonurbanized) watersheds (Schroeder and Massey, 1977; Asquith and Slade, 1997; Asquith, 1998, 2001; Asquith and Thompson, 2008; Asquith and Roussel, 2009). The most refined regional regression equations to date (currently, 2018) for Texas by Asquith and Roussel (2009) are based on frequency analysis of annual peak-streamflow data from 638 U.S. Geological Survey (USGS) streamflow-gaging stations with 8 years or more of data. Those equations include contributing drainage area, channel slope, and mean annual precipitation as predictor variables.

Historical streamflow data from small- to medium-sized (less than a square mile to about a few hundred square miles) rural watersheds in certain parts of Texas are spatially and temporally sparse. Substantial uncertainty, therefore, exists when regional regression equations are used to estimate annual peak-streamflow frequency at ungaged or unmonitored stream crossings, as is often required for culvert design (Schall and others, 2012). A culvert is a self-supporting structure embedded into roadway embankments that allows water to flow under a roadway. A culvert is typically made of corrugated-metal pipe or reinforced concrete. Culverts composed of one or more barrels are one of the most common structures used to convey water under a roadway; the barrels are generally circular or rectangular.

To address the need for additional peak-streamflow-related data, in 2006, the USGS, in cooperation with the Texas Department of Transportation (TxDOT), began collecting annual and approximately quarterly series peak-streamflow data at streamflow-gaging stations in central and western Texas as part of a crest-stage gage (CSG) network, along with selected flood-hydrograph data at a subset of these stations. The network is focused on hydrology of small- to medium-sized watersheds in central and western Texas because additional streamflow data for this semiarid to arid study area will eventually provide for more statistical information and presumably reduced uncertainty in regional regression equations or other regionalized statistical methods for peak-streamflow frequency estimation at ungaged locations.

The objective of the CSG network based on field-acquired data and analyst interpretation is to quantitatively assign a peak-streamflow magnitude to each peak gage height preserved by the deployed CSGs. For the CSG network, interpretations can lead to zero or other thresholds of streamflow for minimum (or possibly maximum) observable streamflow magnitude. Such minimums can be either (1) constant (immutable) values that are set by the constraints of CSG placement (optimal or otherwise) and station-specific hydraulic features or (2) varying (mutable) values because of a combination of event-specific incomplete or missing field data, CSG placement, and station-specific hydraulic features.

The study area consists of a large part of central and western Texas; the locations of the 51 active CSG stations in operation as of September 30, 2015, are shown in figure 1, along with the location of station 08117990, which was discontinued on September 30, 2012. All of the stations that have been operated as part of the CSG network, including the discontinued station, and ancillary information are listed in table 1.

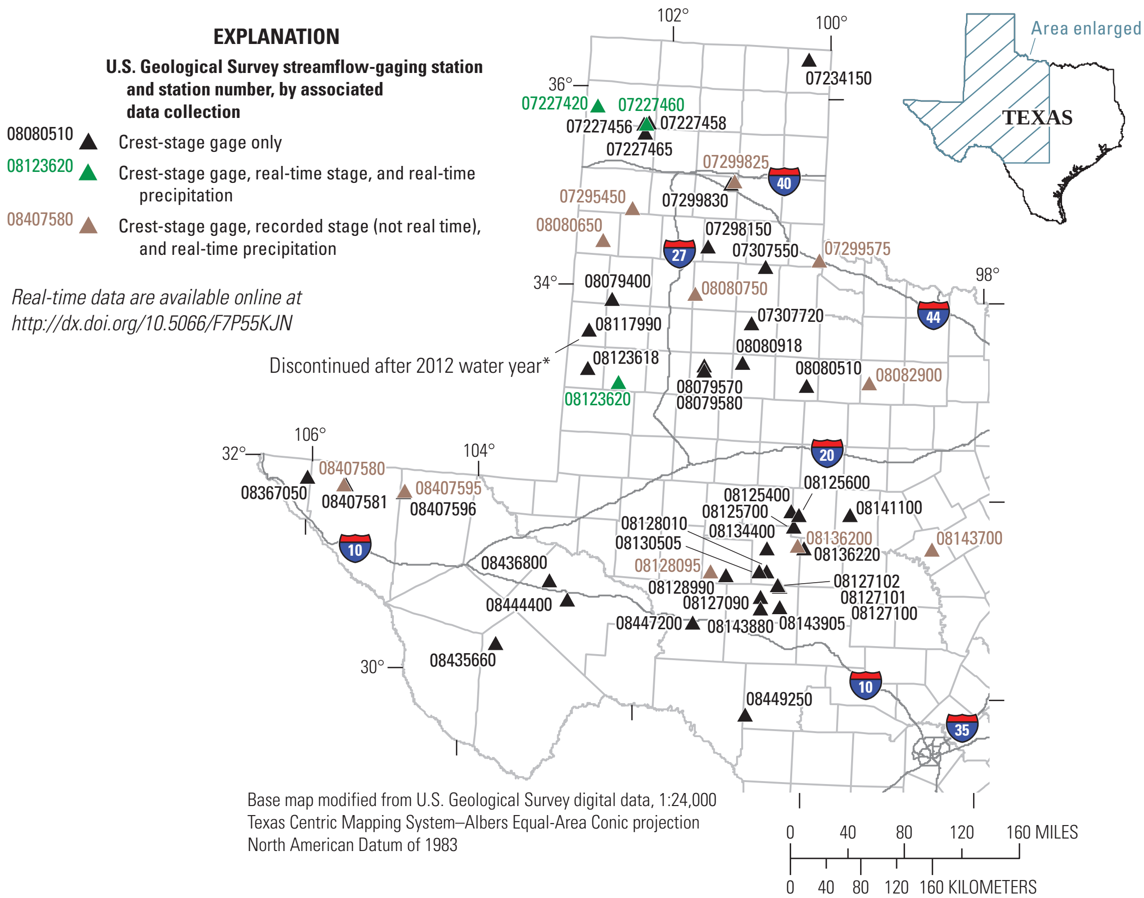
The contributing drainage areas of the 51 active stations where annual and approximately quarterly series peak-streamflow data are collected in central and western Texas range from 0.002 to 194 square miles (mi^2). The mean contributing drainage area for the stations is 12.5 mi^2, and the median area is 1.09 mi^2. The contributing areas are larger than 15 mi^2 at five of the stations: 07227420, 07295450, 08080650, 08080918, and 08123620 (table 1).

Peak-streamflow data were primarily collected from CSG stations, which record one or more peak stages (maximum gage heights) at unique locations proximal to a culvert during runoff from storm events. For this study, the peak gage height is the water-surface elevation of the stream above a local vertical reference datum. A CSG station represents a unique class of streamflow-gaging stations that passively preserves the peak gage height for the largest rise during storm events between service trips. The primary purpose of the CSG station is to record peak gage height—hydraulic methods are used to compute or estimate peak streamflow. The annual peak-streamflow data represent a subset of the approximately quarterly series data; the annual peak-streamflow data represent the highest streamflow recorded by the approximately quarterly data collected each water year. A water year is defined as the 12-month period between October 1 and September 30. The water year is designated by the calendar year in which it ends, and thus, the year ending September 30, 2015, is referred to as the “2015 water year.” The CSG stations are visited on an approximately quarterly basis; that is, about every 3 months throughout the year. Ideally, hydrographers would visit the CSG stations following unique storm events to manually measure the peak gage height and reset the CSG for the next storm event, but this is not feasible given the vast area represented by the CSG network and available hydrographers.

The use of CSG stations for streamflow monitoring is described by Buchanan and Somers (1968, p. 27–28), Sauer (2001), and Sauer and Turnipseed (2010, p. 17–18). Office-based computations and interpretations leading to peak-streamflow estimates from the peak gage heights are required. Harwell and Asquith (2011) described the background and provided a synopsis of the methods and typical operating procedures used within the CSG network (fig. 1). The use of passively functioning CSGs provides for “opportunistic collection of hydrologic [sic] extreme events [that] is a high-return, cost-effective activity, well suited to both the mission and expertise of USGS” (National Research Council, 2004, p. 6). CSGs also contribute to an “alternative paradigm of collecting slightly less accurate information at more geographic sites” (National Research Council, 1999, p. 27).

Data obtained from the CSG network in Texas provide streamflow information where continuous streamflow-gaging stations are scarce. The CSG network characterizes streamflow on relatively small watersheds in arid to semiarid parts of Texas (Larkin and Bomar, 1983) with few perennial streams. The durations of direct runoff events from substantial storms are miniscule compared to total operational times at each of the CSG stations. Given the highly ephemeral nature of streams in the study area, the CSG network provides for a representative count of stations with moderate operational costs compared to continuous streamflow-gaging stations. The stations of the CSG network are a subset of the multipurpose and greater USGS streamflow-monitoring network in Texas (U.S. Geological Survey, 2016a). The CSG network serves the collection of annual peak data, but other stations in Texas are purposed to collect annual streamflow volumes, which are useful in water-supply studies including assessments of droughts (Winters, 2013).

The National Research Council (1999, p. 27) raises the topic of streamflow accuracy at CSG stations. The CSG network is exclusively reliant on indirect methods (postevent hydraulic modeling) of peak-streamflow measurement. Compared to direct measurements of streamflow (Turnipseed and Sauer, 2010), the peak-streamflow estimates from indirect measurements described in this report have more uncertainty or inherent error because of the errors in measurement of peak gage heights, missing data, uncertain field conditions, velocity head (energy gain) and approach energy losses, and energy losses within culvert barrels or channel reaches (Carter, 1957; Jenkins, 1963; Barnes, 1967; Benson and Dalrymple, 1967; Dalrymple and Benson, 1967; Hulsing, 1967; Bodhaine, 1968), and extensive use of inequalities or intervals in the USGS-National Water Information System (NWIS) peak-streamflow database (U.S. Geological Survey, 2018a). The benefits of acquiring slightly less accurate peak-streamflow information at a number of geographic sites in the study area outweigh the inherent shortcomings of indirect measurement methods, and for the intended use of the data, the reduced accuracy relative to the greater USGS streamflow-monitoring network is acceptable.



* A water year is defined as the 12-month period between October 1 and September 30. The water year is designated by the calendar year in which it ends, and thus, the year ending September 30, 2015, is referred to as "2015 water year."

Figure 1. Locations of the 51 active and 1 discontinued U.S. Geological Survey streamflow-gaging stations in the crest-stage gage network in Texas and associated data collection during water year 2015.

Crest-Stage Gage Network Status and Description of Interpretive Data as of September 30, 2015

In the current (2018) CSG network, 13 of the 51 active stations were operating as flood-hydrograph stations as of September 30, 2015. This report provides a summary of data (Asquith and Harwell, 2018—a companion publication to this study) and operations through the 2015 water year for both the (1) current CSG network since initiation in 2006 and (2) historical CSG data collected prior to 2006. The distinctions between CSG-only stations and flood-hydrograph stations are as follows:

1. CSG-only stations are one of the simplest types of streamflow stations. The characteristic structures for these stations are two or more vertical end-threaded pipes with bottom inlets and a top vent. Measuring sticks inserted into the pipes, along with floatable granulated cork at the bottom of the stick, are used to record high-water marks. Removable caps that thread onto the bottom and top of the pipe restrain the stick. The stick and cork passively preserve peak gage height between station visits, and passively means that there is no recording equipment required. CSG equipment is cost effective and reliable. Although CSG-only stations are relatively simple to operate, the interpretation of CSG-derived peak gage heights to compute peak streamflow can be challenging.

2. Flood-hydrograph stations have CSGs and pressure transducers to record gage height during runoff events on ephemeral streams. As of September 30, 2015, most stations require visits to manually download gage height data, but all of the flood-hydrograph stations had a nearby logging and transmitting rain gage on 1-hour satellite telemetry. The flood-hydrograph stations provide cost-effective time series data at risk of partial data loss between station visits.

Table 1. Summary of the 51 active and 1 discontinued U.S. Geological Survey streamflow-gaging stations in the crest-stage gage network in Texas.

[mi², square mile; SH, State Highway; FM, Farm to Market road; No., number]

Station number	Station name	Latitude (decimal degrees)	Longitude (decimal degrees)	Contributing drainage area (mi²)	Station operated as a flood-hydrograph station[1]	Station with precipitation data[2]
07227420	Cramer Creek at U.S. Highway 54 near Dalhart, Tex.	35.7514	102.8931	94.7	**Yes**	**Yes**
07227456	Middle Cheyenne Creek at SH 354 near Channing, Tex.	35.6736	102.3081	2.96	no	no
07227458	East Cheyenne Creek at SH 354 near Channing, Tex.	35.6917	102.2486	1.71	no	no
07227460	East Fork Cheyenne Creek Tributary near Channing, Tex.	35.6750	102.2808	1.60	Yes	**Yes**
07227465	East Cheyenne Creek Tributary at U.S. Highway 385 near Boys Ranch, Tex.	35.5825	102.2847	0.04	no	no
07234150	White Woman Creek Tributary near Darrouzett, Tex.	36.4028	100.2761	4.03	Yes	Yes
07295450	Tierra Blanca Creek at FM 1259 at Hereford, Tex.	34.8131	102.3900	194	**Yes**	**Yes**
07298150	Rock Creek Tributary near Silverton, Tex.	34.4781	101.4300	2.20	no	no
07299575	North Groesbeck Creek Tributary near Kirkland, Tex.	34.3953	100.0564	0.16	**Yes**	**Yes**
07299825	Salt Fork Red River Tributary at FM 294 near Goodnight, Tex.	35.1133	101.1867	1.88	**Yes**	**Yes**
07299830	Patching Creek Tributary at FM 1151 near Claude, Tex.	35.1050	101.2592	0.07	no	no
07307550	Wind River Tributary at FM 656 near Northfield, Tex.	34.3103	100.7094	0.002	no	no
07307720	Cottonwood Creek Tributary near Afton, Tex.	33.7386	100.8414	1.09	no	no
08079400	Bull Draw at FM 303 near Littlefield, Tex.	33.8869	102.5578	0.35	no	no
08079570	Barnum Springs Draw near Post, Tex.	33.2822	101.3931	4.99	no	no
08079580	Rattlesnake Creek near Post, Tex.	33.2289	101.3589	2.77	no	no
08080510	Guest-Flowers Draw near Aspermont, Tex.	33.1247	100.1375	3.02	no	no
08080650	Running Water Draw at SH 214 near Friona, Tex.	34.4744	102.7331	139	**Yes**	**Yes**
08080750	Callahan Draw near Lockney, Tex.	33.9975	101.5489	8.37	**Yes**	**Yes**
08080918	Red Mud Creek near Spur, Tex.	33.3244	100.9250	65.1	no	no
08082900	North Elm Creek near Throckmorton, Tex.	33.1814	99.3697	3.58	**Yes**	**Yes**
08117990	Sulphur Draw near Lehman, Tex. (DISCONTINUED)[3]	33.5658	102.8225	0.01	no	no
08123618	Sulphur Springs Draw near Plains, Tex.	33.1825	102.7975	0.04	no	no
08123620	Sulphur Springs Draw near Wellman, Tex.	33.0594	102.4153	41.8	**Yes**	**Yes**
08125400	Hog Creek Tributary near Bronte, Tex.	31.8561	100.2494	0.43	no	no
08125600	Mesquite Creek Tributary near Bronte, Tex.	31.8236	100.1656	1.24	Yes	Yes
08125700	Red Bank Creek Tributary near Miles, Tex.	31.7053	100.2128	0.44	no	no
08127090	South Concho River Tributary near Eldorado, Tex.	30.9786	100.5750	0.06	no	no
08127100	Dry Creek near Christoval, Tex.	31.0919	100.3483	0.79	no	no
08127101	Dry Creek Tributary No. 1 near Christoval, Tex.	31.0978	100.3592	0.29	no	no
08127102	Dry Creek Tributary No. 2 near Christoval, Tex.	31.0978	100.3678	0.49	Yes	Yes
08128010	South Concho River Tributary near Christoval, Tex.	31.2369	100.5136	0.16	no	no
08128095	Tepee Draw Tributary near Barnhart, Tex.	31.2108	101.1761	0.007	**Yes**	**Yes**
08128990	Wilson Draw near Mertzon, Tex.	31.1786	100.9883	0.02	no	no
08130505	Dove Creek Tributary near Knickerbocker, Tex.	31.2403	100.6022	0.06	no	no
08134400	Gravel Pit Creek near San Angelo, Tex.	31.4653	100.5217	0.19	Yes	Yes
08136200	Puddle Creek near Veribest, Tex.	31.5111	100.1589	12.0	Yes	Yes
08136220	Lipan Creek Tributary near Miles, Tex.	31.4883	100.0819	2.42	Yes	Yes
08141100	McCall Branch near Coleman, Tex.	31.8494	99.5536	2.17	no	no

Table 1. Summary of the 51 active and 1 discontinued U.S. Geological Survey streamflow-gaging stations in the crest-stage gage network in Texas.—Continued

[mi², square mile; SH, State Highway; FM, Farm to Market road; No., number]

Station number	Station name	Latitude (decimal degrees)	Longitude (decimal degrees)	Contributing drainage area (mi²)	Station operated as a flood-hydrograph station[1]	Station with precipi-tation data[2]
08143700	Browns Creek Tributary near Goldthwaite, Tex.	31.5169	98.5669	2.48	**Yes**	**Yes**
08143880	Antelope Draw Tributary near Eldorado, Tex.	30.8553	100.5583	0.04	no	no
08143905	North Valley Prong Tributary near Eldorado, Tex.	30.8797	100.3306	0.03	no	no
08367050	Unnamed Tributary Pow Wow Canyon Arroyo near El Paso, Tex.	31.8389	106.0447	0.64	Yes	Yes
08407580	Unnamed Tributary No. 1 University Draw near Cornudas, Tex.	31.7983	105.5817	0.62	**Yes**	**Yes**
08407581	Unnamed Tributary No. 2 University Draw near Cornudas, Tex.	31.7978	105.5778	0.22	no	no
08407595	Unnamed Tributary No. 1 Guadalupe Arroyo near Salt Flat, Tex.	31.7906	104.8669	0.21	Yes	Yes
08407596	Unnamed Tributary No. 2 Guadalupe Arroyo near Salt Flat, Tex.	31.7822	104.8825	1.98	no	no
08435660	Moss Creek near Alpine, Tex.	30.3411	103.6433	11.6	Yes	Yes
08436800	Courtney Creek Tributary near Fort Stockton, Tex.	31.0111	103.0667	0.44	no	no
08444400	Three Mile Mesa Creek near Fort Stockton, Tex.	30.8381	102.8422	1.04	no	no
08447200	Howards Creek Tributary near Ozona, Tex.	30.6886	101.3478	7.53	no	no
08449250	Riggs Draw at U.S. Highway 377 near Carta Valley, Tex.	29.7850	100.6850	14.2	no	no

[1]Yes indicates that the station has operated as a flood-hydrograph station historically, and bold typeface indicates that the station was operated as a flood-hydrograph station at the end of water year 2015.

[2]Yes indicates that the station has collected precipitation data historically during project tenure, and bold typeface indicates that the station was collecting precipitation data at the end of water year 2015.

[3]Station 08117990 was discontinued at the end of the 2012 water year following review and consideration of hydraulic conditions.

There is one CSG station (07227420) in the network that operates as a continuous-record streamflow-gaging station such as other continuous stations in the greater USGS network in Texas (U.S. Geological Survey, 2016a). Coincidentally, this site (as of 2018) is the most upstream USGS station in the State of Texas.

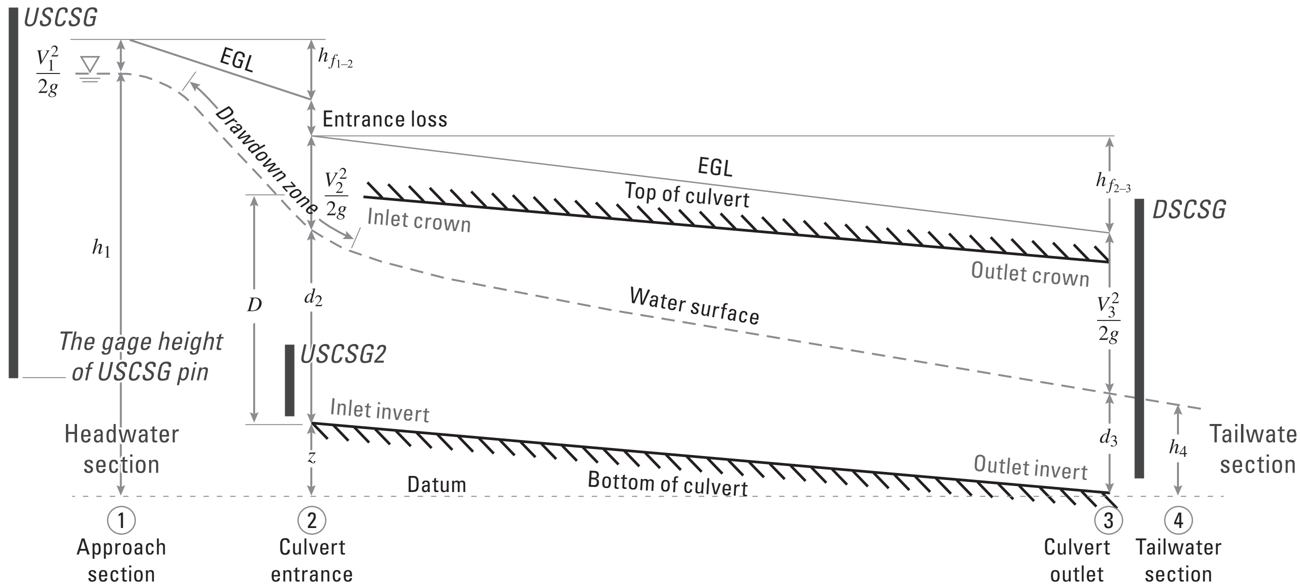
Most CSGs in the network are used in tandem to preserve peak gage height upstream (“headwater” or “approach section”) and downstream (“tailwater”) of a culvert underlying a roadway or other type of crossing (figs. 2*A* and 2*B*). In turn, peak streamflow is computed through manual interpretation that often includes extensive computations and the use of software applications. Two types of interpretive peak-streamflow data result from the CSG network: (1) annual peak streamflow and (2) approximately quarterly series peak streamflow.

Annual peak-streamflow data for a given station represent the maximum streamflow each water year of record. Alternatively, approximately quarterly series peak-streamflow data are represented by two subclasses of peak streamflow: (1) a time series of peak streamflows greater than an unknown, known and varying (mutable), or known and constant (immutable) minimum streamflow value for a given station or (2) a time series of streamflows representing the maximum peak streamflow between station visits.

Purpose and Scope

The purpose of this report is to describe peak-streamflow data (Asquith and Harwell, 2018) obtained from 51 active stations operated during 2006–15 and from 1 discontinued CSG station that operated during water years 2006 through 2012 as part of a current (2018) network of CSG stations in central and western Texas. Many of the stations in the CSG network are at the same locations where peak-streamflow records were obtained during 1966–74, which will facilitate assessments using previously published data from a similar 1966–74 CSG network as part of a cooperative agreement between the USGS and TxDOT, and data from the current (2018) CSG network. The database (Asquith and Harwell, 2018) of annual and approximately quarterly series peak streamflow through water year 2015 published through USGS ScienceBase (U.S. Geological Survey, 2018b) is herein described.

A



DSCSG, downstream crest-stage gage; EGL, energy grade line; USCSG, upstream crest-stage gage; USCSG2, upstream secondary crest-stage gage

B

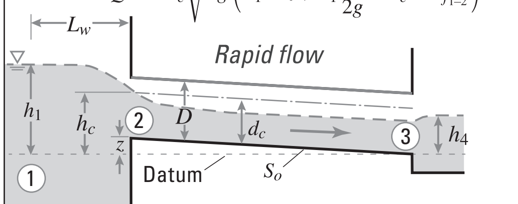
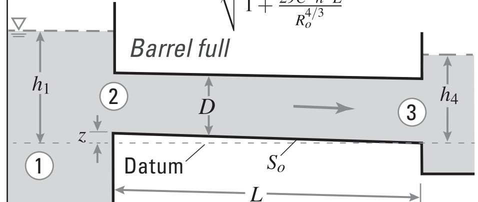
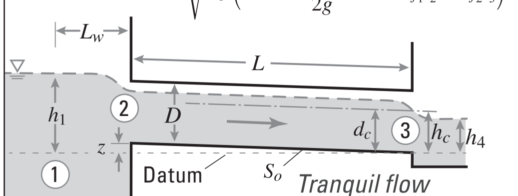
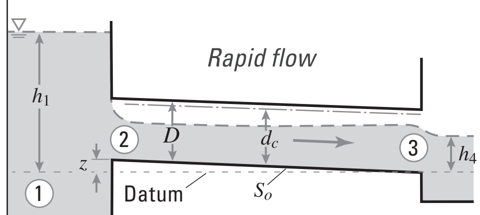
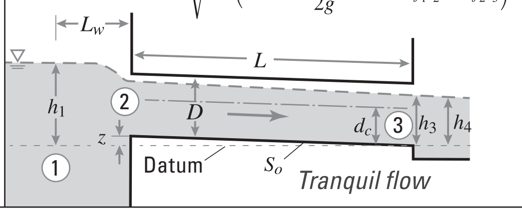
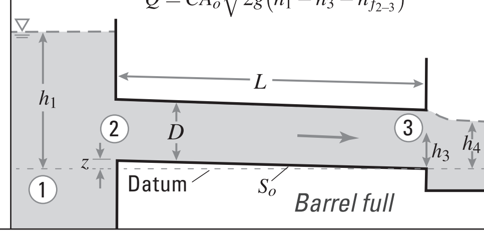
Type	Example	Type	Example
1 **CRITICAL DEPTH AT INLET** $\frac{h_1 - z}{D} < 1.5$ $h_4/h_c < 1.0$ $S_o > S_c$	$Q = CA_c\sqrt{2g\left(h_1 - z + \alpha_1\frac{V_1^2}{2g} - d_c - h_{f_{1-2}}\right)}$ 	**4** **SUBMERGED OUTLET** $\frac{h_1 - z}{D} > 1.0$ $h_4/D > 1.0$	$Q = CA_o\sqrt{\frac{2g(h_1 - h_4)}{1 + \frac{29C^2n^2L}{R_o^{4/3}}}}$ 
2 **CRITICAL DEPTH AT OUTLET** $\frac{h_1 - z}{D} < 1.5$ $h_4/h_c < 1.0$ $S_o < S_c$	$Q = CA_c\sqrt{2g\left(h_1 + \alpha_1\frac{V_1^2}{2g} - d_c - h_{f_{1-2}} - h_{f_{2-3}}\right)}$ 	**5** **RAPID FLOW AT INLET** $\frac{h_1 - z}{D} \geq 1.5$ $h_4/D \leq 1.0$	$Q = CA_o\sqrt{2g(h_1 - z)}$ 
3 **TRANQUIL FLOW THROUGHOUT** $\frac{h_1 - z}{D} < 1.5$ $h_4/D \leq 1.0$ $h_4/h_c > 1.0$	$Q = CA_3\sqrt{2g\left(h_1 + \alpha_1\frac{V_1^2}{2g} - h_3 - h_{f_{1-2}} - h_{f_{2-3}}\right)}$ 	**6** **FULL FLOW FREE OUTFALL** $\frac{h_1 - z}{D} \geq 1.5$ $h_4/D \leq 1.0$	$Q = CA_o\sqrt{2g(h_1 - h_3 - h_{f_{2-3}})}$ 

Figure 2. *A*, culvert-flow hydraulics, select definitions (see “Symbols and Descriptions” in the front matter of this report), and representative crest-stage gage placement (modified after Bodhaine, 1968, fig. 1) and *B*, culvert-flow types as provided by Bodhaine (1968, fig. 2).

This report also documents peak-streamflow data obtained from four stations that were part of a small CSG network from 1994 to about 1997 that were reactivated as part of the network; at two of these four stations, peak-streamflow measurements were made in water year 2005 and are also documented in this report. This report describes the background, operations, and interpretations leading to annual and approximately quarterly series peak-streamflow records for stations currently (2018) operating in the CSG network. Numerous sections in the report provide extensive discussion of how these methods are generally applied as part of analyst-directed interpretations of the peak gage heights from the CSG network.

Discontinued Station

Station 08117990 was discontinued at the end of water year 2012 following a review of the hydraulic conditions at this site. Hydraulic conditions are such that a substantial amount of streamflow might bypass the culvert structure at station 08117990 during large runoff events rendering this station inadequate for long-term monitoring because of potential for ambiguous information to be acquired. Furthermore, the headwater and tailwater peak gage heights indicated nearly level (flat or ponded) water-surface conditions (absence of water-surface slope) for many of the records.

Background and Previous Studies

A CSG network consisting of more than 100 CSG stations throughout Texas was operated by the USGS in cooperation with the Texas Highway Department (the predecessor to TxDOT) from approximately 1966 through 1974; this historical network is hereinafter referred to as the “1966–74 CSG network.” The annual peak data from the 1966–74 CSG network were incorporated into prior USGS statistical analyses (Schroeder and Massey, 1977; Asquith and Slade, 1997). References to the data from the 1966–74 CSG network can be found in Ruggles (1966), Schroeder (1967, 1969, 1971a, b, 1972, 1973, 1974), Gilbert and Hawkinson (1971), and Massey and Schroeder (1977). Many of the stations operated for the 1966–74 CSG network can be identified in Asquith and Slade (1997, table 1) through inspection of those stations having 8 or 9 years of record in that referenced table—although not all stations having these record lengths were in the 1966–74 CSG network (review of the USGS-NWIS peak-streamflow database [U.S. Geological Survey, 2018a] by station identification number and pertinent years would be required). In Asquith and Slade (1997, table 1), those stations operated within the 1966–74 CSG network often contain words such as “tributary” and “branch” in the USGS station name and also tend to have relatively small contributing drainage areas. There were many stations for the 1966–74 CSG network with less than 8 years of record. Some of the stations in the current (2018) CSG network were operated as part of the 1966–74 CSG network and were reactivated.

Between 1994 and about 1997 in western Texas, a much smaller scale CSG network (“the 1990s CSG network”) compared to either the 1966–1974 or the 2006–present (2018) CSG networks was jointly operated by TxDOT and the USGS; whereas the USGS had sole responsibility for data collection in most time periods where TxDOT and the USGS jointly operated a CSG network, personnel from both agencies actively participated in the collection of field data for the 1990s CSG network. Often hydraulic information was generally lacking and then contemporaneous publication of information was not made. Uniquely for this report, previously unpublished peak-streamflow data from four stations that were part of the 1990s CSG network (stations 07227456 [two peaks], 07227458 [two peaks], 07295450 [seven peaks], and 08080650 [two peaks]) are documented. Additional peak streamflows in water year 2005 were available from large runoff events at two of the stations operated in the 1990s (stations 07295450 and 08080650).

All data collected from the 1990s CSG network were oriented around TxDOT maintenance staff making approximately quarterly visits to approximately 13 stations and annually reporting the data to the USGS Texas Water Science Center office in Austin, Tex., through letters of communication. This report represents the first publication of all data from the 1990s CSG network that pass customary data quality standards.

Computational Methods for Indirect Measurement of Peak Streamflow

This section summarizes the computational methods used for indirect measurement of peak streamflow specific to the CSG network. The term “indirect” refers to the use of postevent, peak gage heights and hydraulic methods to estimate peak streamflow (Benson and Dalrymple, 1967). The foundations for peak-streamflow estimation for the CSG network using indirect methods are based on three general types of computations (culvert-flow, slope-area, and flow-over-road methods) and the attendant assumptions associated with local hydraulic controls on water-surface elevations.

The most frequently used indirect method within the CSG network is the culvert-flow method. This method accounts for culvert influences on streamflow such as the horizontal contraction of the flow field immediately upstream from the culvert system. Compared to natural channels, culverts exert relatively complex hydraulic effects on water surfaces and velocities (figs. 2*A* and 2*B*). Hydraulics of idealized culverts are described in the literature (Carter, 1957; Bodhaine, 1968; Normann and others, 1985; Fulford, 1998; Charbeneau and others, 2002, 2006).

The culvert-flow method, although expressible as discrete algebraic solutions based on the type of hydraulic flow (fig. 2*B*, types 1–6), is complex and fraught with difficulties that often preclude fully automated computations; analyst-directed interpretations of culvert-flow data often are required. The interpretation difficulty is increased when applied at the scale of the CSG network. The primary need for analyst-directed interpretations to be made is that analysis of quarterly CSG peak gage height data potentially spans a broad hydrologic/hydraulic spectrum from obvious zero flow periods (quarters or more), to possibly zero flow but otherwise unknown minimum flow periods, to substantial ephemeral flow resulting from storm events.

Another reason for the interpretive nature of culvert-flow hydraulics is that six distinct flow conditions can potentially exist at a given station. These flow types are primarily governed by the presence or absence of critical depth and critical depth location (Robertson and others, 1988) at a given station. The six culvert-flow types are schematically outlined by simplified hydraulic characteristics through idealistic diagrams in figure 2*B*.

In practice, one to three of the flow types often can be logically ruled out after a period of data collection and exploratory hydraulic computations that indicate general hydraulic tendencies at a station. These hydraulic tendencies are controlled by culvert geometry and other features, such as the fixed invert slope of the culvert barrel (the bottom of the culvert barrel or deposited sediment). Such controls and features can make some of the six culvert-flow types implausible.

The second most frequently used indirect method within the CSG network is the slope-area method (Dalrymple and Benson, 1967; Fulford, 1994). The slope-area method (fig. 3*A*) is based on algebraic solutions to steady-state, one-dimensional, open-channel hydraulics. The form of the equation is determined by the number of available cross sections (fig. 3*B*). The equations inherently express the interplay among peak streamflow, peak gage height, cross-sectional area to flow, wetted perimeter of the water contacting the bed and banks, and a generalized flow-resistance roughness coefficient (Manning’s roughness coefficient) (Barnes, 1967; Sturm, 2010). Fulford (1994) published the slope-area computation (SAC) program used for slope-area analysis; an updated version (SAC2.0) was released in 2013, and a graphical user interface exists to assist users in operation of SAC2.0 (U.S. Geological Survey, 2016b). The SAC2.0 program was used for five stations in the CSG network that are exclusively reliant on the slope-area method.

The third and seldom used indirect method within the CSG network is known as the flow-over-road method (Hulsing, 1967) where the roadway is hydraulically treated as a broad-crested weir (a type of low dam) for flow overtopping the roadway (Sturm, 2010). Broad-crested weirs produce a location for which the critical-depth section is reasonably well understood or predictable and streamflow estimation is straightforward.

For the CSG network, approach sections can lack a discernible thalweg within the approach channel. At some CSG stations in small watersheds, the borrow ditch along the roadside right-of-way likely delivers most of the streamflow, and that borrow ditch streamflow is generally perpendicular to the direction of streamflow in the culvert. The perpendicularity of arriving streamflow to streamflow passing through the culvert can be important to know (inferred from field inspections) because such streamflow does not deliver kinetic energy (velocity head) to the culvert inlet.

Many of the approach sections are within the right-of-way of roadsides that TxDOT contractors periodically mow, resulting in temporary changes in vegetation characteristics (shorter grasses and weeds). Mowing the approach section alters the channel roughness. Because rainfall is scarce and highly variable in the study area, the time needed for regrowth varies appreciably. Other changes in vegetative characteristics near inlets and outlets and within culvert barrels can occur. For example, wildfires have completely cleared vegetation at some locations, and years later a return of rainfall causes rapid weedy vegetation regrowth. In many locations scores of tumbleweeds become trapped near inlets and outlets and even within culvert barrels during certain times of the year. Much of the region of the CSG network can undergo hard freezes that kill the vegetation, and successive regrowth in warmer periods is controlled by timing of rainfall.

These observations and other factors inherently hinder the accuracy of indirect measurements of streamflow for this study because it is difficult to quantify the precise conditions at the time of peak streamflow when stations are visited about four times per year. Ubiquitous roadside debris, such as cans and bottles, tires, automotive parts, and the occasional animal carcass, also causes temporal variations in channel “openness” for some of the smaller culverts. Often this debris can be removed by USGS hydrographers during station visits; local TxDOT maintenance staff has frequently assisted with the removal of larger debris by using heavy machinery or additional personnel.

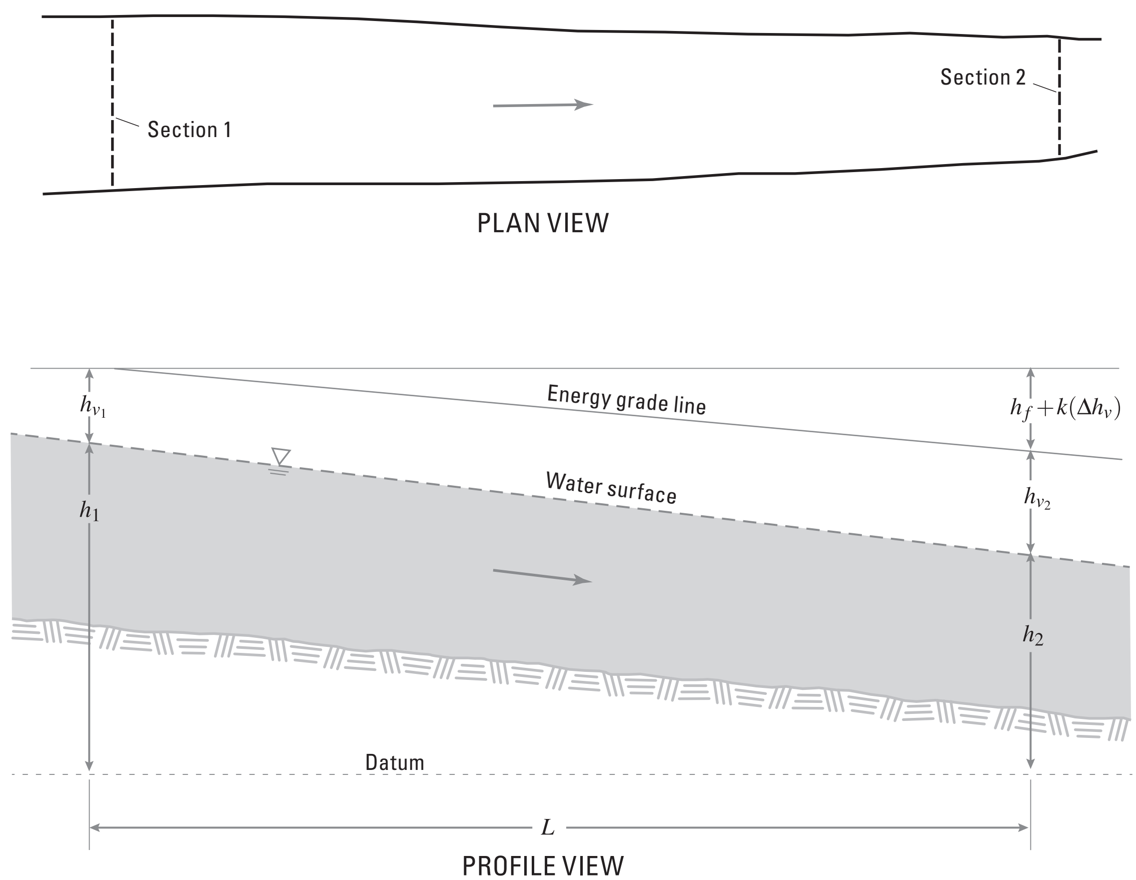
Operation of Crest-Stage Gages

All 51 active stations in the CSG network are equipped with at least two CSGs to passively preserve peak headwater and tailwater gage heights for the largest rise during storm events between station visits. The CSG contains a stick typically made of wood that is usually 0.75 inches (in.) thick by 1.50 in. wide; the length is site specific. The CSG stick is placed within common 2-in., schedule 40, galvanized steel pipe (CSG pipe) that is threaded at both ends.

CSG pipes are installed at the approach section (the primary headwater CSG), and another is optionally installed closer to the inlet and within the potential drawdown zone (at or very near the culvert inlet), which is near the secondary headwater CSG. At least one CSG pipe is installed at the culvert outlet (tailwater CSG).

At the bottom of the CSG stick, a mesh basket is secured with staples and filled with granulated cork (fig. 4). The CSG

A



B

Number of cross sections	
2	$Q = K_2 \sqrt{\Delta h \Big/ \left(\frac{K_2}{K_1} L + \frac{K_2^2}{2gA_2^2} \left[-\alpha_1 \left(\frac{A_2}{A_1} \right)^2 (1-k) + \alpha_2 (1-k) \right] \right)}$
3	$Q = K_3 \sqrt{\Delta h \Big/ \left(\frac{K_3}{K_2} \left[\frac{K_3}{K_1} L_{1\text{–}2} + L_{2\text{–}3} \right] + \frac{K_3^2}{2gA_3^2} \left[-\alpha_1 \left(\frac{A_3}{A_1} \right)^2 (1-k_{1\text{–}2}) + \alpha_2 \left(\frac{A_3}{A_2} \right)^2 (k_{2\text{–}3} - k_{1\text{–}2}) + \alpha_3 (1-k_{2\text{–}3}) \right] \right)}$
Multiple (n)	$Q = K_n \sqrt{\Delta h / (S+T)}$, where

$$S = K_n^2 \left[\left(\frac{L_{1\text{–}2}}{K_1 K_2} \right) + \left(\frac{L_{2\text{–}3}}{K_2 K_3} \right) + \cdots + \frac{L_{(n-2)\text{–}(n-1)}}{K_{(n-2)} K_{(n-1)}} + \frac{L_{(n-1)\text{–}n}}{K_{(n-1)} K_n} \right]$$

$$T = \frac{K_n^2}{2gA_n^2} \left[-\alpha_1 \left(\frac{A_n}{A_1} \right)^2 (1-k_{1\text{–}2}) + \alpha_2 \left(\frac{A_n}{A_2} \right)^2 (k_{2\text{–}3} - k_{1\text{–}2}) + \alpha_3 \left(\frac{A_n}{A_3} \right)^2 (k_{3\text{–}4} - k_{2\text{–}3}) + \cdots \right.$$
$$\left. + \alpha_{(n-1)} \left(\frac{A_n}{A_{(n-1)}} \right)^2 (k_{(n-1)\text{–}n} - k_{(n-2)\text{–}(n-1)}) + \alpha_n (1 - k_{(n-1)\text{–}n}) \right]$$

Figure 3. *A*, plan and profile view of a simplified two-section slope-area computation as provided by Dalrymple and Benson (1967, fig. 1) and *B*, slope-area computation equations as provided by Dalrymple and Benson (1967, table 1) and implemented in the SAC2.0 program (Fulford, 1994; U.S. Geological Survey, 2016b; see “Symbols and Descriptions” in the front matter of this report).

pipes have end caps on the top and bottom that are vented with predrilled holes to allow air to escape or vent through the top cap as water enters through the bottom cap. In the middle of the bottom cap is a pin on which the CSG stick sits, and the height of the pin above gage datum is surveyed (Kenney, 2010) and referenced to a common datum for the station. The pipes are flushed with water as needed keep the intake holes clear.

For the CSG network, the vertical datum is local and not referenced to any geoid datums of the Earth such as the North American Vertical Datum of 1988 (NAVD 88) because such a vertical reference does not add pertinent information to computations or interpretations. For some of the reactivated stations, there is a datum in the USGS-NWIS peak-streamflow database (U.S. Geological Survey, 2018a), but the stored value presumably exists prior to NAVD 88.

Cork lines left on the CSG stick inside the CSG are used to determine the peak gage heights from storm events. As the water surface of a stream rises during a storm event, the cork floats up inside the CSG pipe. After the water recedes, a line or ring of cork remains attached to the CSG stick (fig. 4). The distance from the bottom of the CSG stick (same elevation as the top of the pin) to the cork line plus the vertical distance of the pin above the local datum (pin gage height) is treated as the peak gage height for the event at the location of a given CSG. The CSG stick is removed during a station visit, and the peak gage height (if present) is measured, recorded on field sheets, and subsequently recorded in the USGS-NWIS database. In preparation for future storm events, the cork line is brushed off the stick, and the mesh basket is recharged with fresh cork.

All CSG stations are visited approximately quarterly to perform routine inspection and maintenance as needed (figs. 5–6). For example, at station 07299575, a secondary CSG used for preserving peak gage heights in the approach section is upstream (not visible in fig. 5). A mound of sediment is periodically deposited and eroded within the first 4 feet (ft) inside the inlet—the remaining 47 ft of culvert (not visible in fig. 5) appears to always be clear of sediment. Sediment and earthen material sloughed from the banks partially obstructs flow through far left and far right barrels (fig. 6).

The intakes on the end caps of the CSG pipes are checked for plugging by mud, insects, or other debris, and the CSGs are inspected for damage. Damage to a CSG pipe can occur when bed and bank scour erode the anchor or foundation of the CSG pipe, causing the pipe to tilt from vertical. Substantial debris can accumulate on and around the CSG pipe. Roadside tractor mowers and vandalism can also cause damage to a CSG pipe. A reason that station visits are made on an approximately quarterly basis and substantial amounts of cork are often used is that many of the CSG stations are in windy areas of west Texas where granulated cork can be gradually removed by the wind and transported out through the bottom cap inlets or even up the 6–10 ft of a CSG pipe and out through the top cap vent hole. At some locations ants (or other insects) are known to seasonally collect the

Figure 4. Base of the crest-stage gage (CSG) stick; cork basket; cork marking a peak water-surface elevation (12.87 feet) for the lowest of the three upstream CSGs at U.S. Geological Survey station 08435660 for the November 13, 2013, visit; and a previous peak identified on the October 26, 2011, visit (12.95 feet).

Figure 5. Culvert inlet and crest-stage gage at U.S. Geological Survey station 07299575 in February 2012 during a routine station visit.

Figure 6. Culvert inlet for U.S. Geological Survey station 08079400 on February 27, 2013.

granulated cork. Despite these obstacles, quarterly inspection and maintenance visits have proven to be sufficient during the network's tenure.

The headwater (or tailwater) CSG consists of one or more individual CSG pipes each uniquely located upstream (or downstream) from the culvert inlet (or outlet). Vertical overlap of the CSG pipes is done during gage installation in order to span the potential vertical range of the water surface. Vertical overlap is also done because the use of more than one overlapping and relatively short CSG pipe mitigates the safety concerns arising from servicing tall CSG pipes by using tall stepladders or extension ladders. In addition to the primary CSG located in the approach section, many stations have secondary CSGs closer to the culvert inlet. These secondary headwater (and occasionally tailwater) CSGs often enhance interpretations particularly for small streamflow events.

The headwater peak gage height, when available, is treated as the primary peak record to store in the peak-values file—tailwater peak gage heights are not treated as the primary record even if only tailwater gage height information is known for an individual event. If two or more headwater peak gage heights are contemporaneously available, then the maximum of these should be used as primary record. Individual peak-streamflow and one-directional inequalities are readily stored in the USGS-NWIS peak-streamflow database (U.S. Geological Survey, 2018a).

Every 1–2 years, levels are run to reference marks at the stations to maintain a datum for maintenance of vertical control (Kenney, 2010). If differences in pin gage heights are found, corrections are applied to the station data in the USGS-NWIS station-levels database (internal to agency). The running of station levels every few years or more frequently ensures that contemporaneous pin gage heights are available for proper computation of peak gage heights. Accurate pin gage heights provide for reliable estimates of local peak gage heights and hence slopes of water surfaces as needed.

Application of Culvert-Flow Hydraulics for Indirect Measurement of Peak Streamflow

Fulford (1998) documented the culvert analysis software program (CAP97.08) used for culvert-flow computations, and Bradley (2013) documented the graphical user interface (CAP-GUI) for CAP97.08. The CAP97.08 program and the CAP-GUI user interface lack certain automation features, thereby making its application a time-consuming manual process for certain stations and certain hydrologic conditions. The specific needs of the CSG network required methods to automate peak-streamflow computations from pairs of peak headwater and tailwater gage heights for stations with pressure transducers and accommodate frequent changes to the pin gage heights.

Station-specific project scripts for the CSG network were written and tested. These single-purpose project scripts were written in the R programming language (R Development Core Team, 2018) and support the necessary computations and culvert-flow criteria described in Bodhaine (1968) and Fulford (1998). Much of the project script code is directly derived from the CAP97.08 source code, and many of the project script subroutines retain commented-out CAP97.08 source code for traceability to the algorithmic source.

The project scripts were primarily developed and tested for select project computations within TxDOT "0–6549 Hydraulic Performance of Staggered-Barrel Culverts for Stream Crossings" (Cleveland and others, 2013) by Asquith. The estimates of peak streamflow from project scripts were compared with estimates from CAP-GUI/CAP97.08. About 12 percent (55 peak streamflows at 14 stations) of peaks were compared and included various culvert barrel configurations and different flow types. The mean absolute percent difference between peak-streamflow values estimated by using the project scripts and the peak-streamflow values estimated by using the CAP-GUI/CAP97.08 for the 55 peaks investigated was 1.9 percent. For 50 of the 55 peaks (91 percent), the mean absolute percent difference was 5 percent or less. For 41 of the 55 (75 percent), were within 2 percent. The results from these computations were compared with eight examples in Bodhaine (1968). The mean absolute percent difference between peak-streamflow values estimated by using the project scripts and the peak-streamflow values for the eight Bodhaine (1968) examples was 0.8 percent.

The project scripts were extended for the CSG network to make two-section slope-area computations through the culvert by projecting headwater and tailwater peak gage heights into the upstream and downstream sections of the culvert. The project script computations mimic the SAC2.0 program by Fulford (1994) and are in accordance with accepted practice as outlined in Bodhaine (1968). Two-section slope-area computations through the culvert are made only if the culvert-flow method fails to numerically converge or otherwise seems inappropriate from available data and other site- and event-specific contexts. Another circumstance justifying the use of the two-section slope-area method through the culvert is when the culvert-flow criteria described in Bodhaine (1968) and partially summarized herein (fig. 2*B*) are violated by the recorded peak gage heights.

It is important to point out that the two-section slope-area method is a so-called fallback method or method of last resort for determining peak streamflow through a culvert but is an acceptable method according to Bodhaine (1968, p. 49–51). As part of data processing and analysis for culverts in the CSG network, a two-section slope-area method is almost exclusively used to compute peak streamflow when small gage heights are recorded on CSG sticks or during assessment of minimum recordable peak streamflow. The two-section slope-area computations make it possible to assign a quantitative value of peak streamflow for each preserved storm event recorded by CSGs at most of the stations in the CSG network.

A complication in culvert computations for the CSG network is that for some stations and small peak gage heights the approach section offers an insufficient cross-section area for the streamflow relative to the available cross-section area of the culvert. This insufficient area causes the hydraulic equations involved to produce “numerical” supercritical (rapid) streamflow in the approach. The iterative culvert-flow computations do not converge on a solution. Rapid streamflow in the approach section must generally be a numerical artifact and not necessarily reflective of physical conditions because several of the affected stations show little evidence of erosive capacity of water on the upstream roadside right-of-way. For other peak gage heights, the approach velocity head is often close to being canceled out by the approach-to-inlet losses (fig. 2*A*). In the computation of peak streamflow with the project scripts, it is possible to either turn on or turn off the approach velocity head, which provides energy gain, and approach-to-inlet energy losses. Event-to-event judgment is needed when evaluating whether to turn the approach velocity head and approach-to-inlet energy losses on or off in the project scripts. In time, however, many stations show certain types of repeated “behavior” associated with the ranges in peak stage typically observed.

Application of Slope-Area Method for Indirect Measurement of Peak Streamflow

For five of the stations, culvert-flow computations are not appropriate or possible for the range of anticipated flow conditions. The computations for peak streamflow instead are exclusively (or almost exclusively) based on the slope-area method (Dalrymple and Benson, 1967) by using the SAC2.0 program by Fulford (1994) and follow the methods outlined in Bodhaine (1968).

The stations presently (2018) in the CSG network that are exclusively reliant on the slope-area method—the SAC2.0 program is used—are 07227420, 07227456, 07227458, 07295450, and 08080650. The channels are straight and uniform at each of these five stations. Examples of idealized cross sections are shown in figure 3. Three of the five stations were configured (that is, operated) for two-section slope-area computations until July 2014, when an additional CSG was added to stations 07227456, 07227458, and 08080650 to enable preferable three-section slope-area measurements. Two-section slope-area computations are not as accurate as when three or more sections are available.

Station 07295450 is upstream from a golf-cart stream crossing (a single-barrel culvert underlies the crossing) within a golf course. Analysis of some small storm events could involve culvert-flow computations through the single-barrel culvert. The four other stations have culverts that are large relative to the size and shape of the approach channel. Substantial flow contraction attributable to the stream crossing is not anticipated at these stations, rendering the slope-area method as the preferred technique.

Other circumstances have occurred and are expected to occasionally occur for which special surveys of a station are needed to compute a peak streamflow. For example, in November 2006, a large event overtopped the stream crossing at station 08080918 prior to installation of CSGs. A slope-area survey was conducted and office computations made for that station, which resulted in the water year 2007 annual peak. A photograph depicts the survey section downstream from the two-barrel culvert (fig. 7).

Application of Flow-Over-Road Method for Indirect Measurement of Peak Streamflow

The flow-over-road method project scripts support computations for circumstances in which recorded peak gage heights exceed the crest of the roadway. The project scripts algebraically sum the flow-over-road streamflow and the underlying culvert streamflow. This total is used to compute velocity heads and approach losses. Iterations continue until numerical convergences for both culvert flow solution and flow-over-road are reached, and convergence is an absolute value and is within 10,000th of a cubic foot per second (ft^3/s) or less. Although numerical convergence is obtained, such a small tolerance should not be associated with uncertainty inherent in the resultant peak-streamflow value. The total approach cross-section area is used for the joint velocity head (culvert and roadway). Thus far (as of September 30, 2015) in the history of the CSG network, circumstances requiring refinement by apportioning velocity heads based on left, right, and central channel conveyances have not been encountered. The principal reason is that there are geometric ambiguities in the sense that the channels in the CSG network lack the type of overbank conditions envisioned by Matthai (1967, p. 33) for the suggested procedure. Furthermore, the culverts for the CSG network are at the low point of the vertical curvature of the roadway, and evidence is lacking of flow over the roadway on both sides of the bridge. There is not a separation of the flow into two or more channels over the roadway on either side of the bridge.

As of September 30, 2015, there is one station (08449250 for the 2012 water year) that has required one flow-over-road computation for the peak streamflow. This streamflow is reported as an interval because of substantial uncertainties associated with the peak gage heights.

Additional Comments

Direct measurements of streamflow generally have errors less than about 10 percent (Turnipseed and Sauer, 2010), whereas indirect measurements of peak streamflow can have errors ranging from about ±5 to ±25 percent (Jenkins, 1963; Benson and Dalrymple, 1967). Assigning uncertainty to peak-streamflow estimates from the CSG network is difficult. As a result, the uncertainties associated with individual peak-streamflow estimates are not qualified or quantified.

Figure 7. Location of a survey for a slope-area indirect measurement for U.S. Geological Survey station 08080918 in November 2006.

Stage-discharge (streamflow) relations or “rating curves” (Kennedy, 1984; Sauer, 2001) are an important technical element of streamflow gaging. However, many of the culverts in the CSG network should be thought of as having a “rating surface” of streamflow in headwater-tailwater space (Fulford, 1998, p. 17)—for the CSG network such rating surfaces are irregular or not smooth. Because of inherent limitations with operating the CSG network, for which complex station- and event-specific characteristics are common, the development of rating curves or rating surfaces is outside the scope of this report. Also, non-unique stage-streamflow relations can exist as a result of possible changes in types of culvert-flow conditions (fig. 2*B*) and changes in conditions during the hydrograph rise and subsequent fall at the headwater and tailwater. Non-unique rating curves are anticipated for culvert-flow conditions of types 3 and 4 because of the computational influence of variable tailwater conditions.

Considerations for Interpretation and Determination of Peak Streamflow

The primary objective of the CSG network is to estimate peak streamflow from peak gage heights preserved by the CSGs. There are certain considerations that require discussion to explain the interpretations of peak streamflow for the CSG network.

Small watersheds in the study area generate short-duration storm events on time scales much smaller than the travel time to stations. The drive times from servicing field offices to remote station locations range from 3 to 5 hours, making it difficult to reach stations in time to make direct streamflow measurements or to witness streamflow conditions at or near the peak of an event.

Peak gage heights preserved by the granulated cork on the CSG sticks at a particular station during a storm event are assumed to be contemporaneous with the estimated peak streamflow. The assumption of contemporaneous peak gage heights is not always correct and leads to the qualification of increased error in estimated streamflow. Noncontemporaneous peak gage heights might be attributable to the effects of storage upstream from a culvert (Bodhaine, 1968, p. 45). At many of the CSG stations there is the potential for substantial storage under the roadway and (or) downstream storage, which is a circumstance that is not addressed in Bodhaine (1968), because many of the channels lack a clear thalweg and the culverts are in a low spot relative to the surrounding area.

Flow type criteria in Bodhaine (1968) are not mutually exclusive, and the potential exists for “step” changes as flow type changes. For example, there exist combinations of headwater and tailwater gage heights that could result in a change from culvert-flow type 2 to culvert-flow type 3 with an increase of just 0.01 ft change in tailwater gage height. The two streamflow estimates (type 2 and type 3) could appear substantially divergent, and hence abrupt changes in computed streamflow can occur although the gage heights are nearly equivalent (just 0.01 ft change in tailwater gage height).

During water years 2010–15, there were substantial enhancements to station-specific interpretations of the culvert hydraulics as the number of recorded runoff events increased. The authors regularly reconsidered computations and subsequently revised as understanding of the hydraulics improved on a station-by-station basis.

Peak-streamflow estimates (Asquith and Harwell, 2018) from the CSG network, using station 08447200 as an example, are represented by single numbers (such as 984 ft^3/s in water year 2007), by intervals of streamflow (such as [37.0, 156] ft^3/s in water year 2012—meaning that the best estimate of streamflow lies within the interval of 37.0 to 156 ft^3/s), or by streamflow inequalities, such as less than (<) 234 ft^3/s in water year 2013.

Operation of the CSG network and concurrent data interpretations can require subsequent adjustments to station-specific infrastructure. For example, the addition of an upstream secondary CSG (USCSG2, fig. 2*A*) at a station changes how the data are collected and interpreted. For example, a USCSG2 allows for estimation of streamflow or streamflow inequality by using indirect methods for very small streamflows down to even zero flow between station visits.

A given station might be temporarily or permanently discontinued because of right-of-way or roadway maintenance, new construction, or the replacement of the drainage structure. Such activities can disrupt data collection, data continuity, and even result in a drainage structure unsuitable for estimating peak streamflow. For example, station 08436800 was removed when the culvert was rebuilt by TxDOT between water years 2011 and 2012 and then was reactivated. As a result, there is no designation of an annual peak for the 2011 and 2012 water years when the station was considered inactive.

Additional details are included to expand on operational considerations and interpretations. Station-specific examples from the CSG network are given, which reflect a range of unique circumstances.

Station 08079400—An Example

Not all CSG stations are in locations ideal for monitoring. One example is station 08079400 (fig. 6). This culvert structure is constructed with four circular culverts of identical geometry and material. Sediment and sloughed earthen material partially obstruct flow through the far left and far right barrels. The amount of obstruction is similar on the upstream and downstream sides. On the basis of the evidence of partial flow obstruction and exploratory computations, the authors computationally treated this culvert system as having three barrels.

Station 08079570—An Example

Station 08079570 has a single concrete culvert partially filled with sediment. The general elevation of the unevenly deposited sediment is substantially less than the bottom of the approach section and also less than the elevation of a downstream grass-vegetated berm. Unless water gets over the downstream berm, flow is not considered to have occurred because water effectively pools behind the berm and remains underneath the roadway.

The peak-streamflow records at this station provide evidence that a gage height of zero flow (GZF) exists at this station though with ambiguity to actual elevation. Storm events between February 3, 2012, and May 2, 2012, and again between November 16, 2012, and February 13, 2013, resulted in an approximately flat water surface of 7.13 and 7.12 ft referenced for tailwater gage heights, respectively. It is known from interpretations of a standing pool of water witnessed during site visits that the GZF is at least greater than 5.54 ft, and a topographic-level survey conducted on January 15, 2013, indicated a GZF of at least 7.16 ft. Therefore, the peak streamflow for these two storm events for which peak gage heights were preserved and thus water is known to have been present is a peak streamflow of zero. In other words, for these two essentially flat water-surface storm events, water entered the inlet but did not exit the outlet.

Two storm events with a flat water surface with gage heights higher than the GZF occurred between May 30, 2012, and June 12, 2012 (peak gage heights about 8.72 ft), and between October 8, 2014, and February 9, 2015 (peak gage heights of 7.50 ft). For each of the respective water years (2012 and 2015), larger peak streamflows were observed and reported as the annual peak streamflow. These eliminated the ambiguity of these two events that resulted in flat water surfaces.

Station 08127100—An Example

For the 2012 water year, the annual peak streamflow for station 08127100 is reported as “[44.5, 102] ft^3/s,” which indicates that the best estimate of the annual peak is between 44.5 and 102 ft^3/s. This particular peak provides an illustrative example of the station-by-station, analyst-directed interpretations.

The station has both a primary and secondary headwater CSG. Through water year 2015, however, peak gage heights could not be recorded between 3.44 and 4.01 ft. The primary headwater CSG has a pin gage height of 4.01 ft (this is the gage height on which the stick within the CSG pipe sits). As a result, peak gage heights of 4.01 ft or larger are recorded by this CSG. The secondary headwater CSG has a stick length of 2.02 ft; this length plus the pin gage height of 1.42 ft results in a maximum observable gage height of 3.44 ft (1.42 + 2.02 ft). The maximum observable gage height of 3.44 ft is 0.57 ft less (3.44 – 4.01 ft) than the pin gage height of the primary CSG.

The interval results because of the existence of a range of gage heights that cannot be recorded. The secondary CSG was overtopped during the event, meaning the peak gage height was in excess of the top of the stick but less than the pin gage height of the primary headwater CSG. Computations of peak streamflow were made by using minimum and maximum gage heights that correspond to (1) the pin gage height plus the stick length of the secondary CSG and (2) the pin gage height of the primary CSG.

The authors do not assume in circumstances such as this that the minimum and maximum observable peak gage heights would have produced the minimum and maximum streamflows because culvert-flow type 3 conditions prevailed. Therefore, computations were made through 0.01-ft increments between 3.44 and 4.01 ft and a streamflow computed for each increment. The [44.5, 102] ft^3/s interval was determined from the minimum and maximum of these streamflows.

Station 08136220—An Example

Station 08136220 preserved the peak gage heights of an annual peak streamflow where it was determined that a flow-over-road contribution did not occur because of the placement of a secondary CSG. This particular station has two headwater CSGs and a tailwater CSG. The primary headwater CSG is located in the approach section, and the secondary CSG is mounted to the headwall of the culvert. The elevation of the roadway crest over the culvert has a gage height of 15.59 ft. The annual peak for water year 2012 was computed for the following conditions. The tailwater peak gage height was 13.96 ft, the primary headwater CSG peak gage height was 16.11 ft (hence apparent roadway overtopping), and the secondary headwater CSG peak gage height was 14.25 ft.

The primary headwater CSG peak gage height exceeded the minimum elevation of the roadway crown, and the secondary headwater CSG peak gage height did not. Had the primary CSG been the only headwater gage height available, then flow-over-road computations using a head of 0.52 ft (16.11 – 15.59 ft) over the road crest would have been erroneously used, and substantial streamflow (about 75 ft^3/s) would have been added to the culvert streamflow, which is 76.4 ft^3/s. The secondary headwater CSG (with peak gage height that was 1.34 ft [15.59 – 14.25 ft] lower than the roadway) apparently was located in the drawdown zone (at or very near the culvert inlet) for the magnitude of streamflow and proves that flow over the roadway did not occur. The utility of having a secondary headwater CSG, as schematically shown in figure 2*A*, is in this way demonstrated.

Annual and Approximately Quarterly Series Peak Streamflow From Interpretations of Indirect Measurements Through Water Year 2015

The database (Asquith and Harwell, 2018) of annual and approximately quarterly series peak streamflow through water year 2015 published through USGS ScienceBase (U.S. Geological Survey, 2018b) is herein described. The database represents many years of data collection and iterations of widely used indirect methods for peak-streamflow measurement using the (1) culvert-flow method, (2) slope-area method, and (3) flow-over-road method (embankments or roadways). The database facilitates publication of annual and approximately quarterly series peak-streamflow data because peak gage heights in feet and peak streamflows in cubic feet per second from the CSG network are not fully compatible with existing (2018) storage features of the USGS-NWIS peak-streamflow database (U.S. Geological Survey, 2018a). For example, some of the data are not compatible with the "peak-values file" formats supported by the USGS-PEAKFQ software (Flynn and others, 2006a, b; Veilleux and others, 2014); this software contributes to peak-streamflow frequency analysis (Asquith and Slade, 1997). An incompatibility example is that the USGS-NWIS peak-streamflow database is not currently (2018) compatible with the storage of interval peak-streamflow estimates (defined by simultaneous lower and upper estimates) or approximately quarterly series data, and USGS-NWIS peak-streamflow database cannot simultaneously store headwater and tailwater peak gage heights, which are gage heights of obvious utility in culvert hydraulics.

The fact concerning interval storage is particularly important. Though the Asquith and Harwell (2018) database contains only a few interval estimates, for the important purpose of annual peak storage in the USGS-NWIS peak-streamflow database (U.S. Geological Survey, 2018a) to ensure continuity of annual peak streamflows, the *geometric means of the annual peak intervals* are currently (2018) stored in that database. For example, the interval [44.5, 102] ft^3/s for station 08127100 in water year 2012 is currently (2018) stored in the USGS-NWIS peak-streamflow database as 67.4 ft^3/s. The practice of storing the geometric mean, though suboptimal, provides protection against end users making erroneous computations. However, the authors strongly suggest manually configuring the control settings (Veilleux and others, 2014) of the USGS-PEAKFQ software to use the intervals.

The database (Asquith and Harwell, 2018) contains 764 records (lines of data) composed of peak gage heights (headwater and tailwater), of which 747 peak streamflows are counted (764 – 10 [flat water surface] – 7 [adverse water surface]). These streamflows are counted in the form of a zero (for example, 0 ft^3/s for station 07227420 in water year 2008), a numerical entry other than zero (say, 20 ft^3/s for station 08143905 in water year 2014), an inequality (say, <191 ft^3/s for 08125400 in water year 2009), or an interval (say, [24.5, 30.6] ft^3/s for station 08125700 in water year 2015). The 17 entries not having a streamflow designated are declared as having water-surface conditions of either "flat water surface" or "adverse water surface." For annual peak streamflow, there are 470 peak streamflows designated as annual peaks for the CSG network through water year 2015. Of these annual peaks, none are designated with flat or adverse water-surface conditions. One peak is designated as a negative value (streamflow computed in the upstream direction [–4.32 ft^3/s for 08123618 for water year 2014]). A comment is immediately needed on interpretations germane to statistical analysis of annual peaks for purposes of transportation infrastructure. The authors recommend that the negative streamflow be stored (and thus used in practice) as a positive within the USGS-NWIS peak-streamflow database.

The database (Asquith and Harwell, 2018) is composed of 10 columns of information in a delimited text file. Several of the columns are self-explanatory and follow the column-naming nomenclature of USGS (2018a) for the USGS-NWIS peak-streamflow database; these columns respectively are "agency_cd," "site_no," "peak_va," "peak_dt," which represent the agency code (USGS), USGS station number, value for the peak streamflow, and date or date range of the peak. Another column used in the database is "water_yr," which specifies the water year, though this column is not standard to USGS (2018a).

The other columns require additional context. The "peak_type_designation" column uses two categorical values ("annual" and "otherwise") as the mechanism to identify annual peaks versus those related to an approximately quarterly series ("otherwise"). The peak streamflows identified as annual peaks are those for which statistical analyses can be performed (Veilleux and others, 2014). The "peak_method" column provides information to describe the computation method yielding the peak-streamflow estimate. The two gage height columns of "gage_ht_headwater" and "gage_ht_tailwater" are associated with the headwater and tailwater peak gage heights, respectively. Finally, the "threshold_reference_streamflow" column contains streamflow values representative of a special computation of streamflow associated with CSG minimum recordable elevations and described in more detail herein (see section titled "Details of Peak-Streamflow Data"). This streamflow is not for statistical analysis but used to inform the authors on assigning "peak_va" (the peak streamflows). The remainder of this section provides further background concerning the database (Asquith and Harwell, 2018).

Annual and Approximately Quarterly Series Peak-Streamflow Data

Peak-streamflow computations through the 2015 water year were completed for 52 CSG stations (the 51 active stations and discontinued station 08117990). About twice each year since December 2009, the authors have met to check the peak gage heights acquired from the field, discuss intermediate computations and representative graphics (not reported here), update project scripts, and perform quality-assurance reviews of streamflow estimates. Further between 2006 and the present (2018), all stations have been visited at least once and sometimes multiple times each year by the authors; station visits by the authors have been invaluable for interpreting field data and making operational changes to the CSG network.

Iterative computations were done to evaluate quarterly and annual peak-streamflow data. Partial (incomplete) headwater or tailwater gage height information was used iteratively to compute all potential combinations (at 0.01-ft increments) of logical intervals of potential but unknown gage heights with consideration of the following:

1. Upstream and downstream inverts (bottoms) of the culvert,
2. Upstream and downstream pin gage heights of the CSGs, and
3. Incomplete CSG records of peak gage heights (no high-water mark left on at least one of the CSG sticks).

For example, suppose that a headwater peak gage height of 4.50 ft was recorded, but no tailwater peak gage height was available. The project scripts would use the sequence of potential tailwater gage heights at 0.01-ft increments from the hypothetical 4.50 ft down to the tailwater invert of the culvert or the tailwater pin gage height.

For incomplete CSG records where high-water marks are not available from all of the CSGs at a given station, the project scripts can compute the streamflow for all potential and logical combinations of gage heights and record the maximum of the numerous computed streamflows. This maximum computed streamflow represents an upper limit of streamflow for an individual event that is qualified with the "<" inequality, which implies data censoring. The reporting of inequalities of peak streamflow as "<" is often necessary because of uncertainties associated with peak gage height data, because of uncertainties in peak-streamflow computations, and because long periods of time lapse between substantial runoff-generating storm events in the arid to semiarid climate in the study area. The paucity of such events at many of the stations for many water years implies two general physical circumstances: (1) a commonality of insufficient water for CSGs to preserve evidence of a water surface or (2) a culvert associated with design peak streamflows much larger than actual streamflow conditions yet in CSG network tenure in which the culvert does not function with sufficient flow constriction required for the idealized circumstances of "hydraulics of culvert flow" to be attained.

Details of Peak-Streamflow Data

The graphical interface of CAP-GUI documented by Bradley (2013) for the SAC2.0 program and the project scripts were used for peak-streamflow computations in the database (Asquith and Harwell, 2018). Typical peak gage heights might appear to change over time as a result of datum changes, gage relocations, or substantial equipment modifications, which may be of concern to some database users. For example, at station 07295450 the CSGs were relocated after the 2006 water year, resulting in a change to the local vertical datum. Therefore, headwater and tailwater peak gage heights are of little direct usefulness to most users.

The "threshold_reference_streamflow," also referred to as the "threshold streamflow," at times is the minimum computable streamflow for the station determined by using the headwater and tailwater pin gage heights, upstream and downstream inverts (elevations of culvert bottoms) relative to pin gage heights, or incomplete water-surface profile information. The pin gage heights are the minimum recordable gage heights by the CSGs. When an annual peak streamflow for a given station is reported as equaling the threshold streamflow, then no peak marks were recorded during the water year, and therefore streamflow, if it was nonzero, must have had a gage height less than the CSG pin gage heights.

Dates for the peaks in the "peak_dt" column are either determined as a specific day (almost always from evaluation of the unit values for flood-hydrograph stations or nearby weather stations) or a date range if the specific day of peak could not be determined. For peaks where an "unspecified" value is reported, only the water year is available. The date ranges are reported when information is sparse or uncertain. Most of the date ranges represent the interval between successive station visits.

Identification of Flow Types

Culvert-flow types are considered conventional, mixed, alternative, or not applicable; descriptions of these flow types are provided in this section. The flow type is included when available in the "peak_method" column.

Conventional culvert-flow types—Flow types q1, q2, q3, q4, q5, and q6 respectively refer to USGS culvert-flow types 1 through 6 (Bodhaine, 1968), and these are depicted in figure 2*B* as flow types 1 through 6. These are the standard culvert-flow types for which the hydraulics computed from observed data are assigned. The use of the "q" in the place of an adjective is deliberate because the digital and textual nature of the database prevents confusion of the flow type numbers with some type of numerical value.

Mixed culvert-flow types—For some stations in which complex assemblages of unique culvert geometries are parameterized, the computations may result in the detection of two or more barrel-specific flow types. For example, there are several peaks for station 08123620 that are from multiple flow types; the symbol "+" indicates an "and (or)" condition. The notation "q2+3+SAC" for station 08123620 in Asquith and Harwell (2018) indicates the presence of flow types q2, q3, or both and that the two-section slope-area method (qSAC) for flow through the culvert barrels was used, which is a flow type discussed in detail in the next paragraph. Also, there are some situations for a single-barrel culvert in which a type 2 and type 3 streamflow seemingly proves nonexclusive by the Bodhaine (1968) criteria. Under this situation the arithmetic mean of the two streamflows is reported as the peak streamflow. An interval for the estimated peak streamflow is deliberately not reported in this circumstance.

Alternative culvert-flow types—Flow type qSAC means that the peak streamflow was determined by two-section slope-area computations (Dalrymple and Benson, 1967; Fulford, 1994), and these are depicted in figure 3. The culvert-barrel geometry represents a surrogate for the open channel geometry required. The headwater and tailwater peak gage heights were projected to the culvert inlets and outlets, respectively. This computation was necessary because numerical convergence or acceptance of flow types according to flow type criteria (Bodhaine, 1968) was not possible.

In contrast to the flow type qSAC, the flow type qSAC2 (note the suffix of "2"), streamflow was determined by two-section slope-area computations using the SAC2.0 program. For five of the stations, culvert-flow computations are not appropriate or possible for the range of anticipated flow conditions. The computations for peak streamflow instead are exclusively (or almost exclusively) based on the slope-area method (Dalrymple and Benson, 1967; Fulford, 1994). These computations are designated qSAC2.

Flow type qSAC3 represents a conventional natural and open channel assemblage, three-section slope-area computation using the SAC2.0 program. The nomenclature pattern is consistent; qSAC4 and qSAC5 represent four- and five-section slope-area computations, respectively, and the SAC2.0 program would also be used.

Not applicable culvert-flow types—Flow type "unspecified" indicates that flow type could not be identified; this flow type often is shown in situations in which substantial interpretations using incomplete CSG peak gage height data and with special considerations of culvert geometry related mostly to the culvert invert elevations were required (fig. 2*A*).

Additional Discussion

Adverse water-surface conditions (water surfaces that apparently decrease in the upstream direction) have likely occurred at some of the stations in the active network in Texas during some peak-flow events. Adverse water-surface conditions could indicate backward or upstream flow or more likely represent unusual site-specific hydraulics. It was sometimes difficult to interpret when adverse water-surface conditions might have existed from the available information preserved by the CSG peak gage heights. In addition to adverse water-surface conditions, flat water-surface conditions could represent ponded conditions in the low point of the roadway. During flat water-surface conditions, it was hypothesized that a GZF as summarized by Turnipseed and Sauer (2010, p. 38) exists downstream from the culvert.

The designations of adverse or flat water-surface conditions representing adverse and flat slopes, within about 0.01 ft, are noted on field sheets and have been verified through discussions by the authors with the USGS staff responsible for particular station maintenance and by personal station visits by the authors. Adverse or flat water-surface conditions can be induced by hydraulic conditions such as ponding downstream from culverts and drawdown effects at or very near the culvert inlet (just upstream of a culvert) or other unknown vagaries. An adverse slope for a culvert barrel can also be caused by ground-surface excavation and grading activities during the installation of the culvert. The construction activities can result in elevations of the barrel being lower at the culvert inlet than the elevations of the barrel outlet, whereas flat conditions can also result when the elevations at culvert inlets and outlets are the same and ponding of water is shallow. Adverse or flat water-surface conditions can also result when inflows of water from the borrow ditch on the downstream side of the roadway near the culvert outlets cause the water-surface elevation downstream from the culverts to exceed water-surface elevation upstream from the culverts. For the flat conditions, there might be an unknown GZF downstream from the culverts where the peak gage height is higher than the pin gage height in the closest CSG. Localized excavation and grading of the roadway and right-of-way, natural channel conditions, or agricultural and rangeland land-use changes on downstream private property could create a small berm or dam that might cause ponded conditions through the culverts. Adverse or flat water-surface conditions can be attributable to additional factors such as

1. Small differences in delineations made by hand of the granulated cork line on the CSG stick (estimated uncertainty of ±0.01 ft);

2. Slight measurement errors and variations from the bottom of the CSG stick to the cork line (estimated uncertainty of ±0.01 ft). This uncertainty is in addition to that associated with cork-line delineation; and

3. At a few stations, a small gap might exist between the top of the CSG stick and the inside of the cap on the CSG pipe confining the stick; the gap would allow the stick to slightly float during substantial rises in water level and thus runoff events. A CSG stick that slightly floats during runoff events will record peak gage heights that are slightly less than the actual peak gage heights.

Two final observations for the database (Asquith and Harwell, 2018) are made for two stations (07299575 and 08141100) in relation to the threshold streamflow. The threshold streamflow generally is computed by using the headwater and tailwater CSG pin gage heights. If the elevations of the CSG pin gage heights in the headwater or tailwater sections are too high, there can be gaps in the gage heights recorded in the headwater or tailwater sections, or both, resulting in an artificially high threshold streamflow. Because of gaps in the range of water-surface elevations that can be recorded, there are numerous records for which the reported peak streamflow is a quantity or inequality that is less than the threshold streamflow. Efforts were made over time to lower the threshold streamflow at many stations in the CSG network. For example, during 2009–10, a concerted effort was made to lower installed CSGs as much as possible or to install secondary CSGs, such as USCSG2 (fig. 2*A*), near headwalls or just upstream from inlets to encompass as much of the potential peak gage height range as possible. For some stations, however, the physically plausible range of water-surface elevations cannot be entirely spanned for unique logistical reasons. Analysts of these data are explicitly alerted that circumstances are common in which the reported peak streamflow is an inequality that differs from the threshold streamflow in the database (Asquith and Harwell, 2018).

The threshold streamflow for station 07299575 decreased from <10.3 ft^3/s to smaller values (for example, <1.45 ft^3/s) after water year 2010 because of the addition of the secondary upstream CSG close to the culvert inlet. The location of the secondary CSG at station 07299575 (fig. 5) (USCSG2) is depicted schematically in the representation of culvert-flow hydraulics and CSG placement (fig. 2*A*).

The 2009 water year annual peak streamflow for station 08141100 is listed as <232 ft^3/s, whereas the threshold streamflow for that year is <238 ft^3/s. The difference and justification for markedly different inequalities are that a tailwater peak gage height of 7.57 ft was preserved and that the headwater peak gage height was incomplete and only known to be <8.20 ft. As a result, the listed streamflow in the "peak_va" column as the USGS official annual peak is not equal to the streamflow listed in the column titled "threshold_reference_streamflow."

Summary

In 2006, the U.S. Geological Survey (USGS), in cooperation with the Texas Department of Transportation (TxDOT), began collecting annual and approximately quarterly series peak-streamflow data at streamflow-gaging stations in central and western Texas as part of a crest-stage gage (CSG) network, along with selected flood-hydrograph data at a subset of these stations. The network is focused on hydrology of small- to medium-sized watersheds in central and western Texas because additional streamflow data for this semiarid to arid study area will eventually provide for more statistical information and presumably reduced uncertainty in regional regression equations or other regionalized statistical methods for peak-streamflow frequency estimation at ungaged locations.

Estimates of annual peak-streamflow frequency are needed for flood-plain management, assessment of flood risk, and design of structures, such as roads, bridges, culverts, and other water-conveyance structures. Annual peak (annual maximum instantaneous peak streamflow) data can form the basis of statistical methods for such frequency estimates. In addition to annual peak streamflows, estimates of peak streamflow on a more frequent basis such as quarterly peak streamflow (if nonzero) are also useful for flood-plain management, assessment of flood risk, and other statistical assessments.

Regional regression equations for Texas have been developed and are used extensively to estimate annual peak-streamflow frequency of various annual exceedance probabilities for ungaged sites in natural (unregulated and rural or otherwise nonurbanized) watersheds. Historical streamflow data from small- to medium-sized rural watersheds in certain parts of Texas are spatially and temporally sparse. Substantial uncertainty, therefore, exists when regional regression equations are used to estimate annual peak-streamflow frequency at ungaged or unmonitored stream crossings, as is often required for culvert design.

The objective of the CSG network based on field-acquired data and analyst interpretation is to quantitatively assign a peak-streamflow magnitude to each peak gage height preserved by the deployed CSGs. For the CSG network, interpretations can lead to zero or other thresholds of streamflow for minimum (or possibly maximum) observable streamflow magnitude. Such minimums can be either (1) constant (immutable) values that are set by the constraints of CSG placement (optimal or otherwise) and station-specific hydraulic features or (2) varying (mutable) values because of a combination of event-specific incomplete or missing field data, CSG placement, and station-specific hydraulic features.

The primary purpose of a CSG station is to record peak gage height—hydraulic methods are used to compute or estimate peak streamflow. Office-based computations and interpretations leading to peak-streamflow estimates from the peak gage height data are required. Two types of interpretive peak-streamflow data result from the CSG network: (1) annual peak streamflow and (2) approximately quarterly series peak streamflow.

In the current (2018) CSG network, 13 of the 51 active stations were operating as flood-hydrograph stations as of September 30, 2015. The contributing drainage areas of the 51 active stations where annual and approximately quarterly peak-streamflow data are collected in central and western Texas range from 0.002 to 194 square miles (mi^2) with a mean of 12.5 mi^2, and the median is 1.09 mi^2. The contributing drainage areas are larger than 15 mi^2 at five of the stations. The annual peak-streamflow data represent a subset of the approximately quarterly series data; the annual peak-streamflow data represent the highest streamflow recorded by the approximately quarterly data collected each water year. A water year is defined as the 12-month period between October 1 and September 30. The water year is designated by the calendar year in which it ends, and thus, the year ending September 30, 2015, is referred to as the “2015 water year.”

Annual peak-streamflow data for a given station represent the maximum streamflow each water year of record. Alternatively, approximately quarterly series peak-streamflow data are represented by two subclasses of peak streamflow: (1) a time series of peak streamflows greater than either an unknown, known and varying (mutable), or known and constant (immutable) minimum streamflow value for a given station or (2) a time series of streamflows representing the maximum peak streamflow between station visits.

This report describes the background, operations, and interpretations leading to annual and approximately quarterly series peak-streamflow records for stations currently (2018) operating in the CSG network. The database represents many years of data collection and iterations of widely used indirect methods for peak-streamflow measurement using the (1) culvert-flow method, (2) slope-area method, and (3) flow-over-road method (embankments or roadways). Numerous sections in the report provide extensive discussion of how these methods are generally applied as part of analyst-directed interpretations of the peak gage heights from the CSG network.

The database of annual and approximately quarterly series peak streamflow through water year 2015 published through USGS ScienceBase is described. The database facilitates publication of annual and approximately quarterly series peak-streamflow data because peak gage heights in feet and peak streamflows in cubic feet per second from the CSG network are not fully compatible with existing (2018) storage features of the USGS National Water Information System (NWIS) peak-streamflow database. The database contains 764 records (lines of data) composed of peak gage heights (headwater and tailwater), of which 747 peak streamflows are counted. These streamflows are counted in the form of a zero, a numerical entry other than zero, an inequality, or an interval. The 17 entries not having a streamflow designated are declared as having water-surface conditions of either “flat water surface” or “adverse water surface.” For annual peak streamflow, there are 470 peak streamflows designated as annual peaks for the CSG network through water year 2015.

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For more information about this publication, contact

Director, Texas Water Science Center
U.S. Geological Survey
1505 Ferguson Lane
Austin, TX 78754–4501

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