COLORADO FRONT RANGE FLOOD OF 2013: PEAK FLOWS AND FLOOD FREQUENCIES

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Abstract: In September of 2013, the Colorado Front Range foothills experienced an extensive period of rainfall that culminated in a major flood that peaked in many streams on Friday, the 13th. Rainfall depths of up to 18 inches were recorded over a 10 day period, with a large proportion of the rainfall falling over a 36 hour period. These foothill locations on average receive between 17 and 19 inches of precipitation annually; this event delivered an average year of rainfall at some locations. In response, many streams in the South Platte and Arkansas River basins flooded. To quantify the magnitude of the flood peaks, several entities implemented forensic hydrology methods to develop peak flow estimates, including the NRCS, USGS, and retired USGS hydrologist Bob Jarrett. Peak discharges of up to 60,000 cfs were quantified. Peak flow unit discharges varied by catchment size, as would be expected. Unit discharges as large as 1340 cfs/mi^2 were measured. For locations with streamgages, revised flow frequency estimates were developed using the logPearson methodology as presented in Bulletin 17B. The 2013 peaks were included in this analysis. For the larger streams impacted by the flooding, this flood had return intervals ranging from a 5- to 25-year flood (Fountain Creek), 25- to 50-year flood (Cache la Poudre River, South Platte River), 100-year flood (Big Thompson River), 100- to 200-year flood (Boulder Creek, Coal Creek), and greater than the 200-year flood (Lefthand Creek, Saint Vrain Creek, Fish Creek).

INTRODUCTION

In September of 2013, large portions of the Colorado Front Range foothills (Figure 1) received an unusual amount of rainfall, with up to 18 inches falling in 10 days. Raingage data over the most severely-impacted foothills indicate up to 15 inches fell in Larimer County, 18 inches fell in Boulder County, and 16 inches fell in El Paso County, the three counties most impacted by the flooding. The highest measured rainfall depths are similar to the average annual rainfall for these areas. The majority of the precipitation fell during 36 hours, on September 11th and 12th. These rainfall data were collected in settled areas and primarily within valley bottoms in many portions of the flood extent; rainfall depths and intensities may have been even greater on some mountain slopes (driven by orographic lift) and in remote areas that were void of ground-based data collection.

As a result, large floods occurred in the South Platte and Arkansas basins, in the Cache la Poudre, Little Thompson, Big Thompson, and South Platte Rivers, and in the Saint Vrain, Left Hand, Boulder, Coal, and Fountain Creeks (Figure 1). Peak flow estimates were developed using forensic hydrology methodologies in these and their contributing streams. Using these peak flow estimates, revised flood discharge relationships were developed at streamgage locations. This report provides a summary of peak flow estimates developed primarily by the Natural Resources

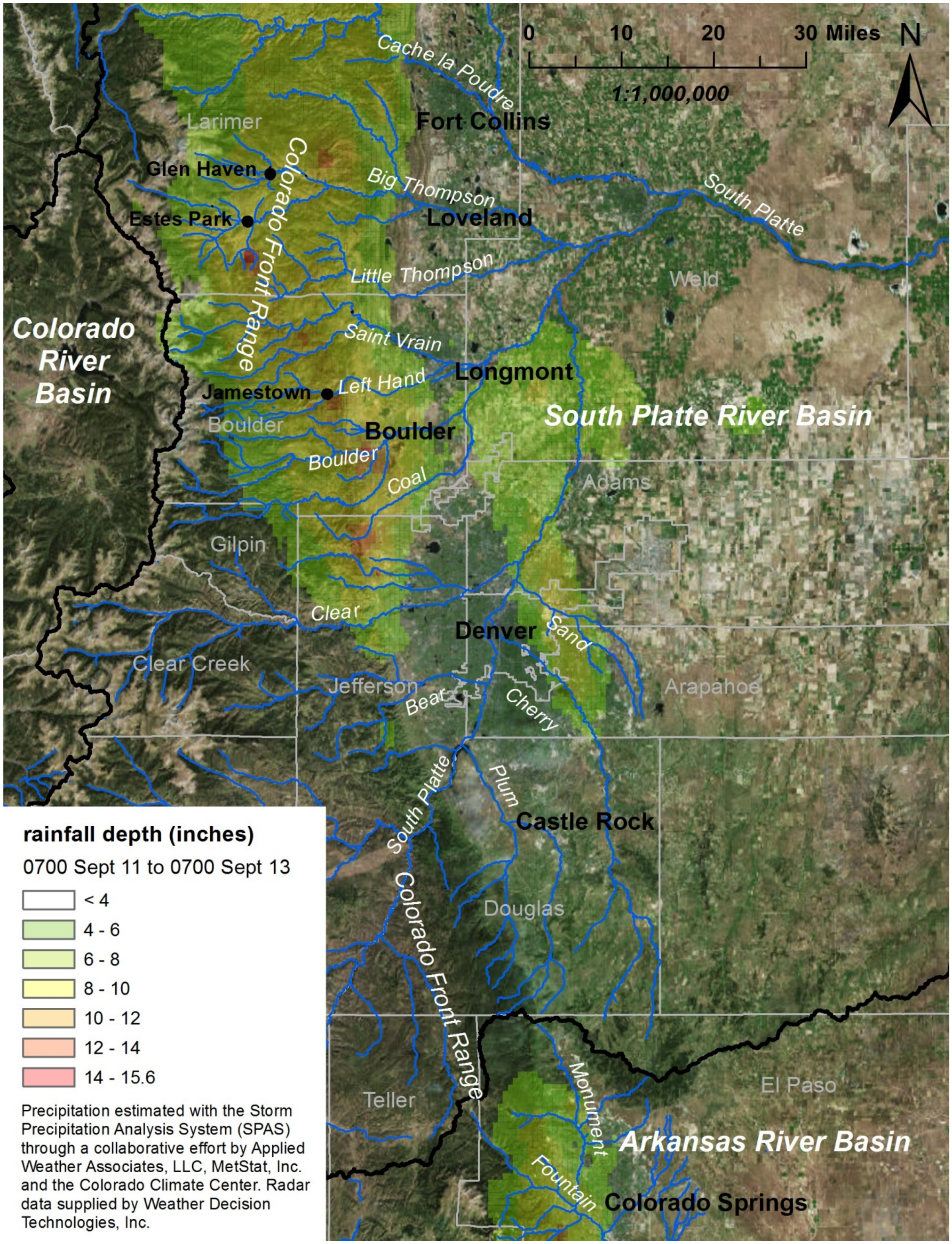

Figure 1 Rainfall depths and streams impacted by the 2013 Colorado Front Range Flood.

Conservation Service (NRCS), the U.S. Geological Survey (USGS) and by Bob Jarrett, a retired USGS research hydrologist. Unit discharges are also presented. Based on updated streamgage analyses, return intervals of the flood peaks are provided.

METHODS

Peak Flow Estimation

Data collection efforts were performed by the NRCS (Steven Yochum and Dan Moore), the USGS, and Bob Jarrett. Peak flow estimates were developed using several methods, including the slope-conveyance, step-backwater, and critical depth methods. Two-dimensional computational modeling was also performed for one site (St. Vrain Creek in Lyons). The slope-conveyance method assumes uniform flow and applies the Manning's equation to cross sectional data. This method requires a Manning's *n* estimate, which is problematic since *n* varies by stage and debris loading (Limerinos, 1970; Bathurst, 1985; Lee and Ferguson, 2002; Wilcox and Wohl, 2006; Reid and Hickin, 2008; Ferguson, 2010; Yochum et al. 2012), and since little field-based data has been collected during large floods for informing the computations. The step-backwater method implements a series of cross sections and 1-dimensional gradually-varied flow computations using such software as HEC-RAS. Discharge is varied until a series of high water marks are matched by the simulated water surface. This method also relies upon uncertain Manning's *n* estimates. The critical depth method assumes critical flow at a control cross section, such as at a constriction or drop off of a channel, or assumes critical flow in a high gradient channel. For slopes over 1 percent, it has been found that a critical depth assumption, with 3 to 6 replicate estimates from multiple cross sections within the reach of interest, can obtain estimates within $\pm 15\%$ of discharges measured with current meters (Jarrett and Tomlinson 2000; Webb and Jarrett 2002; Jarrett and England 2002). This method avoids estimation errors imposed by unknown Manning's *n* coefficients for large flood events, but is instead reliant upon the critical depth assumption and is sensitive to such conditions as backwater and localized supercritical flow. A more detailed discussion of each method is provided in Webb and Jarrett (2002).

Peak flow data were obtained from Jarrett (2014) – Applied Weather Associates, Yochum and Moore (2013) – NRCS, from Kimbrough (2014) – USGS, and from the USGS's National Water Information System (NWIS, http://waterdata.usgs.gov/co/nwis/sw). The majority of the estimates (NRCS, Jarrett) were developed using the critical depth method, in higher-gradient channels (> 1 percent). (The USGS primarily relied upon the slope-conveyance and step-backwater methods.) Using the critical-depth method, peak flow estimates are made using a single cross section, implementing high water marks at each location. Replicate measurements (separate flow estimates developed for several adjacent cross sections) were made for each reach of interest, to assess the reliability of the overall estimate. During floods, higher-gradient channels can flow at or near critical depth, where the Froude number (*Fr*) is unity and the following equation is applied to each cross section:

$$Fr = 1 = \frac{V}{\sqrt{gD}} \tag{1}$$

where, V is the average cross section velocity, D is the average flow depth ($D = A/T_w$), A is the flow area, T_w is the top width, and g is the acceleration due to gravity. Using the continuity equation, $Q = VA$, the Froude number equation can be reformulated to obtain flow rate:

$$Q = A\sqrt{\frac{gA}{T_w}} \tag{2}$$

where Q is the discharge in cubic feet per second (cfs).

Flood-Frequency Analysis

The flood frequency analyses at streamgages where 2013 flood peaks are available were performed using logPearson frequency analyses as described in Bulletin 17B (Interagency Advisory Committee on Water Data, 1982), with the assumptions of independence and stationarity. The Expected Moments Algorithm (EMA) method, to be presented in Bulletin 17C, was not implemented. 2013 peak flows were included in the analyses. Record lengths varied from 131 to 10 years, with an average of 45 years. All of these streamgage records are affected by flow regulation (stream diversions and reservoirs). Weighted generalized skews were implemented for streamgages that had a sufficient number of similar watersheds for grouping, to adjust results for stream gages with a shorter record length. Flagged outliers were typically retained, unless they were confirmed as high outliers associated with significant dam failures. The historic peak algorithm was implemented for records that included historic peaks. Peak flow values for the remainder of the periods of record were obtained from the USGS NWIS system (http://waterdata.usgs.gov/co/nwis/sw), and the Colorado Division of Water Resources (http://www.dwr.state.co.us/Surfacewater/default.aspx).

RESULTS AND DISCUSSION

Peak flow estimates of up to 60,000 cfs (S. Platte River at Fort Morgan) were computed (Appendix A), with the highest discharges measured in the St. Vrain, Left Hand, Boulder, Little Thompson, and Big Thompson watersheds (Figure 1, Table 2), as well as the S. Platte River into which all of these streams drain. Detailed figures illustrating peak flow measurement points, as well as unit discharges and return intervals, are provided (Figures 3 through 6). In some of these streams, this peak flow was the flood of record (St. Vrain, 122 years of record; Left Hand, 17 years; Little Thompson, 18 years), while other impacted streams have higher flows in their streamgage records (Big Thompson River, 1976; Boulder Creek, 1921; S. Platte River, 1935).

Table 1 Peak flow unit discharges by watershed size.

Watshed Size (mi^2)	< 4	4 to 25	25 to 200	> 200
Maximum Unit Discharge (cfs/mi^2)	1340	480	320	114

Unit discharges of up to 1340 cfs/mi^2 were computed, with these unit discharges varying by watershed size (Table 1). The variation by scale illustrates the variation in precipitation depth and intensity by area, with some local areas, such as mountain slopes, receiving substantially more rainfall than other areas through such a mechanism as orographic forcing. The locations with the highest unit discharges were oftentimes associated with the most severe damages, such as the Glen Haven, Fish Creek, upper Little Thompson, and Jamestown areas (Figures 3 and 4), as well as the foothills immediately adjacent to Boulder (Figure 4). Traditionally, it is often assumed that high-intensity rain events are limited to elevations below 7500 feet in the Colorado

Front Range. However, large unit discharges were computed at some locations with higher elevations (upper Little Thompson, Estes Park, Glen Haven areas); relevant catchments with >95 percent of their area above 7500 feet are marked by the red circles (Figure 3).

The peak flow and unit discharge data indicate that available raingage data appear to have missed some of the key watersheds impacted by the flooding. These raingage data are often biased towards valley bottoms, usually do not include rainfall intensity data but rather provide daily depths (CoCoRaHS data), and are absent in many large areas where public land is dominant. Calibrated radar data have also missed some of these locations (Figure 1), though localized extreme rainfall intensity could be a complicating factor. Examples of where large peak flow estimates (and observed damages) differ from precipitation data include Glen Haven (Figures 1 and 2) and the upper Little Thompson (Figure 1).

Table 2 Peak flow and flood frequency estimates for the 2013 Colorado Front Range Floods.

ID	Description	Area (mi^2)	Peak Flow (cfs)	Return Interval (non-regulatory)	Years of Record
06751150	N. F. Cache la Poudre River, blw Halligan Res.	354	1,050	5- to 10-year	15
06751490	N. F. Cache la Poudre River, at Livermore	538	4,510	25- to 50-year	27
06752000	Cache la Poudre River at Canyon Mouth	1,054	9,730	25- to 50-year	131
06752260	Cache la Poudre River at Fort Collins	1,128	8,140	25- to 50-year	39
06752280	Cache la Poudre River above Boxelder Creek	1,244	7,010	10- to 25-year	34
06752500	Cache la Poudre River near Greeley	1,879	3,770	10- to 25-year	95
06734500	Fish Creek near Estes Park	16	6,900	>200-year	49
06735500	Big Thompson River near Estes Park	155	----	>200-year	67
06736000	N. F. Big Thompson River at Drake	85	----	>100-year	52
06738000	Big Thompson River at Canyon Mouth	305	16,200	~100-year	90
06739500	Buckhorn Creek near Masonville	136	11,000	25- to 50-year[2]	30
06741510	Big Thompson River at Loveland	531	19,000	~100-year	35
06721500	N. St. Vrain Creek near Allens Park	33	----	~2-year	17
06724000	St. Vrain Creek at Lyons	216	24,700[1]	>200-year	122
06725400	Left Hand Creek near Boulder	52	----	>200-year	17
06725000	Left Hand Creek at Mouth	73	----	>200-year	19
06727500	Fourmile Creek at Orodell	24	2,510	50- to 100-year	22
06727000	Boulder Creek near Orodell	102	2,020	100- to 200-year	106
06730200	Boulder Creek, at N. 75th St., near Boulder	307	8,400	100- to 200-year	27
06729500	S. Boulder Creek, near Eldorado Springs	109	2,120	50-year	120
06730300	Coal Creek near Plainview	15	----	100- to 200-year	43
06719505	Clear Creek at Golden	394	1,530	5-year	39
06713500	Cherry Creek at Denver	410	1,410	2- to 5-year	61
06710150	Big Dry Creek, below C-470	11	527	5- to 10-year	10
06709000	Plum Creek near Sedalia	275	1,260	5- to 10-year	28
06708800	E. Plum Creek, near Castle Rock	116	930	5- to 10-year	14
06711565	S. Platte River at Englewood	3,391	1,140	< 2-year	31
06714215	S. Platte River at 64th Ave, Commerce City	3,895	5,220	< 2-year	32
06721000	S. Platte River at Fort Lupton	5,043	10,300	~25-year	40
06759500	S. Platte River at Fort Morgan	14,648	60,000	25- to 50-year	28
07103700	Fountain Creek near Colorado Springs	102	1,540	10- to 25-year	56
07103703	Camp Creek at Garden of the Gods	9	339	10- to 25-year	22
07105000	Bear Creek near Colorado Springs	7	222	25- to 50-year	22
07103800	W. Monument Creek at Air Force Academy	15	151	25- to 50-year	44
07104905	Monument Creet at Bijou St, at CO Springs	235	6,150	5- to 10-year	11
07105490	Cheyenne Creek at Evans Ave, at CO Springs	22	1,470	~50-year	22
07105500	Fountain Creek at CO Springs	392	8,670	10- to 25-year	38
07105530	Fountain Creek below Janitell Road	413	10,300	5- to 10-year	24
07105800	Fountain Creek at Security	500	12,600	5- to 10-year	49
07106000	Fountain Creek near Fountain	681	15,300	~25-year	46
07106300	Fountain Creek near Pinon	865	11,800	10- to 25-year	41
07106500	Fountain Creek at Pueblo	925	11,800	5- to 10-year	74

----: data withheld due to contractual obligations
(1): provisional data (2): problematic flood-frequency statistical analysis

The results of the flood frequency analyses where peak flow data are available at the current and historic streamgages operated by the USGS and the Colorado Division of Water Resources (CDWR) are provided (Table 2, Figures 3 through 6). Record lengths varied from 131 to 10 years, with four gages having more than 100 years of record available and the primary impacted streamgages (≥50 year flood) having at least 22 years of data available. Return intervals ranged from <2 years (>50 percent chance of occurrence in any given year) to >200 year flood (<0.5 percent chance of occurrence). Importantly, these results do not refer to regulatory flows but are instead the results of updated statistical analyses of the streamgage records.

In terms of these streamgage analyses, the most severely impacted watersheds were the Big Thompson (16,200 cfs at canyon mouth, ~100-year flood), the St. Vrain (24,700 cfs in Lyons, >200-year flood), Left Hand Creek (>200-year flood), Boulder Creek (8400 cfs just downstream of Boulder, 100- to 200-year flood), and Coal Creek (100- to 200-year flood). The Little Thompson watershed was also severely impacted, though insufficient data were available for the frequency analysis. Few streamgages exist on streams within the foothills; the only higher-elevation gages in this analysis were in the upper Big Thompson and St. Vrain watersheds. The return intervals of most of the peak flows estimated on smaller foothills streams cannot be easily associated within the context of a frequency analysis, due to the lack of annual peak flow data, though comparison with pre-flood regional regressions (Capesius and Stephens, 2009) indicates high return intervals in the most severely-impacted streams (Yochum and Moore, 2013).

The primary watersheds impacted by this rain event drain into the South Platte River. Just downstream of Chatfield Reservoir, the flow was measured to peak at only 552 cfs (1.05- to 1.25-year). Downstream of Denver, the flow increased to 5220 cfs (~ 2-year) before increasing to 10,300 cfs at Fort Lupton (~25-year), upstream of St. Vrain, Big Thompson, and Cache la Poudre confluences, and 60,000 cfs at Fort Morgan (25- to 50-year), downstream of the major runoff inputs. Lesser impacted watersheds include the Cache la Poudre (peak of 9730 cfs, 25- to 50-year), and Monument Creek, in the Arkansas River basin (peak of 15,300 cfs, ~25-year).

Figure 2 Flood damage in Glen Haven, along West Creek (photograph taken on 10/16/2013).

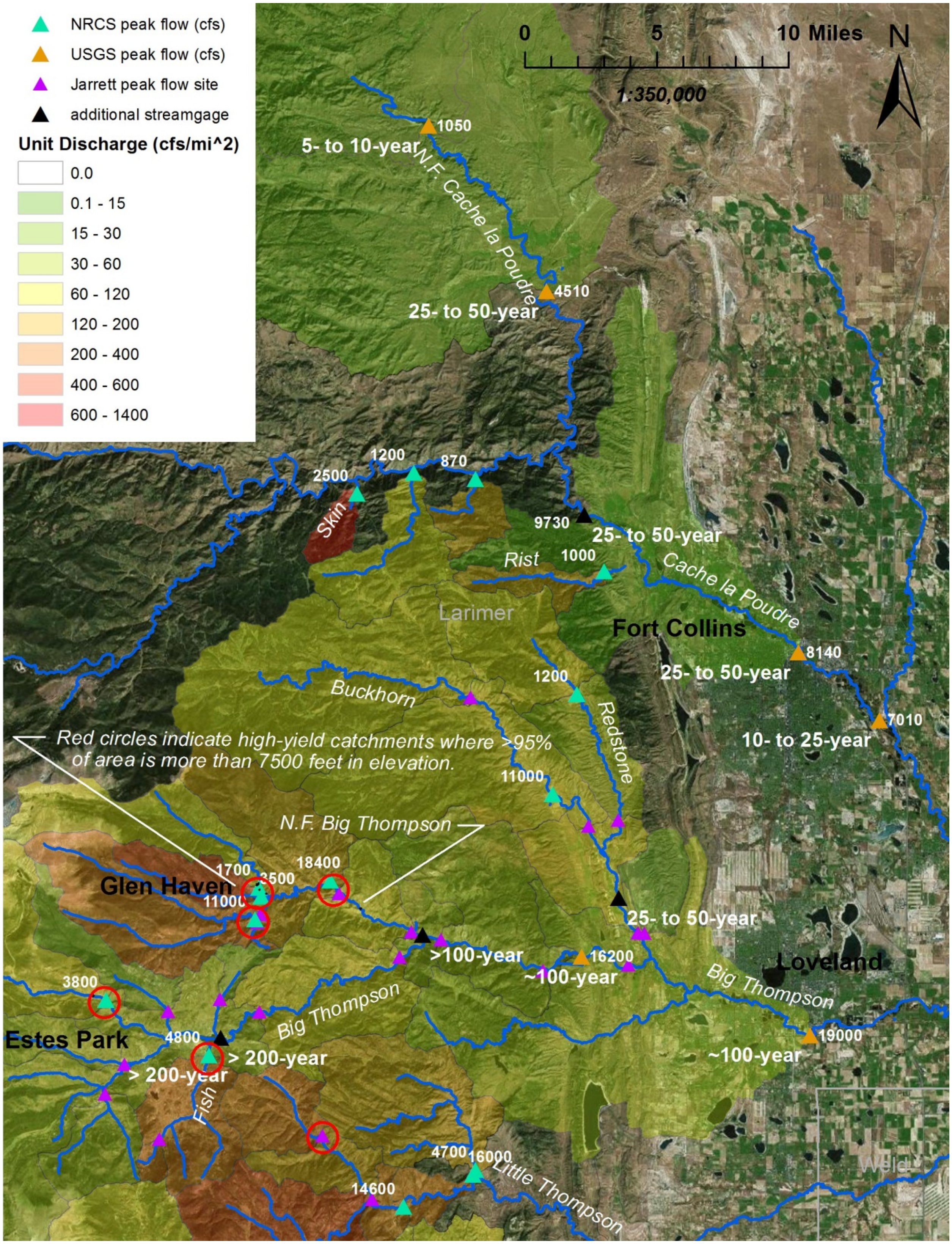

Figure 3 Peak flow estimates, unit discharges, and flood frequencies, northern portion of flood-impacted area.

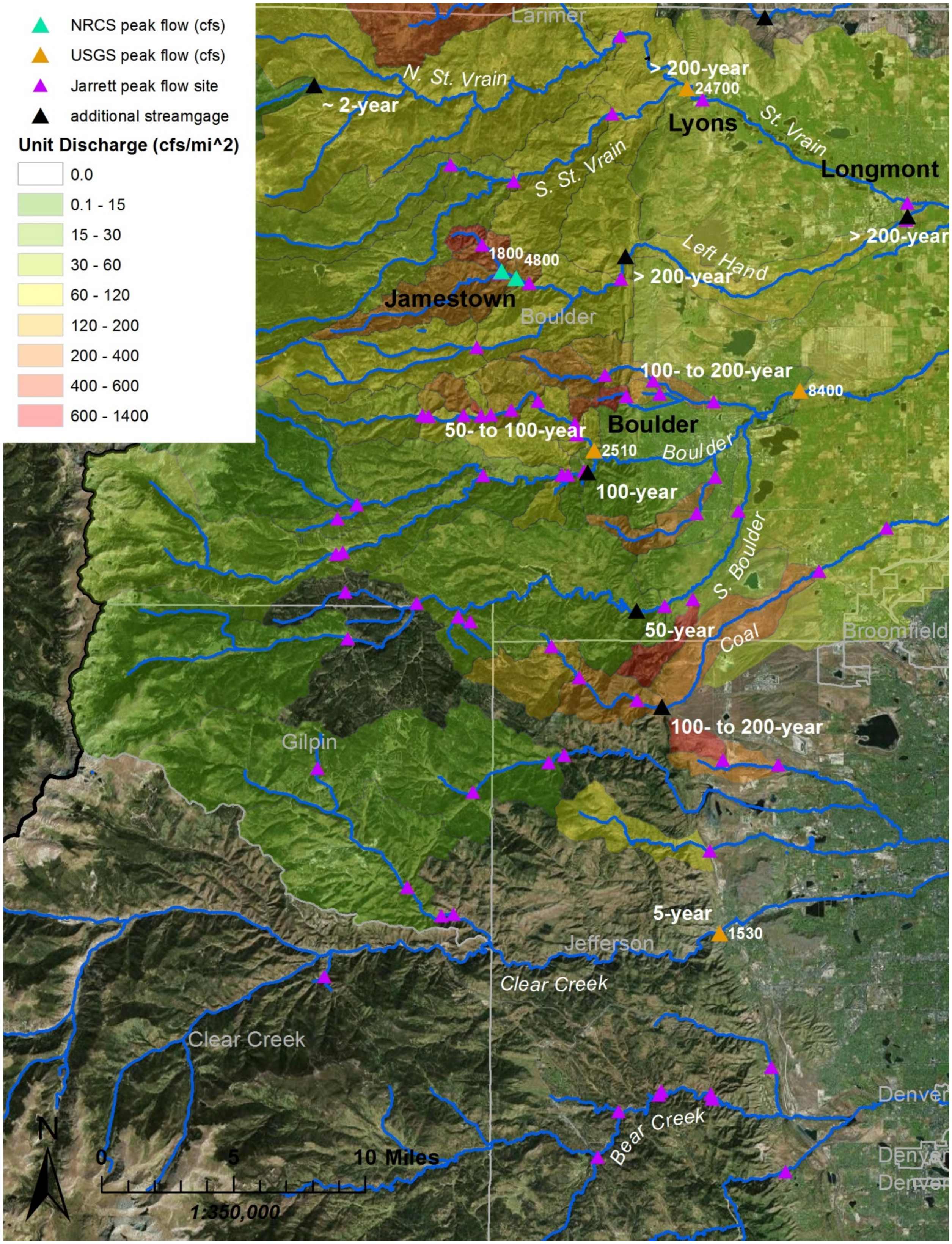

Figure 4 Peak flow estimates, unit discharges, and flood frequencies, central portion of flood-impacted area.

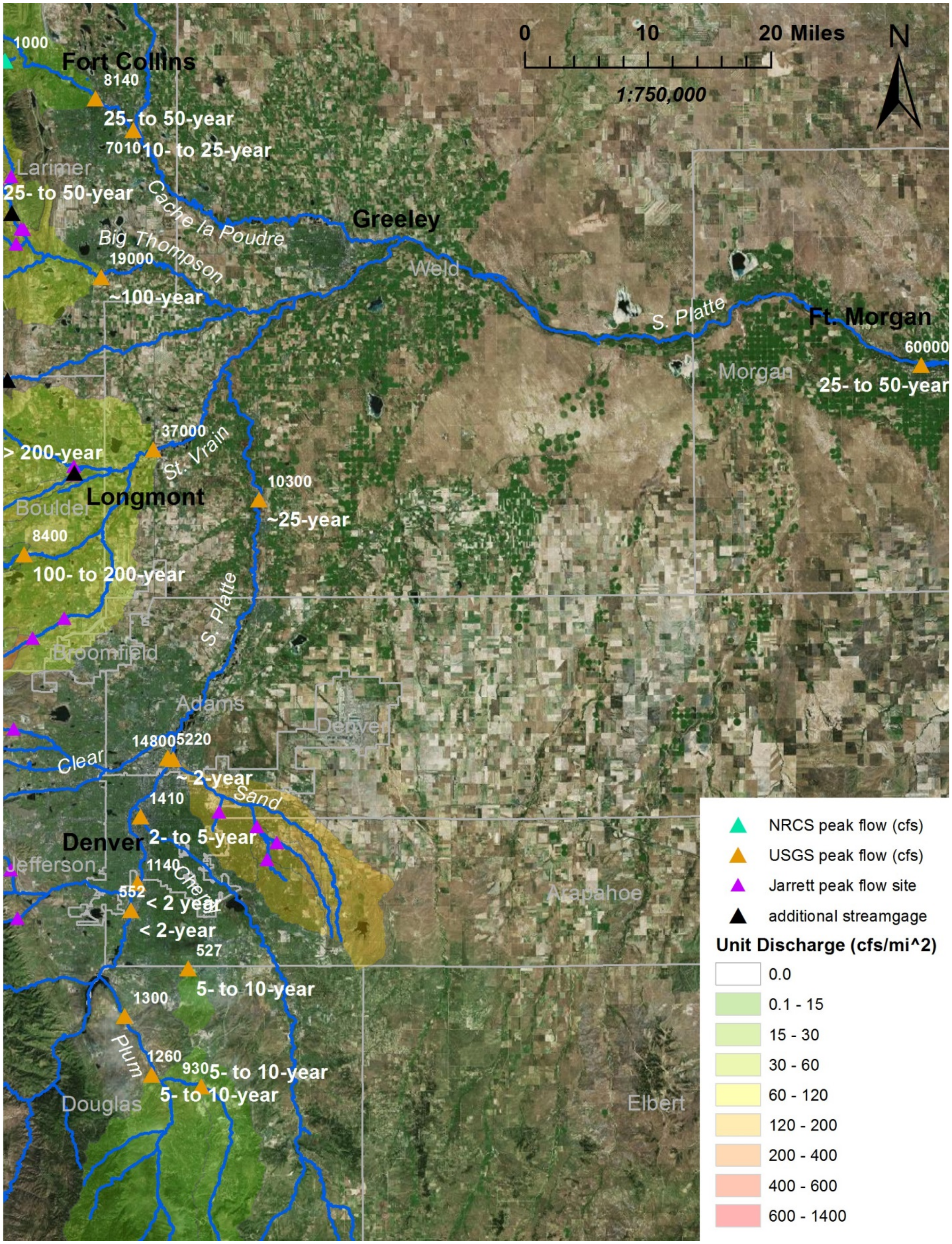

Figure 5 Peak flow estimates, unit discharges, and flood frequencies, S. Platte portion of flood-impacted area.

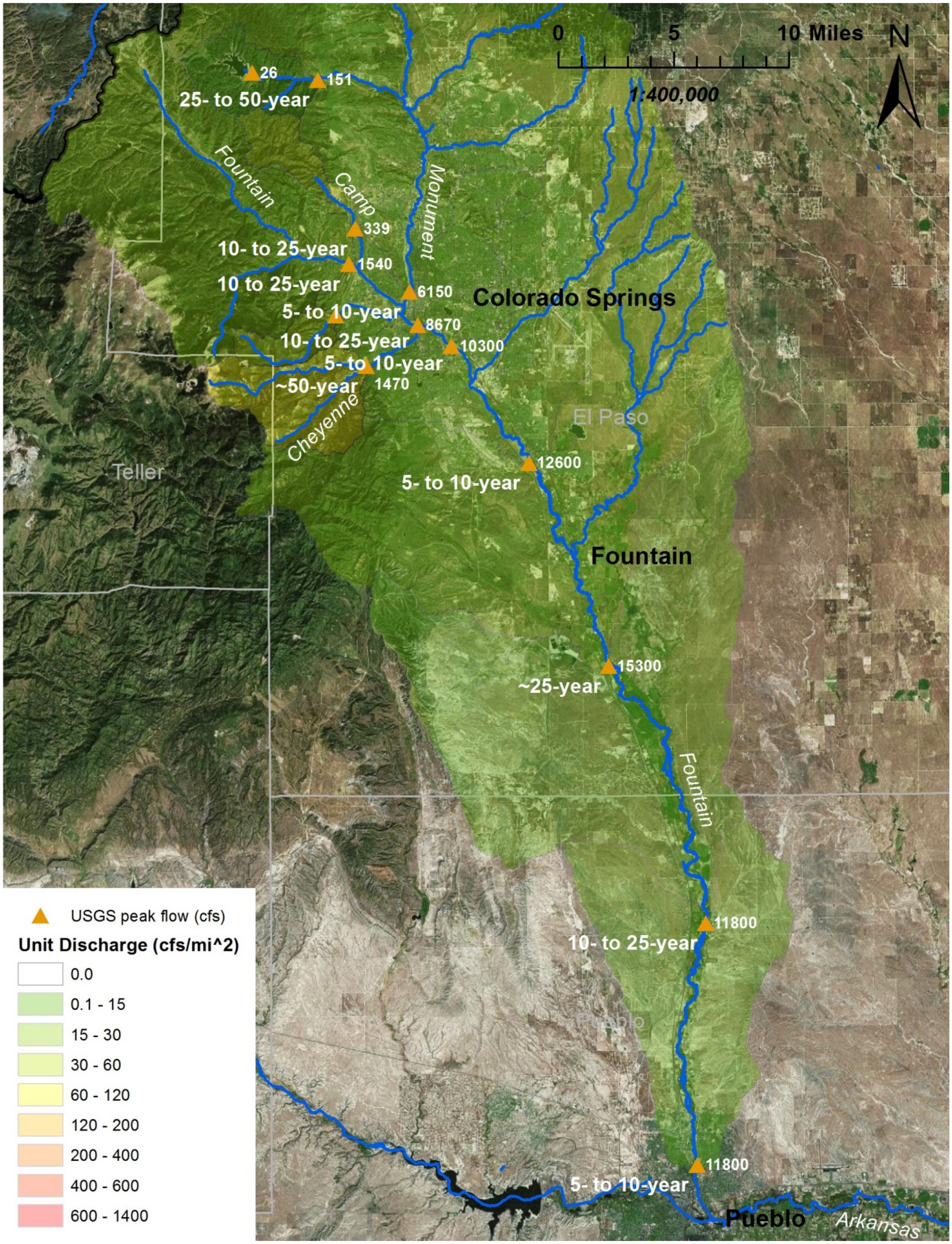

Figure 6 Peak flow estimates, unit discharges, and flood frequencies, southern portion of flood-impacted area.

CONCLUSIONS

Peak flows, peak unit discharges, and flood frequencies have been provided for the spatial extent of the September 2013 Colorado Front Range Flood. Peak flows of up to 60,000 cfs were estimated, with documented unit discharges of up to 1340 cfs/mi^2 (in foothills immediately adjacent to Boulder) and return intervals ≥100-year flood in the most heavily-impacted primary streams draining the rainfall area (Big Thompson, Little Thompson, St. Vrain, Left Hand, Boulder, and Coal). Not addressed in this paper are flood duration values; this event had substantial flood durations, which increased damages.

ACKNOWLEDGEMENTS

Bob Jarrett is appreciated for the great deal of fieldwork and computation time spent collecting the majority of the peak flow estimates from the flood. Appreciation is also expressed for Dan Moore, for data collection and peak flow computations for many of the NRCS peak flow estimates. The hydrologists and hydraulic engineers with the USGS and the Colorado Division of Water Resources are valued for the streamgaging efforts, providing the annual peak flow data required to perform the flood frequency analyses. David Levinson and Marie Garsjo are appreciated for reviewing this manuscript.

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APPENDIX A: SELECTED PEAK FLOW ESTIMATES

Stream	Peak Flow Estimate (cfs)	Unit Discharge (cfs/mi^2)	Location (UTM 13) X (meters)	Y (meters)	Source
Skin Gulch	2,500	720	467155	4502854	NRCS
Hill Gulch	870	159	474406	4503735	NRCS
Young Gulch	1,200	79	470621	4504133	NRCS
Rist Canyon	1,000	182	482260	4498095	NRCS
Redstone Creek	1,200	69	480579	4490599	NRCS
Buckhorn Creek	11,000	125	479119	4484520	NRCS
West Creek	11,000	477	460948	4476858	NRCS
Fox Creek	3,500	486	461339	4478250	NRCS
Upper N.F. Big Thompson	1,700	93	461188	4478801	NRCS
N. F. Big Thompson	18,400	260	465534	4479229	NRCS
Fall River	3,800	104	451855	4471941	NRCS
Fish Creek	4,800	442	458121	4468575	NRCS
Little Thompson at Pinewood Springs	14,600	315	469999	4459309	NRCS
Little Thompson	16,000	316	474247	4461270	NRCS
N. F. Little Thompson	4,700	178	474382	4461560	NRCS
Little James Creek	1,800	579	466539	4440820	NRCS
James Creek	4,800	350	467412	4440397	NRCS
N. F. Cache la Poudre River	1,050	3.0	471518	4525304	USGS
N. F. Cache la Poudre River	4,510	8.4	478721	4515197	USGS
Cache la Poudre River at Canyon Mth.	9,730	9.2	481027	4501541	CDWR
Cache la Poudre River at Fort Collins	8,140	7.2	494102	4493153	USGS
Cache la Poudre River abv. Boxelder	7,010	5.6	499038	4489019	USGS
Big Thompson River at Canyon Mouth	16,200	53	480844	4474578	USGS
Big Thompson River at Loveland	19,000	36	494814	4469781	USGS
St. Vrain Creek at Lyons (**provisional**)	24,700	160	477835	4451976	USGS
Boulder Creek at N 75th St., nr. Boulder	8,400	27	484742	4433505	USGS
Fourmile Creek at Orodell	2,510	104	472162	4429872	USGS
St. Vrain Creek at I-25	37,000	42	501650	4447225	USGS
S. Platte River at Ft. Morgan	60,000	4.1	602082	4458260	USGS
S. Platte River at Ft. Lupton	10,300	2.0	515460	4440658	USGS
S. Platte River at Commerce City	5,220	1.3	503568	4406916	USGS
Sand Creek at mouth, Commerce City	14,800	79	504234	4406669	USGS
Clear Creek at Golden	1,530	3.9	479845	4400375	USGS
Cherry Creek at Denver	1,410	3.4	500001	4399176	USGS
Big Dry Creek below C-470	527	47	506206	4379294	USGS
Plum Creek at Titan Road near Louviers	1,300	4.1	497900	4373096	USGS
Plum Creek near Sedalia	1,260	4.6	501460	4365420	USGS
E. Plum Creek below Haskins Gulch	930	8.0	507916	4363882	USGS
W. Monument Creek at A. F. Academy	151	10	508424	4313513	USGS
Camp Creek at Garden of the Gods	339	36	511037	4303128	USGS
Fountain Creek near CO Springs	1,540	15	510583	4300661	USGS
Monument Creek at Bijou St	6,150	26	514804	4298726	USGS
Bear Creek near Colorado Springs	222	32	509671	4297084	USGS
Fountain Creek at Colorado Springs	8,670	22	515388	4296416	USGS
Fountain Creek below Janitell Rd.	10,300	25	517730	4294941	USGS
Cheyenne Creek at Evans Ave	1,470	68	511799	4293543	USGS
Fountain Creek at Security	12,600	25	523133	4286786	USGS
Fountain Creek near Fountain	15,300	23	528713	4272626	USGS
Fountain Creek near Pinon	11,800	14	535468	4254683	USGS
Fountain Creek at Pueblo	11,800	13	534887	4237821	USGS