BOULDER CREEK FLOODPLAIN MAPPING STUDY

Prepared for:

City of Boulder
Public Works Department
Utilities Division
1739 Broadway
Boulder, Colorado 80306

Prepared by:

Anderson Consulting Engineers, Inc.
375 E. Horsetooth Road, Bldg. 5
Fort Collins, Colorado 80525
(ACE Project No. COBLDR02)

September 2013

ANDERSON CONSULTING ENGINEERS, INC.
Civil • Water Resources • Environmental

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I. INTRODUCTION

1.1 Background

Boulder Creek is a right bank tributary to St. Vrain Creek, which is in turn a left bank tributary to the South Platte River. The Boulder Creek–St. Vrain Creek confluence is located east of the City of Longmont. The Boulder Creek watershed extends west of the City of Boulder to the Continental Divide, with elevations exceeding 13,000 feet. Boulder Creek enters the City of Boulder from the west at the mouth of Boulder Canyon and flows generally east, then northeast through the city. Numerous streams are tributary to Boulder Creek within the City of Boulder. The most significant of these streams is South Boulder Creek, which enters Boulder Creek as a right bank tributary just east of the city limits downstream of Valmont Road. A map showing the general location of the Boulder Creek study area is provided in Figure 1.1. A vicinity map of the current study reach along Boulder Creek is provided as Figure 1.2.

Boulder Creek has experienced five major flood events since 1864. The flood of June, 1894, is the largest flood of record on Boulder Creek with an estimated peak discharge of 13,000 cfs. Other notable floods on Boulder Creek were documented in 1876, 1914, 1921 and 1969 [Muller, 1983].

The effective FEMA Flood Insurance Study for Boulder County and the City of Boulder is dated October 4, 2002. The corresponding effective FEMA Flood Insurance Rate Map (FIRM) panels are dated June 2, 1995. FEMA has completed all technical data for a countywide DFIRM and Flood Insurance Study (FIS) for Boulder County which will become effective on December 18, 2012. Both the effective FIRM panels and the soon-to-be-adopted FIRM panels indicate a detailed 100-year floodplain and 500-year floodplain delineated along Boulder Creek; a floodway is not designated. However, at the local level the City of Boulder administers a conveyance zone, which is equivalent to a ½-foot rise floodway. The City also administers a high hazard zone, which is defined as the portion of the 100-year floodplain where the flow depth multiplied by flow velocity equals or exceeds a value of 4 ft^2/s, or where flood depths equal or exceed four feet. The City of Boulder is also located within the Urban Drainage and Flood Control District (UDFCD), established by the Colorado State legislature, and is subject to additional floodplain oversight and regulations promulgated by the UDFCD.

The City of Boulder has in the past and continues to evaluate and implement flood mitigation measures intended to reduce flooding potential for community residents and businesses. Over the past number of years the City has implemented improvements that serve to reduce flooding along Boulder Creek; these measures include: (a) removing a large apartment building on the right bank of Boulder Creek at Eben G. Fine Park; (b) replacing and enlarging the Broadway Street Bridge; (c) replacing and enlarging the Arapahoe Street Bridge just downstream of Broadway; (d) removing more than a dozen multi-family buildings and re-grading the left overbank to enhance conveyance of flood flows downstream of Central Park through the Boulder High School campus east of Broadway; (e) removing several buildings that represented a significant obstruction to flood flows within the left overbank of Boulder Creek east of 17th Street; (f) substantially enlarging the bridge at 55th Street (formerly Valley View Road); and (g) various bank stabilization and channel widening projects. In addition to the City of

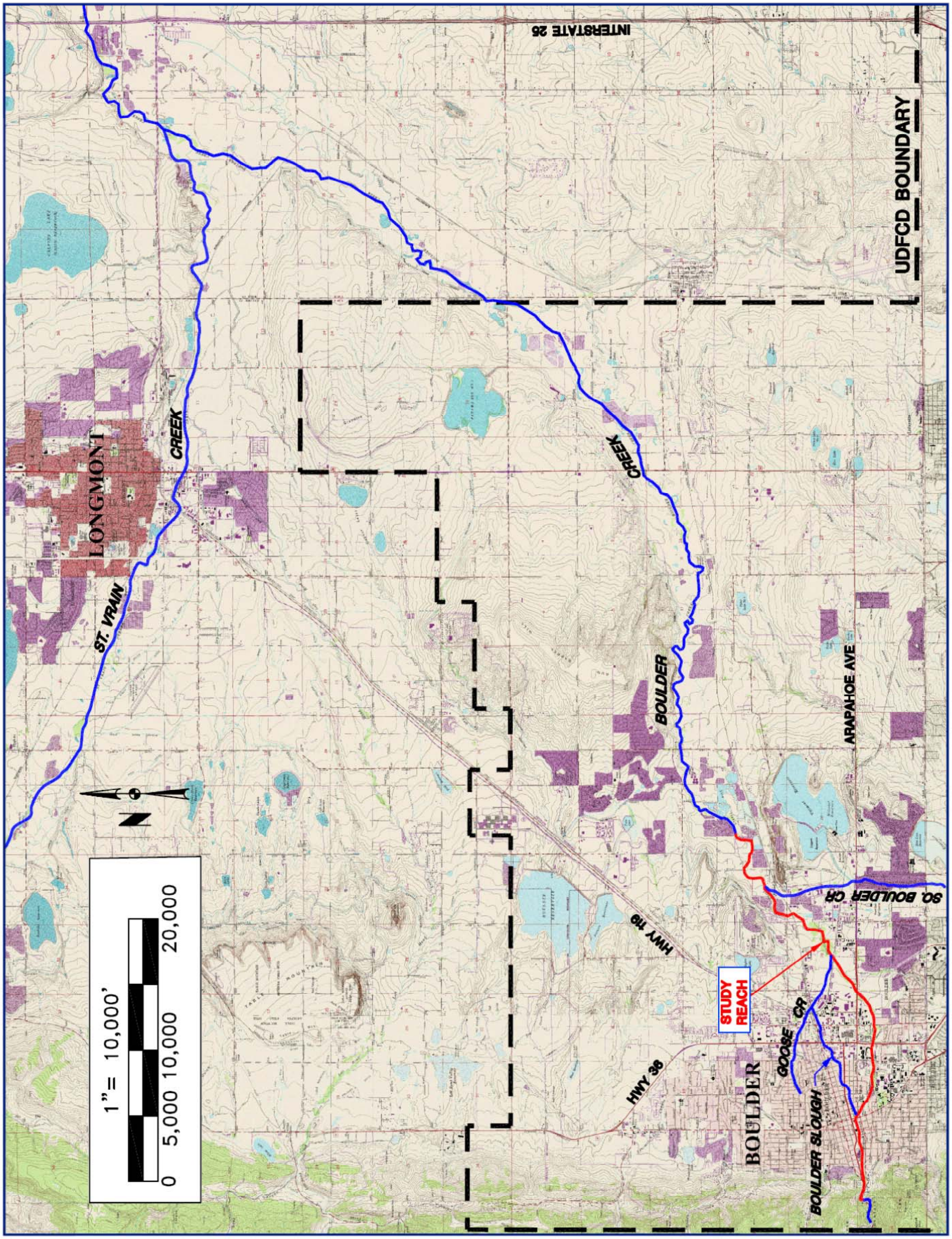

Figure 1.1 Location Map for the Boulder Creek Floodplain Study.

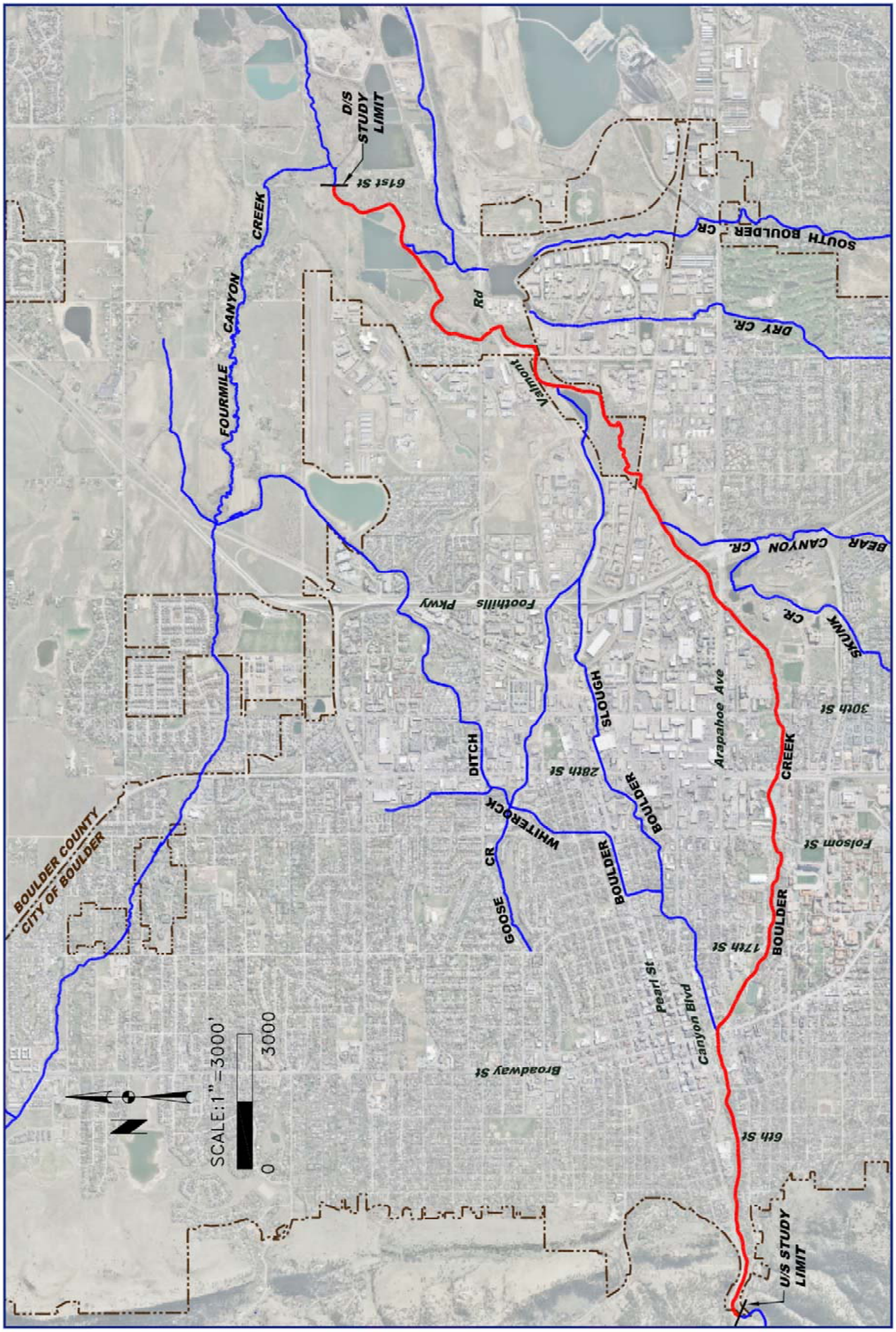

Figure 1.2 Vicinity Map for the Boulder Creek and Boulder Slough Floodplain Study

Boulder's flood mitigation measures, Boulder County recently completed construction of substantially enlarged bridges over both Boulder Creek and South Boulder Creek at Valmont Road.

1.2 Previous Studies

The effective Flood Insurance Study (FIS) and flood hazard delineations shown on the effective FIRM panels for Boulder Creek are based on two studies completed by Muller Engineering Company in 1983. The focus of the first study was delineating flood hazards along Boulder Creek through the City of Boulder, while the second study defined the floodplain along Boulder Creek from the City of Boulder to the Boulder-Weld County Line. The Muller studies utilized discharges defined by a hydrology study completed by the U.S. Army Corps of Engineers (USACE) in 1977. The flood hazard delineations shown on the effective FIRM panels have been modified by two Letter of Map Revision (LOMRs), one for the University of Colorado Research Park near Foothills Parkway, and the other for Boulder Creek and adjacent overbank flooding for the reach between 17th Street and 6th Street. Both of the LOMRs were prepared by Love & Associates; it is noted that the latter was submitted as a Physical Map Revision but was processed as a LOMR. The Muller studies and LOMRs along Boulder Creek have been incorporated into the imminent countywide FIS and DFIRM.

1.3 Purpose and Scope of the Current Study

Anderson Consulting Engineers, Inc. was authorized by the City of Boulder in 2008 to re-study flood hazards along Boulder Creek from 61st Street, upstream to the mouth of Boulder Canyon west of Boulder's city limits totaling a stream reach length of 6.2 miles. This study included hydraulic modeling of the 10-, 25-, 50-, 100-, and 500-year return period events along with the delineation of the associated floodplains, the City's conveyance zone (equivalent to the ½-foot rise floodway), and the City's high hazard zone. The City intends to revise regulatory flood hazard data at the, local, state and federal level, including the adoption by FEMA of the new 10-, 25-, 50-, 100-, and 500-year flood hazard data, floodplain mapping associated with the 100-year and 500-year events, and flood hazard mapping reflecting the conveyance zone/floodway. The City intends to continue to administer the high hazard zone at the local level, while floodplain mapping for the 10-, 25-, and 50-year events will be used locally for emergency management purposes.

All field surveying and supplemental topographic mapping required for this study was provided by King Surveyors, Inc. of Windsor, Colorado. Additional support for the study was provided by Alan Taylor Consulting, LLC of Longmont, Colorado. Mr. Taylor's insight concerning previous floodplain studies and improvement work completed within the Boulder Creek floodplain, as well as his knowledge of previous flood events and application of local floodplain regulations, were valuable assets contributing to the successful completion of this study.

1.4 Topographic Mapping

The primary base topography for both Boulder Creek and Boulder Slough was provided by the City of Boulder and consists of 1-foot contours produced in 2004 using a combination of LiDAR and photogrammetric methods. At the upstream end of the study reach, the 1-foot contours were supplemented with 20-foot contours created in 1993 and provided by the City of Boulder. All topography throughout the study reach was supplemented by field survey data collected at all bridge and culvert crossings, including channel cross sections associated with these structures. In addition, field survey data were collected to supplement the base topography in areas where the base contours did not accurately reflect local topography, or in areas where it was necessary to more closely define specific topographic features.

Within the Boulder Creek floodplain, additional field survey data were collected by King Surveyors at the following locations: (a) the north side of Canyon Boulevard between 6th Street and 9th Street, and east of 9th Street; (b) in the vicinity of the Broadway Street Bridge; (c) the south side of the creek and within the Gold Run development east of 28th Street; (d) the east side of 28th Street adjacent to the 29th Street redevelopment site, including the 28th Street and Canyon Boulevard intersection; (e) the southern portion of the Peloton site, which is located along the north side of Arapahoe Avenue between 33rd and 38th Streets; (f) in the vicinity of the University of Colorado Administrative and Research Center (ARCE) Building and Research Laboratory No. 6, both along Marine Street east of 30th Street; (g) along the Burlington Northern Railroad (BNRR) between 55th Street and Foothills Parkway; (h) Cordry Court neighborhood just north of Boulder Creek; (i) 28th Street median north of Boulder Creek; (j) the Harvest House Property and adjacent areas; and (k) in the vicinity of the two new Valmont Road Bridges over Boulder Creek and South Boulder Creek. Certified drawings showing all of the field survey data collected by King Surveyors for this project are provided in Appendix A.1. These data are also included in the AutoCAD drawing of the flood hazard work maps, as discussed in Section 3.7 of this report.

The base topography and field survey data were further supplemented by as-built topographic data of recent development, roadway improvement, and channel improvement projects. As-built topographic information was utilized to define existing ground in the following areas: (a) the southern portion of the 29th Street redevelopment site, located along the north side of Arapahoe Avenue between 28th and 30th Streets; (b) the southern portion of the Peloton site, located along the north side of Arapahoe Avenue, between 33rd and 38th Streets; (c) the intersection of Foothills Parkway and Arapahoe Avenue; (d) Bear Canyon Creek at, and south of, Arapahoe Avenue; (e) the southeast portion of the hospital complex; (f) the southern portion of the 57th Street properties west of Dry Creek; and (g) in the vicinity of a number of buildings in Flatiron Park, east of 55th Street south of Valmont. Certified drawings for the 29th Street and Peloton sites, the Foothills-Arapahoe intersection, Bear Canyon Creek, and the 57th Street properties are provided in Appendix A.2. Based on information provided by the City of Boulder, survey data in the Flatiron Park area have already been submitted to and approved by FEMA as part of the South Boulder Creek study, which is being incorporated in the Boulder County DFIRM.

1.5 Vertical Datum and Horizontal Coordinate System Considerations

The effective hydraulic study and floodplain mapping for Boulder Creek was based on the National Geodetic Vertical Datum (NGVD) of 1929. All current topographic mapping and, consequently, the current hydraulic modeling and flood hazard mapping is based on the North American Vertical Datum (NAVD) of 1988. All topographic mapping utilized for this study was provided in NAVD 1988, with the exception of the as-built information provided by the City for the southern portion of the 29th Street redevelopment area. The topographic information for that area was converted from the City of Boulder Datum to NAVD 1988 utilizing the datum conversion data provided by the City of Boulder; this datum conversion information is included in Appendix B. The benchmarks close to this location (F2-2-1, F2-5-2, F2-5-4, and WARE-1) all indicate a conversion from the City of Boulder datum to NAVD 1988 of +3.5 feet.

At the outset of the current study, the City's datum conversion data were used to define tie-ins between the previously effective flood profiles in NGVD 1929 and the current study conducted using NAVD 1988 data. At the downstream end of the study reach, Benchmark R-2-3 indicates a conversion from NGVD 1929 to NAVD 1988 of +3.0 feet; this is consistent with other benchmarks in the vicinity. Near the upstream end of the study reach, Benchmark B-3N-1 shows a conversion from NGVD 1929 to NAVD 1988 of +3.25 feet. However, since the new DFIRM will be effective prior to the adoption of this new flood hazard information for Boulder Creek, the current study has been vertically tied directly into the new FIS Flood Profiles which were produced in NAVD 1988.

II. HYDROLOGY

As part of the current Boulder Creek floodplain mapping study, the City of Boulder authorized an evaluation of the 1977 USACE hydrologic model and resulting discharges in an effort to determine whether or not a revised hydrologic modeling effort would be justified prior to conducting the new floodplain study. The result of this effort was the "Hydrology Verification Report for Boulder Creek," [ACE, October 2009] which concluded that "the 1-percent annual chance (100-year) discharges produced by the 1977 USACE study, and currently used as the effective discharges for purposes of flood regulation by the City of Boulder and FEMA, are reasonable and appropriate for conducting the current floodplain study." Both the City of Boulder and the UDFCD concurred with this conclusion. By extension, the USACE discharges for the 10-, 25-, 50- and 500-year events were also retained for the current study. Discharge profiles through the current study reach for all five flood events are presented in Table 2.1.

Table 2.1 Effective Discharge Profiles for Boulder Creek.

Cross Section ID (1983 FHAD)	Cross Section ID (Current)	Peak Discharge (cfs)					Approximate Location
		10-Percent Annual Chance (10-Year)	4-Percent Annual Chance (25-Year)	2-Percent Annual Chance (50-Year)	1-Percent Annual Chance (100-Year)	0.2-Percent Annual Chance (500-Year)	
77	37003	2,000	5,580	7,950	11,650	21,200	U/S Study Limit
73.1	35565	2,000	5,690	8,100	11,950	21,600	Near Arapahoe Ave.
64.1	33036	2,200	5,830	8,100	12,150	22,100	U/S 6th Street
58	31632	2,200	5,810	8,100	12,100	22,100	D/S 9th Street
55	30635	2,200	5,800	8,100	12,000	21,400	U/S Broadway
47	28973	2,200	5,790	8,100	11,950	21,400	BHS Footbridge
43	27520	2,200	5,780	8,100	11,900	21,400	D/S 17th Street
38	25534	2,200	5,670	7,800	11,750	20,600	U/S Folsom
33	24189	2,200	5,620	7,800	11,500	20,600	U/S 28th Street
26	22666	2,200	5,560	7,800	11,200	19,800	U/S 30th Street
21	21676	2,200	5,550	7,800	11,150	19,800	D/S 30th Street
14	18266	3,000	6,200	8,200	11,800	21,200	Bear Creek Confl.
11	16847	3,000	6,200	8,200	11,800	20,700	U/S BNRR
7	14483	3,600	7,070	9,300	13,050	23,000	D/S BNRR
9180	11687	3,450	6,760	8,400	13,050	23,000	D/S 55th Street
128	10988	3,450	7,040	9,400	13,300	27,200	U/S Valmont (new)
118	7577	3,500	7,070	9,400	13,300	27,200	D/S Valmont (old)
116	6512	3,400	7,010	9,400	13,300	27,200	U/S 61st Street

It is noted that after completion of the Hydrology Verification Report, the hydraulic modeling study reach was extended approximately 500 feet downstream of the originally anticipated study limit. Based on the discharges profiles provided in the effective hydraulic models (as documented in the Hydrology Verification Report), this modification required the addition of one additional discharge change, as shown at the bottom of Table 2.1. In addition, further review of the effective discharges revealed that the 500-year discharge of 18,600 cfs identified at effective Cross Section 9180 may have been associated with the evaluation of a 500-year divided flow path in the effective study. Due to the inconsistency of the cited discharge with the upstream and downstream discharges, the 500-year discharge at Cross Section 9180 was increased to 23,000 cfs for use in the current study.

III. HYDRAULIC MODELING AND FLOOD HAZARD MAPPING

Hydraulic modeling for the 6.2-mile study reach along Boulder Creek was conducted using HEC-RAS Version 4.0. Hydraulic modeling included analysis of the 10-, 25-, 50-, 100- and 500-year events, as well as analyses to support delineation of the conveyance zone (equivalent to the ½-foot rise floodway). Due to the relatively large number of flow splits that become hydraulically disconnected from the main flow path along Boulder Creek, 30 distinct reaches representing 7.5 miles of distributary flow paths were modeled utilizing the lateral weir and flow junction functionality of HEC-RAS. In all cases, these 30 split flow paths return to the main channel flow path at a downstream location within the study reach. Figure 3.1 provides an overview of the hydraulic modeling reaches evaluated for the current study.

3.1 Starting Water Surface Elevations and Upstream Water Surface Profile Tie-In

To define a definitive vertical tie-in at the downstream end of the study reach, Cross Section 112 from the Muller study (1983) was added at the downstream end of the current model. Starting water surface elevations for ACE Cross Section–4107 (Muller Cross Section 112) were specified based on water surface elevations taken from the 2012 FIS, as summarized in Table 3.1.

Table 3.1 Starting Water Surface Elevations for Boulder Creek.

Return Period (years)	Water Surface Elevation (ft, NAVD 1988) at ACE Cross Section –296 (Muller Cross Section 112)*
10	5166.1
25	5168.6
50	5170.2
100	5170.8
500	5172.3

*Note: Water surface elevations taken from 2012 FIS Flood Profiles, except for the 25-year WSEL which was interpolated, by discharge, from the 10-year and 50-year WSELs.

Water surface elevation information from the 1983 study for Lower Boulder Creek at the downstream end of the current study reach is provided in Appendix C. It is noted that although City of Boulder benchmark data near the downstream end of the current study reach supports a datum conversion of +3.0 feet from NGVD 1929 to NAVD 1988, the 2012 FIS Flood Profiles indicate a datum conversion of approximately +3.7 feet at ACE Cross Section 4107 (Muller Cross Section 112).

To obtain an acceptable vertical tie-in at the upstream end of the study reach, Cross Section 77 from the Muller study (1983) was added at the upstream end of the current model. The difference in current and effective (2012 FIS) 100-year water surface elevations at ACE Cross Section 37206 is 0.2 feet.

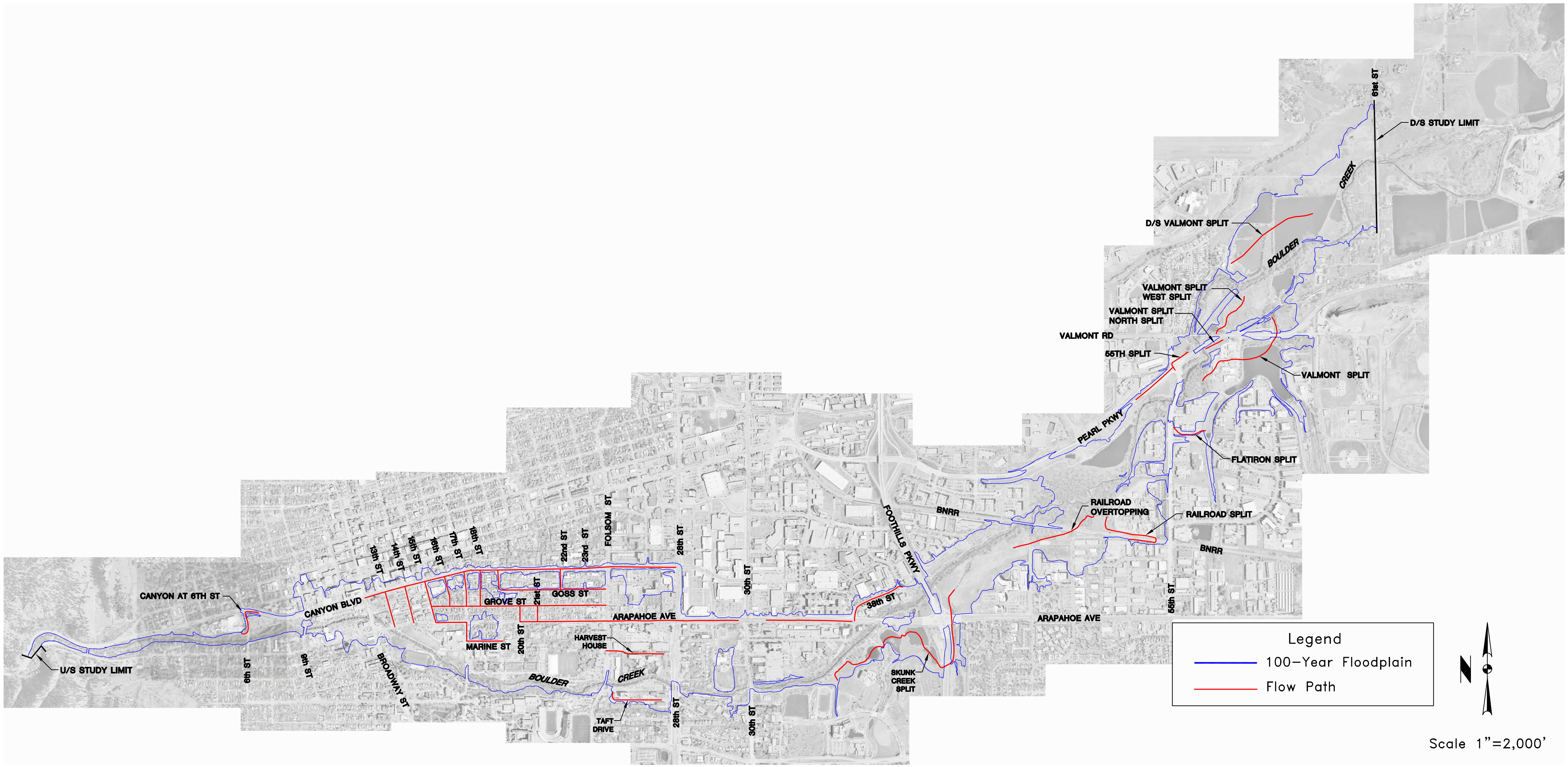

Figure 3.1 Flow Path Summary for the Boulder Creek Floodplain Study

P:\COBLDR02 BOULDER CREEK PH 2\ACAD\FIG.3.1 AERIAL SUMMARY.DWG 07/24/2013 MRC

Water surface elevation information from the 1983 study for Boulder Creek at the upstream end of the current study reach is provided in Appendix C. It is noted that although City of Boulder benchmark data near the upstream end of the current study reach supports a datum conversion of +3.25 feet from NGVD 1929 to NAVD 1988, the 2012 FIS Flood Profiles indicate a datum conversion of +3.4 feet was applied to the 100-year water surface elevation at ACE Cross Section 37206 (Muller Cross Section 77).

3.2 Boulder Creek Roughness Coefficients and Photographic Documentation

A detailed field reconnaissance program for Boulder Creek was conducted by ACE staff as part of the current study. This effort included walking or cycling the entire reach of Boulder Creek and its distributary flow paths, making visual observations of stream corridor conditions and all stream crossings. This field reconnaissance work was completed in addition to the detailed field observations of all stream crossing structures collected by King Surveyors whose notes and sketches are provided in Appendix D.1.

Manning's *n* roughness coefficients for Boulder Creek and natural overbank areas were estimated using Cowen's Method and the "Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains," [USGS, 1989]. Roughness coefficients for urbanized overbank areas within the floodplain were assigned based on generally accepted values presented in "Open-Channel Hydraulics," [Chow, 1959]. For the Boulder Creek channel, Manning's *n* values range from 0.040 to 0.060. For overbank areas within the Boulder Creek floodplain, Manning's *n* values generally range from 0.030 to 0.065, with the following exceptions: (a) where ponds or other water impoundments would result in water flowing over water or where streets provide longitudinal conveyance as part of a broader hydraulic modeling cross section, a roughness coefficient of 0.020 was utilized; (b) for other paved areas such as parking lots where curbs and other appurtenances are present, a Manning's *n* value of 0.025 was utilized; and (c) in the heavily-wooded natural area north of the BNRR where Manning's *n* values of 0.110 and 0.120 were defined.

For all streets that serve as distributary flow paths, the curb-to-curb Manning's *n* value was defined as 0.020. Roughness coefficients for overbank areas along streets range from 0.025 to 0.045. Worksheets showing the Cowen's Method and USGS procedure calculations for defining Manning's *n* values along Boulder Creek are included in Appendix D.2.

Photographic documentation of the stream corridor was also completed as part of the field reconnaissance work. Photographs taken along Boulder Creek are provided in Appendix D.3. These photographs were taken in April 2008 just prior to leaves setting on the trees and shrubs, as well as the emergence of other vegetation along the creek and throughout the floodplain. The effort to define roughness coefficients for the hydraulic model included adjustments to account for the vegetative cover that would be present during flood season.

3.3 Modeling Considerations for Boulder Creek Stream Crossings

A total of 23 bridges over Boulder Creek are included in the HEC-RAS model of the current study reach; an additional three bridges that cross watercourses functioning as distributary flow paths for Boulder Creek flood flows are also included in the current hydraulic model. Twenty of these bridges carry vehicular or train traffic, while seven are fixed bridges that primarily serve pedestrians and bicycles. Field survey notes for each of these bridges, prepared by King Surveyors as part of this study, are provided in Appendix D.1. There are eight additional pedestrian bridges over Boulder Creek and one over the Skunk Creek split flow path that the City of Boulder has constructed to break away during flood events; these bridges are not included in the current hydraulic model.

There is one small culvert installation on the Skunk Creek split flow path which was assumed to be fully obstructed for the purposes of flood hazard analysis and mapping. Finally, in addition to the BNRR Bridge over Boulder Creek, there are two box culverts through the railroad embankment that serve to convey flood flows associated with Boulder Creek. The large box culvert that serves as the pedestrian trail crossing under the railroad was included in the hydraulic model. The small box culvert east of the creek was not modeled due to its relatively limited conveyance capacity which is further restricted by blockage of the downstream end of the culvert by a significant amount of depositional material.

Hydraulic modeling associated with the effective FIS for Boulder Creek considered debris blockage for the bridges through the City of Boulder. As noted in the 1983 report, a debris blockage factor equivalent to 25 percent of the bridge opening was applied to each major stream crossing by lowering the low chord of each bridge to achieve an effective bridge opening equivalent to 75 percent of the actual bridge opening.

Based on historical hydraulic modeling precedent in the City of Boulder, as well as a high degree of debris accumulation at the 30th Street Bridge over Boulder Creek during the 1969 flood, the City of Boulder prescribed the use of the following assumptions and methodology to specify debris blockage for each non-breakaway bridge within the study reach. As directed by City Staff, bridges were assigned a percentage of debris obstruction of 15 percent or higher, except in a limited number of special cases where local conditions would support a lesser degree of obstruction. The relative degree of potential debris obstruction was assigned based on field reconnaissance efforts which identified debris obstruction categories for each bridge. Each bridge was placed in one of four debris obstruction potential categories based on the following: (a) debris production potential upstream of the subject bridge; (b) bank erosion potential upstream of the bridge; (c) shielding of the bridge from debris due to the presence of nearby upstream structures; and (d) pier nose shape. The debris obstruction category defined for each bridge and the percentage of obstruction assigned to each bridge are both identified in Table 3.2.

With the percentage of debris obstruction defined, the hydraulic model was modified as follows. The actual open area below the bridge deck was determined, as shown in Table 3.2. For bridges with

Table 3.2 Debris Obstruction Data for Bridges within the Boulder Creek Study Reach.

Location	Total Open Area Below Bridge Low Chord (SF)	Number of Piers	Debris Obstruction Category	Assumed Debris Obstruction (%)	Width of Debris at Each Abutment (FT)	Total Width of Debris at Each Pier (FT)	Net Open Area Below Bridge Low Chord (SF)
Arapahoe Avenue (near canyon)	1,108	0	2	15	9.5	N/A	944
6th Street	1,236	1	4	25	2.0	29.0	927
9th Street	1,754	1	3	20	2.0	22.0	1,409
Library	1,499	6	4	25	2.0	6.5	1,124
Library Path	350	0	2	15	7.5	N/A	298
Broadway Street	624	0	2	15	8.5	N/A	532
Arapahoe Avenue	601	0	1	5	6.0	N/A	569
Boulder High School Path	586	0	3	20	11.0	N/A	469
17th Street	1,120	0	3	20	14.0	N/A	894
19th Street Pedestrian Bridge	286	0	3	20	5.0	N/A	229
Stadium Path	664	2	4	25	2.0	9.0	497
Folsom Field Path	528	0	3	20	6.5	N/A	422
Folsom Street	561	0	2	15	4.8	N/A	478
28th Street	778	2	4	25	2.0	10.5	581
30th Street	500	0	3	20	6.0	N/A	400
Arapahoe Avenue (upstream)	757	3	4	25	2.0	12.0	564
Arapahoe Avenue (downstream)	831	1	1	5	2.0	2.0	791
Foothills Parkway	2,825	3	2	15	2.0	17.6	2,404
BN Railroad Bridge	275	1	4	25	2.0	12.5	206
55th Street	1,852	1	3	20	2.0	32.5	1,477
Valmont Street (old RR crossing)	1,281	1	2	15	2.0	23.0	1,087
Valmont Street (South Boulder Creek)	1,363	1	1	5	2.0	23.0	1,295
Old Valmont Road	228	0	4	25	5.0	N/A	170
Private Road	133	0	4	25	2.5	N/A	99

piers, a 2-foot encroachment into the bridge opening was assumed at each abutment (represented in the model as a full height flow obstruction at each abutment), while full height debris was applied at the pier(s) effectively increasing the pier width as necessary to achieve the assigned percent obstruction of the actual open area below the bridge deck. For bridges without piers, full height flow obstructions were defined at the abutments to the width necessary to achieve the assigned percent obstruction of the actual open area below the bridge deck.

In addition to the debris obstruction parameters applied to each bridge based on the information provided in the table, all handrails and guardrails associated with each structure were assumed to be completely obstructed by debris. In the case of the large box culvert, which serves as the pedestrian crossing under the BNRR and is largely offline relative to the main channel and bridge, no debris obstruction was assumed.

Standard contraction and expansion coefficients of 0.3 and 0.5, respectively, were used at all stream crossings. General contraction and expansion coefficients of 0.1 and 0.3 were used elsewhere in the hydraulic model, except when two or more bridges were situated in close succession (wherein values of 0.3 and 0.5 were used for the intervening one or two cross sections) or when topographic conditions indicated that more conservative coefficient values of 0.3 and 0.5 were applicable.

3.4 Modeling Considerations in the Vicinity of the Burlington Northern Railroad

Due to the limited conveyance capacity of both the BNRR Bridge over Boulder Creek and the pedestrian trail culvert under the BNRR, flow patterns during relatively large flood events will be fairly complex in the vicinity of the BNRR. During the 100-year event, right overbank flows would become disconnected from the main channel approximately 700 feet upstream of the BNRR. These overbank flows would be conveyed along the Railroad Overtopping Flow Path east of Boulder Creek. As these "railroad overtopping" flows approach the railroad embankment, a secondary flow split occurs whereby a relatively small discharge is carried east along a narrow corridor along the south side of the embankment. These Railroad Split flows pass over the BNRR directly west of 55th Street, returning to the right overbank of Boulder Creek via a swale along the north side of the railroad. Both the Railroad Overtopping and Railroad Split flows rejoin right overbank flows contiguous to Boulder Creek between main channel Cross Sections 15365 and 15958.

In all cases other than the Railroad Overtopping Split Flow Path, discharges for distributary flow paths were defined by HEC-RAS through use of lateral weirs or junctions. For the RR Overtopping Split Flow Path, discharges for the various return periods were defined as a combination of lateral weir flow between Cross Sections 17164 and 16847, and the right overbank bank flow that is already present at Cross Section 17164. The right overbank flow at Cross Section 17164 was added to the lateral weir flow as this right overbank flow would not return to the main channel but simply continue along the Railroad Overtopping Flow Path toward the railroad embankment east of Boulder Creek.

Special consideration was given to the geometric definition of the BNRR embankment crossing of the Boulder Creek floodplain. Due to the limited conveyance capacity of the main channel bridge and pedestrian culvert, approximately 90 percent of the 100-year discharge will overtop the railroad embankment east of the creek and west of 55th Street. Based on discussions between FEMA, City of Boulder, and ACE staff, FEMA required that the railroad embankment overtopping profile be specified using the bottom of ballast profile rather than the existing top of embankment/ballast. As referenced in Section 1.4, the survey data defining the bottom of ballast profile are included in the figures provided in Appendix A.1. It is noted that if the railroad ballast does not fail along the entire railroad frontage over which overtopping occurs, as implied by the assumption mandated by FEMA, actual water surface elevations upstream of the railroad embankment may be higher than those documented by this study.

3.5 Levee Modeling Considerations

Four features are present within the Boulder Creek study area that were identified by City staff as possibly acting as levees or floodwalls during the 100-year event. These features are: (a) a floodwall along the south side of the Boulder County Justice Center west of 6th Street; (b) a berm along the north side of Canyon Boulevard east of 6th Street, known locally as the Canyon Pointe Levee; (c) a levee along the south, west, and north sides of the Corden Pharma Colorado (formerly Roche Pharmaceuticals) Site west of 55th Street and north of the BNRR; and (d) a berm around the north end of the Flatiron Park Site, along South Boulder Creek and Dry Creek, south of Valmont Road.

The Justice Center Floodwall has been provisionally accredited by FEMA as providing protection during the 100-year flood. Consequently, the hydraulic analysis considered the floodwall being effective with respect to containing 100-year flows. For the majority of the frontage along Boulder Creek, water surface elevations associated with the 100-year event do not reach the base of the wall such that what appears to be natural ground contains flooding within the creek corridor. Along the eastern 150 feet of wall that is adjacent to the Justice Center Building 100-year water levels would impinge on the wall to a height of up to about 13 inches. In addition, ground elevations directly behind the wall (north of the wall) are high enough to contain 100-year flood levels. Along the portion of the wall that extends east of the building, ground elevations behind the wall are significantly lower than the adjacent 100-year water levels. However, due to the provisionally accredited status of the floodwall along with an on-going evaluation and floodwall/levee accreditation submittal on behalf of Boulder County regarding the Justice Center Floodwall, **the City of Boulder requested that the 100-year floodplain be delineated assuming the floodwall provides flood protection during the 100-year event.**

Information certifying that the Canyon Pointe Levee provides protection during the 100-year flood is not currently available. However, close inspection of the results of this study indicate that 100-year flood levels are contained within the curb along Canyon Boulevard directly east of 6th Street. Farther east, closer to 9th Street, 100-year flows extend across the north sidewalk but in all cases 100-year flood levels are lower than existing ground landward of the berm. **Consequently, it is concluded that the berm along Canyon Boulevard would not function as a levee during the 100-year event.**

A study is currently being conducted by Corden Pharma Colorado in an effort to certify that the Corden/Roche Levee would provide 100-year flood protection; however, that evaluation has not yet been completed. Results of the current study indicate that the Corden/Roche Levee will largely preclude 100-year flows along Boulder Creek from entering the Corden Site. **Consequently, 100-year floodplain modeling was completed for two scenarios. The first scenario assumed that the Corden/Roche Levee exists in its current configuration; this scenario was used to map 100-year flood levels on the creek side of the levee. The second scenario assumed that the Corden/Roche Levee does not exist. In this case, 100-year flows are allowed to spread through the Corden Site; the results of this scenario were used to delineate the 100-year floodplain landward of the Corden/Roche Levee. It is noted that 100-year flood levels determined with and without the Corden/Roche Levee are nearly identical due to the presence of numerous structures within the Corden Site which dictated the definition of most of the site as ineffective for flood flow conveyance.**

It is our understanding that the berm along the northern perimeter of Flatiron Park was not constructed with the intention of being certified as a regulatory levee. Consequently, this berm was not considered by the current hydraulic analysis as providing flood protection during the 100-year event. Due to its location and configuration relative to the Boulder Creek overflows that impact the area along South Boulder Creek and Dry Creek, all areas behind the berm were assumed to be ineffective for conveying flood flows. However, the 100-year floodplain was delineated landward of the berm to a level commensurate with the highest 100-year flood elevation that would impinge on the berm.

3.6 Boulder Creek Floodplain Modeling

Due to the differing flow patterns associated with the range of flood events analyzed by the current study, the 10-, 25-, 50-, 100- and 500-year events are modeled in HEC-RAS 4.0 using five different geometry files. The geometry used to model the 100-year event is the most complex of the five flood events, utilizing numerous junctions and lateral weirs to route flood flows through 30 distinct flow paths in addition to the Boulder Creek corridor. Due to the proximity of lateral weirs to bridges and junctions, a number of duplicate (or dummy) cross sections are used to properly model all of these features by providing computational separation as required in HEC-RAS.

As mentioned in the previous section, one of the 100-year plans included in the HEC-RAS model evaluates the scenario whereby the Corden/Roche Levee exists in its current configuration, while a second 100-year plan defines the condition that assumes the Corden/Roche Levee does not exist. Due to the complexity of the 100-year hydraulic system, in order to achieve computational convergence of the model, estimates of flow splits were required for virtually all divided flow paths. By incorporating these estimates into the HEC-RAS flow data for the first two scenarios, the original discharge profile is virtually indiscernible. Consequently, a third (non-computational) 100-year plan is included in the HEC-RAS model for the sole purpose of defining the original 100-year discharge profile commensurate with that documented in Chapter 2. This third 100-year plan was added simply to clarify discharge change locations dictated by the effective hydrology.

Flow obstructions are defined at appropriate locations along all cross sections that intersect buildings. Due to the urbanized nature of the upper three-quarters of the study reach, numerous flow obstructions are used in the hydraulic model. Ineffective flows are utilized to represent boundaries between active flow corridors and flooded areas that would not convey flows to a significant degree due to their location in flow shadows of roadway embankments/bridge abutments, buildings, high ground, or other physical features. In the case of water flowing through permanent ponds, the minimum elevation defined within the pond portion of the cross section was the lowest elevation associated with the ground around the downstream perimeter of the pond; thereby placing the pond bottom elevation at the minimum pond outlet elevation.

The geometry defining the hydraulic model for the 50-year event is almost identical to the 100-year geometry, with the only exception being the elimination of the Railroad Split Reach in the 50-year geometry. Due to the reduced number of flow splits and divided flow paths, the geometry associated with the 10-year and 25-year events is substantially different than that used in the 50- and 100-year models. The hydraulic model for the 500-year event utilizes geometry that is a significant departure from the 100-year geometry, using only a limited number of cross sections that are common to the 100-year model. Few split flow paths are defined in the 500-year model, wherein cross sections tend to be broad, encompassing numerous parallel 100-year flow paths and, west of Foothills Parkway, extending a considerable distance north of the 100-year floodplain.

Cross sections were defined for all events using bare earth topography from the sources identified previously in Section 1.4. HEC-RAS Version 4.0 was used to analyze the 10-year through 500-year events in the subcritical flow regime mode. The HEC-RAS floodplain model is provided on the DVD included with this report. Both tabular and graphical water surface profiles have been prepared for Boulder Creek and all distributary flow paths. Tabular water surface profiles for all five events are provided in Appendix E.1. Graphical water surface profiles in Flood Insurance Study format, showing profiles for the 10-, 25-, 50-, 100- and 500-year events, are included in Appendix E.2.

Review of the 100-year hydraulic model revealed that 100-year flows along Canyon Boulevard east of 15th Street would not be entirely contained along the north side of the street. Similarly, the 100-year flow would not be entirely contained at 30th Street just north of Arapahoe Avenue. However, it appears that potential flow splits north of Canyon, as well as the one potential flow split north of Arapahoe, would largely be confined to streets and exhibit flow depths of less than 1 foot; thereby allowing for a FEMA flood hazard designation of Shaded Zone X, rather than a Zone AE (detailed 100-year) floodplain designation. Since the area north of Canyon east of 15th Street, and north of Arapahoe at 30th Street, is encompassed by the Boulder Creek 500-year floodplain (also Shaded Zone X), the 100-year floodplain boundary was defined along the north side of Canyon Boulevard and along the north side of Arapahoe at 30th Street.

Potential flow splits along the north side of Canyon were computed using a separate HEC-RAS model that isolates the flow path along Canyon Boulevard and includes either a lateral weir or a junction with a short conveyance reach defined to the north at all locations were the 100-year flow is shown by the main hydraulic model as not being confined along the north side of the street. The 100-year discharge entering Canyon at Broadway, as computed in the main HEC-RAS model, was used for this modeling effort.

This analysis was conducted using two different assumptions, yielding a range of possible flows spilling to the north at each location. First, the analysis was conducted conventionally allowing flows to leave Canyon at each spill location, resulting in the most likely pattern of (lower) flow splits to the north from Canyon. A second analysis was conducted by allowing each split to occur, but then recharging Canyon with the total 100-year flow directly downstream of the split, essentially isolating and maximizing the potential flow split at each location. Even with the conservative assumptions imbedded in the second split flow analysis, the maximum possible flow split north of Canyon would be 80 cfs; however, the more realistic maximum flow split, as computed for the first scenario is no more than 40 cfs. At 30th Street and Arapahoe, the potential flow split to the north was computed using the weir flow module in the Federal Highways Administration culvert analysis program (HY-8). At this location, a 100-year flow split of approximately 50 cfs was computed.

Due to the relatively small discharges and minimal flow depths associated with these flow splits, it appears valid to delineate the 100-year floodplain along the north side of Canyon, and the one location north of Arapahoe, while including the potential flow split areas in the Shaded Zone X flood hazard area. The range of potential flow splits along Canyon, as well as the potential flow split at 30th and Arapahoe, are identified on the flood hazard work maps included in Appendix F. These additional hydraulic analyses are included on the DVD enclosed with this report.

3.7 Boulder Creek Conveyance Zone Modeling

Hydraulic modeling was conducted (using the 100-year, with-Corden/Roche Levee model as a basis) to define the City of Boulder conveyance zone, a flood hazard designation equivalent to a ½-foot rise floodway. In an effort to avoid computing differing discharges for split flow reaches in the unencroached and encroached analyses, the floodway analysis was conducted using a modified version of the 100-yr floodplain model wherein discharges along all flow paths were hardwired into the floodway model, based on the floodplain modeling results, and all lateral weirs and junctions were disabled.

The HEC-RAS function that determines floodway encroachments based on equal conveyance change was utilized to define the conveyance zone. Adjustments were made to the encroachments generated by HEC-RAS to ensure that the ½-foot rise criterion was met at all locations, and to optimize the floodway where possible. In addition, at the request of the City of Boulder, adjustments were made to the floodway where possible in an effort to contain the floodway to City open space property and public right-of-way, thereby minimizing impacts to private property. Due to the nominal flow within both the Railroad Split Flow Path and the Taft Drive Flow Path during the 100-year event, in the conveyance zone analysis it was possible to direct the flow in the path back into the Railroad

Overtopping Flow Path and Boulder Creek, respectively, such that a conveyance zone did not need to be defined along either the Railroad Split Flow Path or the Taft Drive Flow Path.

At the request of the City of Boulder, the following additional specific adjustments were made to the conveyance zone. In order to maximize the use of public open space for flood flow conveyance, the right side of the conveyance zone from west of 17th Street to Folsom Street was moved outward to generally match the 100-year floodplain boundary. In addition, a conveyance zone island was defined from 29th Street downstream to nearly 33rd Street in an area between Boulder Creek and Arapahoe Avenue where 100-year flood flows are generally shallow and largely obstructed by numerous buildings. Finally, the conveyance zone was not optimized through the open space areas downstream of Foothills Parkway as all existing ponds were encompassed by the conveyance zone.

In order to define the conveyance zone island within the Boulder Creek and adjacent floodplain corridor, between 29th Street and 33rd Street, the two internal "encroachments" required for each of the 4 cross sections were defined using ineffective flow boundaries. The HEC-RAS structure requires that these ineffective flow boundaries be included in both the unencroached and encroached analyses by the conveyance zone model. As a result, the 100-year water surface elevations computed by the unencroached plan in the conveyance zone model are slightly higher (no more than 0.01 feet) than the 100-year water surface elevations computed by the floodplain model at a number of cross sections. To ensure that encroachments and allowable surcharges are accurately determined, rather than use the standard HEC-RAS floodway analysis, the water surface elevations computed by the encroached conveyance zone analysis were compared to the 100-year water surface elevations determined with the floodplain analysis using an off-line Excel® spreadsheet.

At the downstream limit of the current study, defining the conveyance zone required special handling. The 1983 Muller study defined a floodway through the area encompassing the downstream limit of the current study. However, the Muller floodway was not adopted by FEMA; a floodway is not shown on the 2012 DFIRM panels, nor reflected in the 2012 FIS Floodway Data Tables. Furthermore, the Muller floodway appears to have been defined based on a 1-foot rise criterion, rather than the ½-foot rise criterion recently promulgated by the State of Colorado, as used for the current study. Consequently, tying the current floodway into the Muller floodway was not attempted. It is anticipated that the FIRM panels that will be revised pursuant to the current study will reflect the current ½-foot floodway, terminating at the downstream limit of the current study reach.

In an effort to evaluate the impact of floodway encroachments on the downstream cross section utilized in the current model (ACE Cross Section 4107, Muller Cross Section 112), an iterative procedure was first utilized to determine the energy slope required for HEC-RAS to compute the previously-specified 100-year water surface elevation at this cross section. The procedure for defining starting water surface elevations in the floodway model was changed from specifying the water surface elevation to utilizing a normal depth calculation based on the computed energy slope. Encroachments at the downstream cross section were then defined by equal conveyance change, allowing HEC-RAS to compute the surcharged water surface elevation using normal depth as the downstream boundary condition.

The Boulder Creek HEC-RAS conveyance zone model is provided on the DVD included with this report. Results of the Boulder Creek conveyance zone analysis are summarized in tabular format in Appendix E.1.

3.8 Boulder Creek High Hazard Zone Analysis

In support of the high hazard zone determination for Boulder Creek, the 100-year floodplain model was utilized to determine the velocity distribution for each cross section along Boulder Creek and all distributary flow paths. Working with the limitation in HEC-RAS of 45 slices per cross section, nine slices were specified within the channel banks, while 18 slices were requested for each of the left and right overbanks. The HEC-RAS High Hazard Zone Tool developed by Anderson Consulting Engineers (ACE) as part of this project was utilized to evaluate the results of the velocity distribution analysis in order to define the areas within each cross section where the product of velocity and flow depth equals or exceeds 4 ft^2/s. The results generated by the ACE High Hazard Tool are provided in the spreadsheets included on the DVD enclosed with this report.

The high hazard zone boundaries were delineated based on the results of the ACE High Hazard Zone Tool. Adjustments to these boundaries were made in a number of locations to: (a) match either the adjacent 100-year floodplain boundary or ineffective flow boundary; (b) encompass ponded areas and significant watercourses within the study area; (c) encompass areas where the flow depth equals or exceeds 4 feet; and (d) provide generally smooth transitions where topography and site conditions allow. In addition, at the City's request, high hazard zone islands are defined east of 30th Street and between 29th and 30th Streets. Finally, two areas that could have been designated as high hazard zone are not included on the flood hazard map. These would have been narrow, isolated areas confined to one or both gutters along the following streets: (a) Goss Street between 22nd and 23rd Streets; and (b) Marine Street between 17th and 18th Streets. Finally, for any building not entirely surrounded by the High Hazard Zone, in accordance with directions provided by City Staff, the High Hazard Zone boundary was moved off of the face of the building a distance one-half foot.

3.9 Boulder Creek Flood Hazard Mapping

Flood hazard work maps were prepared based on the floodplain and conveyance zone modeling, as well as the high hazard zone analysis, conducted for the current study. These work maps show boundaries for the 100-year floodplain, the 500-year floodplain, the conveyance zone (½-foot rise floodway), and high hazard zone. Selected base flood elevations are also shown, along with cross sections used to define geometry for the 100-year hydraulic model. Due to the substantial differences in modeling geometry between the 100-year and 500-year events discussed in Section 3.6, cross sections used in the 500-year model are not shown on the hard copy work maps provided in Appendix F.1; however, the 500-year cross sections are included in the AutoCAD® file containing the flood hazard work maps. Also included in the CAD file are floodplain delineations for the 10-year, 25-year, and

50-year events, and identification of all lateral weirs used in the model. The CAD file containing the Boulder Creek flood hazard work maps is included on the enclosed DVD.

Once adopted, portions of the current study will result in changes to the flood hazard information in unincorporated Boulder County, as well as the City of Boulder. Consequently, the City of Boulder provided the hydraulic modeling and flood hazard mapping prepared for this study to Boulder County for review and comment. Boulder County commissioned a third-party review which was conducted by Short Elliott Hendrickson, Inc. (SHE) who produced a review report (July, 2012) which is provided with this submittal. In general, the County concurs with the hydraulic modeling and flood hazard mapping presented in the current report.

In a letter to the City of Boulder dated August 6, 2012 (included in Appendix F.2), Boulder County concurred with SEH that the "ACE report and model are technically sound and meet engineering standards for floodplain delineation." In this letter, the County also requested that the detailed flood hazard zone shown along the Valmont Split Flow Path upstream of Valmont Road be represented as a shallow flooding zone and that the conveyance zone (floodway) not be mapped in this area. In addition, the County requested that a flow split be investigated over Valmont Road between the two Valmont Road bridges (where shallow flooding over the road is currently shown).

FEMA review comments rejected the approximate floodplain mapping in this area and requested additional detailed analysis of the Valmont Split. Upon further discussions with the County pursuant to FEMA comments, it was decided to eliminate the approximate mapping of the Valmont Split. It was also decided to investigate the split flow over Valmont and include this split as part of a more detailed modeling and mapping effort for the Valmont area. This more detailed flood hazard mapping is provided in Appendix F.1.

Floodplain boundary tie-ins for the 100-year and 500-year events are included on the flood hazard work maps at both the upstream and downstream ends of the current study reach. Electronic copies of both the effective FIRM panels rectified to the City's base map information, and the 2012 DFIRM panels, are included in the flood hazard work map CAD file.

Due to the incorporation of effective cross sections at both the upstream and downstream ends of the current hydraulic model, along with the use/computation of equivalent water surface elevations at the downstream/upstream cross sections, current floodplain boundaries correlate closely to effective floodplain boundaries at the current study limits. Floodplain boundary tie-ins for both the 100-year and 500-year events at the upstream and downstream ends of the current study reach are shown on the flood hazard work maps, where the current detailed study meets the effective detailed study.

IV. TWO-DIMENSIONAL HYDRAULIC MODELING FOR BOULDER CREEK

The first phase of this study included preparation of a preliminary one-dimensional (HEC-RAS) hydraulic model for the entire study reach of Boulder Creek, as well as a preliminary two dimensional (FLO-2D) hydraulic model for the upper portion of Boulder Creek. The intention of these two initial modeling efforts was to provide the City of Boulder with sufficient information to determine whether or not the preparation and adoption of a detailed two-dimensional hydraulic model would be appropriate for Boulder Creek.

The FLO-2D model for Boulder Creek was limited to the potential 100-year floodplain corridor extending from approximately 6th Street downstream to Foothills Parkway. This preliminary model utilized 100-foot square grid elements with ground elevations defined using the City's 1-foot contours. Area reduction factors were applied to each grid element, where appropriate, to reflect blocked obstructions associated with buildings and other structures identified on the 2006 aerial photographs. Roughness coefficients were defined for each grid element based on those used in the preliminary HEC-RAS model, ranging from 0.020 to 0.120.

Geometry for Boulder Creek was incorporated into the FLO-2D model by defining channel cross sections identical to those used in the HEC-RAS model, with additional cross sections interpolated for grid elements lacking a cross section from HEC-RAS. Additional cross sections were defined using the interpolation routine available in FLO-2D. All interpolated cross sections were reviewed and adjusted as necessary to reflect local channel geometry. All bridges within the study reach were represented by stage-discharge rating curves developed from a multiple profile analysis conducted using the preliminary HEC-RAS model.

Inflows to the FLO-2D model were defined based on the 100-year hydrograph computed in the SWMM model for Boulder Creek near 6th Street. The SWMM model for the Boulder Creek watershed is discussed in detail in the previously mentioned "Hydrology Verification Report for Boulder Creek" [ACE 2009] completed as part of the current study.

The 100-year peak outflow at the downstream end of the two-dimensional study reach, as computed by the FLO-2D model, compared reasonably well with the 100-year peak discharge determined by the SWMM model at approximately the same location. While direct comparison of the 100-year peak discharge computed by SWMM to the peak discharge extracted from the FLO-2D model is not precise, their values were within approximately 10 percent of each other; thereby indicating reasonably close correlation of flood routing through the preliminary study reach by the one-dimensional and two-dimensional models.

A comparison of 100-year water surface elevations generated by the one-dimensional and two-dimensional models was conducted to evaluate the relative flood hazard computed by the two methodologies. A sampling of 100-year water surface elevations from the two models indicated close correlation in the water surface elevation results from the HEC-RAS and FLO-2D models. Approximate floodplain mapping for the 100-year event was prepared based on the results of both initial hydraulic modeling efforts. Comparison of floodplain boundaries defined by the one-dimensional and two-dimensional hydraulic models indicated generally close comparison between the two floodplains. In selected areas, the area of inundation defined by FLO-2D was somewhat larger than the floodplain defined based on the HEC-RAS model. This appeared to be partly due to the relatively coarse two-dimensional grid system inadequately defining local topographic features that may have otherwise confined the floodplain. In addition, the initial version of the HEC-RAS model did not fully contain the 100-year flows at all locations along the north side of the floodplain, likely resulting in a somewhat smaller floodplain defined by the one-dimensional analysis than would actually be experienced during the 100-year event.

The conclusion of this initial modeling effort was that the 100-year flood hazard area for Boulder Creek, whether defined by the one-dimensional or two-dimensional model, would be comparable. It was the informed opinion of the Project Team that any additional accuracy that might be gained by analyzing this reach of Boulder Creek using a two-dimensional model would not be sufficient to outweigh the long term benefits of using a one-dimensional model from the standpoint of: (a) defining a conveyance zone/floodway that could be adopted by FEMA; (b) the utility of the one-dimensional model with respect to future floodplain modifications and flood hazard information updates; and (c) facilitating current and future administration of flood hazards associated with Boulder Creek. Based on the results of this analysis, the City of Boulder elected to move the study forward using a one-dimensional model for analyzing Boulder Creek.

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