Prepared in cooperation with the Fountain Creek Watershed, Flood Control and Greenway District

Remediation Scenarios for Attenuating Peak Flows and Reducing Sediment Transport in Fountain Creek, Colorado, 2013

Scientific Investigations Report 2014–5019

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

FRONT COVER. Looking upstream (north) from U.S. Geological Survey streamgage Fountain Creek near Piñon, Colorado (07106300). Photograph by Robert W. Stogner, Sr., U.S. Geological Survey.
BACK COVER. Upper Fountain Creek, just downstream from Cascade, Colorado, looking upstream (northwest). Photograph by Robert W. Stogner, Sr., U.S. Geological Survey.

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SALLY JEWELL, Secretary

U.S. Geological Survey
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Conversion Factors

Inch/Pound to SI

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	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
acre-foot per day (acre-ft/d)	0.01427	cubic meter per second (m^3/s)
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year (hm^3/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [(ft^3/s)/mi^2]	0.01093	cubic meter per second per square kilometer [(m^3/s)/km^2]
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
	Mass	
ton per day (ton/d)	0.9072	metric ton per day
ton per day (ton/d)	0.9072	megagram per day (Mg/d)
ton per day per square mile [(ton/d)/mi^2]	0.3503	megagram per day per square kilometer [(Mg/d)/km^2]
ton per year (ton/yr)	0.9072	megagram per year (Mg/yr)
ton per year (ton/yr)	0.9072	metric ton per year

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD83).

Elevation, as used in this report, refers to distance above the vertical datum.

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Initialisms and Acronyms

AEP	Annual exceedance probability
FCWFCGD	Fountain Creek Watershed, Flood Control and Greenway District
HEC	Hydrologic Engineering Center
HMS	Hydrologic Modeling System
NAVD88	North American Vertical Datum of 1988
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resource Conservation Service
NWIS	National Water Information System
RAS	River Analysis System
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey

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Abstract

The U.S. Geological Survey (USGS) in cooperation with the Fountain Creek Watershed, Flood Control and Greenway District assessed remediation scenarios to attenuate peak flows and reduce sediment loads in the Fountain Creek watershed. To evaluate these strategies, the U.S. Army Corps of Engineers Hydrologic Engineering Center (HEC) hydrologic and hydraulic models were employed.

The U.S. Army Corps of Engineers modeling system HEC-HMS (Hydrologic Modeling System) version 3.5 was used to simulate runoff in the Fountain Creek watershed, Colorado, associated with storms of varying magnitude and duration. Rain-gage precipitation data and radar-based precipitation data from the April 28–30, 1999, and September 14–15, 2011, storm events were used in the calibration process for the HEC-HMS model. The curve number and lag time for each subwatershed and Manning's roughness coefficients for each channel reach were adjusted within an acceptable range so that the simulated and measured streamflow hydrographs for each of the 12 USGS streamgages approximated each other.

The U.S. Army Corps of Engineers modeling system HEC-RAS (River Analysis System) versions 4.1 and 4.2 were used to simulate streamflow and sediment transport, respectively, for the Fountain Creek watershed generated by a particular storm event. Data from 15 USGS streamgages were used for model calibration and 7 of those USGS streamgages were used for model validation. The calibration process consisted of comparing the simulated water-surface elevations and the cross-section-averaged velocities from the model with those surveyed in the field at the cross section at the corresponding 15 and 7 streamgages, respectively. The final Manning's roughness coefficients were adjusted between –30 and 30 percent at the 15 calibration streamgages from the original left, right, and channel-averaged Manning's roughness coefficients upon completion of calibration.

The U.S. Army Corps of Engineers modeling system HEC-RAS version 4.2 was used to simulate streamflow and sediment transport for the Fountain Creek watershed generated by a design-storm event. The Laursen-Copeland sediment-transport function was used in conjunction with the Exner 5 sorting method and the Ruby fall-velocity method to predict sediment transport. Six USGS streamgages equipped with suspended-sediment samplers were used to develop sediment-flow rating curves for the sediment-transport-model calibration. The critical Shields number in the Laursen-Copeland sediment-transport function and the volume of sediment available at a given cross section were adjusted during the HEC-RAS sediment-model calibration process.

HEC-RAS model simulations used to evaluate the 14 remediation scenarios were based on unsteady-state streamflows associated with a 24-hour, 1-percent annual exceedance probability (100-year) National Oceanic and Atmospheric Administration Type II precipitation event. Scenario 0 represents the baseline or current conditions in the watershed and was used to compare the remaining 13 scenarios. Scenarios 1–8 and 12 rely on side-detention facilities to reduce peak flows and sediment transport. Scenario 9 has a diversion channel, and scenario 10 has a reservoir. Scenarios 11 and 13 incorporate channel armoring and channel widening, respectively. Scenarios 8 and 10, the scenario with the most side-detention facilities, and the scenario with the reservoir, respectively, were the most effective at reducing sediment transport and peak flow at the Pueblo, Colorado, streamgage. Scenarios 8 and 10 altered the peak flow by –58.9 and –56.4 percent, respectively. In turn, scenarios 8 and 10 altered the sediment transport by –17.7 and –62.1 percent, respectively.

Introduction

The Fountain Creek watershed, Colorado, is characterized by steep channel slopes and varied land use. Spatially distributed precipitation events result in varying rates of direct runoff. These dynamics contribute to large streamflows and sediment transport, which has caused periodic flooding, and sediment aggradation and deposition in Fountain Creek and its tributary streams. The U.S. Geological Survey (USGS) in cooperation with the Fountain Creek Watershed, Flood Control and Greenway District (FCWFCGD) assessed remediation scenarios to attenuate peak flows and reduce sediment loads in the Fountain Creek watershed.

To evaluate these strategies, the U.S. Army Corps of Engineers (USACE) Hydrologic Engineering Center (HEC) hydrologic and hydraulic models were employed. Supplemental data were needed to characterize (1) the suspended-sediment loads in Fountain Creek and its tributaries and (2) precipitation data associated with two precipitation events. These datasets were used to parameterize a hydrologic and hydraulic model consisting of 72 subwatersheds and approximately 130 river miles (mi), respectively. Stage, streamflow, and velocity data collected by the USGS were used to calibrate existing HEC Hydrologic Modeling System (HMS) (USACE, 2010a) and River Analysis System (RAS) (USACE, 2010b) models (URS, Inc., 2006a,b) for two storms of varying magnitudes and durations. The simulated results were used to evaluate the impact of 14 management scenarios on peak flows and sediment loads.

Purpose and Scope

The purpose of this report is to evaluate selected management scenarios to assist water resource managers in reducing peak flows and sediment transport caused by storms in the Fountain Creek watershed. The scope includes utilizing previously developed HEC models, calibrating and validating those models, and providing 14 management scenarios that could be used to reduce peak flows and sediment transport.

Previous Studies and Background Information

The baseline hydrology for Fountain Creek and its tributary watersheds was established by URS, Inc., for the USACE, Albuquerque District; the results of which were contained in a summary report by URS, Inc. (2006a). The report documented the development of a HEC-HMS surface-water model consisting of 22 subwatersheds in the Fountain Creek watershed and simulated flood hydrographs related to various rainfall-runoff processes for selected storm events. These results augment the USACE (2004) findings, which included the analysis of 21 tributary watersheds that were simulated using current land use, topographic and soils data, storm events and reservoir elements, inclusion of baseflow, and model calibration.

URS, Inc. (2006b), simulated the hydraulics and water-surface profiles for 21 streams in the Fountain Creek watershed in response to the 2-, 5-, 10-, 25-, 50-, 100-, and 500-year (yr) annual-recurrence flood events (annual exceedance probabilities [AEP] of 50 to 0.2 percent) assuming mixed-flow conditions (subcritical, supercritical). A similar study (URS, Inc., 2003) was conducted in Monument Creek watershed. The results from these studies provided estimates on various hydraulic variables including channel velocity, flow depth, top width, and Froude number as a function of forcings specified during the HEC-HMS analysis (URS, Inc., 2006a, 2003).

The fluvial geomorphology of the Fountain Creek watershed, which included 21 water bodies, was described by URS, Inc. (2007). The study included field investigations including streambed grain-size analysis and analysis of aerial photography and sediment transport. Existing channel conditions, which included sediment analyses, were documented. Physical observations were recorded to estimate bankfull-flow conditions and geometries, stream centerline locations, and vegetation-roughness factors. An accounting of sediment transport in each reach was completed to determine aggradation and degradation potential.

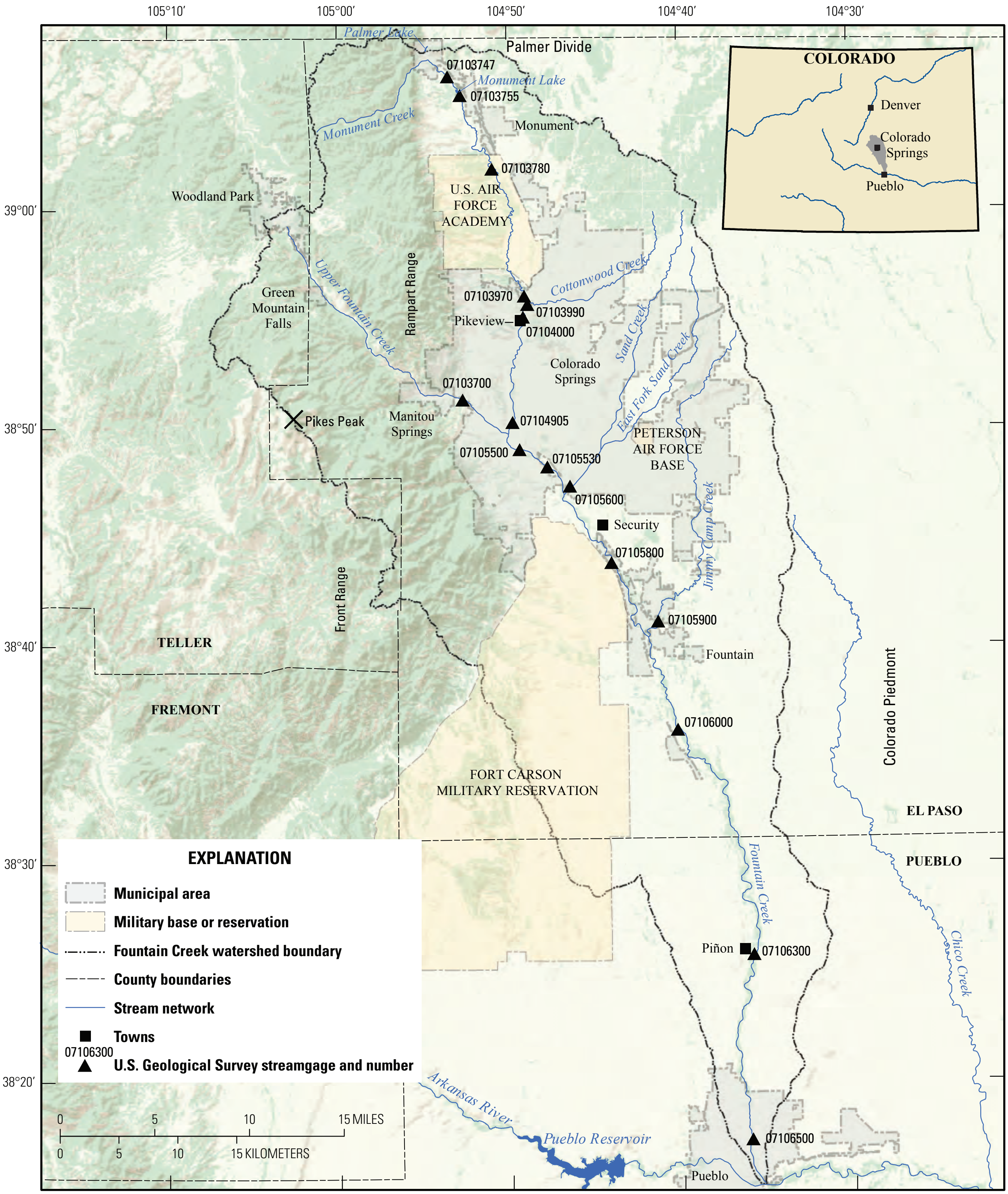
URS, Inc. (2006c), USACE (2009), and THK Associates, Inc., and Matrix Design Group, Inc. (2011), identified restoration alternatives and potential areas of access in the Fountain Creek watershed where scenarios could be implemented to reduce peak streamflow and sediment transport. The purpose of those studies was to document the existing characteristics, general conditions, and health of the Fountain Creek watershed.

A comprehensive summary of previous activities and studies in the Fountain Creek Watershed Study was prepared by the USACE (2009). The study began in 2003 and is a collaboration of 13 sponsors, representing a variety of public entities in the watershed, with the objectives of addressing flooding, erosion, and sedimentation based on principles outlined in the Watershed Management Plan (USACE, 2009). This plan is a compilation of existing information and data and describes the problems and opportunities that exist in the watershed. The objectives for improved management in the Fountain Creek watershed include the following:

- Reduce flood risk,
- Reduce erosion,
- Reduce sedimentation, and
- Improve water management.

Study Area Description

The Fountain Creek watershed (fig. 1) is characterized by a drainage area of 927 square miles with elevations ranging from 4,700 feet (ft) at the confluence with the Arkansas River to 14,109 ft at the summit of Pikes Peak (Stogner, 2000). Two significant physiographic landforms exist in the region and include the Front Range and the Colorado Piedmont (Hansen and Crosby, 1982). The Front Range is underlain principally by granite and makes up the western one-third of the watershed. In general, the soil veneer in this area is well drained and occurs on steep slopes (Larsen, 1981; von Guerard, 1989). The Colorado Piedmont is a subrange of the Front Range and makes up the remaining eastern two-thirds of the watershed (Zuellig and others, 2008). The region is underlain by sandstone and shale and alluvial and windblown deposits; the overlying soils are sandy and well drained with gentle slopes (Larsen, 1981; von Guerard, 1989). The soils and geologic formations in the Colorado Piedmont are readily erodible.



Basemap modified from ESRI ArcGIS Online, 2013
Colorado State Plane Central, North American Datum of 1983

Figure 1. Study area, Fountain Creek watershed, Colorado.

Stream Network

Fountain Creek and Monument Creek flow southeast along the Front Range and are the two principal streams that form the watershed; several tributary streams drain the watershed. The metrics of Fountain Creek and its major tributaries are summarized in table 1. Fountain Creek is partitioned into upper, middle, and lower segments and is intermittent in portions of the upper segment. The upper segment of Fountain Creek transitions from an intermittent stream at Woodland Park to a perennial stream approximately midway through the reach near Green Mountain Falls and is characterized by a sequence of riffles, pools, and runs (Stogner, 2000). The bed material ranges from sand and gravels to cobbles and boulders. The middle segment begins at the confluence of Monument Creek and continues downstream to USGS streamgage 07105800 (fig. 1), where it becomes braided. The creek is channelized and dominated by runs with intermittent pools. The banks in some locations are engineered and lined with concrete and other energy dissipaters. The bed material is variable consisting of cobble, sand, and gravel that have been scoured to bedrock. The lower segment of Fountain Creek begins immediately downstream from USGS streamgage 07105800 (fig. 1) and continues to the confluence with the Arkansas River in Pueblo, Colorado. The channel in the lower segment is wider and exhibits a more meandering and braided character than the upper or middle segments. The creek is shallow, composed almost exclusively of sequences of runs (substantial pools are uncommon). Several reaches have been channelized for irrigation and transportation purposes. The streambed material in this lower segment is composed almost exclusively of sand and gravel. Large woody-debris piles accumulate in the channel and along the banks. These debris piles, however, are not stable and frequently are moved or buried during high flows. Periods of little or no flow were not unusual along the lower segment prior to about 1980, especially during the late-summer irrigation season (Stogner, 2000).

Monument Creek, the main tributary to Fountain Creek, is a perennial stream that originates in the Rampart Range and flows eastward toward Palmer Lake, then south to Colorado Springs (fig. 1). Upstream from the confluence with Cottonwood Creek, Monument Creek is meandering and contains pools, riffles, and runs, and bed material consisting of sand, gravel, and cobble. Downstream from the confluence with Cottonwood Creek, the channel is braided; sand and small gravel compose the streambed along with manmade materials—the stream banks are intermittently lined with concrete, and extensive channelization has occurred. The braided channel conditions occur intermittently throughout the remaining length of channel with few areas of pools and riffles. In the middle section and at the upper end of the lower segment of Fountain Creek, two other major tributaries, Sand and Jimmy Camp Creeks, flow into Fountain Creek. Sand and Jimmy Camp Creeks are ephemeral, braided streams that have bed material composed mostly of sand-sized sediments (Stogner, 2000).

Land Use and Climate

The watershed is characterized by a variety of land uses including plains, forested areas, and urban-related cover. East of the foothills, streams in the watershed flow through floodplains composed of erodible alluvial sediments, and there is very rapid urban development in the watershed that has the potential to exacerbate the rainfall-runoff rates, increase storm-runoff peaks, and undermine the natural geomorphic protections against uncontrolled incision provided by bed

Table 1. Stream network and study area metrics, Fountain Creek, Colorado.

[mi^2, square miles; mi, miles; NA, Cottonwood Creek was not in the hydraulic model so the slope and Manning's roughness coefficients could not be determined; the drainage area was determined from the StreamStats Program (U.S. Geological Survey, 2013); the reach length, mean slope and Manning's roughness coefficient were all determined from the calibrated Hydrologic Engineering Center-River Analysis System model]

Stream name	Drainage area (mi^2)	Reach length (mi)	Mean slope (percent)	Manning's roughness coefficient
Fountain Creek	927	47.5	0.45	0.044–0.154
Tributaries included in project				
Upper (West) Fountain Creek	118	11.4	2.29	0.033–0.156
Monument Creek	228	20.0	0.77	0.021–0.195
Cottonwood Creek	18.8	8.0	NA	NA
Sand Creek	61.9	13.7	1.48	0.014–0.100
East Fork Sand Creek	26.5	12.4	1.27	0.040–0.100
Jimmy Camp Creek	66.7	8.6	0.51	0.014–0.098

armoring and floodplain vegetation (THK Associates, Inc., and Matrix Design Group, Inc., 2011). Sand Creek and Jimmy Camp Creeks, in particular, are in the process of converting from agriculture and undeveloped land uses to more urbanized land use (Stogner and others, 2013). On average, orographically induced rainfall generally tracks the terrain patterns in the area, with annual precipitation ranging from 12 to 14 inches at the lower elevation, downstream portions of the Fountain Creek watershed to 32 to 34 inches in the highest elevations on the western ridge near the Palmer Divide and the Rampart Range (fig. 1). The 2012 Waldo Canyon and 2013 Black Forest fires in the Fountain Creek watershed occurred toward the end of the study, so their effect on the land use and hydrology was not incorporated into the modeling (Verdin and others, 2012).

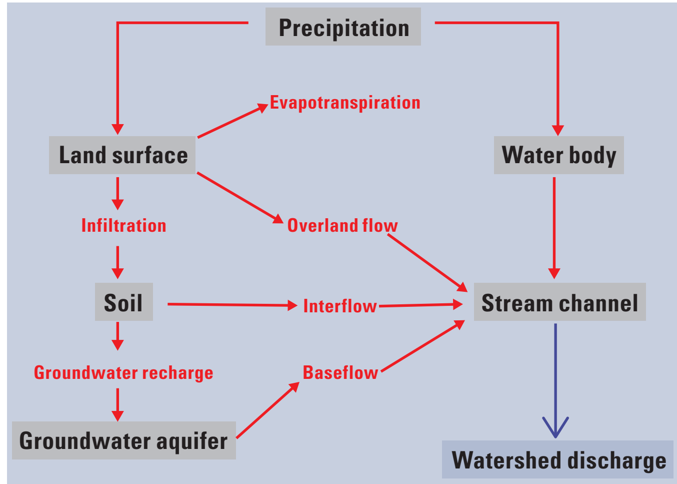


Figure 2. The different components of the precipitation-runoff process as described by the U.S. Army Corps of Engineers (USACE) Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) model. Modified from figure 3-2 in the HEC-HMS Technical Reference Manual (USACE, 2000).

Hydrologic Model

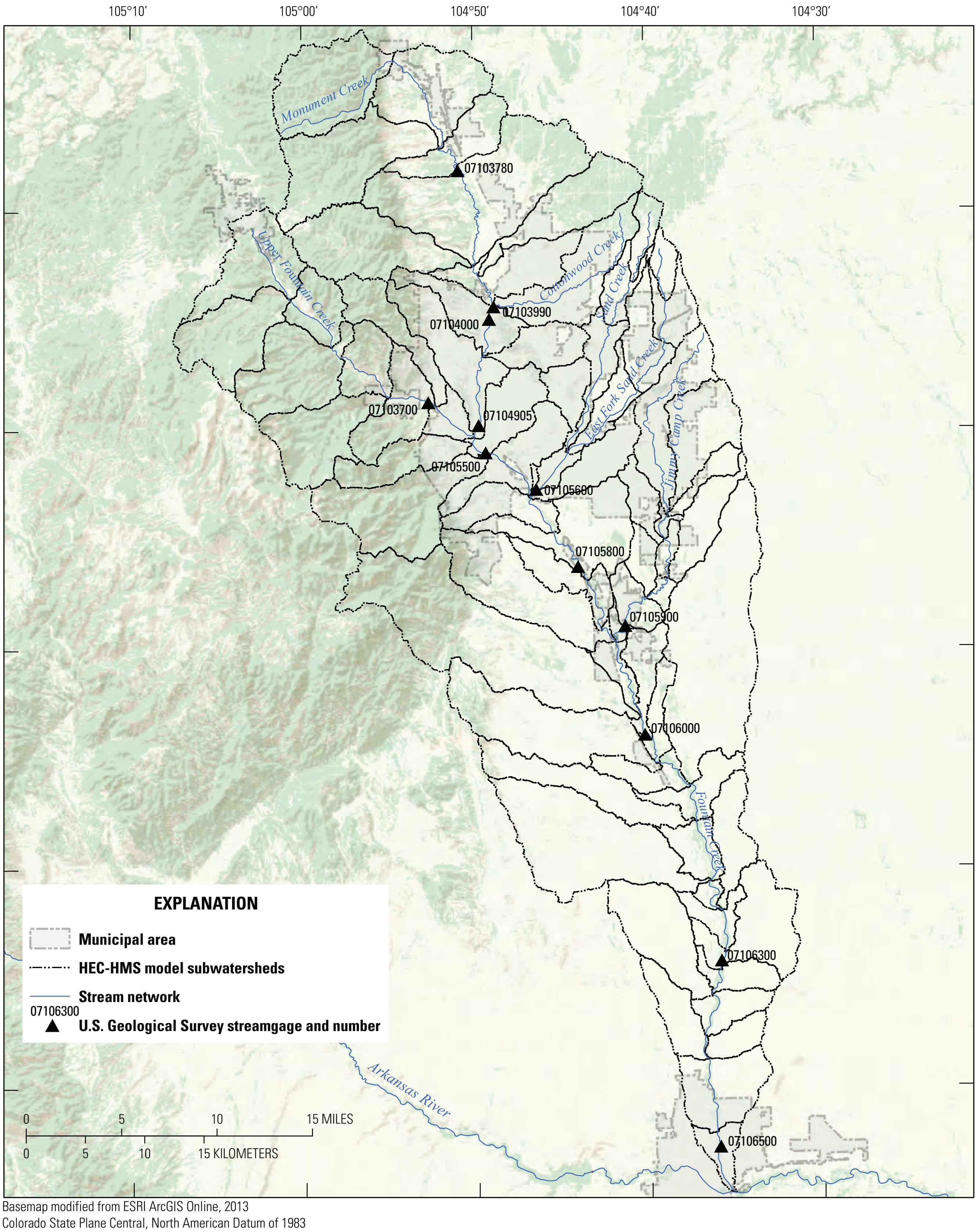
A hydrologic model was used to predict the runoff expected from a given land surface when precipitation was applied to the watershed. The USACE modeling system HEC-HMS version 3.5 was used to simulate runoff in the Fountain Creek watershed associated with storms of varying magnitude and duration. Applicable to a wide range of scenarios, including natural-watershed runoff and urban hydrology (USACE, 2010a), HEC-HMS was selected because (1) an existing HEC-HMS model constructed by URS, Inc. (2003, 2006a), both included documented model development and input data such as land use, soils data, Natural Resource Conservation Service (NRCS) curve numbers, design storm events, baseflow, physical characteristics of the watershed, and model calibration and (2) HEC-HMS is one of the most common and widely accepted hydrologic models in use today (Muñoz, 2012).

HEC-HMS Model Description

HEC-HMS is designed to simulate the precipitation-runoff process of watershed systems. It is applicable for a wide range of geographic areas and problems including large-river water supply and flood hydrology and small-urban or natural-watershed runoff (USACE, 2010a). Hydrographs produced by HEC-HMS are used directly for studies of water availability, urban drainage, flow forecasting, urbanization impact, reservoir spillway design, flood damage reduction, floodplain regulation, and systems operation (USACE, 2010a). HEC-HMS uses different watershed variables to describe each component of the runoff process (fig. 2) (USACE, 2000).

HEC-HMS models, developed by URS, Inc. (2006a), for Fountain Creek, Upper Fountain Creek, Monument Creek, Sand Creek, East Fork Sand Creek, and Jimmy Camp Creek were combined and updated to form a composite 72-subwatershed HEC-HMS model of the Fountain Creek watershed (fig. 3). Curve numbers (USACE, 2000) were assigned to each subwatershed and were dependent on antecedent moisture condition (Chow, 1964), soil type, and land use. An average antecedent moisture condition was assumed in accordance with the URS, Inc. (2006a), study, and land use and soil type were static and did not vary significantly enough since 2006 to justify the expense of generating new land-use data. As a result, the curve numbers (Chow, 1964) and time lag compiled by URS, Inc. (2006a), served as an initial condition for calibration. Similarly, the Manning's roughness coefficients (Chow, 1959) for each channel reach were initially assumed to be the same as in the URS, Inc. (2006a), report. Other variables such as the reach length and channel dimensions of the reach were physically based, and varying them could not be justified because collecting new cross-section data to replace data collected for the URS, Inc. (2006b), study was outside the project scope. Other loss methods were tested to assess the sensitivity of the loss term: the initial and constant loss method (USACE, 2000) and the Green-Ampt loss method (Viessman and Lewis, 2003). Of the three, the curve-number loss method was the most versatile for the storms applied to this watershed in terms of matching the peak streamflows and volumes predicted by the model to those recorded by the streamgage.

Rain-gage precipitation data and radar-based precipitation data from the April 28–30, 1999, and September 14–15, 2011, storm events were used in the calibration process for the HEC-HMS model (fig. 4). These storms will be referred to as the 1999 and 2011 storms, respectively. Because of the greater number of rain gages and streamgages available, the 2011 storm was used to calibrate the model. The 1999 storm was used to validate the Fountain Creek HEC-HMS model. In the URS, Inc. (2006a), HEC-HMS models of Fountain Creek, eight detention facilities were included in the model. The HEC-HMS model was updated by adding an additional detention facility on Sand Creek creating a total of nine detention



Basemap modified from ESRI ArcGIS Online, 2013
Colorado State Plane Central, North American Datum of 1983

Figure 3. The composite 72-subwatershed Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) model of the Fountain Creek watershed and the streamgages used for calibration.

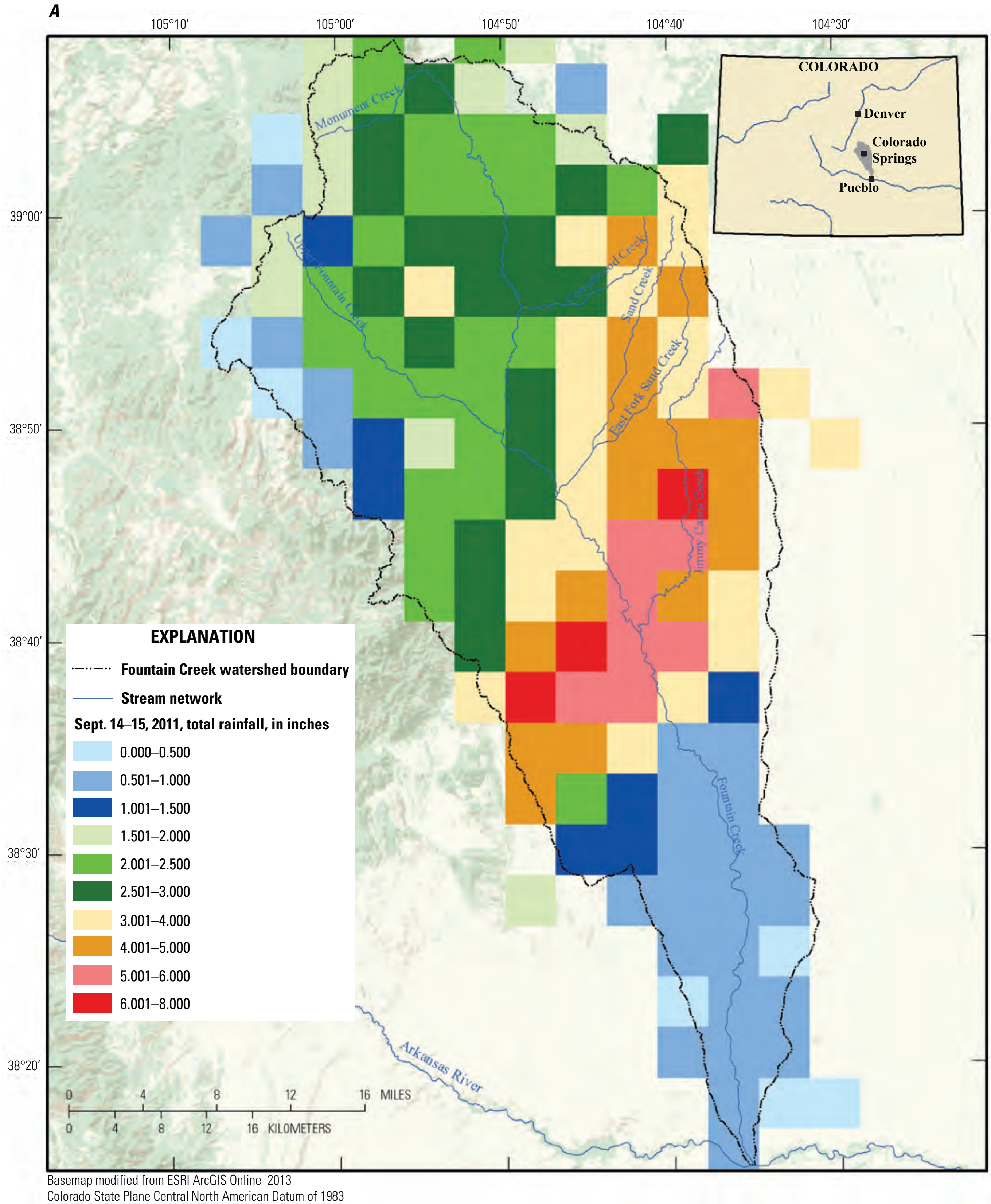
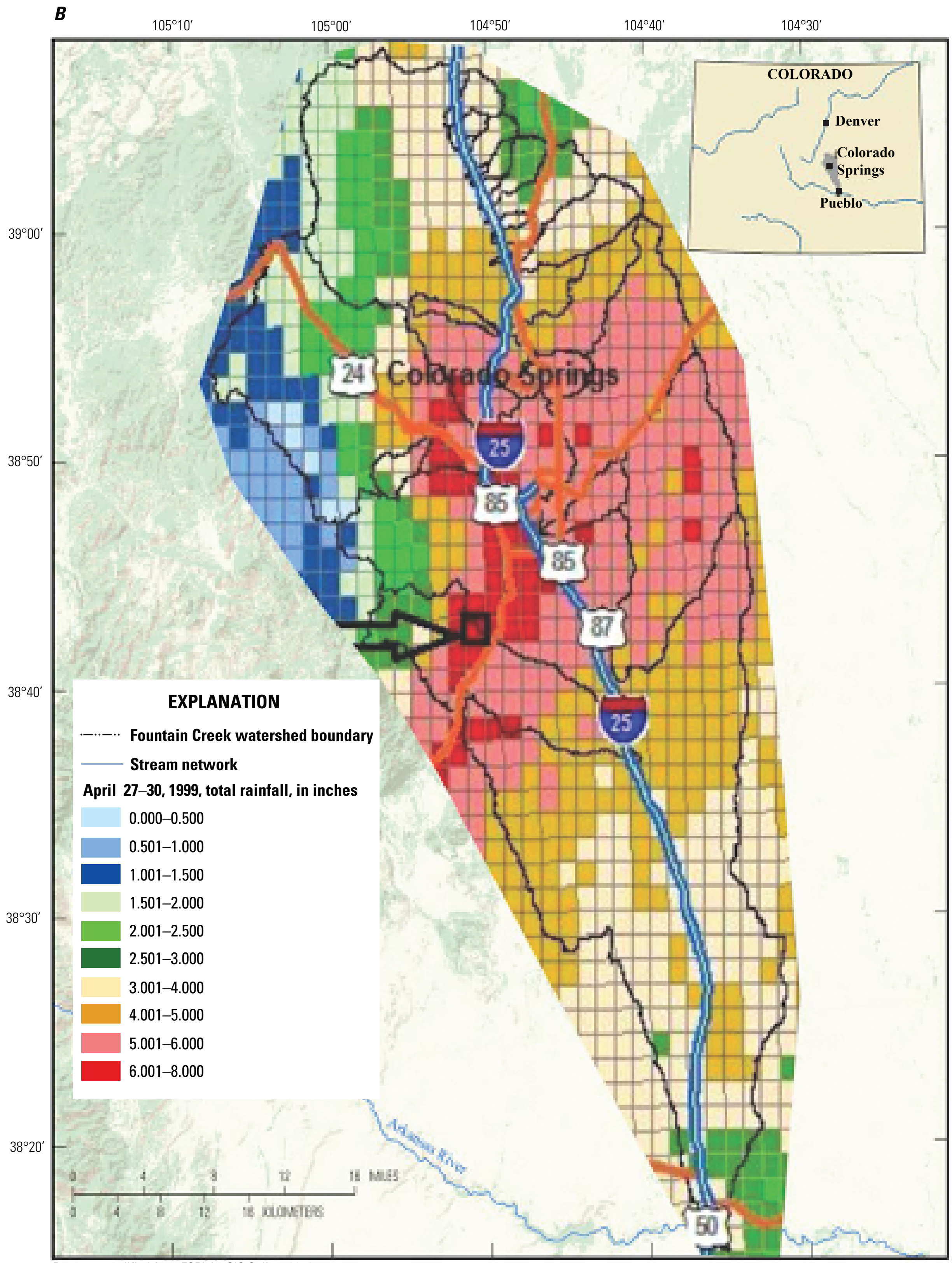


Figure 4. Distribution and total precipitation depth for storms of (*A*) September 14–15, 2011, and (*B*) April 28–30, 1999, which were used for Hydrologic Engineering Center-Hydrologic Modeling System model calibration and validation, respectively. Modified from figure 13-1 of Carlton Engineering, Inc. (2011).



Basemap modified from ESRI ArcGIS Online 2013
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Figure 4. Distribution and total precipitation depth for storms of (*A*) September 14–15, 2011, and (*B*) April 28–30, 1999, which were used for Hydrologic Engineering Center-Hydrologic Modeling System model calibration and validation, respectively. Modified from figure 13-1 of Carlton Engineering, Inc. (2011).

facilities in the Fountain Creek HEC-HMS model to describe the current (2013) conditions (fig. 5 and table 2). Only detention facilities and lakes whose design criteria (area, initial water-surface elevation, maximum elevation, volume, and so on) was provided by the FCWFCGD Technical Advisory Committee was included in the HEC-HMS model, and it is possible other flood-detention facilities that may contribute to flood control were not included in the HEC-HMS model.

Model Calibration and Validation

At least two, and sometimes more, datasets are required to adequately calibrate and validate a numerical model. The HEC-HMS models developed by URS, Inc. (2006a), were not calibrated using measured precipitation and streamflow data but rather were calibrated where possible to the flow determined by a flood-frequency statistical analysis at each streamgage for a given return period (URS, Inc., 2006a). The hydrologic model developed for this study was calibrated using precipitation data from an actual storm event and corresponding streamflow record at USGS streamgages.

A total of 12 USGS streamgages were available for use for model calibration and only 5 USGS streamgages were available for use for the model validation (table 3). This difference is due to the fact that in 1999 seven of the streamgages were not yet operational, and several of the streamgages were unable to collect data during the 1999 storm due to its magnitude. Model output generated at the 12 calibration locations were used to guide model calibration. The streamflow hydrographs produced by the model were adjusted in the calibration process to match the streamflow hydrographs from each of the 12 calibration streamgages as closely as possible. Particular emphasis was given to matching the peak flow, volume, and shape of the hydrographs of the model at the 12 calibration streamgages.

The curve number and lag time for each subwatershed and the Manning's roughness coefficients for each channel reach were adjusted during the HEC-HMS calibration procedure. The lag time was adjusted by changing the basin-average Manning's roughness coefficient in the lag time equation (Cubworth, 1989). After initial iterations, it was determined that the lag time and Manning's roughness coefficients were insensitive variables. As a result, the curve number served as the primary calibration variable.

Data Collection and Interpretation

Using the composite 72-subwatershed HEC-HMS model of the Fountain Creek watershed (fig. 3), model resolution of the major tributaries of Fountain Creek was increased. This permitted HEC-RAS models to be created in these tributaries so that remediation scenarios could be built in the major tributaries of Fountain Creek as well as on the main stem of the creek. As previously stated, the initial curve numbers were not changed from the original values cited by URS, Inc. (2006a). The addition of new storm-event precipitation data were the primary new boundary condition data used in the development of the 72-subwatershed HEC-HMS model of the Fountain Creek watershed.

The 2-mi, gridded 1-hour (h) radar-based rainfall data for the 2011 storm throughout the Fountain Creek watershed for the entirety of the storm was provided by Weather Genesis Solutions, LLC. This grid of 151 data points was adjusted and calibrated to hourly data from nearby rain gages in the watershed. Precipitation gage data with the sampling frequency (15 minutes [min]) at 61 locations throughout the Fountain Creek watershed for the 2011 storm was provided by the USGS (*http://waterdata.usgs.gov/nwis*, accessed January 2012), National Oceanic and Atmospheric Administration (NOAA) (*http://www.ncdc.noaa.gov/cdo-web/*, accessed January 2012), the El Paso County, Colo., OneRain, Inc., network (*http://elpasoco.onerain.com/home.php*, accessed January 2012; no longer available), WeatherForYou.com (*http://www.weatherforyou.com/*, accessed January 2012), and Weather Underground, Inc. (*http://www.wunderground.com/wundermap/*, accessed January 2012). The USGS precipitation data used were obtained from the USGS National Water Information System (NWIS) database (*http://waterdata.usgs.gov/nwis*). The location and distribution of all the rainfall data for the 2011 storm are located on figure 6.

Carlton Engineering, Inc. (2011) generated 1-mi, gridded 15-min radar-based rainfall data of the 1999 storm for the northern part of the Fountain Creek watershed. This grid of 744 data points was adjusted and calibrated to nearby rain gages in the watershed. NOAA provided precipitation gage data with sampling frequencies ranging from 15 min to 24 h at seven locations throughout the Fountain Creek watershed for the 1999 storm (*http://www.ncdc.noaa.gov/cdo-web/*, accessed November 2010). The location and distribution of all the rainfall data for the 1999 storm are located on figure 7.

Boundary Conditions

For implementation of the HEC-HMS model, this study used inverse distance as the meteorological method to distribute precipitation in the watershed, the NRCS curve number as the loss method, the NRCS unit hydrograph as the transform-function method, constant monthly as the base-flow method, Muskingum-Cunge as the routing method, and the Bureau of Reclamation method (Cubworth, 1989) as the lag-time method. The curve number, transform function, baseflow, and routing methods were used in the URS, Inc. (2006a), study, and the methods provided a reasonable approximation of the physical processes in the watershed. The inverse-distance method was used because it provided the most accurate and efficient distribution of rainfall onto the landscape when using actual rain-gage data from a real storm event. The Bureau of Reclamation lag-time method was used because it was developed specifically for applications in the Rocky Mountain region making it particularly applicable to this study area (Cubworth, 1989).

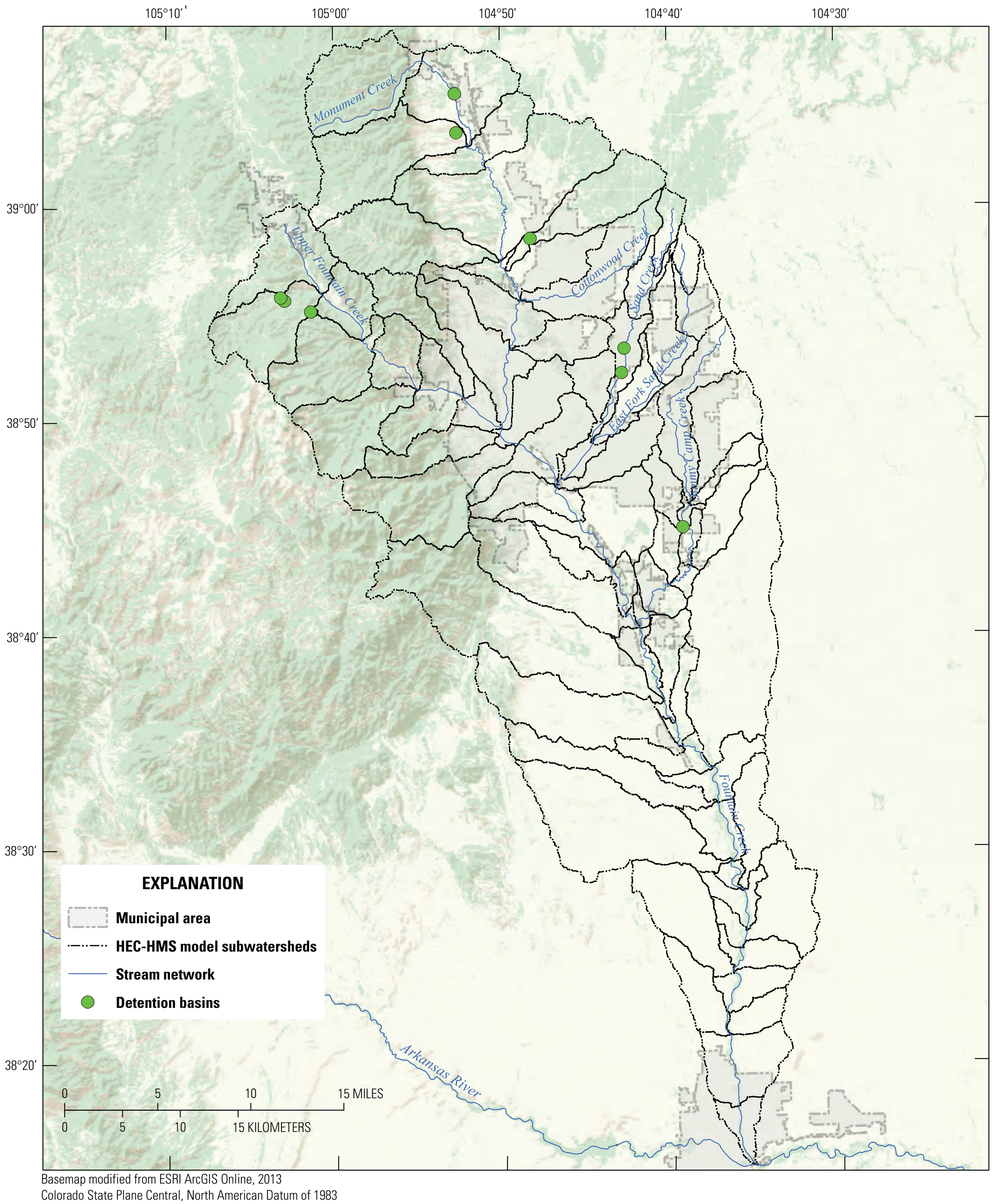


Figure 5. Location of the nine detention facilities currently (2013) employed in the Fountain Creek watershed Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) model.

Table 2. The nine detentions basins in the Fountain Creek watershed that were incorporated into the Hydrologic Engineering Center-Hydrologic Modeling System model.

[USAF, U.S. Air Force]

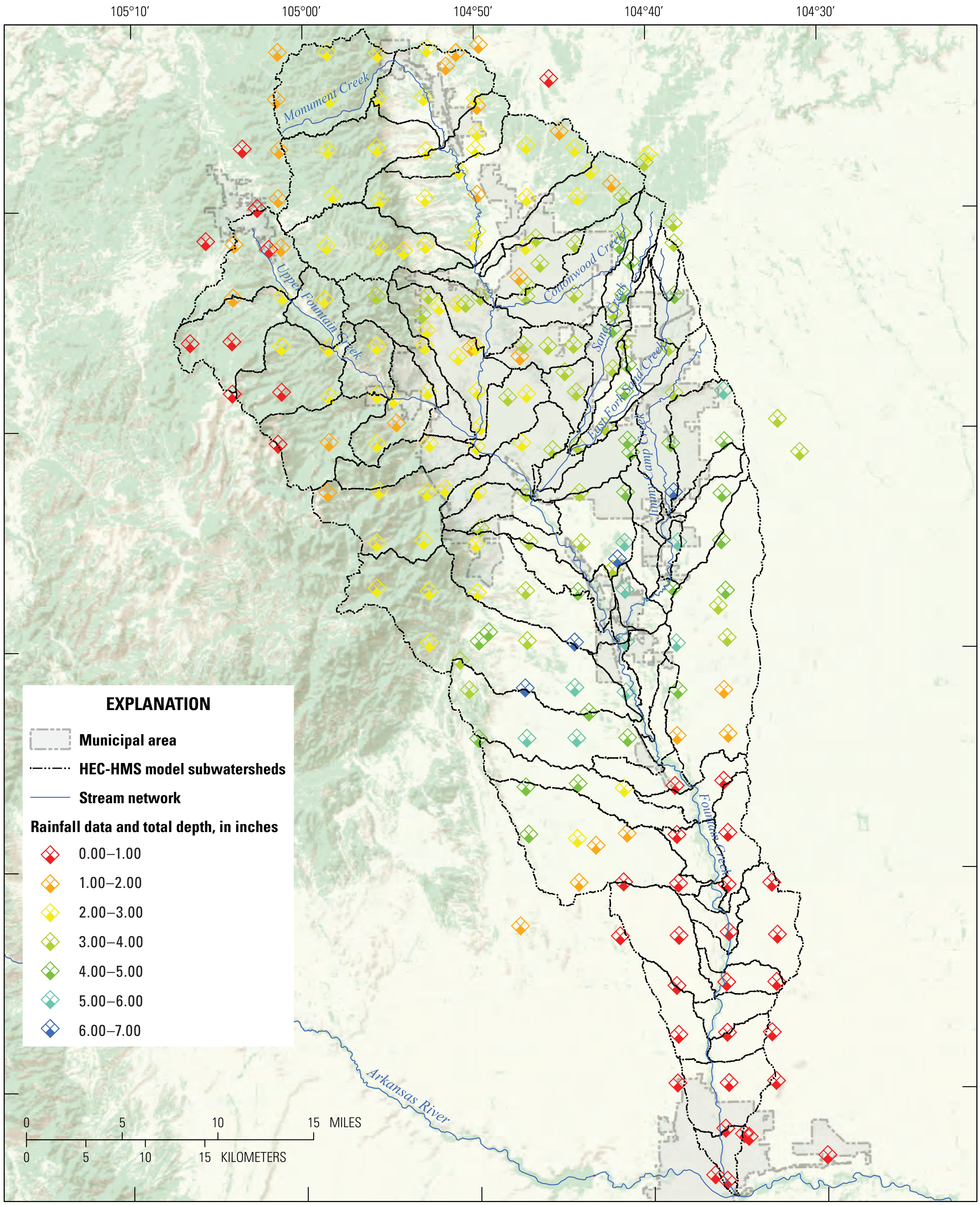
Name	River	Latitude (°)	Longitude (°)	Flood storage (acre-feet)
Bristlecone Reservoir	Monument	39.058423	–104.87727	474
Constitution Detention Pond	Sand	38.870751	–104.713748	500
Crystal Creek Reservoir	Upper Fountain	38.919466	–105.023353	2,200
Jimmy Camp Creek Detention Facility	Jimmy Camp	38.750334	–104.654107	130
Monument Lake	Monument	39.088793	–104.878686	560
North Catamount Reservoir	Upper Fountain	38.930456	–105.053071	3,300
Sky Sox Detention Facility[1]	Sand	38.889634	–104.711165	400
South Catamount Reservoir	Upper Fountain	38.927925	–105.049294	1,600
USAF Academy Kettle Creek Detention Facility	Monument	38.975616	–104.804076	2,700

[1]New detention basin added to model that was not present in URS, Inc. (2006a), models.

Table 3. U.S. Geological Survey (USGS) streamgages used in the hydrologic model calibration and validation.

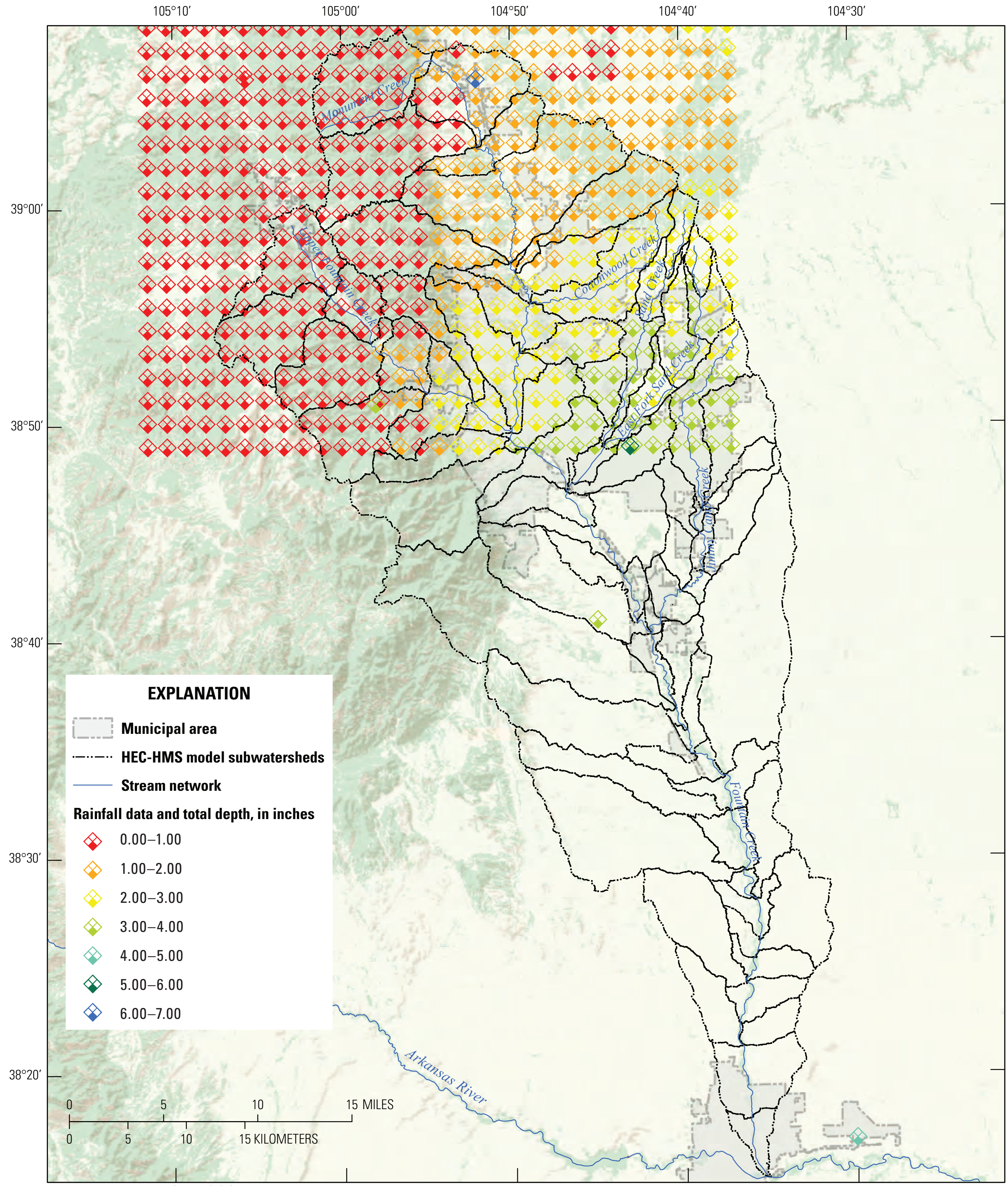
[ft, feet; mi^2, square miles; Colo., Colorado; USAF, U.S. Air Force. Drainage area determined from USGS National Water Information System database]

USGS streamgage	Streamgage name	Latitude (°)	Longitude (°)	Drainage area (mi^2)	Elevation (ft)	Calibration	Validation
07103700	Fountain Creek near Colorado Springs, Colo.	38.85471357	–104.87803140	102	6,110	X	
07103780	Monument Creek above North Gate Boulevard at USAF Academy, Colo.	39.03102778	–104.84661110	81.4	6,640	X	
07103990	Cottonwood Creek at mouth at Pikeview, Colo.	38.92722220	–104.81416670	18.9	6,240	X	
07104000	Monument Creek at Pikeview, Colo.	38.91777057	–104.81858770	203	6,203	X	X
07104905	Monument Creek at Bijou Street at Colorado Springs, Colo.	38.83721474	–104.82941920	235	5,980	X	
07105500	Fountain Creek at Colorado Springs, Colo.	38.81638158	–104.82275190	392	5,900	X	X
07105600	Sand Creek above mouth at Colorado Springs, Colo.	38.78832768	–104.77386200	52.4	5,837	X	
07105800	Fountain Creek at Security, Colo.	38.72944040	–104.73386110	500	5,640	X	
07105900	Jimmy Camp Creek at Fountain, Colo.	38.68444130	–104.68858300	65.4	5,530	X	X
07106000	Fountain Creek near Fountain, Colo.	38.60166470	–104.67025030	672	5,355	X	X
07106300	Fountain Creek near Piñon, Colo.	38.42944444	–104.59805560	865	4,990	X	
07106500	Fountain Creek at Pueblo, Colo.	38.28778010	–104.60108490	925	4,705	X	X



Basemap modified from ESRI ArcGIS Online, 2013
Colorado State Plane Central, North American Datum of 1983

Figure 6. The nine detention basins in the Fountain Creek watershed that were incorporated into the Hydrologic Engineering Center-Hydrologic Modeling System model.



Basemap modified from ESRI ArcGIS Online, 2013
Colorado State Plane Central, North American Datum of 1983

Figure 7. Location and distribution of all the rainfall data for the 1999 storm. HEC-HMS, Hydrologic Engineering Center-Hydrologic Modeling System.

Hydrologic Model Results

The curve number and lag time for each subwatershed and Manning's roughness coefficients for each channel reach were adjusted within an acceptable range so that the simulated and measured streamflow hydrographs for each of the 12 USGS streamgages approximated each other (table 4). After analysis of the hydrographs of more than 30 individual storm events and from the study by Kuhn and others (2007), it was determined that the lower part of Fountain Creek is on average a losing stream. This was true of the calibration and validation storms as well. To accurately model this phenomenon, stream losses were added to the model during calibration. The stream losses were applied only in Fountain Creek below the Monument Creek confluence and in Jimmy Camp Creek as a fraction of the flow and a single constant loss. The same exact loss rates were applied to the calibration event, validation event, and the remediation scenario event. Since all three of these events are very large, these losses would not be appropriate for small events.

The final curve numbers and lag times for each subwatershed, and the final Manning's roughness coefficients of each channel reach, were adjusted to plus or minus 30 percent, 150 percent, and 300 percent, respectively, at each of the 12 streamgages after model calibration. After a sensitivity analysis, the lag time and Manning's roughness coefficient are very insensitive, whereas the curve number is very sensitive and thus the primary component driving runoff peaks and volumes.

To perform the model validation, the same set of variables was then used to determine the runoff created by the 1999 storm. Metrics (Anderson and Woessner, 1992; Krause and others, 2005) describing the error (difference between simulated and streamgage values) from the 12 streamgages for the 2011 storm (calibration storm) and the 5 streamgages for the 1999 storm (validation storm) are summarized in table 5. Absolute mean error is the average error between model results and recorded values; this metric does not allow positive and negative errors to cancel each other out. The absolute mean errors of the peak streamflow for the calibration and validation storms were 13 and 25 percent, respectively. The absolute mean errors of the volume for the calibration and validation storms were 36 and 51 percent, respectively. The primary limitation for the calibration was lack of precipitation data. The Nash-Sutcliffe coefficient (Moriasi and others, 2007) was also determined for both storms. The Nash-Sutcliffe coefficient for the calibration was near or above zero, which means the model calibration is fair. The reason the validation storm has higher uncertainty is simply due to less data being available for that event. The errors in the calibration can be used to determine the uncertainty in the flows resulting from the 24-h, 1-percent AEP (100-yr) storm to be modeled to analyze the scenarios. Figure 8 displays the HEC-HMS calibration model output for the 2011 and 1999 storms for the Fountain Creek at Pueblo streamgage (07106500).

Table 4. Ranges of curve numbers and lag times for each subwatershed and Manning's roughness coefficients for each channel in the calibrated Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) model.

[min, minutes]

Range of variables used in calibrated HEC-HMS model		
Curve number	**Lag time (min)**	**Manning's roughness coefficient**
42.9–91.4	27.7–561	0.020–0.080

Table 5. Mean error, absolute mean error, root-mean squared error, and the Nash-Sutcliffe coefficient of the peak streamflow and volume for the 2011 and 1999 storms.

[%, percent; the Nash-Sutcliffe coefficient was determined from Moriasi and others (2007)]

Stream name	2011 storm	1999 storm
Peak streamflow		
Mean error (%)	7.3	–22
Absolute mean error (%)	13	25
Root-mean squared error (%)	17	31
Nash-Sutcliffe coefficient	0.98	0.24
Volume		
Mean error (%)	20	–51
Absolute mean error (%)	36	51
Root-mean squared error (%)	46	57
Nash-Sutcliffe coefficient	0.87	–1.37

Hydraulic Model

A hydraulic model is used to predict streamflow characteristics including water-surface elevation of a free-flowing channel given a particular flow or flow time series. The USACE modeling system HEC-RAS versions 4.1 and 4.2 were used to simulate streamflow and sediment transport, respectively, for the Fountain Creek watershed generated by a particular storm event. The model is applicable to a wide range of scenarios, including large networks of regulated or naturally flowing streams or rivers to constructed channels (USACE, 2010b). HEC-RAS version 4.1 was selected based on (1) the availability of 22 HEC-RAS models, previously constructed by URS, Inc. (2006b, 2003), which documented model-development and input data such as topographic data, Manning's roughness coefficients, and survey data and (2) application of a model that is widely used and accepted would provide the most benefit in the future because it would provide the greatest ease if the model needed to be updated or increased in scope.

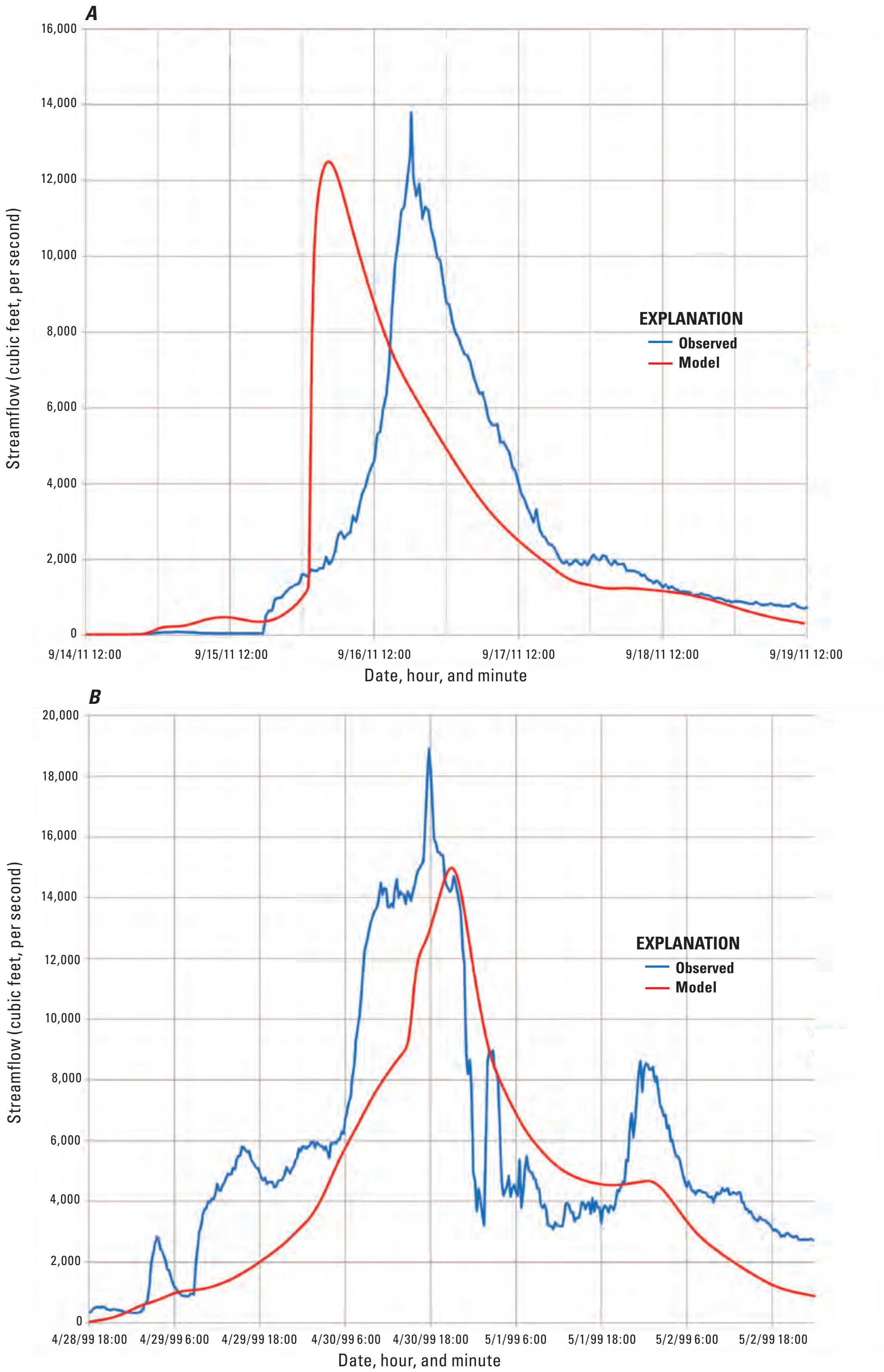


Figure 8. The Hydrologic Engineering Center-Hydrologic Modeling System calibration model output (red) and the observed output (blue) for the (*A*) 2011 and (*B*) 1999 storms for the Fountain Creek at Pueblo, Colorado, streamgage (07106500).

HEC-RAS Model Description

HEC-RAS is a one-dimensional depth-averaged hydraulic model capable of computing water-surface elevations and horizontal-velocity components for subcritical and supercritical free-surface flow regimes (USACE, 2010c). The model is designed for problems in which vertical accelerations are negligible, and velocity vectors generally point in the same direction over the entire depth of the water column at any discrete period in time (USACE, 2010c). The HEC-RAS system contains four one-dimensional river-analysis-model components for (1) steady-flow simulation, (2) unsteady-flow simulation, (3) sediment-transport computation, and (4) water-quality computation (USACE, 2010b).

Typical applications of HEC-RAS include calculating water-surface elevations and flow distributions related to bridge openings in contracting and expanding reaches and at river junctions. The model is not intended for applications in which vortexes, vibrations, or vertical accelerations are the primary interests. The simulation of vertically stratified flow-fields is beyond the capabilities of the model (USACE, 2010c).

HEC-RAS models developed by URS, Inc. (2006b, 2003), for Fountain Creek, Upper Fountain Creek, Monument Creek, Sand Creek, East Fork Sand Creek, and Jimmy Camp Creek were combined and updated to form a new composite HEC-RAS model comprising approximately 1,900 cross sections, bridges, culverts, and inline structures in the Fountain Creek watershed, which covered approximately 130 river miles (fig. 9). For initial model runs, it was assumed that the overall cross-section shape and elevation derived from remote sensing and photogrammetry techniques, the Manning's roughness coefficients at each cross section, and downstream reach lengths between cross sections had not changed significantly since the URS, Inc., data had been compiled allowing the URS, Inc., datasets and variables to be used as a starting point for model calibration. The initial Manning's roughness coefficients were based on the tables from Chow (1959). The Manning's roughness coefficients were estimated taking into consideration several factors such as channel-bed materials, type, density, and height of existing vegetation and existing structures in the overbanks. Unlike the sediment-transport model to be discussed later, the cross sections in the HEC-RAS hydraulic model are static throughout the simulation and do not change. Other variables used in the model, such as channel length and cross-section dimensions, were physically based, and adjusting them could not be justified without collection of additional data, which was outside the project scope. The Manning's roughness coefficient was the only variable adjusted during the calibration process.

Several tasks were performed to update the HEC-RAS model. The URS, Inc. (2006b, 2003), models had several cross sections where unreasonably high Manning's roughness coefficients (10 and greater) occurred; these were deemed to be erroneous and changed to a more reasonable value (0.100) (Mark Kempton, Anderson Consulting Engineers, Inc., written commun., May 24, 2011). Some of the cross sections in the URS, Inc. (2006b), and URS, Inc. (2003), models had up to 15 different roughness coefficients per cross section. To simplify the model, each cross section was updated to include only three Manning's roughness coefficients per cross section—an average for the left bank, an average for the right bank, and an average for the channel (Moore, 2011). The URS, Inc. (2003, 2006b), studies used the North American Vertical Datum of 1929 (NAVD29) and the North American Vertical Datum of 1988 (NAVD88) to reference the elevations of all the cross sections in El Paso and Pueblo Counties, respectively. To create a model using only one vertical datum, all elevations in El Paso County were adjusted from NAVD29 to NAVD88, resulting in a model referencing only NAVD88. The HEC-RAS models obtained from the URS, Inc. (2003, 2006b), studies were run as steady-flow hydraulic models. In other words, the models were developed to solve the water-surface elevation for a single flow that is independent of time. For this study, the models needed to pass a hydrograph from a storm event where the flows would vary with time. As a result, the new composite 1,900-cross-section HEC-RAS model of the Fountain Creek watershed had to be updated from a steady-flow model to an unsteady-flow model.

Model Calibration and Validation

At least two datasets are required to adequately calibrate and validate a numerical model. The HEC-RAS models developed by URS, Inc., were not calibrated as part of the scope of work for those projects (URS, Inc., 2006b, 2003). The general procedure used to calibrate and validate the HEC-RAS model was to first collect field data to develop the model geometry, which was provided by URS, Inc. (2006b). Then the model was calibrated to the water-surface elevations and velocities observed in the field for the initial flow. A second flow condition then was simulated without changing the computational mesh or model parameters, and the simulated water-surface elevations and velocities were compared with those observed in the field for this second flow condition. Data from 15 USGS streamgages were used for model calibration and 7 of those USGS streamgages were used for model validation (table 6).

Data Collection and Interpretation

Model construction and simulations were based on a variety of field measurements, which included water-surface elevations reported for USGS streamgages, cross-section surveys, and streamflow measurements; however, the vast majority of the data collection occurred with the procurement of all the computer models, modeling results, sampling data, survey and control data, and additional data from the URS, Inc., studies (URS, Inc., 2006a, 2003). HEC-RAS models developed by URS, Inc. (2006b, 2003), of Fountain Creek, Upper Fountain Creek, Monument Creek, Sand Creek, East Fork Sand Creek, and Jimmy Camp Creek were combined and updated to form

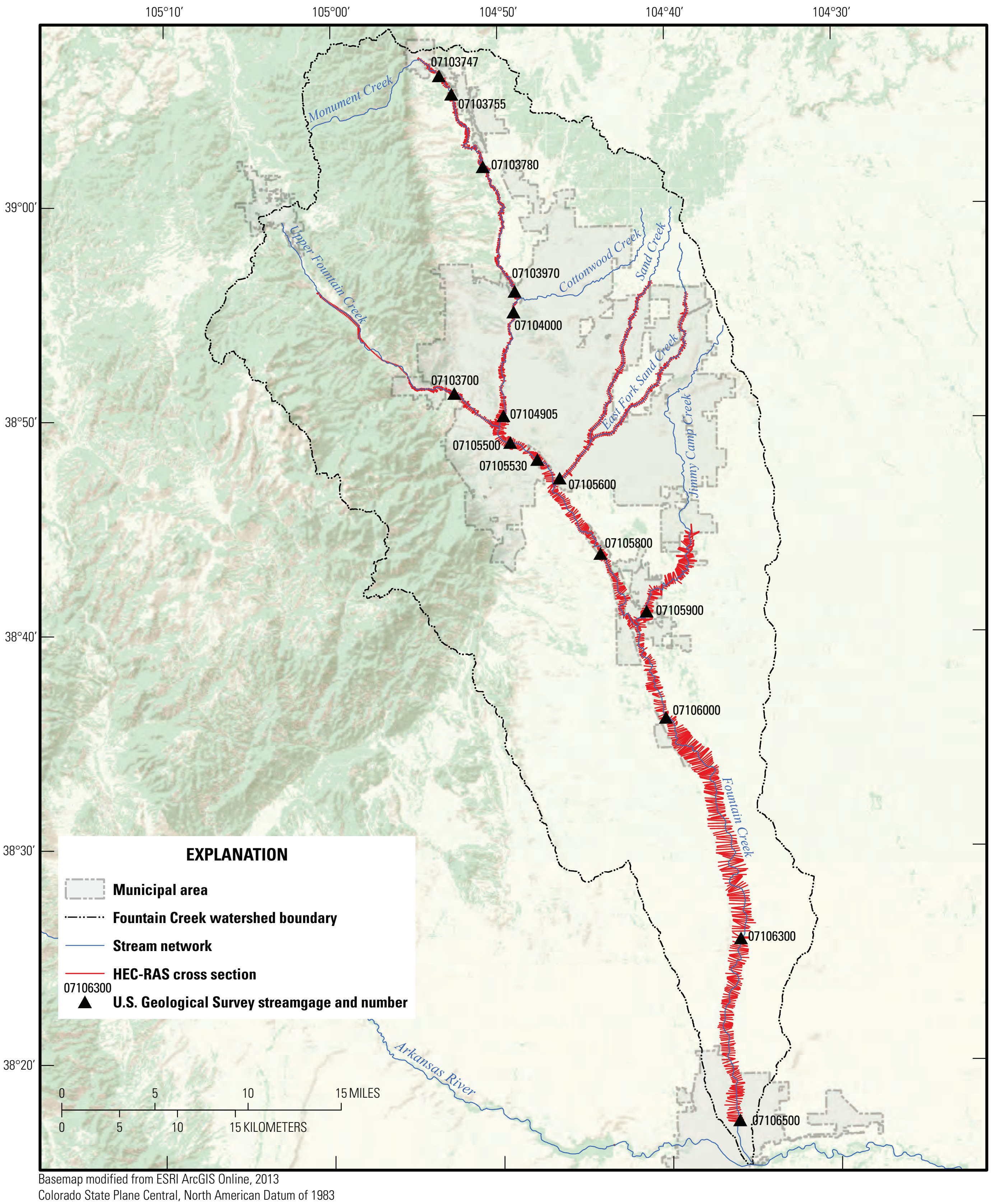


Figure 9. The new composite 1,900-cross-section Hydrologic Engineering Center-River Analysis System (HEC-RAS) model of the Fountain Creek watershed, which covers approximately 130 river miles, and the streamgages used for calibration.

Table 6. U.S. Geological Survey (USGS) streamgages used in the hydraulic-model calibration and validation.

[mi², square miles; ft, feet; Colo., Colorado. Drainage area determined from USGS National Water Information System database]

USGS streamgage	Streamgage name	Latitude (°)	Longitude (°)	Drainage area (mi²)	Elevation (ft)	Calibration	Validation
07103700	Fountain Creek near Colorado Springs, Colo.	38.8547136	–104.8780314	102	6,110	X	X
07103747	Monument Creek at Palmer Lake, Colo.	39.1019363	–104.8913698	25.7	6,950	X	
07103755	Monument Creek below Monument Lake near Monument, Colo.	39.0875000	–104.8791667	30.2	6,885	X	
07103780	Monument Creek above North Gate Boulevard at USAF Academy, Colo.	39.0311035	–104.8483128	81.4	6,640	X	
07103970	Monument Creek above Woodmen Road at Colorado Springs, Colo.	38.9272222	–104.8141667	18.9	6,240	X	
07104000	Monument Creek at Pikeview, Colo.	38.9177706	–104.8185877	203	6,203	X	X
07104905	Monument Creek at Bijou Street at Colorado Springs, Colo.	38.8372147	–104.8294192	235	5,980	X	
07105500	Fountain Creek at Colorado Springs, Colo.	38.8163816	–104.8227519	392	5,900	X	X
07105530	Fountain Creek below Janitell Road below Colorado Springs, Colo.	38.8030491	–104.7958069	413	5,840	X	X
07105600	Sand Creek above mouth at Colorado Springs, Colo.	38.7883277	–104.7738620	52.4	5,837	X	
07105800	Fountain Creek at Security, Colo.	38.7294404	–104.7338611	500	5,640	X	
07105900	Jimmy Camp Creek at Fountain, Colo	38.6844413	–104.6885830	65.4	5,530	X	X
07106000	Fountain Creek near Fountain, Colo.	38.6016647	–104.6702503	672	5,355	X	X
07106300	Fountain Creek near Piñon, Colo.	38.4294444	–104.5980556	865	4,990	X	
07106500	Fountain Creek at Pueblo, Colo.	38.2877778	–104.6005556	925	4,705	X	X

a new composite 1,900-cross-section HEC-RAS model of the Fountain Creek watershed (fig. 9). This was done to provide better model resolution in the major tributaries of Fountain Creek so individual remediation scenarios could be located in the tributaries in addition to the main stem of Fountain Creek.

Water-Surface Elevations, Velocity, and Streamflow

Water-surface-elevation data at the 15 gages were the primary field data that needed to be collected for the HEC-RAS model calibration. All 15 USGS streamgages used in the HEC-RAS calibration report water-surface elevation in terms of a gage height referenced above a local gage datum, and the data are available in the USGS NWIS database (*http://waterdata.usgs.gov/nwis*). To be consistent with the URS, Inc., models, the local datum was tied into NAVD88 gage-datum elevation by using real-time kinematic global positioning system surveys and adding the local gage-datum elevation in NAVD88 to the gage height at the gage.

Streamflow and velocity data were collected at each of the 15 USGS calibration streamgages from 1999 through 2012 (Turnipseed and Sauer, 2010; Rantz and others, 1982). The USGS typically measures the streamflow at each gage approximately 10–15 times per year. The cross-section-averaged velocity of every streamflow measurement at all 15 gages was collected to aid in the calibration process. These velocities were used to compare with the velocity generated from the model output.

Bathymetry—Light Detection and Ranging

Topographic data for the Fountain Creek watershed from the Palmer Lake area to the El Paso-Pueblo County line were provided by Colorado Springs Utilities and included 2-ft digital-contour data with a reported accuracy of ±2.5 ft horizontally and 1 ft vertically. A vertical control datum of National Geodetic Vertical Datum of 1929 and a horizontal control datum of North American Datum of 1983 (NAD83) was assumed (URS, Inc., 2006b). The El Paso dataset was converted to NAVD88, so all geometry data would be referenced to NAVD88.

Other areas in Pueblo County were provided by Pueblo County and included 2-ft and 5-ft digital-contour data based on the vertical control datum NAVD88 and the horizontal control datum NAD83. In some areas of Pueblo County (from the El Paso-Pueblo County line south to approximately 1,000 ft upstream from Pinion Road), only 5-ft digital-contour data were available, with unknown accuracy. In the downstream portion of Pueblo County, the topographic data were based on 2-ft digital-contour data. Using the root mean square error as a parameter for the accuracy of the results, the reported accuracy of these data are 0.62 ft (URS, Inc., 2006b). The contour data for Pueblo County were generated by Sanborn Company, using a combination of light detection and ranging (lidar), a remote sensing technique, and photogrammetry techniques. Colorado Springs Utilities and Pueblo County also provided aerial orthophotography and street and road shapefiles (URS, Inc., 2006b).

Model Geometry

The surveys established that the lidar and photogrammetry datasets were deemed valid for the applications of this study. However, during modeling it was determined that large uncertainties exist in the cross-section geometry, and this geometry is probably the largest source of uncertainty in the HEC-RAS model. The uncertainty from the model geometry was determined to be the primary source of the large errors in the model calibration (discussed in the Hydraulic Model Results section). Any collection of new geometry data on such a large scale was outside the scope of the project.

Whereas the cross sections were collected using remote sensing techniques, all significant hydraulic structures (bridges, major culverts, detention facilities, improved channels, and drop structures) along the studied streams were surveyed on the ground by survey crews and geospatially referenced between February and November 2005 (URS, Inc., 2006b).

Boundary Conditions

The HEC-RAS hydraulic models require upstream and downstream boundary conditions for simulation. The upstream boundary condition was flow at the most upstream cross section of each tributary and stage at the most downstream cross section of the model. The largest 24-h mean streamflows for the 2011 and 1999 flood events were calculated as a moving average from the gage record of the most upstream gage on Upper Fountain Creek, Monument Creek, Sand Creek, and Jimmy Camp Creek. The 2011 and 1999 storms were used as the upstream boundary conditions of the model for the calibration and validation runs, respectively. The downstream boundary condition of the hydraulic model was based on the stage-streamflow rating curve at the USGS streamgage Fountain Creek at Pueblo (07106500), where the stage was referenced to the NAVD88.

Streamflow was computed as a moving average at each of the 15 streamgages used in the calibration process and at each of the 7 streamgages used in the validation process. The moving average is preferred over a daily average because some storms occur over two days and were variably distributed. In this case a daily average would provide a much smaller value than the 24-h moving average. These 15 moving-averaged steady-state streamflows were input into the model at the cross section for the streamgage that was used to compute the water-surface profile and velocities. These 15 calibration flows were then used at each cross section upstream from that gage until the next gage upstream or the upstream model boundary was reached. The model was then run to simulate the water-surface elevations based on moving-average streamflows.

Calibration for the 2011 storm was completed by adjusting the left, right, and channel-averaged Manning's roughness coefficients originating from the URS, Inc. (2006b), study. The 1999 storm (validation storm) was modeled in the same way as the 2011 storm, using the Manning's roughness coefficients computed from the 2011 calibration model run. The comparison of the modeled water-surface elevations and the elevations determined from the gage record from the validation storm is presented in the Hydraulic Model Results section.

One of the drawbacks of using HEC-RAS is model stability when using the unsteady-flow model. This problem is exacerbated when working in steep reaches typical of Rocky Mountain streams like Fountain Creek (USACE, 2010b). HEC-RAS was recently updated (2010) to include a hydrologic routing method that can be used in place of traditional hydraulic routing. The hydrologic routing technique, Modified Puls, was designed specifically for steep mountain reaches where the model has trouble maintaining stability or where it is simply not possible to generate a converged and well-posed model (USACE, 2010b). In places where stability was a concern, interpolated cross sections were added to help the model determine the solution.

Hydraulic Model Results

Even though the modelling for this study was intended for unsteady flow (storm events would be modeled and the flow would be dependent on time) for simplicity, the composite HEC-RAS model was calibrated in steady flow. Calibrating a model in the unsteady-flow regime leads to a larger uncertainty because both flow and stage are dynamic resulting in

Manning's roughness coefficients that vary with time. As a consequence, the Manning's roughness coefficients would also change with stage and time creating a difficult and uncertain calibration process, particularly for a model of this scale, with a mean channel slope near 1 percent.

Data from the September 14–15, 2011, storm, which had streamflows ranging from 80 percent to 1 percent AEP (also described as a recurrence interval of 1.25 to 100 years, or 1.25- to 100-year flow) at the USGS streamgages (based on gage record from the USGS NWIS database; http://waterdata.usgs.gov/nwis), were used to calibrate the model, and data from the April 28–30, 1999, storm, which had streamflows ranging from 50 percent to 0.5 percent AEP (2- to 200-year flow) at the USGS streamgages (based on gage record from the USGS NWIS database; http://waterdata.usgs.gov/nwis) were used to validate the model. Streamflow or precipitation AEP, typically given in percent, is the probability a streamflow or precipitation event with a particular magnitude will occur in any given year, a statistic determined using the streamflow or precipitation record. The recurrence interval is the inverse of the AEP, given in years, to make it easier to understand the magnitude of the event. However, it is important to note that a recurrence interval event (whether streamflow or precipitation) of 100 years is equally likely to occur every year and is not a storm that simply happens once every 100 years. Also, it is important to note that a 100-year streamflow event does not necessary result from a 100-year precipitation event and vice versa. The calibration process consisted of comparing the simulated water-surface elevations and the cross-section-averaged velocities from the model with those surveyed in the field at the cross section at the corresponding 15 and 7 streamgages, respectively.

The final Manning's roughness coefficients were adjusted between –30 and 30 percent at the 15 calibration streamgages from the original left, right, and channel-averaged Manning's roughness coefficients upon completion of calibration. To perform the model validation, the same set of variables was then used to determine the water-surface elevations created by the 1999 storm. The absolute mean and mean difference (Anderson and Woessner, 1992) in water-surface elevation from the 15 streamgages between observed and modeled water-surface elevations was 1.8 and 0.9 ft, respectively, for the 2011 storm (the calibration storm). The absolute mean and mean difference in water-surface elevation from the seven validation streamgages between observed and modeled water-surface elevations was 1.7 and 0.3 ft, respectively, for the 1999 storm (validation storm). The calibration and validation results for each streamgage are displayed in table 7. The uncertainty from the model geometry was determined to be the primary source of the large errors in the model calibration. In order to substantially reduce the errors, collection of new geometry data would be necessary, and such a task was outside the scope of the project.

Table 7. Calibration and validation results from the Hydrologic Engineering Center-River Analysis System model for each streamgage.

[ft, feet; a positive error indicates the model water-surface elevation is higher than the streamgage record, and a negative error indicates the modeled stage is less than the streamgage record]

Streamgage	Error (ft)	
	2011 storm	1999 Storm
07103700	–3.2	–3.6
07103747	–1.2	NA
07103755	1.8	NA
07103780	–1.9	NA
07103970	0.8	NA
07104000	–0.2	–1.2
07104905	2.3	NA
07105500	2.1	–0.3
07105530	2.9	2.2
07105600	0.1	NA
07105800	2.1	NA
07105900	1.4	0.6
07106000	2.9	1.8
07106300	2.1	NA
07106500	1.9	2.5
Absolute mean	1.8	1.7
Mean difference	0.9	0.3

Sediment-Transport Model

A sediment-transport model is used to predict sediment erosion, deposition, and geomorphic change in a river system given a particular flow regime and the sediment composi tion of the system. The USACE modeling system HEC-RAS version 4.2 was used to simulate streamflow and sediment transport for the Fountain Creek watershed generated by a design-storm event. HEC-RAS version 4.2 includes a one-dimensional-model component for moveable-boundary sediment-transport computations. HEC-RAS was the sediment-transport model of choice because it was used as the hydraulic model and could be adapted with ease to perform moveable-boundary sediment-transport computations.

Sediment-Transport Model Description

The composite 1,900-cross-section HEC-RAS model of the Fountain Creek watershed was used to simulate sediment transport. The same model characteristics used in the HEC-RAS hydraulic model are used in the HEC-RAS sediment-transport model. Suspended-sediment data were collected at six sampling locations at USGS streamgages in the Fountain Creek watershed (fig. 10). Suspended-sediment-streamflow rating curves were developed at these six locations and were used to calibrate the HEC-RAS sediment-transport model.

Model Calibration and Validation

The general procedure used to calibrate and validate the HEC-RAS sediment-transport model was to first collect field data to develop an understanding of the sediment supply of the river system. The model was then calibrated to the suspended-sediment rating curves at six USGS streamgages for a large range of flows (table 8). This calibration assumes that the majority of the sediment load at these locations is transported in suspension, an assumption that is met in the context of the scale of the 95-confidence intervals of the sediment rating curves. The range in the 95-confidence intervals of the sediment rating curves is larger than any portion that the bedload would contribute.

Sediment transport was represented by the Laursen-Copeland sediment-transport function in the HEC-RAS sediment-transport model as (USACE, 2010c):

$$C_m = 0.010\gamma\left(\frac{d_s}{D}\right)^{7/6}\left(\frac{\tau'_O}{\tau_C}-1\right)f\left(\frac{\mu_*}{\omega}\right) \qquad (1)$$

where

C_m is the sediment discharge concentration, in weight per volume,
γ is the unit weight of water,
d_s is the mean particle diameter,
D is the effective depth of flow,
τ'_O is the bed shear stress due to grain resistance,
τ_C is the critical Shields number or critical bed-shear stress (default of 0.039), and
$f\left(\frac{\mu_*}{\omega}\right)$ is the function of the ratio of the shear velocity (μ_*) to fall velocity (ω).

The Laursen-Copeland equation predicts total sediment load based on a combination of flume and field studies for systems with a median particle diameter from 0.00039 to 1.142 inches (0.01 to 29 millimeters [mm]) (Thomas and others, 2002), which is consistent with the majority of the bed material in the Fountain Creek watershed (Stogner and others, 2013). The Laursen-Copeland equation was chosen over the other seven sediment-transport functions in HEC-RAS because it was most applicable to the sediment grain-size classes present in the Fountain Creek channel system and is one of the four transport functions currently (2013) available for calibration in HEC-RAS. Additionally, it was recommended as the most robust transport function by experts responsible for model development and support (Stanford Gibson, USACE Hydrologic Engineering Center, written commun., May 1, 2012).

The Laursen-Copeland equation does not predict the sediment wash load, only the suspended load and the bed load components of the total sediment load (Williams and others, 2013). The sediment samplers located at six USGS streamgages measure only the washload and the suspended load. These data are stored in the USGS NWIS database (*http://waterdata.usgs.gov/nwis)* and then used to generate the sediment rating curves. Regression analysis was used to characterize the suspended-sediment loads (Cohn, 2005; Dalby, 2006; Runkel and others, 2004). Transport equations predict suspended-sediment load, which is a mixture of the washload and bedload. The critical Shields number in the sediment-transport function of HEC-RAS and the amount of sediment available for transport in the stream were adjusted in the sediment-transport function to calibrate the sediment discharge to the transport determined by the suspended-sediment rating curves (USACE, 2010c).

Suspended-Sediment Transport Equations

Standard techniques used to measure suspended-sediment concentration and flux require the continuous measurement of streamflow and systematic measurement of suspended-sediment concentration (Porterfield, 1972). Daily mean streamflow data were obtained from the USGS NWIS database (*http://waterdata.usgs.gov/nwis*) and instantaneous suspended-sediment concentrations were collected manually using standard field techniques (Edwards and Glysson, 1999).

Suspended-Sediment-Flux Transport Equations

Within the USGS-developed LOADEST program (the FORTRAN program LOAD ESTimator, Runkel and others, 2004), the general equation (identified as eq. 1 in LOADEST) relates the natural logarithm of suspended-sediment flux to daily mean streamflow and other explanatory variables using maximum likelihood estimation methods. The general equation form used in this report is similar to Runkel and others (2004), Cohn (2005), and Dalby (2006). Step-wise regression techniques were used to develop sediment rating curves where each explanatory variable was highly significant (p-value <0.05).

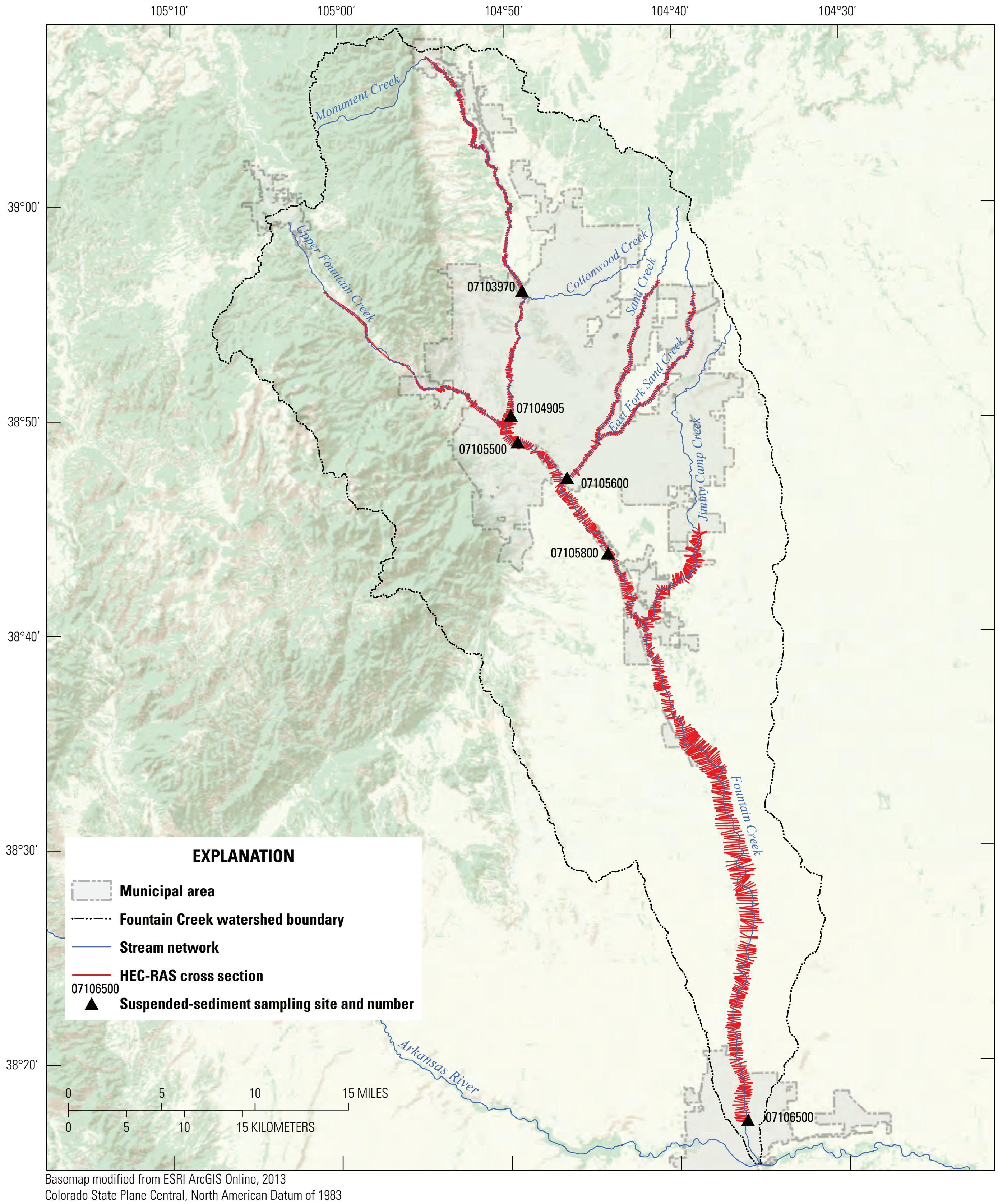


Figure 10. Location of the six suspended-sediment sampling locations used for calibration. HEC-RAS, Hydrologic Engineering Center-River Analysis System.

Table 8. The six U.S. Geological Survey (USGS) streamgages used in the sediment-model calibration.

[mi^2, square miles; ft, feet; ft^3/s, cubic feet per second; Colo., Colorado. Drainage area determined from USGS National Water Information System database]

USGS streamgage	Streamgage name	Latitude (°)	Longitude (°)	Drainage area (mi^2)	Elevation (ft)	Flow range (ft^3/s)
07103970	Monument Creek above Woodmen Road at Colorado Springs, Colo.	38.9272222	–104.8141667	18.9	6,240	12.3–8,150
07104905	Monument Creek at Bijou Street at Colorado Springs, Colo.	38.8372147	–104.8294192	235	5,980	31.2–32,000
07105500	Fountain Creek at Colorado Springs, Colo.	38.8163816	–104.8227519	392	5,900	60.3–71,900
07105600	Sand Creek above mouth at Colorado Springs, Colo.	38.7883277	–104.7738620	52.4	5,837	7.00–14,400
07105800	Fountain Creek at Security, Colo.	38.7294404	–104.7338611	500	5,640	148–112,000
07106500	Fountain Creek at Pueblo, Colo.	38.2877778	–104.6005556	925	4,705	202–183,000

Data Collection and Interpretation

As previously stated, all input data used to develop the hydraulic model were used in the HEC-RAS sediment-transport model. Sediment data were the only new data that were required to be collected to perform sediment-transport modeling with HEC-RAS. Two types of sediment data were collected: (1) suspended-sediment data were collected at 6 locations and (2) bed-material samples were collected at 52 locations. Of the 52 samples, 37 of them were obtained from URS, Inc. (2007), and the remaining 15 were collected for this study.

Suspended-Sediment Samples

Suspended-sediment samples were collected using conventional USGS methods described in Guy and Norman (1970), Edwards and Glysson (1999), and Nolan and others (2005). Suspended-sediment concentrations and size analyses were done by the USGS Iowa Sediment Laboratory in Iowa City, Iowa, following procedures outlined in Guy (1969).

Bed-Material Samples

In addition to the bed-material data collected by URS, Inc. (2007), bed material was sampled using a shovel and bag at selected locations along Fountain Creek to obtain a broad distribution of bed-material samples throughout the modeled reaches in the watershed. Multiple sampling sites were selected within each reach to characterize any dramatic change in bed material. Characterization of the bed material was done to determine the size distribution and spatial extent of the bed materials within each reach. Bed-material size analysis was performed by volumetric techniques (dry sieving) for each sample at the USGS Geomorphology and Sediment Transport Laboratory in Golden, Colo. Bed-material sampling locations are presented in figure 11. Sediment-particle-size data of bed-material samples collected by the USGS for the sediment-transport model can be found in appendix 1.

Boundary Conditions

The sediment-transport model required upstream and downstream boundary conditions to compute the hydraulics and several sediment boundary conditions to determine the sediment transport. For this model, the upstream boundary conditions were flow and sediment rating curves at the upstream-most cross section of each tributary and stage at the most downstream cross section of the model. Flow from the 24-h, 1-percent AEP (100-yr) precipitation event determined using HEC-HMS was inputted at the upstream-most cross section on Upper Fountain Creek, Monument Creek, Sand Creek, and Jimmy Camp Creek and used as the upstream boundary conditions of the HEC-RAS model for the sediment-transport model calibration. Lateral inflows were input throughout the HEC-RAS model at the cross section corresponding to the outlet of each subwatershed in the HEC-HMS model for the 1-percent AEP (100-yr) storm. Because HEC-RAS must maintain flow in the channel at all times, a minimum flow of 10 cubic feet per second (ft^3/s) was set for all inflows to HEC-RAS. At the upstream-most cross section on Upper Fountain Creek, Monument Creek, Sand Creek, and Jimmy Camp Creek, suspended-sediment discharge rating curves were developed and used as the upstream boundary condition. The downstream-boundary condition of the sediment-transport model was the stage-streamflow rating curve at the USGS streamgage Fountain Creek at Pueblo (07106500), where the stage was referenced to NAVD88. The sediment-transport model in HEC-RAS used quasi-unsteady-flow simulations during the sediment-model routine, so no unsteady-flow routing was required during the sediment-transport modeling.

The 52 bed-material grain-size-distribution curves were used to define the bed material in the model. Each gradation curve was assigned to the cross section nearest to its sampling location. From there, the remaining approximately 1,900 cross sections had gradation curves assigned to them based on the 52 gradation curves. If a cross section fell between two gradation curves, an interpolated gradation curve was assigned to

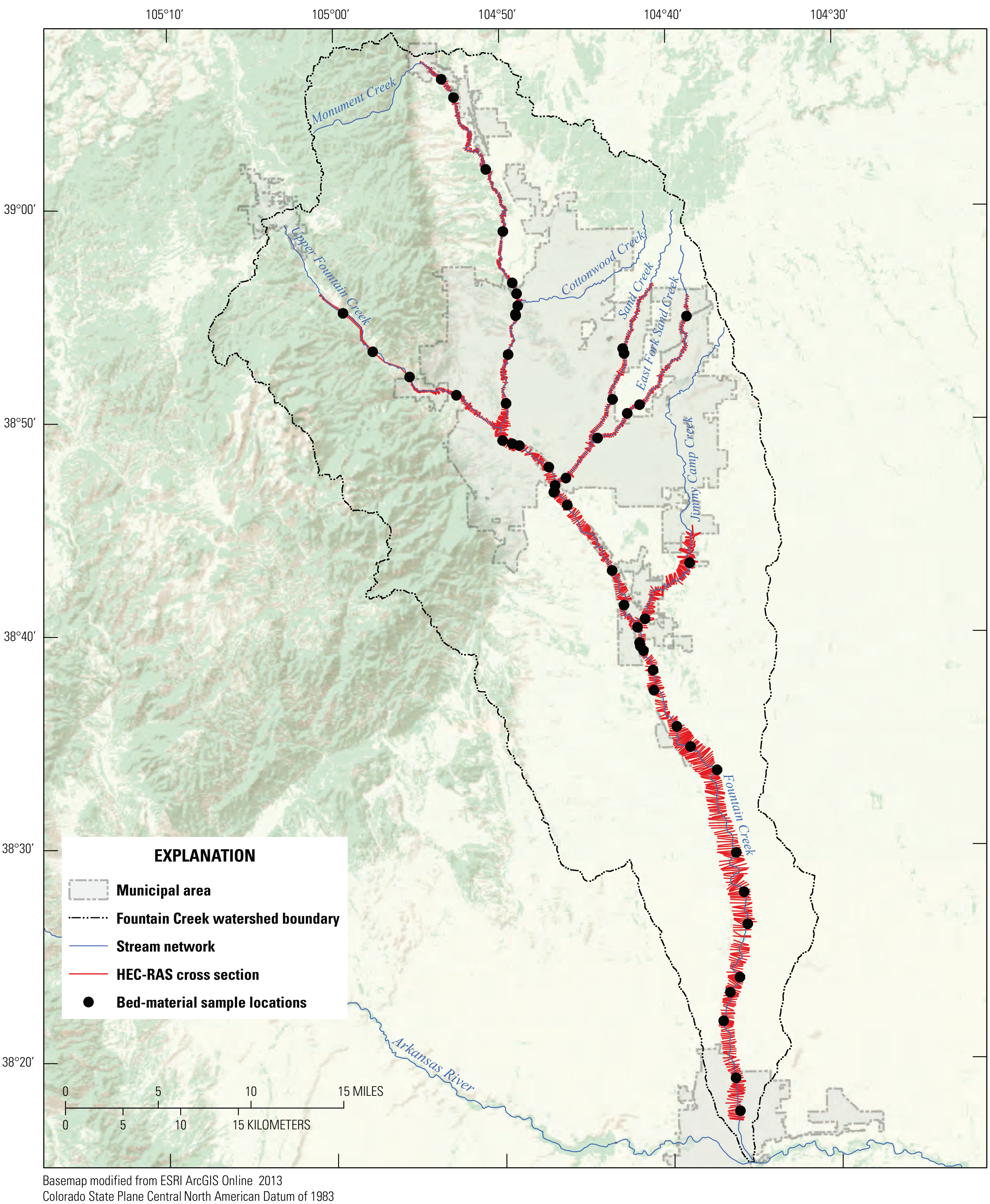


Figure 11. Location of the 52 bed-material samples used to develop the Hydrologic Engineering Center-River Analysis System (HEC-RAS) sediment-transport model of Fountain Creek.

that cross section based on its location between those original two gradation curves. If a cross section fell between one gradation curve and the upstream or downstream end of a reach, the nearest gradation curve was applied at that cross section. To provide stability in the upstream reaches, the upstream sediment-boundary condition was set to artificially derived sediment rating curves for the upstream-most cross section of Upper Fountain Creek, Monument Creek, East Fork Sand Creek, Sand Creek, and Jimmy Camp Creek (Stanford Gibson, USACE Hydrologic Engineering Center, written commun., February 8, 2013). Water temperature is also needed for the sediment-transport computation. Based on the period of record of the water temperature at the USGS streamgage Fountain Creek at Pueblo (07106500) from the NWIS database (*http://waterdata.usgs.gov/nwis*), the average temperature for all months was approximately 50 degrees Fahrenheit. As a result, this was the temperature assigned to the HEC-RAS sediment-transport model for the 1-percent AEP (100-yr) storm.

Unlike the HEC-RAS hydraulic model, all the cross sections in the model are dynamic throughout the simulation and change due to the amount of aggradation or degradation occurring at a particular cross section at any given time. The sediment mass plus the amount of aggradation or degradation at a particular cross section is equal to the amount of sediment delivered to the next cross section downstream.

Sediment-Transport Model Results

The Laursen-Copeland sediment-transport function was used in conjunction with the Exner 5 sorting method and the Ruby fall-velocity method to predict sediment transport (USACE, 2010c). To debug the model, the channel-forming streamflow, approximated as the 50-percent AEP (2-yr) flow based on the results from the URS, Inc. (2006b), study, was run through the model for a period of 2 months. Due to the channel slopes and magnitude of this model, this reduced model instability and assisted in identifying troublesome cross sections or hydraulic structures that caused model divergence. As a result, several bridges in the model geometry were converted to lidded cross sections during the sediment-transport modeling. Due to model instability near several bridges, several bridges had to be removed for the model to resolve a solution; this was done only in the HEC-RAS sediment-transport model and not for the HEC-RAS hydraulic model. Several of the upstream bed gradation curves were coarsened to mimic armoring that occurs along the channel bed during storm events as recommended by HEC staff (Stanford Gibson, USACE Hydrologic Engineering Center, written commun., April 11, 2013).

Six USGS streamgages equipped with suspended-sediment samplers were used to develop sediment-flow rating curves for the sediment-transport-model calibration. Sediment discharge and streamflow generated by the model at the six calibration locations were used to guide model calibration. The sediment discharge in tons per day as a function of streamflow in cubic feet per second produced by the model was adjusted in the calibration process to match the suspended-sediment rating curves, which describe sediment discharge in tons per day as a function of streamflow in cubic feet per second, at each of the six calibration streamgages as closely as possible.

The critical Shields number in the Laursen-Copeland sediment-transport function and the volume of sediment available at a given cross section were adjusted during the HEC-RAS sediment-model calibration process. The flow from the 24-h, 1-percent AEP (100-yr) precipitation event (URS, Inc., 2006a) computed using HEC-HMS was used to drive the HEC-RAS sediment-transport model. The critical Shields number in the Laursen-Copeland sediment-transport function was assumed to be constant throughout the model domain, but the amount of sediment available for transport was adjusted on a cross-section by cross-section basis. The default critical Shields number (0.039) in the Laursen-Copeland sediment-transport function (eq. 1) was adjusted throughout the model during the calibration process so that the final Laursen-Copeland sediment-transport function was defined as the following with the final critical Shields number of 0.045:

$$C_m = 0.010\gamma\left(\frac{d_s}{D}\right)^{7/6}\left(\frac{\tau_O'}{0.045}-1\right)f\left(\frac{\mu_*}{\omega}\right) \qquad (2)$$

The amount of sediment available for transport of each cross section in the model was limited laterally to the channel, which was defined as the area between the left and right top of bank, and vertically to 10 ft below the initial cross-section elevation except for Upper Fountain Creek where it was assigned a value of 1 ft due to the cobbles and bedrock that are prevalent in that reach. The comparison plots of sediment discharge in tons per day as a function of streamflow in cubic feet per second produced by the model and the suspended-sediment rating curves, which describe sediment discharge in tons per day as a function of streamflow in cubic feet per second, at each of the six calibration streamgages are shown in figure 12.

Model Simulations

HEC-RAS was used to build and simulate 14 remediation scenarios within the Fountain Creek watershed. The unsteady-flow simulation and sediment-transport model were the two model components that were used to perform the scenario runs. Hydrographs generated from the calibrated HEC-HMS model were used as the primary input for the HEC-RAS model simulations for both the hydraulic model and the sediment-transport model. Channel hydraulics were computed as an unsteady-flow condition; whereas, sediment transport was computed as a quasi-unsteady flow with no channel routing.

The remediation scenarios consist of side-detention facilities, channel widening, bank stabilization, drop structures, a diversion channel at the lower end of Fountain Creek to Chico Creek, and a reservoir located at the lower end of Fountain

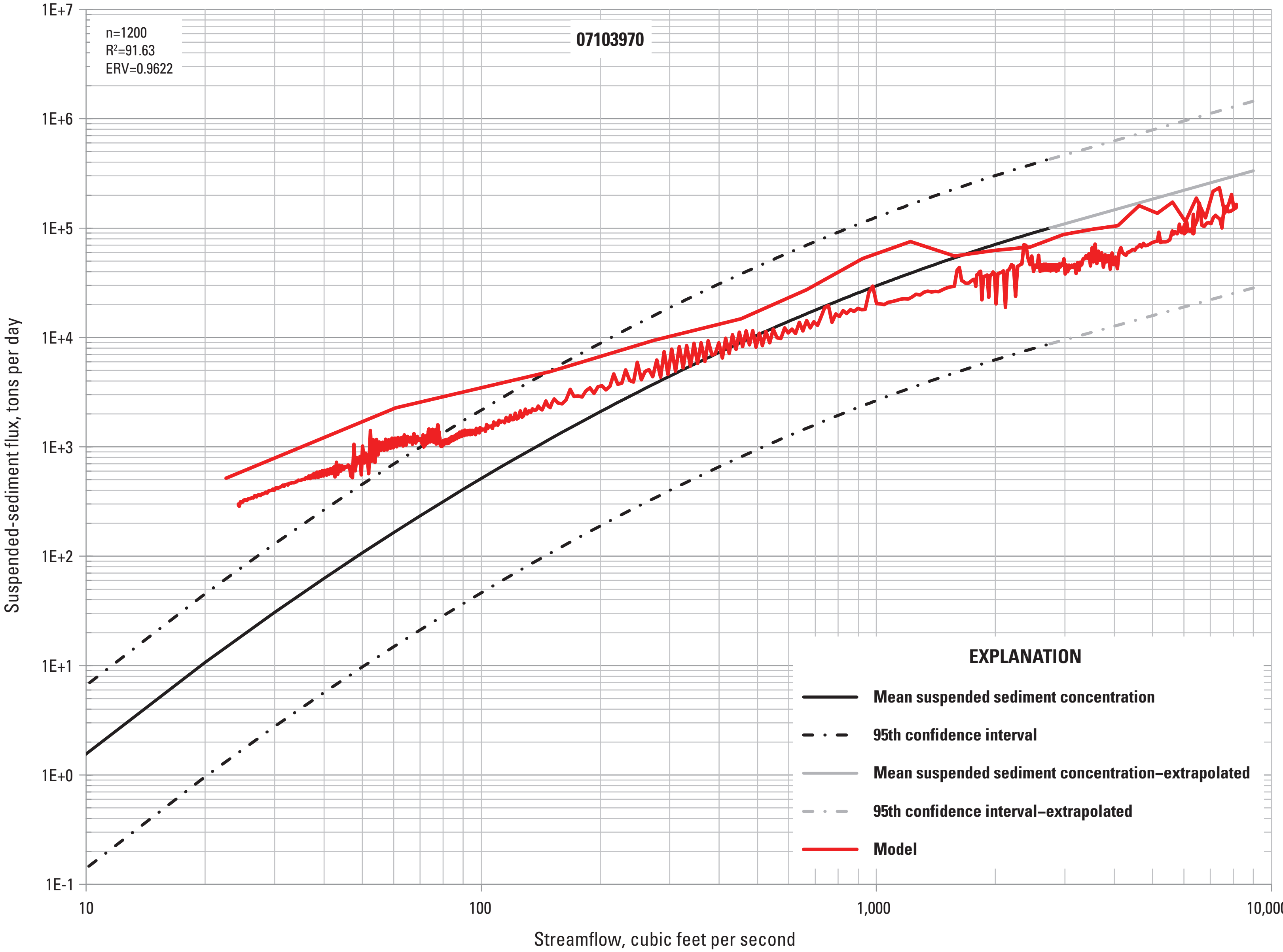


Figure 12. Sediment discharge and flow from Hydrologic Engineering Center-River Analysis System model results and sediment rating curves determined from samplers located at six U.S. Geological Survey streamgages.

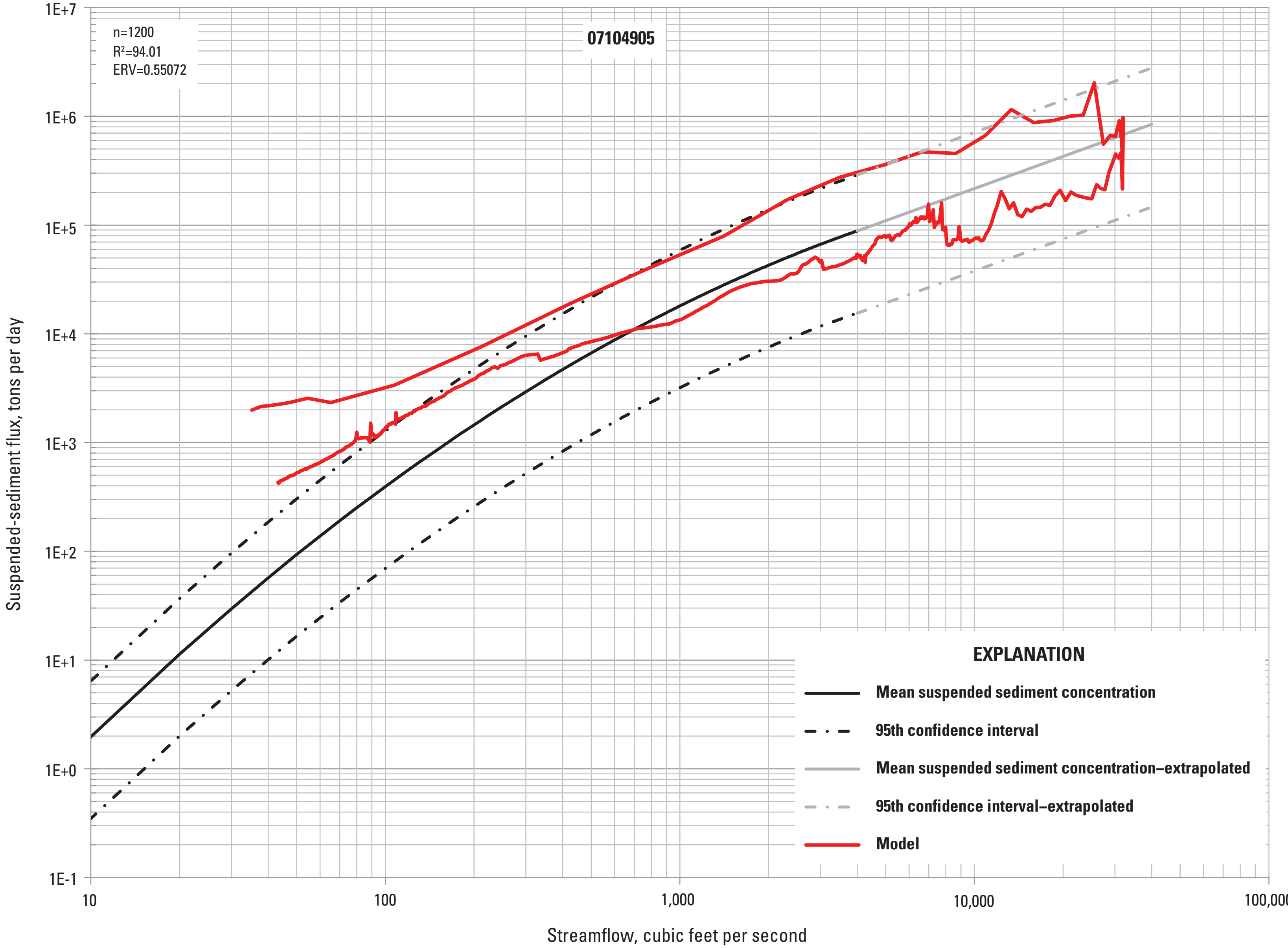


Figure 12. Sediment discharge and flow from Hydrologic Engineering Center-River Analysis System model results and sediment rating curves determined from samplers located at six U.S. Geological Survey streamgages.

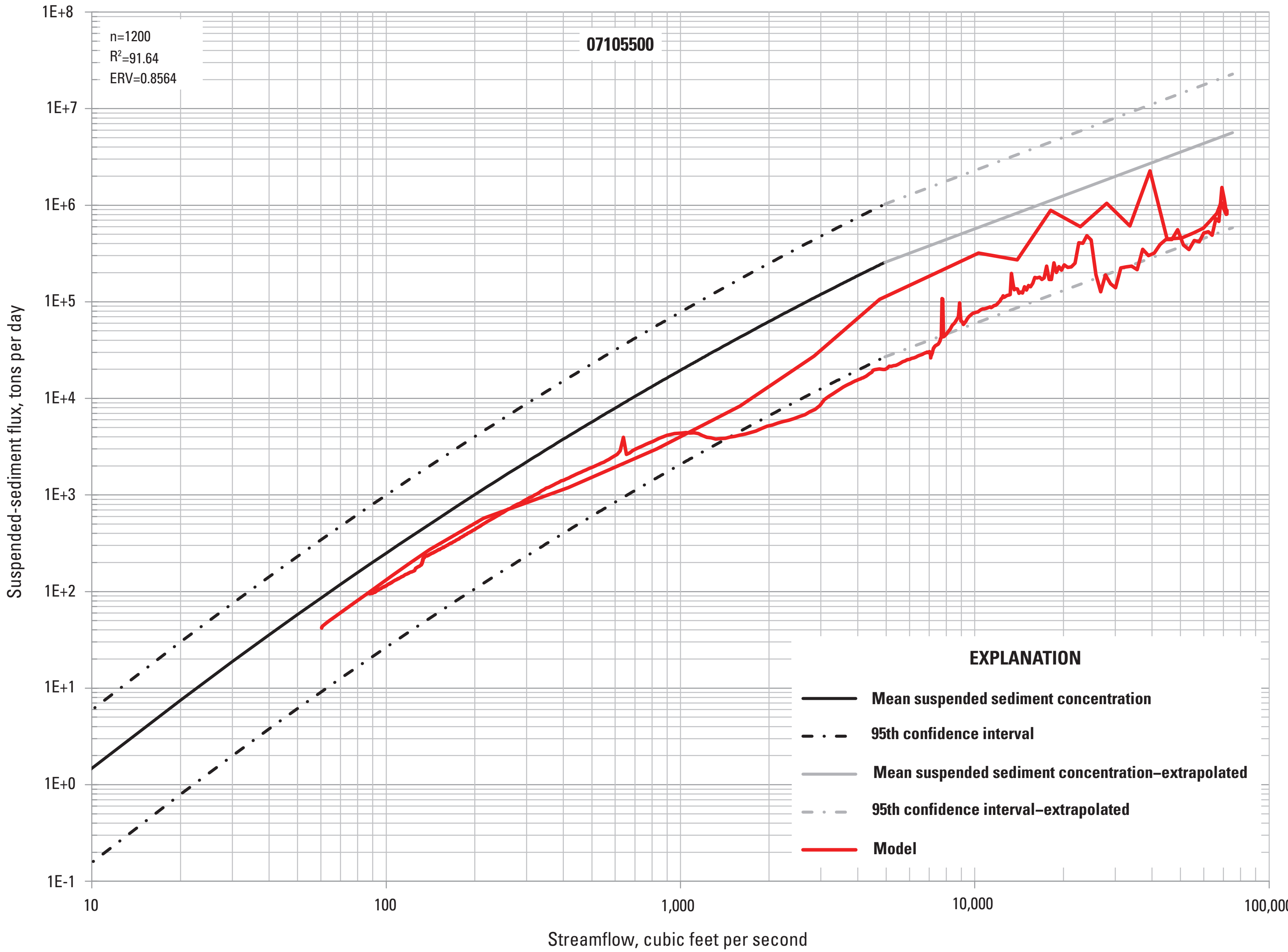


Figure 12. Sediment discharge and flow from Hydrologic Engineering Center-River Analysis System model results and sediment rating curves determined from samplers located at six U.S. Geological Survey streamgages.

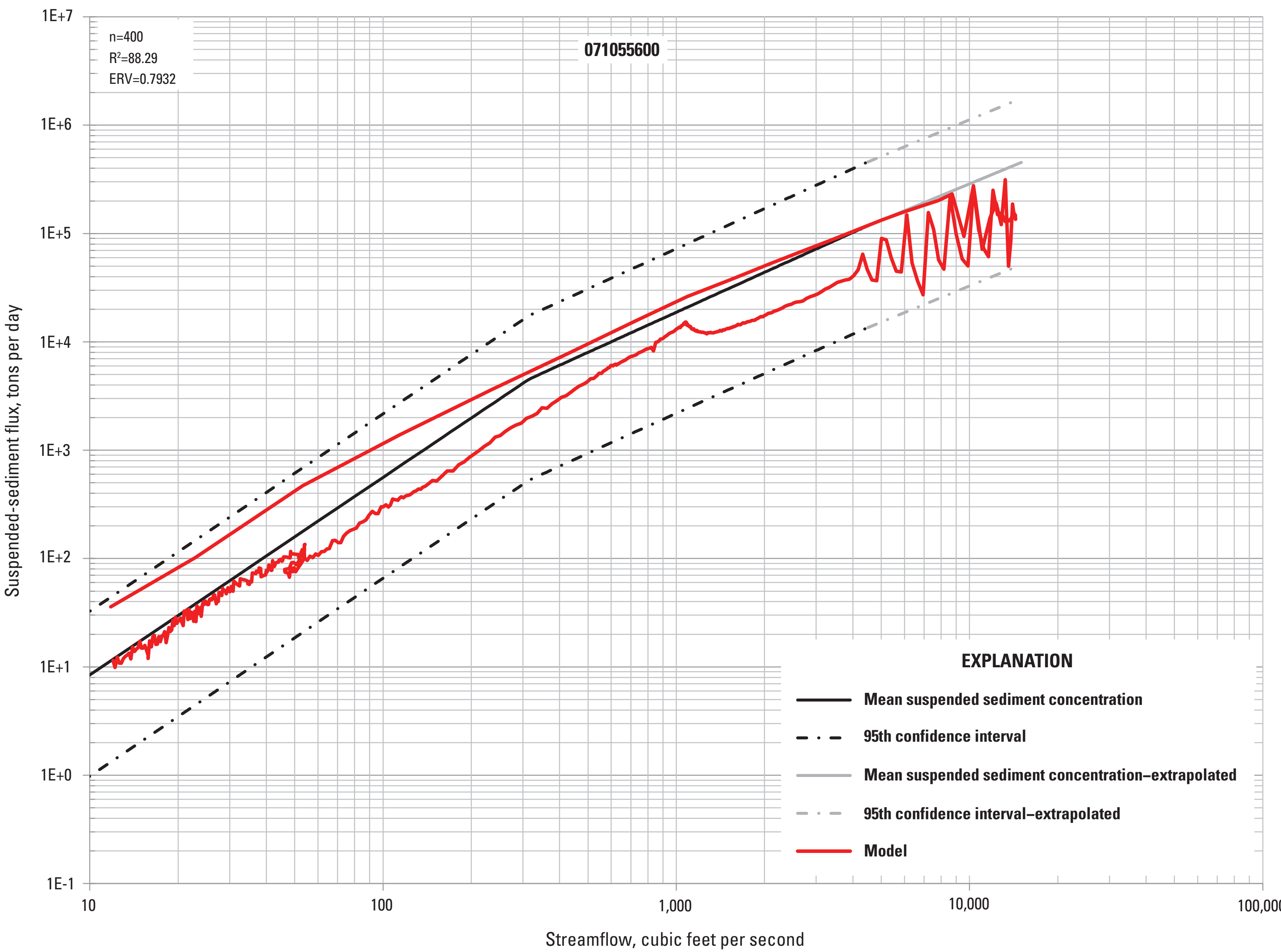


Figure 12. Sediment discharge and flow from Hydrologic Engineering Center-River Analysis System model results and sediment rating curves determined from samplers located at six U.S. Geological Survey streamgages.

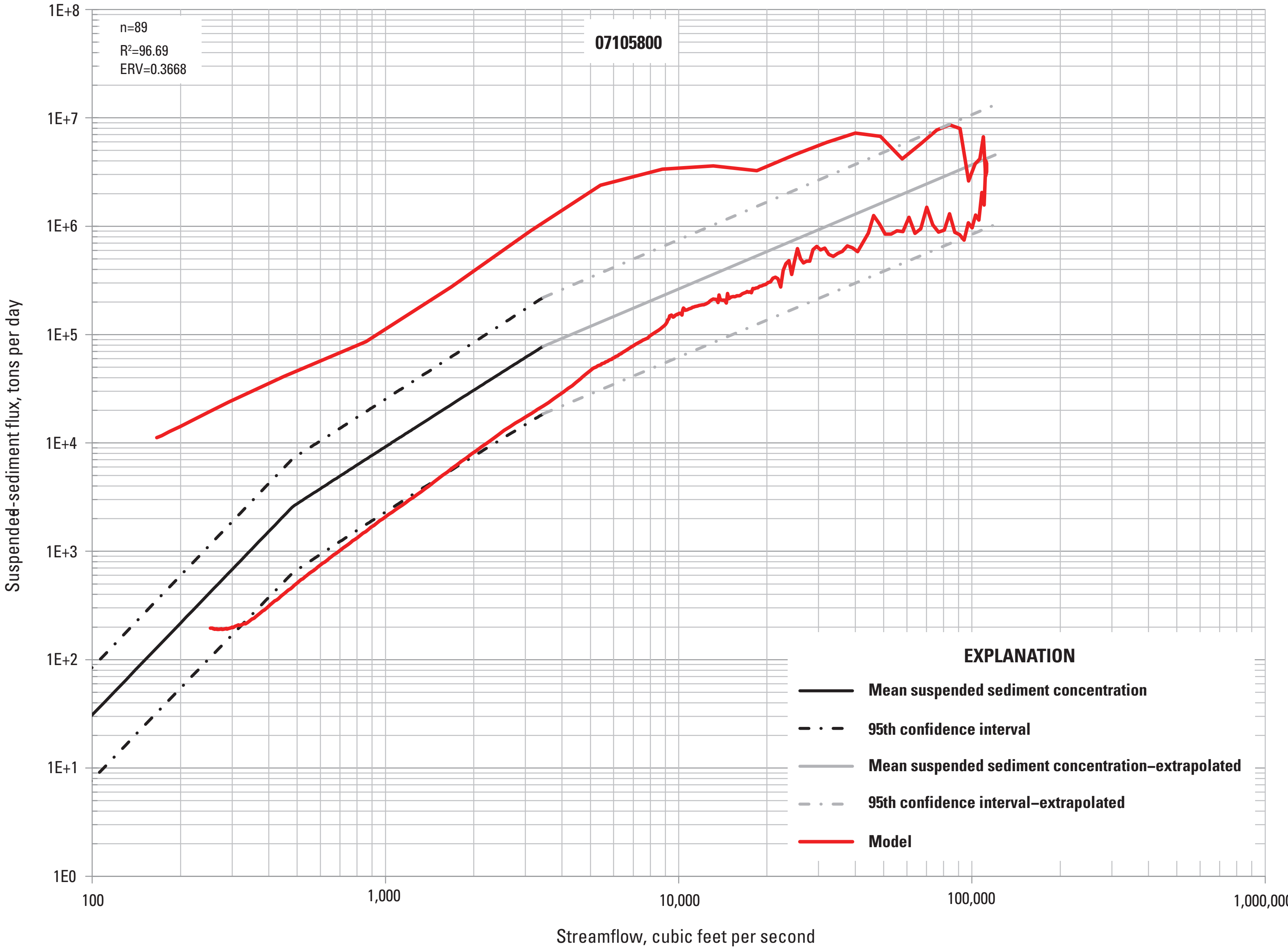


Figure 12. Sediment discharge and flow from Hydrologic Engineering Center-River Analysis System model results and sediment rating curves determined from samplers located at six U.S. Geological Survey streamgages.

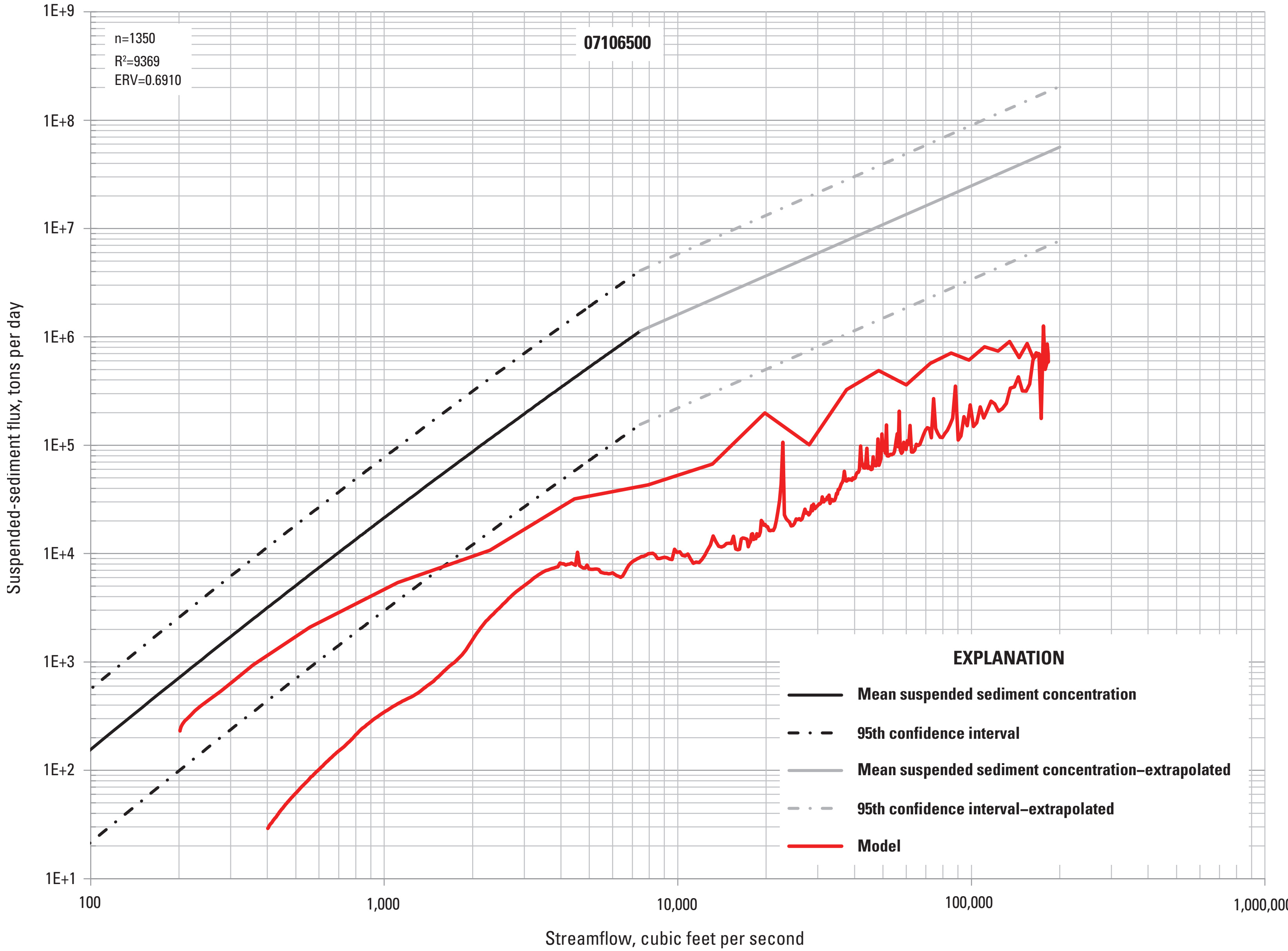


Figure 12. Sediment discharge and flow from Hydrologic Engineering Center-River Analysis System model results and sediment rating curves determined from samplers located at six U.S. Geological Survey streamgages.

Creek. Each of the 14 remediation scenarios was built within the model geometry of HEC-RAS. These scenarios and their locations were chosen by the FCWFCGD Technical Advisory Committee and are based on recommendations referenced in USACE (2009) or in THK Associates, Inc., and Matrix Design Group, Inc. (2011). The objectives of the models are to determine how much reduction of the total sediment flux and peak streamflow occurs in each scenario. For the purpose of presentation, results are presented for the downstream extent of the model domain, which coincides with the USGS streamgage at Pueblo, Colorado. It should be noted that results are available for every cross section in the model. Results for each of the 15 USGS streamgages used in the HEC-RAS calibration (fig. 9 and table 6) can be found in appendix 2. The results of each scenario are only valid for the prescribed storm event, and a storm event with a different magnitude, duration, or location would change the results of the scenarios.

Boundary Conditions

When modeling the remediation scenarios, the final curve numbers, lag times, Manning's roughness coefficients, and critical Shields number in the Laursen-Copeland sediment-transport function derived during the calibration process were used. Following the HEC-HMS calibration, channel losses were included to simulate losing reaches. HEC-RAS model simulations used to evaluate the 14 remediation scenarios were based on unsteady-state streamflows associated with a 24-h, 1-percent AEP (100-yr) NOAA Type II precipitation event, from here on referred to as "precipitation event." This precipitation event is consistent with the URS, Inc. (2006a), hydrologic study of Fountain Creek. The event was centered over the centroid of the watershed and included an areal reduction factor that was applied to all subwatersheds based on their location. It is important to note that a 1-percent AEP (100-yr) precipitation event is not equal to a 1-percent AEP (100-yr) flow event; however, a 1-percent AEP (100-yr) precipitation modeled with HEC-HMS coupled with HEC-RAS does allow for the effective evaluation of remediation alternatives using HEC-RAS. Also, it is important to keep in mind that the calibration and validation storms did not have an AEP uniformly equal to 1-percent, but they were used to model a storm with an AEP of 1-percent. Upstream and downstream boundary conditions of the HEC-RAS models were the same as discussed previously (fig. 13).

Remediation Scenarios

Fourteen remediation scenarios were evaluated to determine the relative effectiveness of each to reduce peak flows and sediment transport. Scenario 0 represents the baseline or current conditions in the watershed and was used to compare the remaining 13 scenarios. Scenarios 1–8 and 12 rely on side-detention facilities to reduce peak flows and sediment transport. Scenario 9 has a diversion channel, and scenario 10 has a reservoir. Scenarios 11 and 13 incorporate channel armoring and channel widening, respectively. Locations of all the remediation elements in the remediation scenarios are shown in appendix 3.

Scenario 0

The current conditions in the watershed are described by scenario 0 and include no new remediation elements. However, scenario 0 does include the nine detention facilities in figure 5 and table 2 that were included in the HEC-HMS model and already constructed in the watershed. Scenario 0 will be used as the baseline scenario to compare the other scenarios, which incorporate some degree of remediation.

Scenario 1

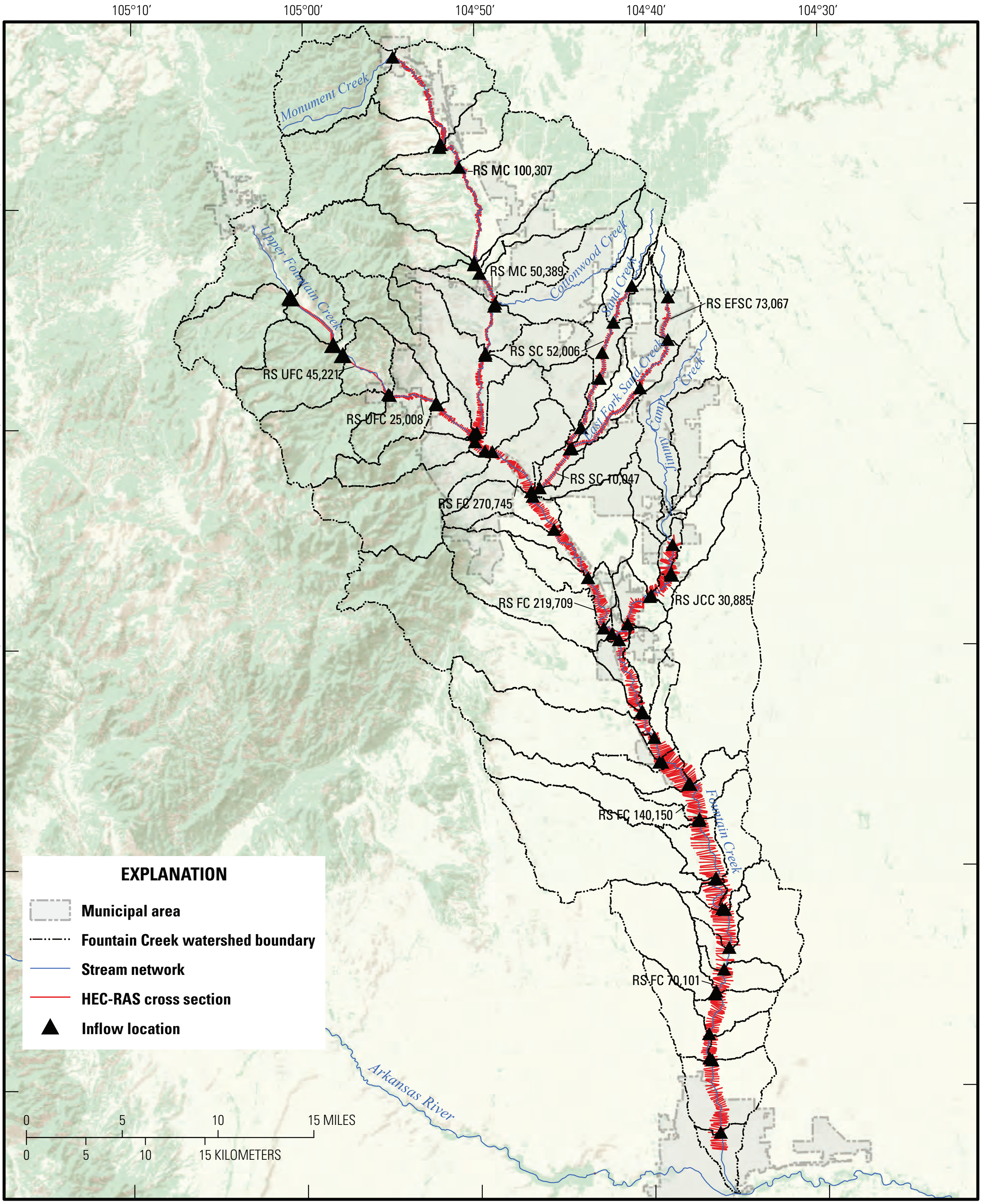
Scenario 1 includes seven side-detention facilities at prescribed locations consistent with USACE (2009) recommendations along Monument Creek. Side-detention facilities are storage ponds that are empty and only hold water during floods. Side-detention facilities are located to the side of the channel connected to the stream only by a lateral hydraulic structure such as a broad-crested weir. The detention facilities have a total of 3,520 acre-ft of storage spanning 352 acres of surface area assuming a maximum depth of 10 ft in each detention facility. The size, surface area, depth, and location (reach and river station) of all the detention facilities in scenario 1 can be found in table 9. River station refers to the distance in feet upstream from the confluence of the named reach and Fountain Creek or the mouth of Fountain Creek.

Scenario 2

Scenario 2 includes 7 side-detention facilities along Monument Creek and 4 along Upper Fountain Creek for a total of 11. The detention facilities have a total of 5,480 acre-ft of storage and 548 acres of surface area assuming a maximum depth of 10 ft in each detention facility. The size, surface area, depth, and location (reach and river station) of all the detention facilities in scenario 2 can be found in table 9.

Scenario 3

Scenario 3 includes 7 side-detention facilities along Monument Creek, 4 along Upper Fountain Creek, 3 along East Fork Sand Creek, and 4 along Sand Creek for a total of 18. The detention facilities have a total of 6,350 acre-ft of storage on 635 acres of surface area assuming a maximum depth of 10 ft in each detention facility. The size, surface area, depth, and location (reach and river station) of all the detention facilities in scenario 3 can be found in table 9.



Basemap modified from ESRI ArcGIS Online 2013
Colorado State Plane Central North American Datum of 1983

Figure 13. Location of the 72 Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) subbasins, 1,900 Hydrologic Engineering Center-River Analysis System (HEC-RAS) cross sections, and 72 inflows (determined from rainfall runoff computed with the HEC-HMS model) used in the HEC-RAS model. RS, river station; EFSC, East Fork Sand Creek; JCC, Jimmy Camp Creek; FC, Fountain Creek; MC, Monument Creek; SC, Sand Creek; UFC, Upper Fountain Creek.

Table 9. Location, characteristics, and general description of each remediation element used in the 14 remediation scenarios.

[ft, feet; River station refers to the distance in feet upstream from the confluence of the named reach and Fountain Creek or the mouth of Fountain Creek]

Remediation element name	Element type	Element location (reach and river station)	Total volume (acre-ft)	Maximum depth (ft)	Surface area (acre)	Scenario(s)
MC153783	Detention pond	Monument Creek 153,783	100	10	10	1–8
MC119592	Detention pond	Monument Creek 119,592	130	10	13	1–8
MC115900	Detention pond	Monument Creek 115,900	360	10	36	1–8
MC74310	Detention pond	Monument Creek 74,310	900	10	90	1–8
MC39128	Detention pond	Monument Creek 39,128	980	10	98	1–8
MC26026	Detention pond	Monument Creek 26,026	50	10	5	1–8
MC15387	Detention pond	Monument Creek 15,387	1,000	10	100	1–8
UFC33659	Detention pond	Upper Fountain Creek 33,659	490	10	49	2–8
UFC18875	Detention pond	Upper Fountain Creek 18,875	500	10	50	2–8
UFC7475	Detention pond	Upper Fountain Creek 7,475	580	10	58	2–8
UFC5900	Detention pond	Upper Fountain Creek 5,900	390	10	39	2–8
USC69585.75	Detention pond	Upper Sand Creek 69,585.75	40	10	4	3–8
USC32211.28	Detention pond	Upper Sand Creek 32,211.28	60	10	6	3–8
USC23733.07	Detention pond	Upper Sand Creek 23,733.07	260	10	26	3–8
LSC14832.64	Detention pond	Lower Sand Creek 14,832.64	380	10	38	3–8
ESC63832.95	Detention pond	East Fork Sand Creek 63,833	60	10	6	3–8
ESC41958.73	Detention pond	East Fork Sand Creek 41,959	60	10	6	3–8
ESC31159.02	Detention pond	East Fork Sand Creek 31,159	10	10	1	3–8
JCC45187	Detention pond	Jimmy Camp Creek 45,187	1,000	10	100	4–8
JCC35582	Detention pond	Jimmy Camp Creek 35,582	850	10	85	4–8
JCC25503	Detention pond	Jimmy Camp Creek 25,503	1,000	10	100	4–8
JCC13399	Detention pond	Jimmy Camp Creek 13,399	640	10	64	4–8
JCC7963	Detention pond	Jimmy Camp Creek 7,963	370	10	37	4–8
JCC5186	Detention pond	Jimmy Camp Creek 5,186	40	10	4	4–8
FC283919	Detention pond	Fountain Creek 283,919	100	10	10	5–8
FC281349	Detention pond	Fountain Creek 281,349	150	10	15	5–8
FC279731	Detention pond	Fountain Creek 279,731	400	10	40	5–8
FC276802	Detention pond	Fountain Creek 276,802	1,000	10	100	5–8
FC267681	Detention pond	Fountain Creek 267,681	1,200	10	120	5–8
FC260750	Detention pond	Fountain Creek 260,750	200	10	20	6–8
FC255703	Detention pond	Fountain Creek 255,703	990	10	99	6–8
FC248849	Detention pond	Fountain Creek 248,849	1,000	10	100	6–8
FC230349	Detention pond	Fountain Creek 230,349	1,000	10	100	6–8
FC223849	Detention pond	Fountain Creek 223,849	1,000	10	100	6–8

Table 9. Location, characteristics, and general description of each remediation element used in the 14 remediation scenarios.—Continued

[ft, feet; River station refers to the distance in feet upstream from the confluence of the named reach and Fountain Creek or the mouth of Fountain Creek]

Remediation element name	Element type	Element location (reach and river station)	Total volume (acre-ft)	Maximum depth (ft)	Surface area (acre)	Scenario(s)
FC192849	Detention pond	Fountain Creek 192,849	1,000	10	100	7–8,12
FC179652	Detention pond	Fountain Creek 179,652	990	10	99	7–8,12
FC147349	Detention pond	Fountain Creek 147,349	990	10	99	7–8,12
FC125690	Detention pond	Fountain Creek 125,690	1,000	10	100	7–8,12
FC120940	Detention pond	Fountain Creek 120,940	100	10	10	8,12
FC107049	Detention pond	Fountain Creek 107,049	2,500	10	250	8,12
FC89851	Detention pond	Fountain Creek 89,851	2,500	10	250	8,12
FC64131	Detention pond	Fountain Creek 64,131	2,000	10	200	8,12
FC40049	Detention pond	Fountain Creek 40,049	2,000	10	200	8,12
FC26354	Detention pond	Fountain Creek 26,354	150	10	15	8,12

Remediation element name	Element type	Element location (reach and river station)	Weir elevation (ft)	Downstream weir length (ft)		Scenario
FC125000	Diversion weir	Fountain Creek 125,000	5,162.92	700		9

Remediation element name	Element type	Element location (reach and river station)	Total volume (acre-ft)	Flood storage (acre-ft)	Dam height (ft)	Scenario
FC59139	Reservoir	Fountain Creek 59,139	52,700	27,000	84.5	10

Remediation element name	Element type	Element location (reach and river station)	Total length (mile)	Manning's roughness coefficient		Scenario
FC256116	Bank armoring	Fountain Creek 256,116 to the confluence with Jimmy Camp Creek	9.4	0.033		11

Remediation element name	Element type	Element location (reach and river station)	Total length (mi)	Channel width (ft)	Elevation of new flood plain (ft)	Scenario
FC188916	Flood-plain expansion	Fountain Creek 118,916 to Fountain Creek 59,140	10.0	5,300	10-year flow	13

Scenario 4

Scenario 4 includes 7 side-detention facilities along Monument Creek, 4 along Upper Fountain Creek, 3 along East Fork Sand Creek, 4 along Sand Creek, and 6 along Jimmy Camp Creek for a total of 24. The detention facilities have a total of 10,250 acre-ft of storage on 1,025 acres of surface area assuming a maximum depth of 10 ft in each detention facility. The size, surface area, depth, and location (reach and river station) of all the detention facilities in scenario 4 can be found in table 9.

Scenario 5

Scenario 5 includes 7 side-detention facilities along Monument Creek, 4 along Upper Fountain Creek, 3 along East Fork Sand Creek, 4 along Sand Creek, 6 along Jimmy Camp Creek, and 5 along Fountain Creek between the confluence with Monument Creek and the confluence with Sand Creek for a total of 29. The detention facilities have a total of 13,100 acre-ft of storage on 1,310 acres of surface area assuming a maximum depth of 10 ft in each detention facility. The size, surface area, depth, and location (reach and river station) of all the detention facilities in scenario 5 can be found in table 9.

Scenario 6

Scenario 6 includes 7 side-detention facilities along Monument Creek, 4 along Upper Fountain Creek, 3 along East Fork Sand Creek, 4 along Sand Creek, 6 along Jimmy Camp Creek, 5 along Fountain Creek between the confluence with Monument Creek and the confluence with Sand Creek, and 5 along Fountain Creek between the confluence with Sand Creek and the confluence with Jimmy Camp Creek for a total of 34. The detention facilities have a total of 17,290 acre-ft of storage on 1,729 acres of surface area assuming a maximum depth of 10 ft in each detention facility. The size, surface area, depth, and location (reach and river station) of all the detention facilities in scenario 6 can be found in table 9.

Scenario 7

Scenario 7 includes 7 side-detention facilities along Monument Creek, 4 along Upper Fountain Creek, 3 along East Fork Sand Creek, 4 along Sand Creek, 6 along Jimmy Camp Creek, 5 along Fountain Creek between the confluence with Monument Creek and the confluence with Sand Creek, 5 along Fountain Creek between the confluence with Sand Creek and the confluence with Jimmy Camp Creek, and 4 along Fountain Creek in El Paso County below the confluence with Jimmy Camp Creek for a total of 38. The detention facilities have a total of 21,270 acre-ft of storage on 2,127 acres of surface area assuming a maximum depth of 10 ft in each detention facility. The size, surface area, depth, and location (reach and river station) of all the detention facilities in scenario 7 can be found in table 9.

Scenario 8

Scenario 8 includes 7 side-detention facilities along Monument Creek, 4 along Upper Fountain Creek, 3 along East Fork Sand Creek, 4 along Sand Creek, 6 along Jimmy Camp Creek, 5 along Fountain Creek between the confluence with Monument Creek and the confluence with Sand Creek, 5 along Fountain Creek between the confluence with Sand Creek and the confluence with Jimmy Camp Creek, 4 along Fountain Creek in El Paso County below the confluence with Jimmy Camp Creek, and 6 along Fountain Creek in Pueblo County below the confluence with Jimmy Camp Creek for a total of 44. The detention facilities have a total of 30,520 acre-ft of storage on 3,052 acres of surface area assuming a maximum depth of 10 ft in each detention facility. The size, surface areas, depth, and location (reach and river station) of all the detention facilities in scenario 8 can be found in table 9.

Scenario 9

Scenario 9 contains no detention facilities but includes a trans-watershed diversion to Chico Creek along the main stem of Fountain Creek (fig. 3-9). The diversion weir is modeled as a lateral structure located near the El Paso-Pueblo County line at river station 125,000. This location was chosen by the FCWFCGD Technical Advisory Committee because the topography in the area provides the most feasible location to build a diversion channel. The location (reach and river station) and size of the remediation element in scenario 9 can be found in table 9.

Scenario 10

Scenario 10 includes a reservoir on the main stem of Fountain Creek and no diversion channel or side-detention facilities. The reservoir is located at river station 59,139, which is approximately 5.5 mi north of Colorado State Highway 47 and 9.6 mi upstream from the mouth of Fountain Creek. The emergency spillway was modeled as an ogee spillway with a length of 500 ft. Thirteen radial gates, which remained completely open throughout the simulation, were used to model the main outlet structure. The flood storage required to mitigate the flow caused by the 24-h, 1-percent AEP (100-yr) precipitation event was 27,000 acre-ft. The permanent storage, which is the volume located below the outlet structure and would be used for recreation and water supply, was about 25,700 acre-ft. This value was determined because it was approximately equal to the flood storage. The storage between the outlet structure and the spillway was designed only for the streamflow associated with capturing the 24-h, 1-percent AEP (100-yr) precipitation event. Any additional flow could not be contained in the reservoir and would pass through the spillway. The permanent storage could be increased or decreased based on the demand for this water, which in turn would change the dam and reservoir characteristics. The total storage, the sum of the permanent storage and flood storage, was equal to 52,700 acre-ft. The height of the dam from the channel invert to the spillway invert and the top of dam was 79.5 ft and 84.5 ft, respectively. The invert of the 13 outlet gates, which makes up the outlet structure, was located 58.5 ft above the invert of the channel. Each of the outlet gates was 10 ft high and 5 ft wide. The reservoir was approximately 4 mi in length upstream from the dam along the channel thalweg; however, this was probably overestimated because the reservoir was restricted to a width of approximately 1 mi because that was the widest surveyed cross-section data that were available in the reach near the dam. The location (reach and river station) and size of the remediation element in scenario 10 can be found in table 9.

Scenario 11

Scenario 11 includes no detention facilities, channel diversion, or dams. Nine miles of Fountain Creek between Sand and Jimmy Camp Creeks were armored in the simulation to reduce the sediment supply. In the hydraulic model and the sediment-transport model, the Manning's roughness coefficient in the channel of the armored section was set at 0.033 following the recommendation of Chow (1959). In the sediment-transport model, this reach of Fountain Creek had no sediment available for transport. The location (reach and river station) of the remediation elements in scenario 11 can be found in table 9.

Scenario 12

Scenario 12 includes 4 detention facilities along Fountain Creek in El Paso County below the confluence with Jimmy Camp Creek and 6 detention facilities along Fountain Creek in Pueblo County for a total of 10. These 10 detention facilities are the same as the 10 most downstream detention facilities located in scenario 8. The 10 detention facilities have a total of 13,230 acre-ft of storage and 1,323 acres of surface area assuming a maximum depth of 10 ft in each detention facility. The size, surface area, depth, and location (reach and river station) of all the detention facilities in scenario 12 can be found in table 9.

Scenario 13

Scenario 13 includes widening the channel cross section for 10 mi on the main stem of Fountain Creek. The downstream end of the channel widening was located at Fountain Creek river station 59,139, which is approximately 5.5 mi north of Colorado State Highway 47 and 9.6 mi upstream from the mouth. At approximately the water-surface elevation of the 10-percent AEP (10-yr) flow, the channel width was increased in this 10-mi reach so the trapezoidal flood-plain channel had a bottom width that was 5,300 ft and 3:1 side slopes. On average, this increased the channel width by approximately a factor of 20 in the 10-mi reach. The location (reach and river station) and description of the remediation elements in scenario 13 can be found in table 9.

Remediation Scenarios for Attenuating Peak Flows and Sediment Transport

The results of 14 remediation scenarios are reported in table 10 for the USGS streamgage Fountain Creek at Pueblo, Colorado (07106500) (referred to hereafter as Pueblo streamgage), and include the reduction of peak streamflow and total sediment transport based on a 24-h, 1-percent AEP (100-yr recurrence-interval) design storm. The results for the remaining 14 USGS streamgages (fig. 9 and table 6) can be found in appendix 2. Small increases (2 percent) in sediment transport or peak streamflow are due to model uncertainties, but some increases in sediment transport can be attributed to local deposition that has occurred upstream from the gage caused by reduced streamflow. The local deposition creates a slightly larger slope locally upstream and near the gage causing increased sediment transport at the gage.

Scenario 0 served as the baseline scenario because it represents the watershed as of 2013, with no new remediation elements. However, scenario 0 does include the nine detention facilities in figure 5 and table 2 that were included in the HEC-HMS model and already constructed in the watershed.

In general, peak streamflow decreases and sediment reduction increases from scenario 1 to scenario 8, which correspond to the gradual increase in side-detention facilities from scenario 1 to scenario 8. Scenario 1 reduces the peak streamflow and total sediment load on Monument Creek; however, no change occurs on Upper Fountain Creek, Sand Creek, or Jimmy Camp Creek. The impact Scenario 1 has on Fountain Creek is evident at the very upstream end of the channel but becomes negligible toward Pueblo because the change in peak flow and sediment transport at the Pueblo streamgage is +0.2 and –2.2 percent, respectively (table 10 and appendix 2).

Scenario 2 reduces the peak streamflow and total sediment load on Monument Creek and Upper Fountain Creek; however, no change occurs on Sand Creek or Jimmy Camp Creek. Scenario 2 has an impact on Fountain Creek at the very upstream end but becomes insignificant toward the mouth of Fountain Creek because the change in peak flow and sediment transport at the Pueblo streamgage is –0.4 and +1.3 percent, respectively.

Scenario 3 reduces the peak streamflow and total sediment load on Monument Creek, Upper Fountain Creek, and Sand Creek. However, no impact occurs on Jimmy Camp Creek. Scenario 3 influences both the peak streamflow and sediment transport on Fountain Creek at the very upstream end but is ineffective at the lower end of Fountain Creek because the change in peak flow and sediment transport at the Pueblo

Table 10. Peak streamflow, change in peak streamflow, total sediment transport, and change in total sediment transport predicted by the models at the U.S. Geological Survey streamgage Fountain Creek at Pueblo, Colorado (07106500), for each of the 14 remediation scenarios.

[ft^3/s, cubic feet per second. NA, the change in peak streamflow and total sediment transport was determined from scenario 0 so that scenario did not have the change computed]

Scenario	Peak streamflow (ft^3/s)	Change (percent)	Total sediment transport (tons)	Change (percent)
0	37,100	NA	104,000	NA
1	37,200	+0.2	101,000	–2.2
2	36,900	–0.4	105,000	+1.3
3	36,200	–2.4	103,000	–0.2
4	30,300	–18.2	99,000	–4.4
5	30,200	–18.5	96,400	–6.9
6	27,800	–24.9	94,600	–8.6
7	21,300	–42.5	92,100	–11.1
8	15,200	–58.9	85,200	–17.7
9	21,300	–42.5	94,800	–8.4
10	16,200	–56.4	39,200	–62.1
11	37,100	0.0	102,000	–1.1
12	19,400	–47.7	95,000	–8.0
13	35,300	–4.8	92,000	–11.3

streamgage is –2.4 and –0.2 percent, respectively (table 10 and appendix 2). Scenarios 2 and 3 provide less capture of sediment due to the location of the source material; changing the location of sediment erosion and deposition changes the channel slopes locally, which in turn can create greater rates of sediment transport downstream.

Scenario 4 reduces the peak streamflow and total sediment load on Monument Creek, Upper Fountain Creek, Sand Creek, and Jimmy Camp Creek. The impact on Fountain Creek is very noticeable (table 10 and appendix 2) at the very upstream end and becomes less noteworthy downstream closer to the confluence with Jimmy Camp Creek. For Scenario 4, below Jimmy Camp Creek, the reduction of peak flow and sediment transport is substantial all the way to the mouth of Fountain Creek because the change in peak flow and sediment transport at the Pueblo streamgage is –18.2 and –4.4 percent, respectively.

Scenario 5 reduces the peak streamflow and total sediment load on Monument Creek, Upper Fountain Creek, Sand Creek, Jimmy Camp Creek, and Fountain Creek. In scenario 5, the reduction of sediment transport and peak streamflow is most noticeable on Fountain Creek above the confluence with Sand Creek, but the change of peak flow and sediment transport is still –18.5 and –6.9 percent, respectively, at the Pueblo streamgage.

Scenario 6 reduces the peak streamflow and total sediment load on Monument Creek, Upper Fountain Creek, Sand Creek, Jimmy Camp Creek, and Fountain Creek. In scenario 6, the reduction of sediment transport and peak streamflow is largest in the upper part of Fountain Creek, between the confluence with Monument Creek and the El Paso-Pueblo County line, but the change of peak flow and sediment transport is still –24.9 and –8.6 percent, respectively, at the Pueblo streamgage (table 10 and appendix 2).

Scenario 7 reduces the peak streamflow and total sediment load on Monument Creek, Upper Fountain Creek, Sand Creek, Jimmy Camp Creek, and Fountain Creek. In scenario 7, the reduction of sediment transport and peak streamflow is most evident in the upper part of Fountain Creek, between the confluence with Monument Creek and the El Paso-Pueblo County line, but the change of peak flow and sediment transport is still –42.5 and –11.1 percent, respectively, at the Pueblo streamgage (table 10 and appendix 2).

Scenario 8 reduces the peak streamflow and total sediment load on Monument Creek, Upper Fountain Creek, Sand Creek, Jimmy Camp Creek, and Fountain Creek. For scenario

8, the change of peak flow and sediment transport is –58.9 and –17.7 percent, respectively, at the Pueblo streamgage.

Scenario 9 has no impact on the watershed in terms of reduction in flow or sediment transport except in Pueblo County, because the diversion channel is located near the El Paso-Pueblo County line. For scenario 9, the change in peak flow and sediment transport at the Pueblo streamgage is –42.5 and –8.4 percent, respectively (table 10 and appendix 2).

Scenario 10 has no impact on the watershed in terms of reduction in flow or sediment transport except in Pueblo County, because the upstream end of the reservoir created by the dam is approximately 7 mi south of the El Paso-Pueblo County line. However, below the dam, flows and sediment transport are reduced significantly by scenario 10, by –56.4 and –62.1 percent, respectively, at the Pueblo streamgage.

Scenario 11 does not change flow in any part of the watershed as it is a sediment-specific scenario. Scenario 11 has no impact on sediment transport on Monument Creek or Upper Fountain Creek. No impact on sediment transport on Fountain Creek occurs until near the Sand Creek confluence, and sediment transport actually increases at the very lower end of Fountain Creek to compensate for the lack of sediment in Fountain Creek created by the armoring. In scenario 11, locally, armoring noticeably reduces the sediment transport in the armored reach and immediately downstream from it. The streamgages at Security, near the town of Fountain, Colo., and on Jimmy Camp Creek have 83.0, 28.6, and 71.8 percent reduction in sediment transport (table 10 and appendix 2). However, Fountain Creek compensates for this large reduction in sediment by transporting additional sediment along the lower reaches of Fountain Creek so that at Pueblo, the change in sediment transport in only –1.1 percent. This points to the conclusion that locally, the effect of bank armoring can be very substantial; however, a stream such as Fountain Creek will tend to compensate for a reduced sediment load through an armored section by eroding additional sediment downstream from the armored section so that far enough downstream from the armored section, no change is observed.

Scenario 12 has no pronounced impact on flow or sediment except for Fountain Creek below the confluence of Jimmy Camp Creek. The reduction of peak flow increases from the streamgage near Fountain to the streamgages near Piñon, Colo., and at Pueblo, whereas small reductions in sediment transport are observed at all three streamgages. In scenario 12, the change in peak flow and sediment transport at the Pueblo streamgage is –47.7 and –8.0 percent, respectively.

Scenario 13 has no discernible impact on flow or sediment except for Fountain Creek in Pueblo County, because that was where the channel widening was located. The reduction of peak flow is minor but present at the streamgages near Piñon and Pueblo. A moderate reduction in sediment transport occurs at the streamgage at Pueblo, whereas the large increase in sediment transport at the Piñon streamgage can be attributed to the Piñon streamgage being located at a bridge, which is now near a very large expansion in the channel because the channel width is approximately 20 ft wider than before, which increases the sediment transport locally. However, downstream from the 10-mi reach where the channel expansion occurs, the sediment transport is slightly smaller. For scenario 13, the change in peak flow and sediment transport at the Pueblo streamgage is –4.8 and –11.3 percent, respectively (table 10 and appendix 2).

Scenarios 8 and 10, the scenario with the most side-detention facilities and the scenario with the reservoir, respectively, were the most effective at reducing sediment transport and peak flow at the Pueblo, Colorado streamgage. Scenarios 8 and 10 altered the peak flow by –58.9 and –56.4 percent, respectively. In turn, scenarios 8 and 10 altered the sediment transport by –17.7 and –62.1 percent, respectively (table 10 and appendix 2).

Summary

The Fountain Creek watershed, Colorado, is characterized by steep channel slopes and varied land use. These dynamics contribute to large streamflows and sediment transport, which has caused periodic flooding and sediment aggradation and deposition in Fountain Creek and its tributary streams. The U.S. Geological Survey (USGS) in cooperation with the Fountain Creek Watershed, Flood Control and Greenway District assessed remediation scenarios to attenuate peak flows and reduce sediment loads in the Fountain Creek watershed.

To evaluate these strategies, the U.S. Army Corps of Engineers Hydrologic Engineering Center (HEC) hydrologic and hydraulic models were employed. The U.S. Army Corps of Engineers modeling system HEC-HMS (Hydrologic Modeling System) version 3.5 was used to simulate runoff in the Fountain Creek watershed, Colorado, associated with storms of varying magnitude and duration. Rain-gage precipitation data and radar-based precipitation data from the April 28–30, 1999, and September 14–15, 2011, storm events were used in the calibration process for the HEC-HMS model. The curve number and lag time for each subwatershed and Manning's roughness coefficients for each channel reach were adjusted within an acceptable range so that the simulated and measured streamflow hydrographs for each of the 12 USGS streamgages approximated each other. The absolute mean errors of the peak streamflow for the calibration and validation storms were 13 and 25 percent, respectively. The absolute mean errors of the volume for the calibration and validation storms were 36 and 51 percent, respectively.

The U.S. Army Corps of Engineers modeling system HEC-RAS (River Analysis System) versions 4.1 and 4.2 were used to simulate streamflow and sediment transport, respectively, for the Fountain Creek watershed generated by a particular storm event. Data from 15 USGS streamgages were used for model calibration and 7 of those USGS streamgages were used for model validation. The calibration process consisted of comparing the simulated water-surface elevations and the cross-section-averaged velocities from the model with those surveyed in the field at the cross section at the corresponding 15 and 7 streamgages, respectively. The final Manning's roughness coefficients were adjusted between –30 and 30 percent at the 15 calibration streamgages from the original left, right, and channel-averaged Manning's roughness coefficients upon completion of calibration. The absolute mean and mean difference in water-surface elevation from the 15 streamgages between observed and modeled water-surface elevations was 1.8 and 0.9 ft, respectively, for the 2011 storm (calibration storm). The absolute mean and mean difference in water-surface elevation from the seven validation streamgages between observed and modeled water-surface elevations was 1.7 and 0.3 ft, respectively, for the 1999 storm (validation storm).

The U.S. Army Corps of Engineers modeling system HEC-RAS version 4.2 was used to simulate streamflow and sediment transport for the Fountain Creek watershed generated by a design-storm event. The Laursen-Copeland sediment-transport function was used in conjunction with the Exner 5 sorting method and the Ruby fall-velocity method to predict sediment transport. Six USGS streamgages equipped with suspended-sediment samplers were used to develop sediment-flow rating curves for the sediment-transport-model calibration. The critical Shields number in the Laursen-Copeland sediment-transport function and the volume of sediment available at a given cross section were adjusted during the HEC-RAS sediment-model calibration process.

HEC-RAS was used to build and simulate 14 remediation scenarios within the Fountain Creek watershed. HEC-RAS model simulations used to evaluate the 14 remediation scenarios were based on unsteady-state streamflows associated with a 24-hour, 1-percent annual exceedance probability (100-year) National Oceanic and Atmospheric Administration Type II precipitation event. Scenario 0 represents the baseline or current conditions in the watershed and was used to compare the remaining 13 scenarios. Scenarios 1–8 and 12 rely on side-detention facilities to reduce peak flows and sediment transport. Scenario 9 has a diversion channel, and scenario 10 has a reservoir. Scenarios 11 and 13 incorporate channel armoring and channel widening, respectively.

The impact Scenario 1 has on Fountain Creek is evident at the very upstream end of the channel but becomes negligible toward Pueblo because the change in peak flow and sediment transport at the Pueblo streamgage is +0.2 and –2.2 percent, respectively. Scenario 2 has an impact on Fountain Creek at the very upstream end but becomes insignificant toward the mouth of Fountain Creek because the change in peak flow and sediment transport at the Pueblo streamgage is –0.4 and +1.3 percent, respectively. Scenario 3 influences both the peak streamflow and sediment transport on Fountain Creek at the very upstream end but is ineffective at the lower end of Fountain Creek because the change in peak flow and sediment transport at the Pueblo streamgage is –2.4 and –0.2 percent, respectively. For Scenario 4, below Jimmy Camp Creek, the reduction of peak flow and sediment transport is substantial all the way to the mouth of Fountain Creek because the change in peak flow and sediment transport at the Pueblo streamgage is –18.2 and –4.4 percent, respectively. In scenario 5, the reduction of sediment transport and peak streamflow is most noticeable on Fountain Creek above the confluence with Sand Creek, but the change of peak flow and sediment transport is still –18.5 and –6.9 percent, respectively, at the Pueblo streamgage. In scenario 6, the reduction of sediment transport and peak streamflow is largest in the upper part of Fountain Creek, between the confluence with Monument Creek and the El Paso-Pueblo County line, but the change of peak flow and sediment transport is still –24.9 and –8.6 percent, respectively, at the Pueblo streamgage. In scenario 7, the reduction of sediment transport and peak streamflow is most evident in the upper part of Fountain Creek, between the confluence with Monument Creek and the El Paso-Pueblo County line, but the change of peak flow and sediment transport is still –42.5 and –11.1 percent, respectively, at the Pueblo streamgage. For scenario 8, the change of peak flow and sediment transport is –58.9 and –17.7 percent, respectively, at the Pueblo streamgage. For scenario 9, the change in peak flow and sediment transport at the Pueblo streamgage is –42.5 and –8.4 percent, respectively. Below the dam, flows and sediment transport are reduced significantly by scenario 10, by –56.4 and –62.1 percent, respectively, at the Pueblo streamgage. In scenario 11, locally, armoring noticeably reduces the sediment transport in the armored reach and immediately downstream from it. However, Fountain Creek compensates for this large reduction in sediment by transporting additional sediment along the lower reaches of Fountain Creek so that at the Pueblo streamgage, the change in sediment transport is only –1.1 percent. In scenario 12, the change in peak flow and sediment transport at the Pueblo streamgage is –47.7 and –8.0 percent, respectively. For scenario 13, the change in peak flow and sediment transport at the Pueblo streamgage is –4.8 and –11.3 percent, respectively.

Scenarios 8 and 10, the scenario with the most side-detention facilities and the scenario with the reservoir, respectively, were the most effective at reducing sediment transport and the peak flow at the Pueblo streamgage. Scenarios 8 and 10 altered the peak flow by –58.9 and –56.4 percent, respectively. In turn, scenarios 8 and 10 altered the sediment transport by –17.7 and –62.1 percent, respectively.

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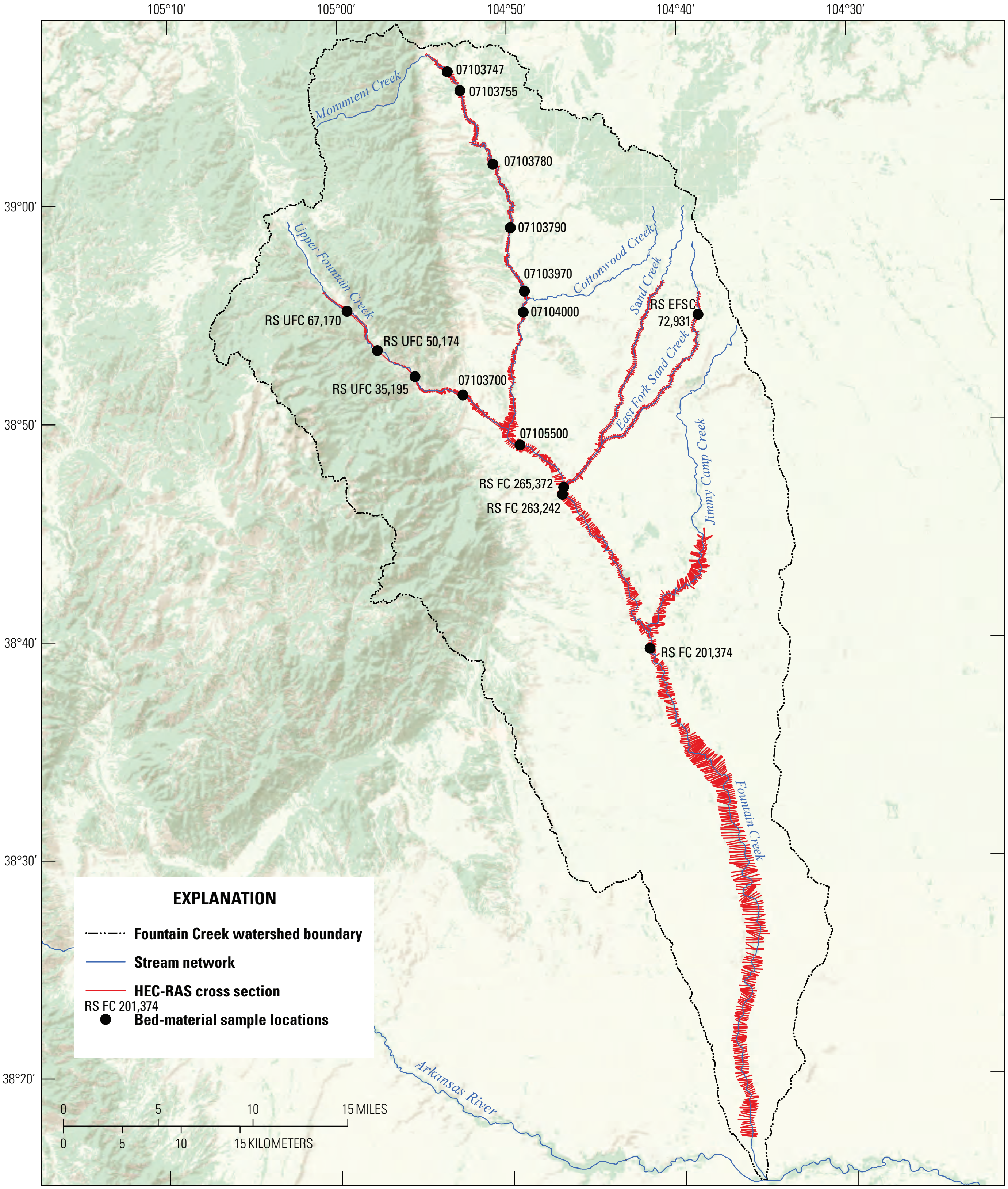
Appendixes

Appendix 1. Channel-Bed Sediment Data Collected in the Fountain Creek Watershed

Table 1-1. Sediment-particle-size-distribution summary statistics of bed-material samples collected by the U.S. Geological Survey at selected locations in Fountain Creek watershed and its tributaries in 2012 located in figure 1-1.

[in, inches; NA, the pan catches all material finer than the smallest diameter pan; RS, river station; UFC, Upper Fountain Creek; EFSC, East Fork Sand Creek; FC, Fountain Creek]

Site number	Size distribution, in percent finer, shown for the sieves and their diameters								
	Sieve identification								
	7/8 in	7/16 in	No. 5	No. 10	No. 20	No. 45	No. 100	No. 200	Pan
	Diameter (in)								
	0.8750	0.4375	0.1570	0.0787	0.0335	0.0139	0.00295	0.00295	NA
07103700	100.0	99.0	77.7	55.5	29.1	8.1	0.7	0.3	0.0
07103747	95.4	79.9	48.8	32.8	20.8	12.0	4.2	1.6	0.0
07103755	100.0	74.8	51.4	34.9	17.4	7.8	2.3	1.0	0.0
07103780	100.0	89.3	43.7	19.6	5.7	1.8	0.4	0.2	0.0
07103790	96.2	92.0	68.9	36.7	8.1	1.9	0.5	0.3	0.0
07103970	100.0	100.0	96.9	75.0	27.8	3.6	0.7	0.3	0.0
07104000	91.7	85.3	70.8	50.7	24.0	6.9	0.6	0.2	0.0
07105500	100.0	88.1	59.4	37.4	15.5	3.4	1.0	0.6	0.0
RS UFC 67,170	100.0	97.7	85.8	73.4	48.7	17.5	3.5	1.4	0.0
RS UFC 50,174	100.0	79.4	29.4	14.9	7.2	2.7	0.9	0.6	0.0
RS UFC 35,195	100.0	97.9	82.9	57.5	21.2	2.7	0.2	0.1	0.0
RS EFSC 72,931	100.0	98.6	87.8	75.6	56.5	37.3	7.3	1.4	0.0
RS FC 265,372	100.0	91.4	61.6	39.5	17.7	5.9	0.8	0.5	0.0
RS FC 263,242	100.0	98.3	79.7	53.3	24.9	6.8	0.7	0.2	0.0
RS FC 201,374	100.0	98.5	75.8	51.8	17.2	3.6	0.8	0.3	0.0



Basemap modified from ESRI ArcGIS Online, 2013
Colorado State Plane Central, North American Datum of 1983

Figure 1-1. Location of the 15 bed-material samples collected by the U.S. Geological Survey used to develop the Hydrologic Engineering Center-River Analysis System (HEC-RAS) sediment-transport model of Fountain Creek. RS, river station; EFSC, East Fork Sand Creek; FC, Fountain Creek; UFC, Upper Fountain Creek.

Appendix 2. Remediation Scenario Results at U.S. Geological Survey Streamgages in the Fountain Creek Watershed

Table 2–1. Peak streamflow, change in peak streamflow, total sediment transport, and change in total sediment transport predicted by the models at the U.S. Geological Survey streamgage Fountain Creek near Colorado Springs, Colorado (07103700), for each of the 14 remediation scenarios.

[ft^3/s, cubic feet per second. NA, the change in peak streamflow and total sediment transport was determined from scenario 0 so that scenario did not have the change computed]

Scenario	Peak streamflow (ft^3/s)	Change (percent)	Total sediment transport (tons)	Change (percent)
0	5,790	NA	3,240	NA
1	5,790	0.0	3,240	0.0
2	1,910	–67.0	2,780	–14.1
3	1,910	–67.0	2,780	–14.1
4	1,910	–67.0	2,780	–14.1
5	1,910	–67.0	2,780	–14.1
6	1,910	–67.0	2,780	–14.1
7	1,910	–67.0	2,780	–14.1
8	1,910	–67.0	2,780	–14.1
9	5,790	0.0	3,240	0.0
10	5,790	0.0	3,240	0.0
11	5,790	0.0	3,240	0.0
12	5,750	–0.6	3,240	0.0
13	5,790	0.0	3,240	0.0

Table 2–2. Peak streamflow, change in peak streamflow, total sediment transport, and change in total sediment transport predicted by the models at the U.S. Geological Survey streamgage Monument Creek at Palmer Lake, Colorado (07103747), for each of the 14 remediation scenarios.

[ft^3/s, cubic feet per second. NA, the change in peak streamflow and total sediment transport was determined from scenario 0 so that scenario did not have the change computed]

Scenario	Peak streamflow (ft^3/s)	Change (percent)	Total sediment transport (tons)	Change (percent)
0	1,080	NA	14,500	NA
1	827	–23.7	13,800	–4.7
2	827	–23.7	13,800	–4.7
3	827	–23.7	13,800	–4.7
4	827	–23.7	13,800	–4.7
5	827	–23.7	13,800	–4.7
6	827	–23.7	13,800	–4.7
7	827	–23.7	13,800	–4.7
8	827	–23.7	13,800	–4.7
9	1,080	0.0	14,500	0.0
10	1,080	0.0	14,500	0.0
11	1,080	0.0	14,500	0.0
12	1,080	0.0	14,500	0.0
13	1,080	0.0	14,500	0.0

Table 2–3. Peak streamflow, change in peak streamflow, total sediment transport, and change in total sediment transport predicted by the models at the U.S. Geological Survey streamgage Monument Creek below Monument Lake near Monument, Colorado (07103755), for each of the 14 remediation scenarios.

[ft^3/s, cubic feet per second. NA, the change in peak streamflow and total sediment transport was determined from scenario 0 so that scenario did not have the change computed]

Scenario	Peak streamflow (ft^3/s)	Change (percent)	Total sediment transport (tons)	Change (percent)
0	947	NA	16,900	NA
1	726	–23.3	16,500	–2.0
2	726	–23.3	16,500	–2.0
3	726	–23.3	16,500	–2.0
4	726	–23.3	16,500	–2.0
5	726	–23.3	16,500	–2.0
6	726	–23.3	16,500	–2.0
7	726	–23.3	16,500	–2.0
8	726	–23.3	16,500	–2.0
9	947	0.0	16,900	0.0
10	947	0.0	16,900	0.0
11	947	0.0	16,900	0.0
12	947	0.0	16,900	0.0
13	947	0.0	16,900	0.0

Table 2–4. Peak streamflow, change in peak streamflow, total sediment transport, and change in total sediment transport predicted by the models at the U.S. Geological Survey streamgage Monument Creek above North Gate Boulevard at U.S. Air Force Academy, Colorado (07103780), for each of the 14 remediation scenarios.

[ft^3/s, cubic feet per second. NA, the change in peak streamflow and total sediment transport was determined from scenario 0 so that scenario did not have the change computed]

Scenario	Peak streamflow (ft^3/s)	Change (percent)	Total sediment transport (tons)	Change (percent)
0	2,870	NA	28,300	NA
1	1,880	–34.7	30,300	+6.8
2	1,880	–34.7	30,300	+6.8
3	1,880	–34.7	30,300	+6.8
4	1,880	–34.7	30,300	+6.8
5	1,880	–34.7	30,300	+6.8
6	1,880	–34.7	30,300	+6.8
7	1,880	–34.7	30,300	+6.8
8	1,880	–34.7	30,300	+6.8
9	2,870	0.0	28,300	0.0
10	2,870	–0.1	28,400	+0.1
11	2,870	0.0	28,300	0.0
12	2,870	0.0	28,300	0.0
13	2,870	0.0	28,300	0.0

Table 2–5. Peak streamflow, change in peak streamflow, total sediment transport, and change in total sediment transport predicted by the models at the U.S. Geological Survey streamgage Monument Creek above Woodmen Road at Colorado Springs, Colorado (07103970), for each of the 14 remediation scenarios.

[ft³/s, cubic feet per second. NA, the change in peak streamflow and total sediment transport was determined from scenario 0 so that scenario did not have the change computed]

Scenario	Peak streamflow (ft³/s)	Change (percent)	Total sediment transport (tons)	Change (percent)
0	7,100	NA	64,600	NA
1	7,080	–0.3	58,800	–9.1
2	7,080	–0.3	58,800	–9.1
3	7,080	–0.3	58,800	–9.1
4	7,080	–0.3	58,800	–9.1
5	7,080	–0.3	58,800	–9.1
6	7,080	–0.3	58,800	–9.1
7	7,080	–0.3	58,800	–9.1
8	7,080	–0.3	58,800	–9.1
9	7,100	0.0	64,600	0.0
10	7,100	0.0	64,600	–0.1
11	7,100	0.0	64,600	0.0
12	7,100	–0.1	64,600	0.0
13	7,100	0.0	64,600	0.0

Table 2–6. Peak streamflow, change in peak streamflow, total sediment transport, and change in total sediment transport predicted by the models at the U.S. Geological Survey streamgage Monument Creek at Pikeview, Colorado (07104000), for each of the 14 remediation scenarios.

[ft³/s, cubic feet per second. NA, the change in peak streamflow and total sediment transport was determined from scenario 0 so that scenario did not have the change computed]

Scenario	Peak streamflow (ft³/s)	Change (percent)	Total sediment transport (tons)	Change (percent)
0	11,200	NA	162,000	NA
1	7,370	–34.4	147,000	–9.3
2	7,370	–34.4	147,000	–9.3
3	7,370	–34.4	147,000	–9.3
4	7,370	–34.4	147,000	–9.3
5	7,370	–34.4	147,000	–9.3
6	7,370	–34.4	147,000	–9.3
7	7,370	–34.4	147,000	–9.3
8	7,370	–34.4	147,000	–9.3
9	11,200	0.0	162,000	0.0
10	11,200	0.0	165,000	+2.0
11	11,200	0.0	162,000	0.0
12	11,100	–1.1	162,000	0.0
13	11,200	0.0	162,000	0.0

Table 2–7. Peak streamflow, change in peak streamflow, total sediment transport, and change in total sediment transport predicted by the models at the U.S. Geological Survey streamgage Monument Creek at Bijou Street at Colorado Springs, Colorado (07104905), for each of the 14 remediation scenarios.

[ft³/s, cubic feet per second. NA, the change in peak streamflow and total sediment transport was determined from scenario 0 so that scenario did not have the change computed]

Scenario	Peak streamflow (ft³/s)	Change (percent)	Total sediment transport (tons)	Change (percent)
0	14,500	NA	120,000	NA
1	9,780	–32.5	120,000	–0.1
2	9,780	–32.5	122,000	+1.0
3	9,780	–32.5	121,000	+0.9
4	9,780	–32.5	121,000	+0.9
5	9,780	–32.5	123,000	+2.3
6	9,780	–32.5	123,000	+2.3
7	9,780	–32.5	123,000	+2.3
8	9,780	–32.5	123,000	+2.3
9	14,500	0.0	120,000	0.0
10	14,500	0.0	121,000	+0.5
11	14,500	0.0	120,000	0.0
12	14,400	–0.7	120,000	0.0
13	14,500	0.0	120,000	0.0

Table 2–8. Peak streamflow, change in peak streamflow, total sediment transport, and change in total sediment transport predicted by the models at the U.S. Geological Survey streamgage Fountain Creek at Colorado Springs, Colorado (07105500), for each of the 14 remediation scenarios.

[ft³/s, cubic feet per second. NA, the change in peak streamflow and total sediment transport was determined from scenario 0 so that scenario did not have the change computed]

Scenario	Peak streamflow (ft³/s)	Change (percent)	Total sediment transport (tons)	Change (percent)
0	26,000	NA	143,000	NA
1	23,800	–8.5	129,000	–10.2
2	20,600	–20.6	131,000	–8.6
3	20,600	–20.6	131,000	–8.5
4	20,700	–20.5	131,000	–8.5
5	20,700	–20.5	126,000	–12.3
6	20,700	–20.5	126,000	–12.3
7	20,700	–20.5	126,000	–12.3
8	20,700	–20.5	126,000	–12.3
9	26,000	0.0	143,000	0.0
10	25,800	–0.6	143,000	–0.5
11	26,000	0.0	143,000	0.0
12	25,900	–0.2	143,000	0.0
13	26,000	0.0	143,000	0.0

Table 2–9. Peak streamflow, change in peak streamflow, total sediment transport, and change in total sediment transport predicted by the models at the U.S. Geological Survey streamgage Fountain Creek below Janitell Road below Colorado Springs, Colorado (07105530), for each of the 14 remediation scenarios.

[ft^3/s, cubic feet per second. NA, the change in peak streamflow and total sediment transport was determined from scenario 0 so that scenario did not have the change computed]

Scenario	Peak streamflow (ft^3/s)	Change (percent)	Total sediment transport (tons)	Change (percent)
0	26,800	NA	168,000	NA
1	24,800	–7.6	147,000	–12.6
2	24,300	–9.5	131,000	–22.0
3	24,300	–9.6	131,000	–22.0
4	24,300	–9.6	131,000	–22.0
5	17,800	–33.6	110,000	–34.7
6	17,800	–33.6	110,000	–34.7
7	17,800	–33.6	110,000	–34.7
8	17,800	–33.6	110,000	–34.7
9	26,800	0.0	168,000	0.0
10	26,700	–0.5	168,000	–0.2
11	26,800	0.0	168,000	0.0
12	26,700	–0.4	168,000	0.0
13	26,800	0.0	168,000	0.0

Table 2–10. Peak streamflow, change in peak streamflow, total sediment transport, and change in total sediment transport predicted by the models at the U.S. Geological Survey streamgage Sand Creek above mouth at Colorado Springs, Colorado (07105600), for each of the 14 remediation scenarios.

[ft^3/s, cubic feet per second. NA, the change in peak streamflow and total sediment transport was determined from scenario 0 so that scenario did not have the change computed]

Scenario	Peak streamflow (ft^3/s)	Change (percent)	Total sediment transport (tons)	Change (percent)
0	3,790	NA	32,400	NA
1	3,790	0.0	32,600	+0.5
2	3,790	0.0	32,600	+0.5
3	2,120	–43.9	28,400	–12.4
4	2,120	–43.9	28,400	–12.4
5	2,120	–43.9	28,400	–12.4
6	2,120	–43.9	28,400	–12.4
7	2,120	–43.9	28,400	–12.4
8	2,120	–43.9	28,400	–12.4
9	3,790	0.0	32,400	0.0
10	3,800	+0.3	32,400	0.0
11	3,790	0.0	40,600	+25.1
12	3,790	0.0	32,400	0.0
13	3,790	0.0	32,400	0.0

Table 2–11. Peak streamflow, change in peak streamflow, total sediment transport, and change in total sediment transport predicted by the models at the U.S. Geological Survey streamgage Fountain Creek at Security, Colorado (07105800), for each of the 14 remediation scenarios.

[ft^3/s, cubic feet per second. NA, the change in peak streamflow and total sediment transport was determined from scenario 0 so that scenario did not have the change computed]

Scenario	Peak streamflow (ft^3/s)	Change (percent)	Total sediment transport (tons)	Change (percent)
0	32,700	NA	585,000	NA
1	32,600	–0.4	601,000	+2.7
2	32,600	–0.5	620,000	+6.1
3	31,800	–3.0	646,000	+10.5
4	31,800	–2.9	646,000	+10.5
5	26,100	–20.2	640,000	+9.4
6	18,800	–42.5	651,000	+11.3
7	18,800	–42.5	651,000	+11.0
8	18,800	–42.5	651,000	+11.3
9	32,700	0.0	585,000	0.0
10	33,100	+1.3	584,000	–0.2
11	32,700	0.0	99,600	–83.0
12	32,400	–0.9	585,000	0.0
13	32,700	0.0	585,000	0.0

Table 2–12. Peak streamflow, change in peak streamflow, total sediment transport, and change in total sediment transport predicted by the models at the U.S. Geological Survey streamgage Jimmy Camp Creek at Fountain, Colorado (07105900), for each of the 14 remediation scenarios.

[ft^3/s, cubic feet per second. NA, the change in peak streamflow and total sediment transport was determined from scenario 0 so that scenario did not have the change computed]

Scenario	Peak streamflow (ft^3/s)	Change (percent)	Total sediment transport (tons)	Change (percent)
0	9,550	NA	54,800	NA
1	9,550	0.0	54,900	+0.2
2	9,550	0.0	55,000	+0.2
3	9,550	0.0	54,900	+0.1
4	1,490	–84.4	35,600	–35.2
5	1,490	–84.4	35,600	–35.1
6	1,490	–84.4	35,600	–35.1
7	1,490	–84.4	35,600	–35.1
8	1,490	–84.4	35,600	–35.1
9	9,550	0.0	54,800	0.0
10	9,550	0.0	54,900	+0.1
11	9,550	0.0	15,500	–71.8
12	9,550	+0.1	54,800	0.0
13	9,550	0.0	54,800	0.0

Table 2–13. Peak streamflow, change in peak streamflow, total sediment transport, and change in total sediment transport predicted by the models at the U.S. Geological Survey streamgage Fountain Creek near Fountain, Colorado (07106000), for each of the 14 remediation scenarios.

[ft^3/s, cubic feet per second. NA, the change in peak streamflow and total sediment transport was determined from scenario 0 so that scenario did not have the change computed]

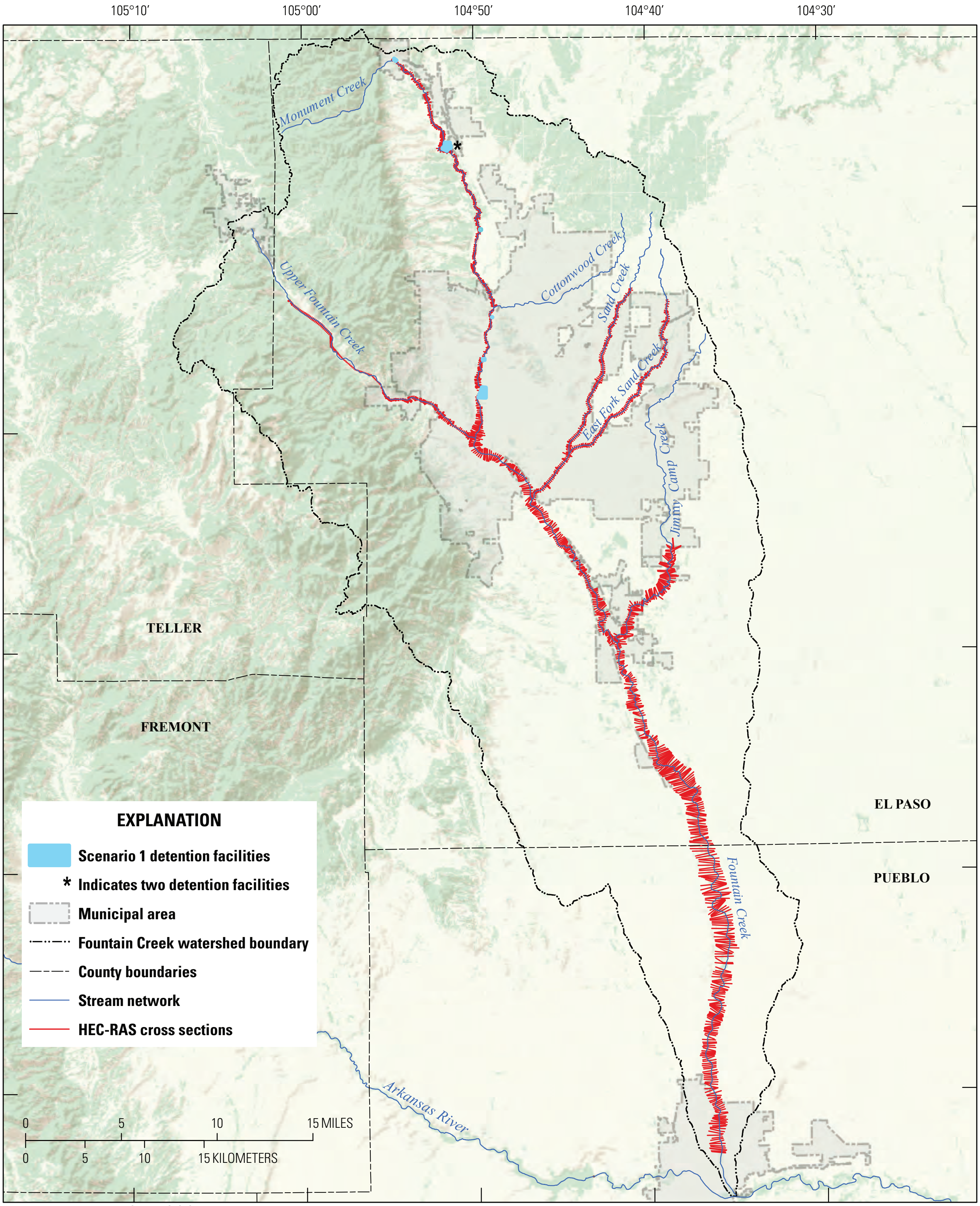
Scenario	Peak streamflow (ft^3/s)	Change (percent)	Total sediment transport (tons)	Change (percent)
0	38,200	NA	228,000	NA
1	38,100	–0.4	229,00	+0.1
2	38,000	–0.5	226,000	–0.9
3	37,500	–1.8	213,000	–6.7
4	30,200	–21.1	206,000	–9.9
5	28,600	–25.1	234,000	+2.5
6	19,500	–48.9	229,000	+0.4
7	13,800	–64.0	221,000	–3.3
8	13,800	–64.0	221,000	–3.3
9	38,200	0.0	228,000	0.0
10	38,700	+1.3	227,000	–0.7
11	38,200	0.0	163,000	–28.6
12	32,200	–15.7	221,000	–3.1
13	38,200	0.0	228,000	0.0

Table 2–14. Peak streamflow, change in peak streamflow, total sediment transport, and change in total sediment transport predicted by the models at the U.S. Geological Survey streamgage Fountain Creek near Piñon, Colorado (07106300), for each of the 14 remediation scenarios.

[ft^3/s, cubic feet per second. NA, the change in peak streamflow and total sediment transport was determined from scenario 0 so that scenario did not have the change computed]

Scenario	Peak streamflow (ft^3/s)	Change (percent)	Total sediment transport (tons)	Change (percent)
0	35,200	NA	314,000	NA
1	35,300	+0.3	297,000	–5.2
2	35,100	–0.3	258,000	–17.6
3	34,300	–2.5	253,000	–19.4
4	27,900	–20.8	279,000	–10.9
5	27,800	–21.0	258,000	–17.7
6	25,600	–27.2	238,000	–24.1
7	16,900	–52.0	223,000	–29.0
8	10,700	–69.6	206,000	–34.4
9	15,700	–55.4	251,000	–20.0
10	35,200	0.0	331,000	+5.4
11	35,200	0.0	277,000	–11.6
12	22,300	–36.7	282,000	–9.9
13	34,200	–2.8	457,000	+45.7

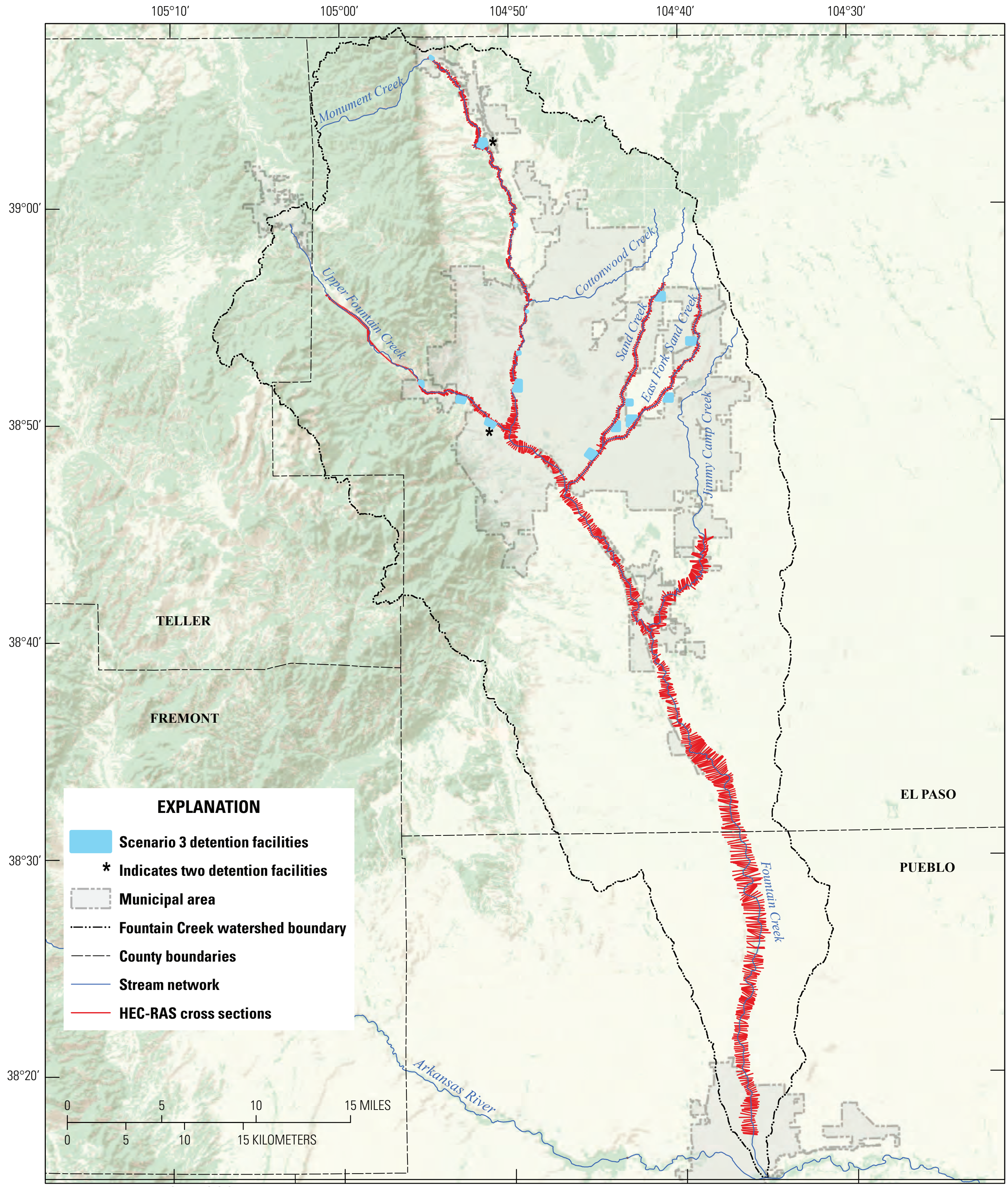
Appendix 3. Location of the Remediation Elements in the Remediation Scenarios



Basemap modified from ESRI ArcGIS Online, 2013
Colorado State Plane Central, North American Datum of 1983

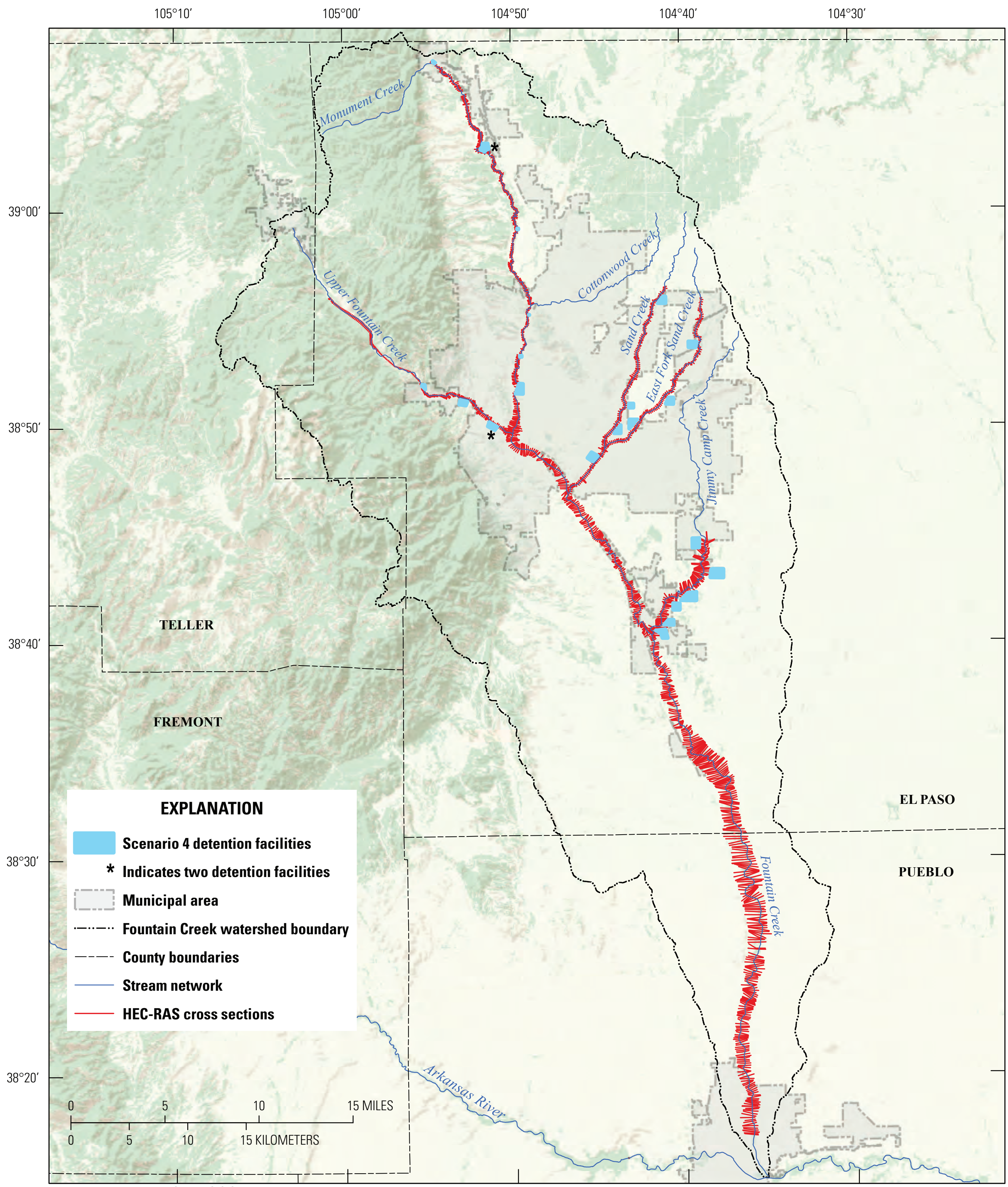
Figure 3-1. Location of the seven detention facilities in scenario 1. HEC-RAS, Hydrologic Engineering Center-River Analysis System.

Figure 3-2. Location of the 11 detention facilities in scenario 2. HEC-RAS, Hydrologic Engineering Center-River Analysis System.



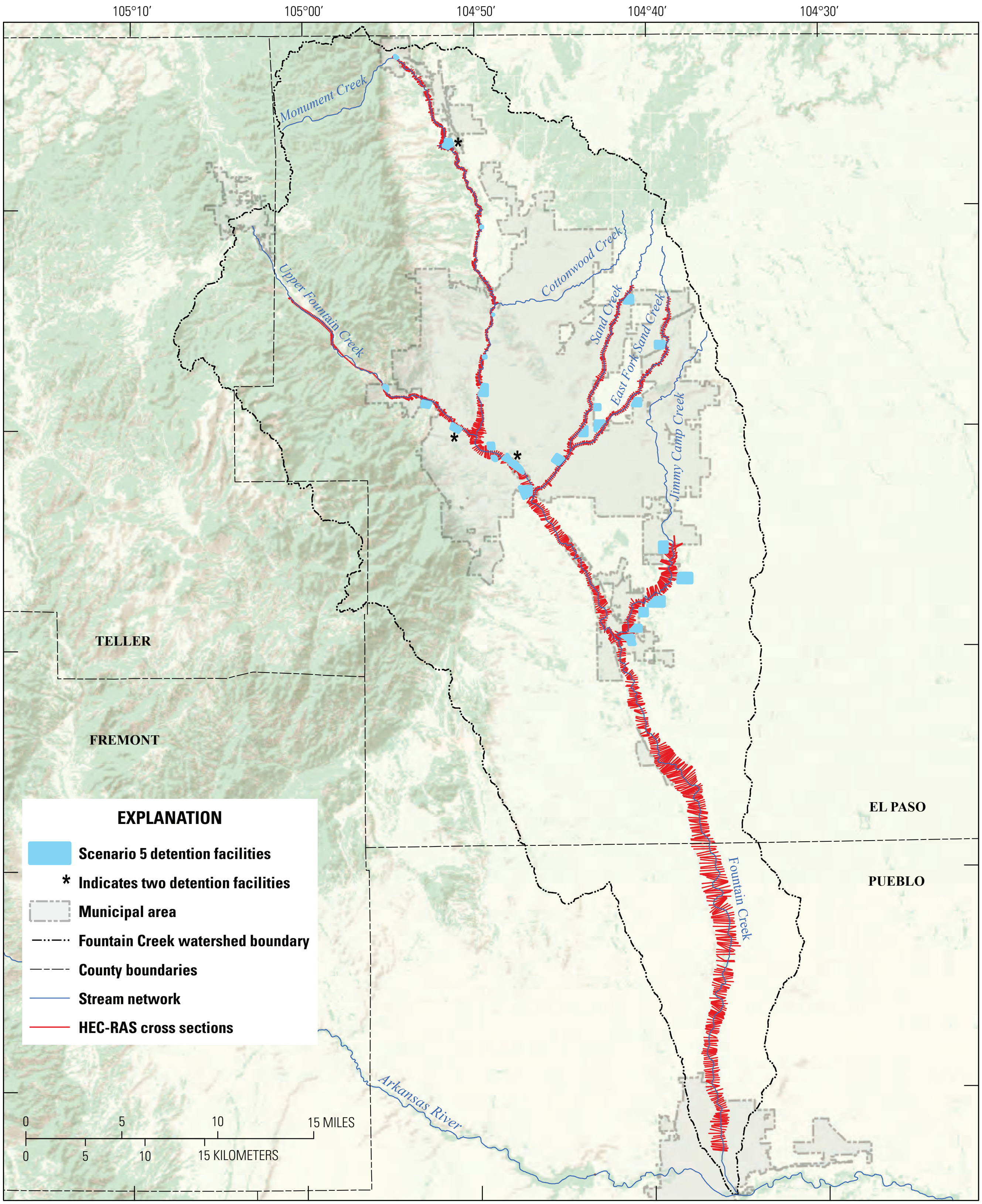
Basemap modified from ESRI ArcGIS Online, 2013
Colorado State Plane Central, North American Datum of 1983

Figure 3-3. Location of the 18 detention facilities in scenario 3. HEC-RAS, Hydrologic Engineering Center-River Analysis System.



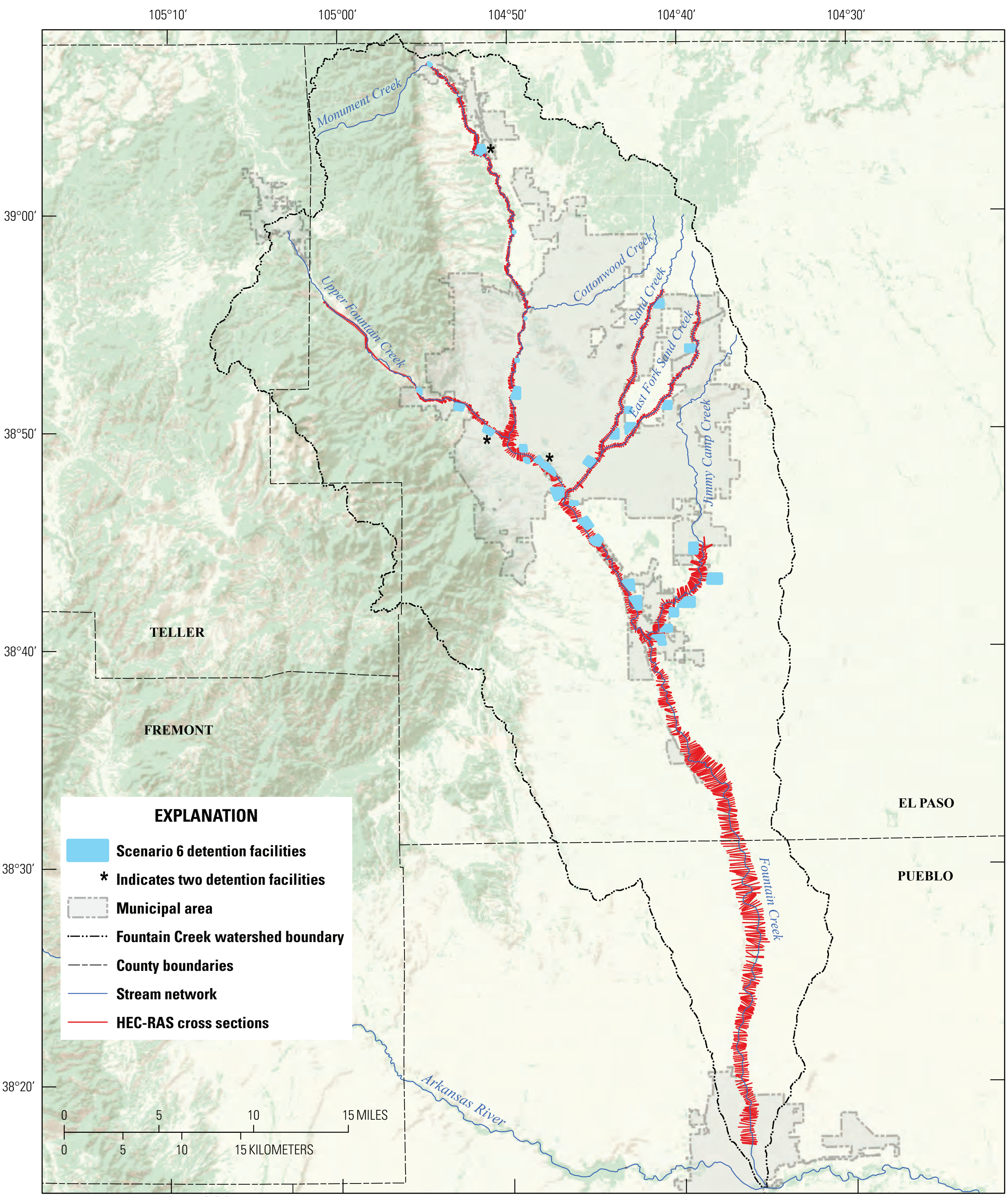
Basemap modified from ESRI ArcGIS Online, 2013
Colorado State Plane Central, North American Datum of 1983

Figure 3-4. Location of the 24 detention facilities in scenario 4. HEC-RAS, Hydrologic Engineering Center-River Analysis System.



Basemap modified from ESRI ArcGIS Online, 2013
Colorado State Plane Central, North American Datum of 1983

Figure 3-5. Location of the 29 detention facilities in scenario 5. HEC-RAS, Hydrologic Engineering Center-River Analysis System.



Basemap modified from ESRI ArcGIS Online, 2013
Colorado State Plane Central, North American Datum of 1983

Figure 3-6. Location of the 34 detention facilities in scenario 6. HEC-RAS, Hydrologic Engineering Center-River Analysis System.

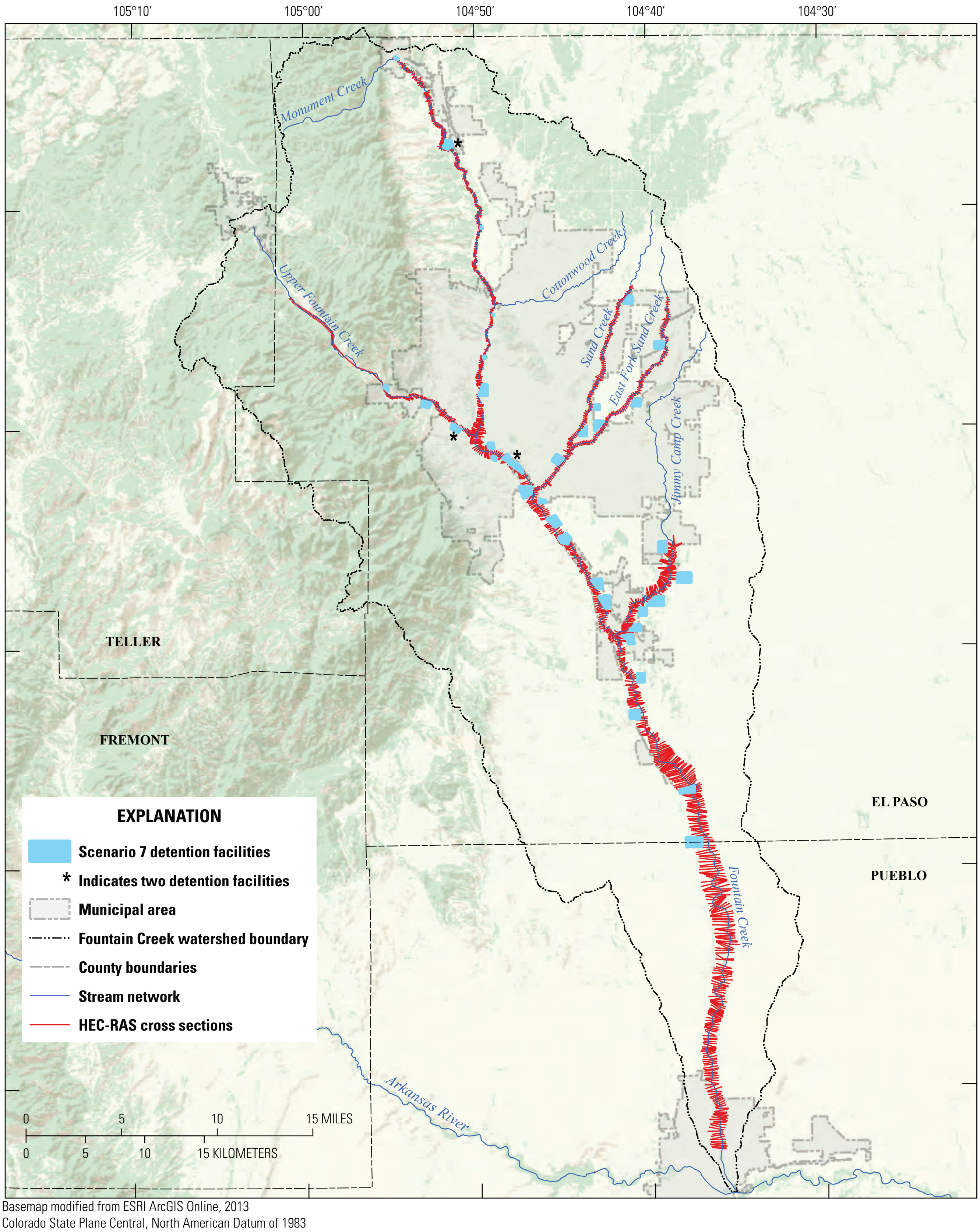
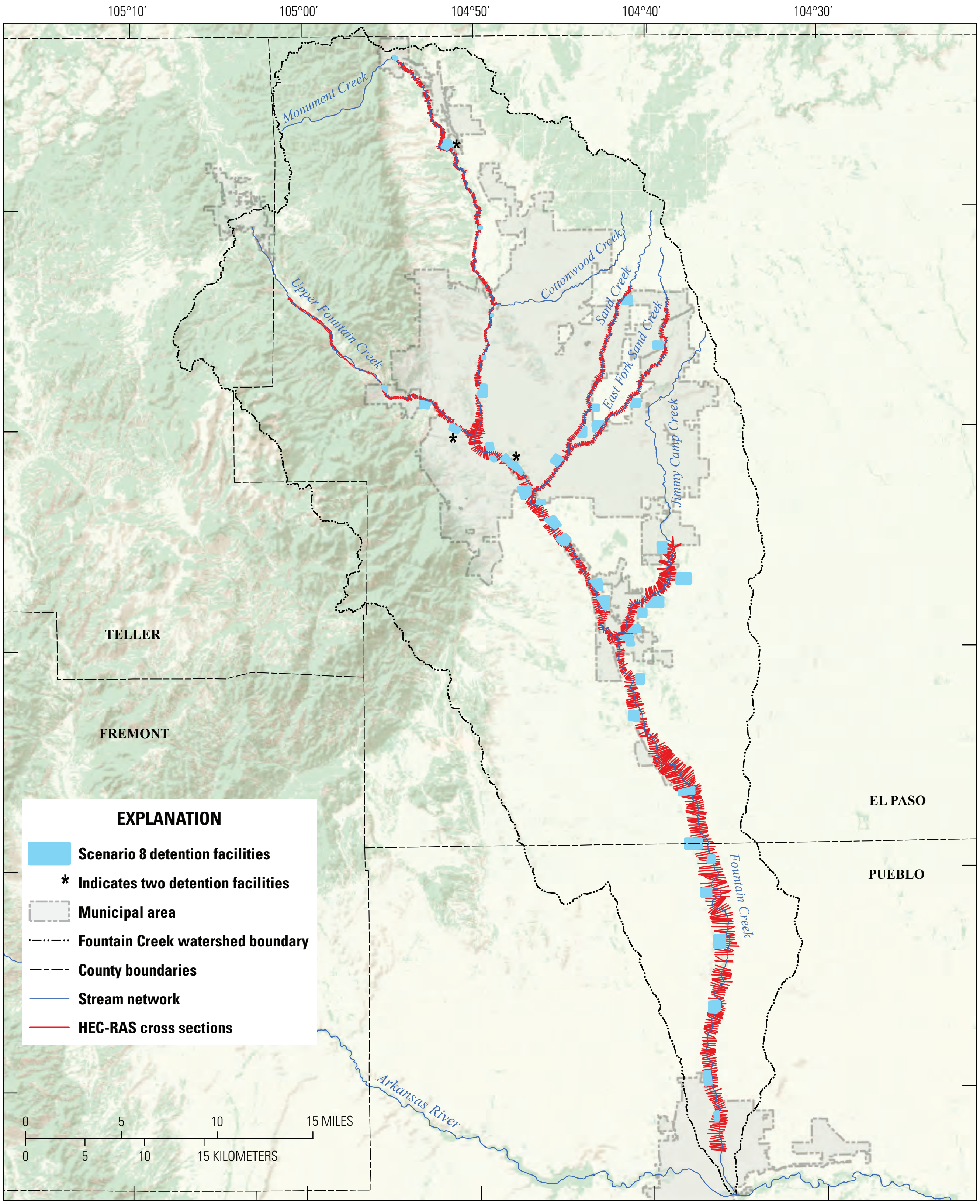
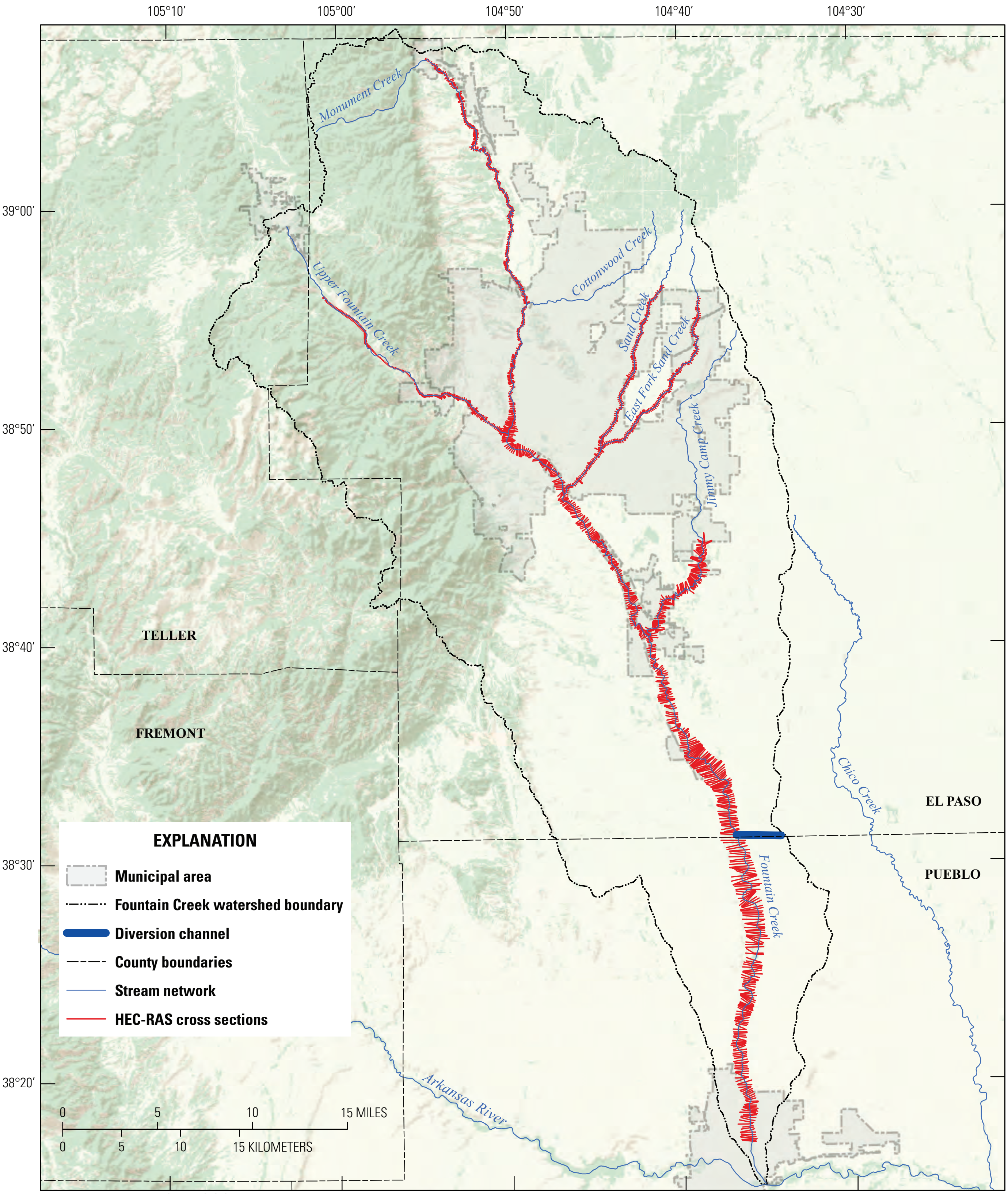


Figure 3-7. Location of the 38 detention facilities in scenario 7. HEC-RAS, Hydrologic Engineering Center-River Analysis System.



Basemap modified from ESRI ArcGIS Online, 2013
Colorado State Plane Central, North American Datum of 1983

Figure 3-8. Location of the 44 detention facilities in scenario 8. HEC-RAS, Hydrologic Engineering Center-River Analysis System.



Basemap modified from ESRI ArcGIS Online, 2013
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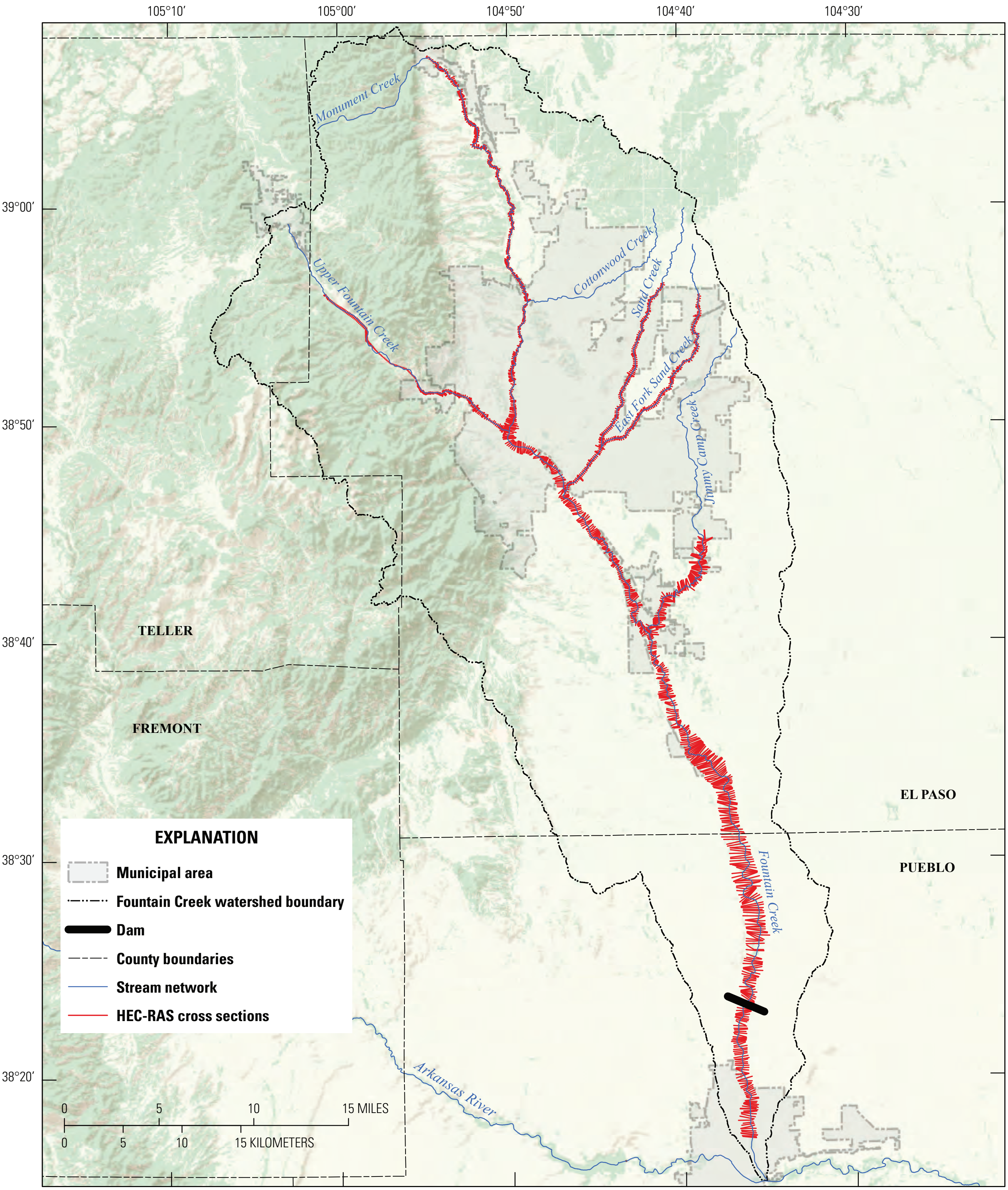
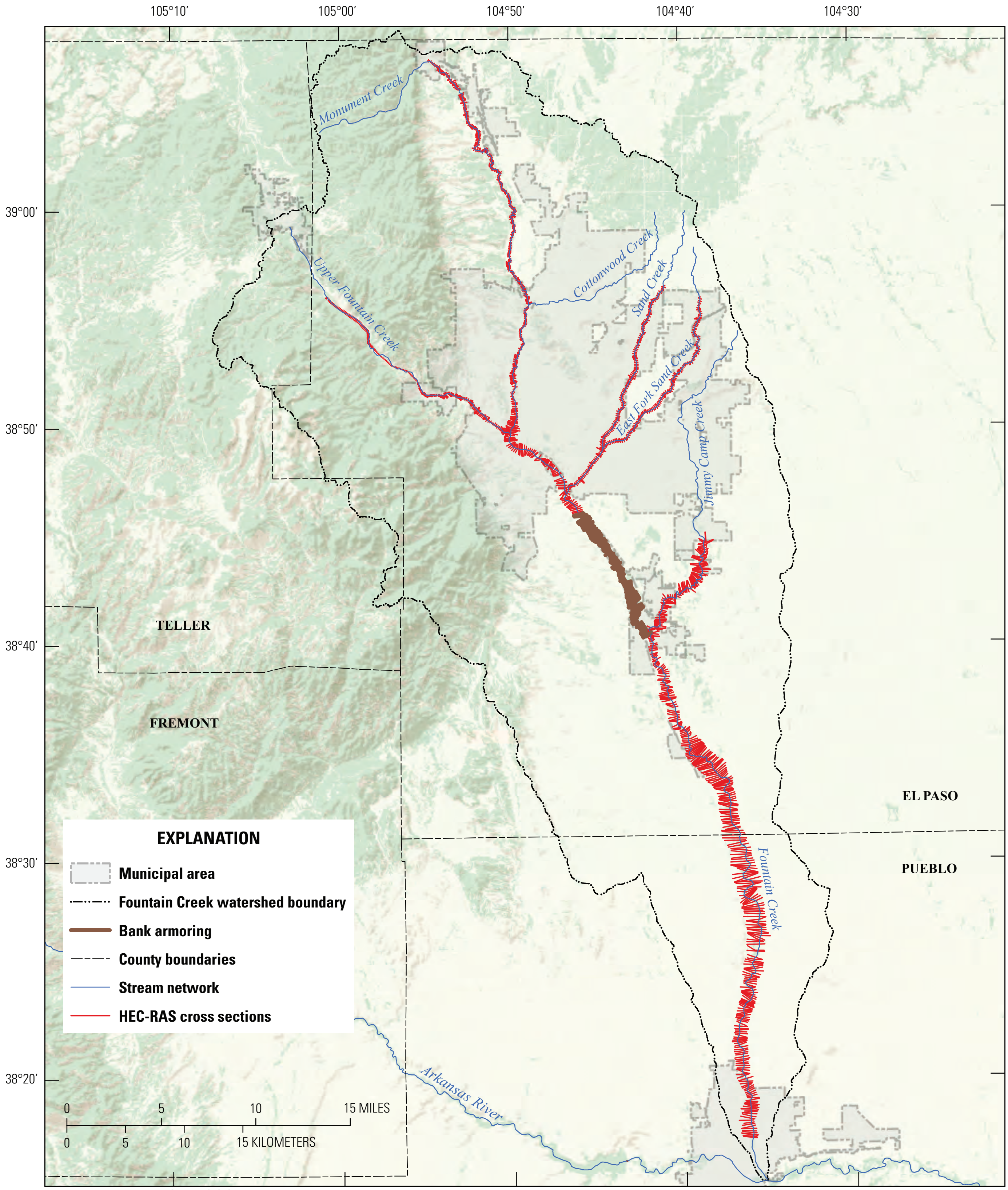
Figure 3-9. Location of the trans-watershed diversion to Chico Creek along the main stem of Fountain Creek in scenario 9. HEC-RAS, Hydrologic Engineering Center-River Analysis System.



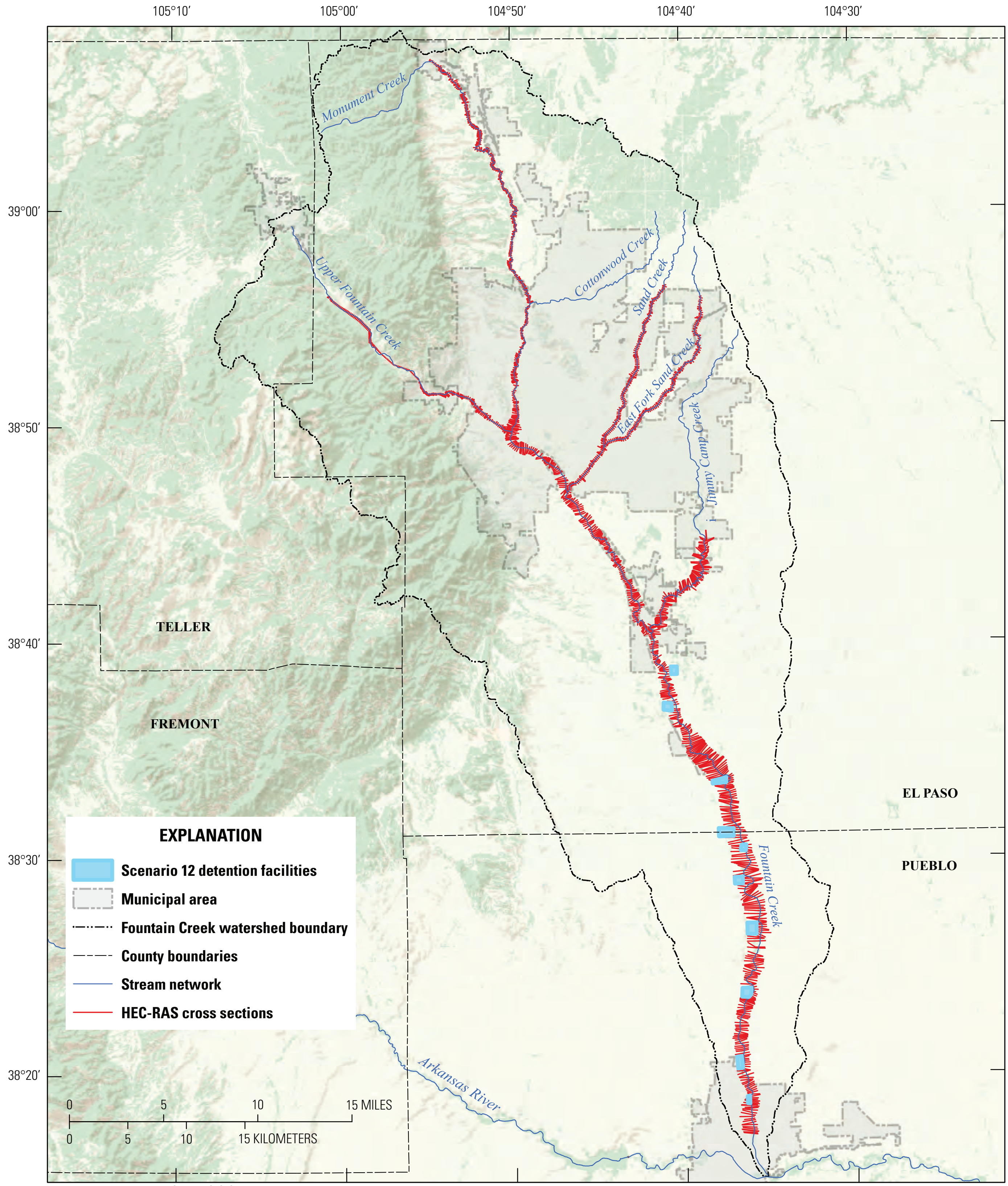
Basemap modified from ESRI ArcGIS Online, 2013
Colorado State Plane Central, North American Datum of 1983

Figure 3-10. Location of the reservoir dam on the main stem of Fountain Creek in scenario 10. HEC-RAS, Hydrologic Engineering Center-River Analysis System.



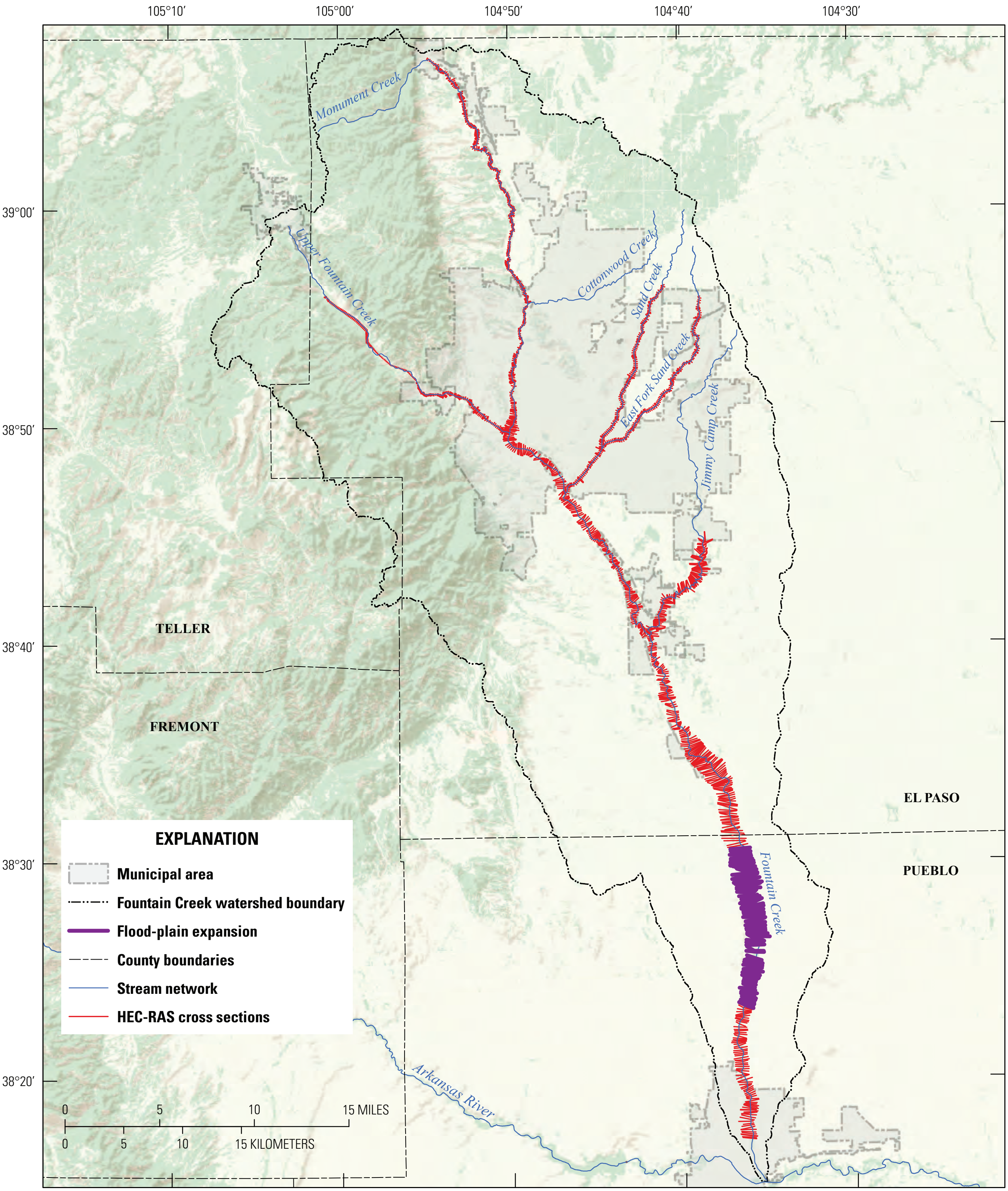
Basemap modified from ESRI ArcGIS Online, 2013
Colorado State Plane Central, North American Datum of 1983

Figure 3-11. Location of the 9 miles of armoring on Fountain Creek between Sand and Jimmy Camp Creeks in scenario 11. HEC-RAS, Hydrologic Engineering Center-River Analysis System.



Basemap modified from ESRI ArcGIS Online, 2013
Colorado State Plane Central, North American Datum of 1983

Figure 3-12. Location of the 10 detention facilities in scenario 12. HEC-RAS, Hydrologic Engineering Center-River Analysis System.



Basemap modified from ESRI ArcGIS Online, 2013
Colorado State Plane Central, North American Datum of 1983

Figure 3-13. Location of the floodplain expansion where the channel cross sections were widened for 10 miles on the main stem of Fountain Creek in scenario 13. HEC-RAS, Hydrologic Engineering Center-River Analysis System.

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