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Elevation and Elevation-Change Maps of Fountain Creek, Southeastern Colorado, 2015–19

Pamphlet to accompany
Scientific Investigations Map 3456

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

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DAVID BERNHARDT, Secretary

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James F. Reilly II, Director

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International System of Units to U.S. Customary Units

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	35.31	cubic foot (ft^3)
	Flow rate	
meter per second (m/s)	3.281	foot per second (ft/s)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)

Datum

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

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

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

Abbreviations

CSU	Colorado Springs Utilities
DEM	digital elevation model
ME	mean error
NAD 83	North American Datum of 1983
NAVD 88	North American Vertical Datum of 1988
RTK-GNSS	real-time kinematic Global Navigation Satellite Systems
RMSE	root-mean square error
SDE	standard deviation of error
SDS	Southern Delivery System
TIN	triangulated irregular network
USGS	U.S. Geological Survey

Elevation and Elevation-Change Maps of Fountain Creek, Southeastern Colorado, 2015–19

By Laura A. Hempel

Abstract

The U.S. Geological Survey, in cooperation with Colorado Springs Utilities, has been collecting topographic data at 10 study areas along Fountain Creek, Colorado, annually since 2012. The 10 study areas are located between Colorado Springs and the terminus of Fountain Creek at the Arkansas River in Pueblo. The purpose of this report is to present elevation maps based on topographic surveys collected in 2015 and 2019 and to present maps of elevation change that occurred between 2015 and 2019 at all 10 study areas. Elevation and elevation-change maps were developed in ArcGIS from topographic surveys collected at each study area using real-time kinematic Global Navigation Satellite Systems during the winter months (January through April) of 2015 and 2019. Elevation-change maps were created using statistically defined minimum levels of change detection associated with the 68-percent confidence limit and the 95-percent confidence limit. Study areas along Fountain Creek underwent a range of geomorphic responses between 2015 and 2019 that often depended on the dominant channel pattern of the study area. The results of this ongoing monitoring effort can be used to assess long-term changes in land-surface elevation and to advance understanding of the geomorphic response to possible alterations in flow conditions on Fountain Creek.

Introduction

Fountain Creek is a perennial stream that flows through contrasting landscapes of the Colorado Front Range (fig. 1). A combination of natural events and anthropogenic activities throughout the Fountain Creek Basin, including urbanization, wildfire, transmountain diversions that bring water from the West slope, and more recently, treated wastewater discharge, have led to alterations in its hydrologic conditions since the late 1970s (Stogner, 2000; Sanderson and others, 2011). To accommodate growing water demands caused by population growth in Colorado Springs, the Southern Delivery System (SDS) program was completed in 2016 after 20 years of planning (Water Technology, 2019). The SDS brings water through an 80-kilometer pipeline from the Pueblo Reservoir to a water treatment plant in Colorado Springs for municipal use and returns the treated wastewater to the Arkansas River through Fountain Creek (fig. 1) (Water Technology, 2019). The SDS water treatment plant has a full capacity of 50-million gallons per day, although initially it only operates at 10 percent capacity (SDS Water Treatment, 2019).

The U.S. Geological Survey (USGS), in cooperation with Colorado Springs Utilities (CSU), established a monitoring program to increase understanding of the pace and style of geomorphic change on Fountain Creek by documenting baseline channel conditions beginning in 2012 and tracking geomorphic changes following the implementation of the SDS in 2016. Annually, the USGS collects topographic data at 10 study areas located between Colorado Springs and the terminus of Fountain Creek at the Arkansas River in Pueblo and uses those data to generate elevation and elevation-change maps. The results of this ongoing monitoring effort can be used to assess long-term changes in land-surface elevation and to advance understanding of the geomorphic response to possible alterations in flow conditions on Fountain Creek following the completion of the SDS. More broadly, these data can be used to determine whether the current rate of change in channel morphology is similar or more rapid than past changes, determine the extent to which changes in channel morphology can be modeled based on existing channel characteristics or streamflow patterns, and identify riparian areas with infrastructure that may be susceptible to damage caused by changes in the position or size of the channel.

Previous Studies

Previous flow assessment studies have been conducted in the Fountain Creek Basin that found overall increases in a range of flows since the development of water projects around 1980. In 2011, an environmental flow assessment was conducted for the Fountain Creek Basin using the Watershed Flow Evaluation Tool (Sanderson and others, 2011). Sanderson and others (2011) found that mean annual flows, peak flows, and seasonal flows during late-summer (August and September) and winter (January) have increased during the transition from natural to developed conditions and during the start of major water-supply projects. Sanderson and others (2011) used data collected from four USGS streamgages within the Fountain Creek Basin located between Colorado Springs and Pueblo (USGS streamgages 07103700, 07105800, 07106300, and 07106500) operating between 1975 and 2005 (fig. 1). Increases in mean annual flow

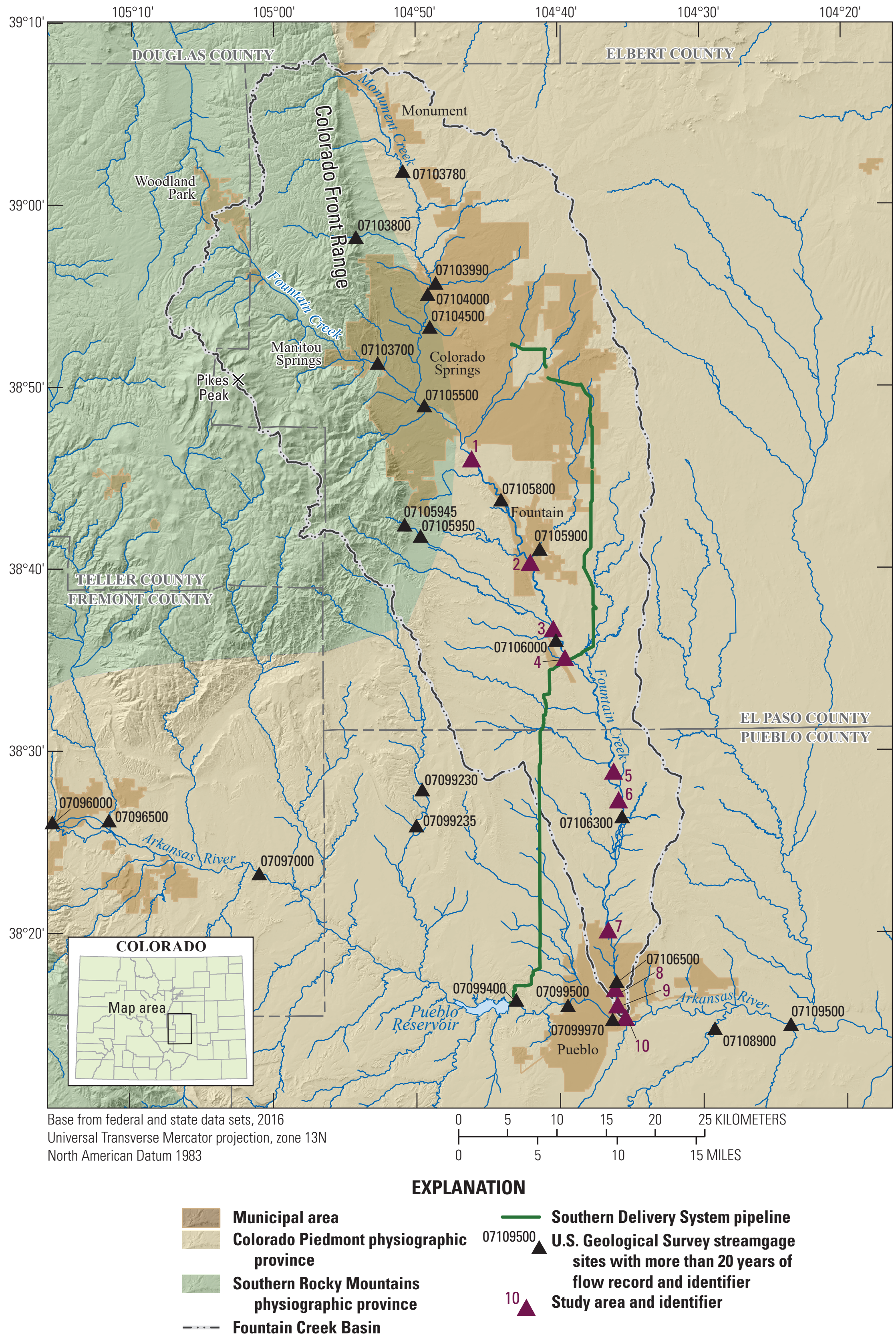

Figure 1. Map showing the ten study areas along Fountain Creek between Colorado Springs and the terminus of Fountain Creek at the Arkansas River south of Pueblo, Colorado. Physiographic provinces adapted from Fenneman and Johnson, 1946. Southern Delivery System Pipeline location from SDS Pipeline, 2014.

were greater at the two southern sites located near Pueblo (180–200 percent increase) compared to the two upper sites located near Colorado Springs (30-45 percent increase); increases in winter, summer, and peak flows occurred at all sites and varied from 30 to 330 percent (Sanderson and others, 2011). As a result of increases in sub-bankfull flows, the erosion potential downstream from Colorado Springs has increased four- to fivefold (Sanderson and others, 2011).

Stogner (2000) studied flow patterns at USGS streamgages from 1976 to 1999 and similarly found significant increases in daily mean flow corresponding to the 0th, 10th, 40th, 70th, 90th, and 100th percentiles. Stogner (2000) also found significant increases in the 7-, 14-, and 30-day high daily mean flow durations and increases in the 7-, 14-, and 30-day low-flow durations. Stogner (2000) analyzed data from six USGS streamgages with complete flow records during the study period located within the Fountain Creek Basin between Colorado Springs and Pueblo (USGS streamgages 07104000, 07103700, 07105500, 07105800, 07106300, and 07106500) (Stogner, 2000). Trends during the post-1976 period were roughly coincident with the timing of urbanization, population growth, and the implementation of water-supply projects marked by a shift in the relation between precipitation and flow from 1980 to 1982 based on a double mass curve analysis (Stogner, 2000).

The geomorphic effects of changes in flow on Fountain Creek are pronounced in some cases but difficult to disentangle from natural variability in other cases. For example, increases in sediment transport capacity and coarsening of the mean particle size on the streambed between 1999 and 2005 have been attributed to increases in treated wastewater discharge at a streamgage site located immediately downstream from a wastewater treatment plant and upstream from the current study areas (Mau and others, 2007), but other changes have been more spatially distributed making them difficult to attribute to a single factor. For example, downcutting was found to be the dominant channel-shaping process throughout the urbanized section of Fountain Creek, located upstream from Fountain, between 1999 and 2005, but no clear cause was identified (Mau and others, 2007).

Superimposed on more recent geomorphic changes to Fountain Creek are longer-term responses to catastrophic flooding. Results from a study of historical aerial photos (1947–99) indicate that peak flow events with a recurrence interval of once every 5 years based on the USGS streamgage record at Pueblo (streamgage site 07106500) (greater than 283 cubic meters per second [10,000 cubic feet per second]) caused substantial morphologic changes including channel widening, rapid lateral migration, loss of mature riparian vegetation, and sediment deposition on the floodplain (Stogner, 2000). In contrast, during quiescent periods when peak flows did not exceed 283 cubic meters per second, more muted changes were observed, such as vegetation regrowth and localized bank erosion (Stogner, 2000). Changes in channel morphology may therefore be tied to flood cycles on Fountain Creek, changing rapidly during high-flow events and re-establishing a more stable channel pattern during low-flow periods (Stogner, 2000). Consequently, the current morphology of Fountain Creek may be closely related to the time since the last flood event.

Purpose and Scope

The purpose of this report is to present elevation maps based on topographic data collected in 2015 and 2019 and to present elevation-change maps between 2015 and 2019 at 10 study areas located between Colorado Springs and the terminus of Fountain Creek at the Arkansas River in Pueblo (fig. 1). The methods used to generate elevation and elevation-change maps are also presented, as is a summary of the geomorphic changes that occurred between 2015 and 2019.

Elevation and elevation-change maps were developed in ArcGIS from topographic surveys collected at each study area during the winters of 2015 and 2019 (Kohn, 2017; Hempel and others, 2020). Topographic surveys were completed using real-time kinematic Global Navigation Satellite Systems (RTK-GNSS). Uncertainties in the elevation maps were calculated using root-mean square error and standard deviation of error, and minimum levels of detectable change in the elevation-change maps were calculated using a probabilistic thresholding method. This report includes (1) a detailed description of the methods used to develop maps and estimate uncertainty in the maps, (2) elevation maps from 2015 and 2019 and elevation-change maps between 2015 and 2019 at all 10 study areas, and (3) a summary of geomorphic changes between 2015 and 2019 based on high certainty (95 percent confidence limit) elevation-change maps.

Study Area

The Fountain Creek Basin is 2,401 square kilometers (927 square miles) and ranges in elevation from 1,414 to 4,301 meters (4,640 to 14,110 feet [Stogner, 2000]). The upper portion of Fountain Creek, upstream from its confluence with Monument Creek in Colorado Springs, flows southeast from Woodland Park (fig. 1). Monument Creek is a major tributary to Fountain Creek that originates near Monument and flows south along the mountain front. Downstream from the confluence of Fountain Creek and Monument Creek in Colorado Springs, the lower portion of Fountain Creek flows south–southeast through the communities of Fountain and Pueblo to its terminus at the Arkansas River in Pueblo (fig. 1).

Like many Colorado Front Range streams, Fountain Creek spans two physiographic provinces. The upper portion of the basin is located in the steep Southern Rocky Mountains, and the lower portion of the basin is located east of the mountains in the Colorado Piedmont (Fenneman, 1917; Trimble, 1980). Flow in the upper Fountain Creek Basin originates along the northern slopes of Pikes Peak where well-drained soils are underlain by the Middle Proterozoic-age Pikes Peak Granite (Larsen, 1981; Hansen and others, 1982; von Guerard, 1989). Land cover in the upper basin is predominantly alpine forest and shrubland (Sanderson and others, 2011), and stream morphology includes a mix of pool-riffle and bedrock-constricted step-pool morphologies.

All 10 study areas are located in the lower Fountain Creek Basin (fig. 1) and span a range of geomorphic channel patterns based on the classification developed by Schumm (1985) (table 1). In contrast to the upper portion of the basin, the lower portion of the basin is in the low gradient Colorado Piedmont province where highly erodible soils and alluvial deposits are underlain by sedimentary rocks (Larsen, 1981; Hansen and others, 1982; von Guerard, 1989). Land cover in the lower portion of the basin is composed of arid grassland and prairie (Larsen, 1981; Hansen and others, 1982; von Guerard, 1989), and stream morphology is characterized as a meandering sand-bedded channel that is braided along several reaches.

Methods

Digital elevation models (DEMs) of the 10 Fountain Creek study areas were developed from topographic point-survey data acquired in 2015 (Kohn, 2017) and 2019 (Hempel and others, 2020). Elevation-change maps were then created by comparing DEMs for the two periods by applying two confidence limit thresholds (68 and 95 percent). The following sections discuss the methods used to conduct the topographic survey, to create the DEMs and elevation maps, and to create the elevation-change maps.

Topographic Survey

Topography of the 10 study areas was surveyed January 20–April 21, 2015, and January 30–April 4, 2019, using RTK-GNSS. Survey techniques followed the methods outlined by Rydlund and Densmore (2012) and were consistent with techniques used in previous surveys of Fountain Creek from 2012 to 2017 (Kohn, 2017). The study area extents (sheets 1–10) were loaded on all GNSS survey controllers to ensure consistency in the area surveyed from previous years.

The topographic surveys conducted in 2015 and 2019 were performed using a morphologically based sampling scheme to capture topographic complexities while minimizing errors (Brasington and others, 2000; Brasington and others, 2003; Heritage and others, 2009; Wheaton and others, 2010; Milan and others, 2011). The overall sampling scheme involved surveying land-surface elevations along transect lines perpendicular to the flow direction. Individual points were surveyed in a grid pattern, such that transects were roughly 4–12 meters (13–39 feet) apart, and points within each transect were spaced roughly 6–12 meters (20–39 feet) apart. Points surveyed at the transition between abrupt breaks in slope, such as the tops or toes of streambanks, were coded as break lines to improve the accuracy of interpolation during data analysis. Points that outlined man-made infrastructure, such as bridges or piles of construction materials, were often characterized by complex topography and poor RTK-GNSS reception. Those areas were noted in a field notebook for further consideration during the analysis phase.

Regions with smooth, even terrain, such as point bars, were captured with a slightly lower point-sampling density compared to regions that were topographically complex, including braided river sections or complex side channels. All survey data were collected in meters and in Universal Transverse Mercator coordinates. The horizontal coordinate system used was North American Datum 1983 (NAD 83) Zone 13 North, and the vertical coordinate system used was the North American Vertical Datum of 1988 (NAVD 88), Geoid 12A.

At the start and end of each field day, a minimum of two control points were surveyed by each surveyor for quality assurance and to ensure measurement uncertainty was less than the user-defined tolerance for vertical and horizontal precisions (less than 0.1 meter [0.3 feet]). Survey points with horizontal or vertical precisions greater than 0.5 meter (1.6 feet) were removed from the analyses, unless those points were the only ones within a roughly 20-meter (65-foot) area that provided important topographical information by capturing the edge of a survey area or a steep break in slope. Rarely, in less than 10 cases, instrument or user error led to survey points that were 3 or more meters (10 feet) higher or lower than the surrounding topography. In those instances, the elevation of the surrounding points and the aerial imagery covering the points were examined closely to determine whether or not the elevation value was anomalous, and if so, that point was removed.

At the completion of RTK-GNSS surveys, the survey data were processed into tabular format, checked for quality by ensuring that the check-in and check-out control points were within measurement uncertainty, and then submitted to the Online Positioning User Service (OPUS) for correction (https://www.ngs.noaa.gov/OPUS/). The resulting topographic-survey data from 2015 and 2019 are published in Kohn (2017) and Hempel and others (2020), respectively.

Table 1. Summary of channel patterns for all 10 study areas on Fountain Creek, southeastern Colorado, based on the alluvial channel pattern classification developed by Schumm, 1985.

[The dominant channel pattern, or the pattern present in the majority of the study area, appears first for study areas where more than one channel pattern is listed]

Study area	Channel pattern
01	Meandering, straight
02	Straight
03	Straight
04	Meandering
05	Meandering
06	Braided, meandering
07	Meandering
08	Meandering, straight
09	Straight, meandering
10	Straight

Elevation Maps

The topographic-survey data points were used to generate DEMs of each study area in ArcGIS (Esri, 2019). First, hard break lines were delineated along steep breaks in slope that were coded in the field. Next, the Create TIN tool was used to generate a triangulated irregular network (TIN) using survey points and break lines as inputs (Esri, 2019). The 2015 DEM was used as the template, or snap raster, for each study area so that the position of pixels from both study years were aligned, and the exact same areas could be compared from year to year. Lastly, a DEM was created using the Natural Neighbor interpolation method within the TIN to Raster tool and clipped to the study area boundary so that only the surveyed area was considered by the interpolation method (Esri, 2019). Elevation maps were generated with a 2.0-meter (6.6-foot) pixel size, which was found to be the best balance between accuracy and detail. For example, larger pixel sizes resulted in a loss of sharp topographic detail along breaks in slope and increases in error in the DEM. In contrast, smaller pixel sizes resulted in decreases in error in the DEM, but also resulted in lower point densities per pixel, which meant that interpolated pixel values were not well-constrained. Point densities in terms of survey points per pixel ranged from 0.08 to 0.29 and are listed in table 2. This workflow yielded the best results in terms of minimizing errors in the DEM and produced more physically realistic elevation maps when compared with other interpolation methods such as Topo to Raster, Empirical Bayesian Kriging, and Inverse Distance Weighting (Esri, 2019).

Lastly, areas encompassing man-made infrastructure characterized by poor survey quality and complex topography, that may have contributed to uncertainty in the DEM, were only present at study areas 2 and 10. Those areas were delineated and added to elevation maps. Elevation maps generated using the break line and TIN to Raster method are presented in sheets 1–10.

The root-mean square error (RMSE) and standard deviation of error (SDE) were used to estimate the levels of uncertainty in the DEM (Brasington and others, 2000; Brasington and others, 2003; Lane and others, 2003; Fisher and Tate, 2006; Wheaton and others, 2010; Milan and others, 2011). While RMSE is a widely used measure of error in mapping applications, more recent studies favor the use of the SDE,

Table 2. Summary of input survey data and errors in digital elevation models from Fountain Creek, southeastern Colorado, 2015 and 2019.

Study area	Survey year	Number of data points used to generate elevation map	Number of data points used in error analysis	Analysis area in square meters	Survey density, in number of survey points per pixel	Root mean square error, in meters[1]	Standard deviation of error, in meters[1]	Mean error, in meters[1]
01	2015	5,902	5,748	84,225	0.28	0.13	0.13	6.8E-03
02	2015	2,773	2,576	62,344	0.18	0.15	0.15	8.3E-03
03	2015	6,595	6,365	91,142	0.29	0.13	0.13	3.5E-03
04	2015	7,721	7,534	170,774	0.18	0.13	0.13	3.3E-03
05	2015	7,819	7,557	166,489	0.19	0.13	0.13	3.2E-03
06	2015	15,728	15,374	377,960	0.17	0.12	0.12	-4.4E-04
07	2015	5,787	5,523	104,440	0.22	0.13	0.13	5.8E-03
08	2015	5,363	5,148	178,896	0.12	0.14	0.14	5.5E-03
09	2015	4,920	4,752	86,045	0.23	0.13	0.13	2.6E-03
10	2015	5,999	5,771	137,219	0.17	0.18	0.18	-9.5E-03
01	2019	3,930	3,710	87,973	0.18	0.12	0.12	1.9E-03
02	2019	1,973	1,780	50,968	0.15	0.12	0.12	3.7E-04
03	2019	2,855	2,688	80,565	0.14	0.10	0.10	-2.0E-03
04	2019	4,108	3,760	163,366	0.10	0.08	0.08	4.7E-03
05	2019	4,293	4,119	149,018	0.12	0.10	0.10	-3.2E-04
06	2019	8,705	8,392	462,301	0.08	0.10	0.10	-2.9E-03
07	2019	3,771	3,568	112,798	0.13	0.11	0.11	-2.5E-03
08	2019	7,656	7,447	194,968	0.16	0.11	0.11	2.1E-03
09	2019	3,505	3,215	88,567	0.16	0.11	0.11	1.9E-03
10	2019	6,519	6,405	186,588	0.14	0.12	0.12	-6.1E-03

[1] Calculated using formulas reported in Fisher and Tate, 2006.

because it is a more complete statistical description of error (Fisher and Tate, 2006). The SDE was calculated from the mean error (ME), which can be positive or negative depending on systematic errors in elevation (Fisher and Tate, 2006). The RMSE and SDE values were equivalent for all study areas within survey precision, which indicates there were no systematic biases in errors within the DEMs (table 2).

The RMSE, SDE, and ME were all calculated in terms of the error because of interpolation of the DEM, which was based on the difference (expressed in meters) between RTK-GNSS point-survey elevations located within the bounds of each study area and the DEM elevation at those same locations (Fisher and Tate, 2006; table 2). Errors caused by the accuracy of topographic-survey points were relatively small compared to interpolation errors within the DEM, and consequently were not included in calculations to estimate uncertainty in the DEM (table 2). For example, 90 percent of all horizontal and vertical precisions from the 2015 and 2019 topographic surveys were smaller than 0.05 meter (0.16 foot) (Kohn, 2017; Hempel and others, 2020). In comparison, the mean RMSE of all 20 elevation maps was 0.12 meter (0.4 foot) and ranged from 0.08 to 0.18 meter (0.26 to 0.59 foot) (table 2).

Elevation-Change Maps and Uncertainty Estimates

A probabilistic thresholding method, developed specifically for elevation-change detection, was used to distinguish real elevation changes caused by geomorphic processes from noise caused by interpolation errors within the DEM (Li, 1988; Fisher, 1998; Brasington and others, 2000; Brasington and others, 2003; Lane and others, 2003; Fisher and Tate, 2006; Wechsler and Kroll, 2006; Wheaton and others, 2010; Milan and others, 2011). First, the level of uncertainty associated with an individual DEM was estimated as the SDE (table 2). Then, the uncertainty associated with the DEM for each study area was propagated to elevation-change maps by calculating minimum levels of change detection based on user-defined confidence limits. For each study area, elevation-change maps were computed with user-defined confidence limits of 68 and 95 percent (table 3). Elevation-change maps for each study area (sheets 1–10) were then generated in ArcGIS (Esri, 2019) by first subtracting the 2015 DEM from the 2019 DEM using the Raster Calculator tool (Esri, 2019). Each raw elevation-change map was then thresholded to remove elevation changes smaller than the minimum levels of detection associated with the 68-percent and 95-percent confidence limits reported in table 3 using the Raster Calculator tool, and overlaid on the 2019 hillshade raster (Esri, 2019). Consequently, areas colored in gray hillshade represent areas with no detectable elevation change during the period from 2015 and 2019. Color scale-bars were adjusted to linearly span the maximum and minimum elevation-change values within each study area. Lastly, areas encompassing man-made infrastructure characterized by complex topography that may have contributed to added uncertainty in elevation-change estimates at study areas 2 and 10 were added to the elevation-change maps.

Elevation-change maps created using the minimum level of detection associated with the 68-percent confidence limit contained wider-spread changes because fewer changes were filtered out compared to elevation-change maps created using the minimum level of detection associated with the 95-percent confidence limit. As a result, elevation-change maps generated using the 68-percent confidence limits contained double the area of detectable change on average compared with elevation-change maps generated using the 95-percent confidence limit (table 3). The minimum level of detection was treated as spatially uniform in this study for replicability, although previous studies have shown that error in DEMs is often spatially variable (Brasington and others, 2003; Wheaton and others, 2010) For example, areas with high slopes, low point densities, and high roughness tend to have higher levels of uncertainty in elevation; whereas, flat and smooth areas with high point densities tend to have lower levels of uncertainty in elevation (Wheaton, 2008; Wheaton and others, 2010). As a result, elevation-change maps generated using the lower change detection threshold (the 68-percent confidence limit) may over-represent areas where uncertainty in elevation is high and under-represent areas where uncertainty in elevation is low (Wheaton and others, 2010). Furthermore, elevation-change maps generated using the higher change detection threshold (the 95-percent confidence limit) may under-represent even greater areas where uncertainty in elevation is low and may exclude more areas where true elevation changes have occurred (Wheaton and others, 2010).

Consequently, elevation-change maps generated with different detection thresholds contain different information and have different applications. For example, a user interested in the extent of small-scale elevation changes on the floodplain, similar to the changes that occurred at study area 07, may find the lower confidence limit maps more useful; whereas, a user interested in identifying elevation changes with a high degree of certainty would find the higher confidence limit maps more useful.

Elevation-Change Maps and Geomorphic Changes

Study areas along Fountain Creek underwent a range of geomorphic responses between 2015 and 2019, some of which were more common depending on the dominant channel pattern (table 4). Only high certainty (95-percent confidence limit), large-scale elevation-changes that represent significant geomorphic change were considered in this section (table 4). Lateral migration occurred in all study areas where meandering or braided was the dominant channel pattern (study areas 01, 04, 05, 06, 07, and 08; tables 1 and 4). In this context, lateral migration refers to a combination of bank erosion, streambed erosion, and on the opposite side of the channel, streambed deposition. Sediment deposition within a side

Table 3. Elevation-change detection thresholds and percentage of the study area that underwent detectable change associated with the 68-percent and 95-percent confidence limits for Fountain Creek elevation-change maps, 2015–19.

Study area	Survey years	Minimum level of change detection (standard deviation of error) associated with the 68-percent confidence limit, in meters[1]	Minimum level of change detection (standard deviation of error) associated with the 95-percent confidence limit, in meters[1]	Percentage of study area that underwent detectable change using the 68-percent confidence limit	Percentage of study area that underwent detectable change using the 95-percent confidence limit
01	2015–19	0.18	0.35	47	32
02	2015–19	0.20	0.38	18	7
03	2015–19	0.17	0.33	24	11
04	2015–19	0.15	0.30	34	19
05	2015–19	0.17	0.33	51	29
06	2015–19	0.16	0.30	41	26
07	2015–19	0.17	0.34	56	27
08	2015–19	0.18	0.35	41	29
09	2015–19	0.17	0.34	27	8
10	2015–19	0.21	0.41	26	7

[1]Calculated using equation 1 reported by Milan and others, 2011.

Table 4. Summary of geomorphic responses at all study areas on Fountain Creek, southeastern Colorado, based on the 95 percent confidence limit elevation-change maps.

Study area	Survey years	Summary of geomorphic response based on the 95 percent confidence limit elevation-change maps
01	2015–19	Lateral migration; erosion within the bankfull channel; deposition within side-channel
02	2015–19	Bank erosion
03	2015–19	Bank erosion; deposition within the bankfull channel
04	2015–19	Lateral migration; minor deposition on the floodplain
05	2015–19	Lateral migration
06	2015–19	Lateral migration; deposition within side-channel
07	2015–19	Lateral migration; deposition on the floodplain
08	2015–19	Lateral migration; mixture of erosion and deposition within the bankfull channel
09	2015–19	Minor deposition within the bankfull channel; minor bank erosion
10	2015–19	Minor deposition on the floodplain; minor bank erosion

channel occurred less often and exclusively within study areas characterized as meandering or braided (study areas 01 and 06; tables 1 and 4). Overall, elevation changes in meandering or braided study areas were also wider spread, occurring over roughly double the percentage of the study area that underwent change compared to straight study areas (tables 1 and 3). In comparison, localized bank erosion occurred in all study areas characterized as straight (study areas 02, 03, 09, and 10; tables 1 and 4). Several geomorphic responses including deposition and (or) erosion within the bankfull channel and deposition on the floodplain occurred in both straight and meandering study areas (study areas 01, 03, 04, 06, 07, 08, 09, and 10; tables 1 and 4). Most elevation changes occurred within the bankfull channel, although all study areas contained small areas of elevation change that were disconnected from the main channel. Those changes on the floodplain were likely caused by localized sediment reworking during overland flow, the growth or death of vegetation, movement of soil or rip-rap on steep slopes, or anthropogenic earth movement. Lastly, there was no apparent longitudinal pattern in geomorphic responses throughout the study areas. Although it was beyond the scope of this report to determine potential causes of geomorphic change on Fountain Creek, this dataset provides important information for long-term monitoring efforts.

Summary

The U.S. Geological Survey, in cooperation with Colorado Springs Utilities, has been collecting topographic data at 10 study areas along Fountain Creek, Colorado, annually since 2012. The purpose of this report is to present elevation maps based on topographic surveys collected in 2015 and 2019 and to present maps of elevation change between 2015 and 2019 at 10 study areas located in southeastern Colorado, between Colorado Springs and the terminus of Fountain Creek at the Arkansas River in Pueblo. The methods used to generate elevation and elevation-change maps are also presented, as is a summary of the geomorphic changes the occurred between 2015 and 2019. Elevation and elevation change maps can be used to monitor long-term changes in land-surface elevation and channel morphology on Fountain Creek following the implementation of the Southern Delivery System, which brings water from the Pueblo reservoir to Colorado Springs for municipal use and returns the treated wastewater to the Arkansas River by Fountain Creek.

Elevation and elevation-change maps were developed in ArcGIS from topographic surveys collected at each study area using real-time kinematic Global Navigation Satellite Systems during the winter months (January through April) of 2015 and 2019. Elevation-change maps were created using statistically defined minimum levels of change detection associated with the 68-percent confidence limit and the 95-percent confidence limit. Study areas along Fountain Creek underwent a range of geomorphic responses between 2015 and 2019 that often depended on the dominant channel pattern of the study area, and no longitudinal pattern in geomorphic responses was detected based on high certainty (95-percent confidence limit) elevation-change maps. Although it was beyond the scope of this report to determine potential causes of geomorphic change on Fountain Creek, this dataset provides important information for long-term monitoring efforts.

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