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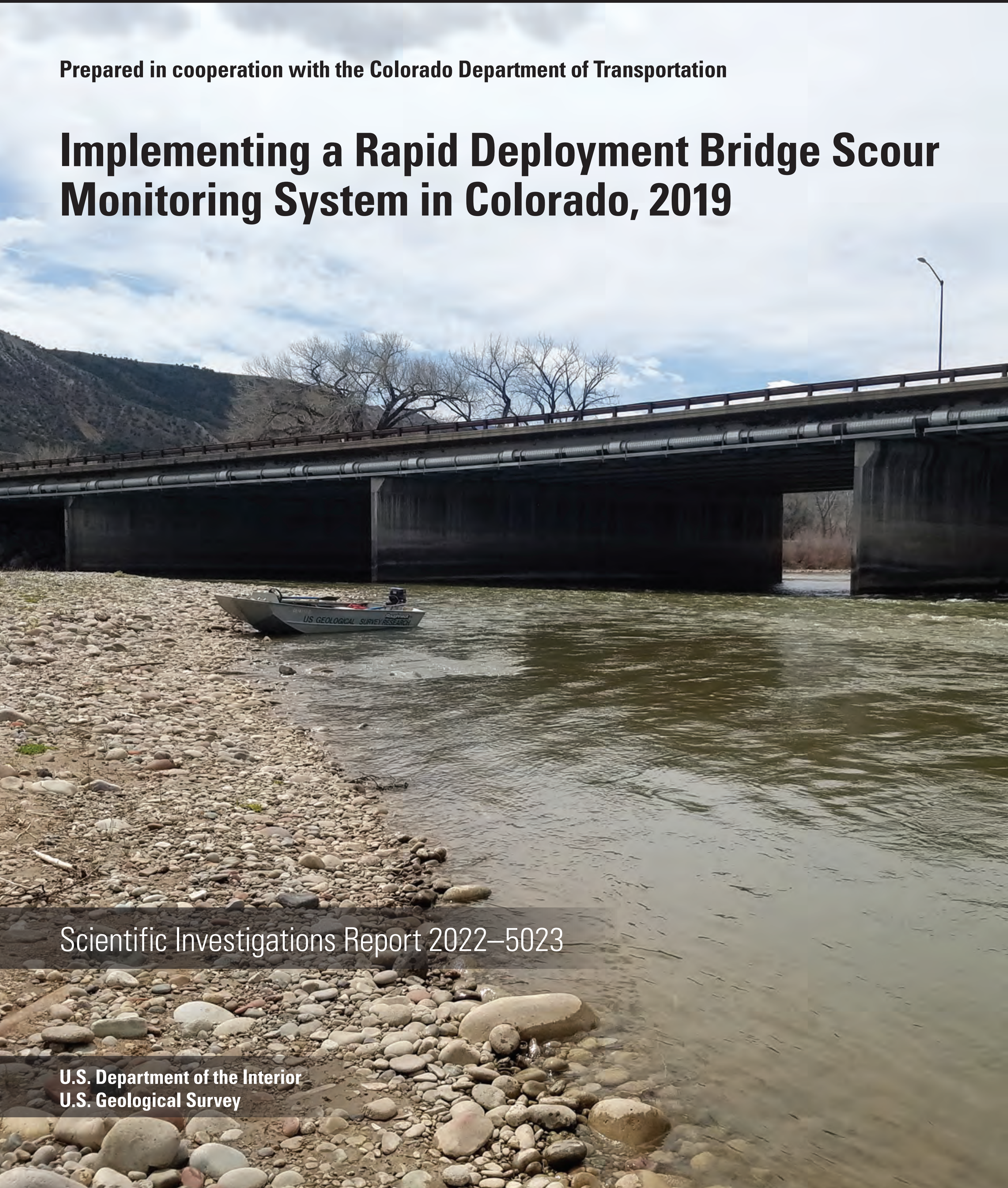
# Implementing a Rapid Deployment Bridge Scour Monitoring System in Colorado, 2019




Scientific Investigations Report 2022–5023

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

**Cover.** Photograph of bridge F-05-R, in Colorado. Photograph by Mark Henneberg, U.S. Geological Survey.

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By Mark F. Henneberg and Rodney J. Richards

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# Contents



# Figures

## Conversion Factors

U.S. customary units to International System of Units

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| inch (in.) | 2.54 | centimeter (cm) |
| foot (ft) | 0.3048 | meter (m) |
| mile (mi) | 1.609 | kilometer (km) |
| | Area | |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |
| | Flow rate | |
| cubic foot per second ($ft^3/s$) | 0.02832 | cubic meter per second ($m^3/s$) |

## 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

| | |
|---|---|
| CDOT | Colorado Department of Transportation |
| DCP | data collection platform |
| FNU | Formazin Nephelometric Units |
| GOES | Geostationary Operational Environmental Satellite |
| NWIS | National Water Information System |
| RDBSMS | rapid deployment bridge scour monitoring system |
| RTK–GNSS | real-time kinematic Global Navigation Satellite System |
| USGS | U. S. Geological Survey |

# Implementing a Rapid Deployment Bridge Scour Monitoring System in Colorado, 2019

By Mark F. Henneberg and Rodney J. Richards


## Abstract

The U.S. Geological Survey, in cooperation with the Colorado Department of Transportation, installed and operated real-time scour monitoring instrumentation at two bridges in Colorado in 2016 and 2017 to measure streambed elevations in real-time. The instrumentation included acoustic echosounder depth sensors mounted to the bridge substructure units with rigid conduit and fittings. Although functional, the rigid mounting configuration took several days to install at each site, which limits the instrumentation to long-term deployments at previously determined sites. To address this limitation and allow for greater flexibility in bridge selection, a rapid deployment bridge scour monitoring system (RDBSMS) was developed by the U.S. Geological Survey in cooperation with the Colorado Department of Transportation. The RDBSMSs were installed at two other bridges in Colorado in 2019, which were selected by using specific scoring criteria to rank candidate bridges and the potential for high streamflow based on accumulated snowpack. A matrix was developed to rank candidate bridges based on factors including depth, foundation type, average daily traffic, detour route, and scour critical condition. Colorado Department of Transportation bridges F-05-R and P-01-G were selected as the final candidate bridges for installation and testing of the rapid deploy scour monitoring system.

Bridge F-05-R carries Colorado Highway 13 over the Colorado River near the town of Rifle, Colorado. Because of the misalignment of the pier wall with respect to the river, pier number 4 was instrumented on the left side (looking downstream) to monitor scour conditions. Bridge P-01-G carries U.S. Route 160 over the San Juan River near the Four Corners area in Colorado. Because of misalignment of the pier wall with respect to the river, pier number 4 was instrumented on the right side (looking downstream) to monitor scour conditions. The RDSMSs were installed in approximately 3 hours at each bridge.

Scour conditions at both bridges were monitored during the snowmelt runoff period in 2019 using the installed RDBSMSs. No major scour events occurred at either structure, but minor scour and fill was measured at each. Sensor performance at F-05-R was excellent, with no missing or erroneous data. Sensor performance at P-01-G was good for most of the period, with some missing and erroneous data during periods of high turbidity.

Both RDBSMSs were successfully deployed and produced reliable data, demonstrating that both the technology and the installation methods can work in two different riverine environments. Pre-installation of mounting plates would make the installation process faster at flood prone bridges. Having flood prone bridges preconfigured and several RDBSMSs ready to deploy could allow for rapid monitoring during floods such as those which occurred in 2013.


## Introduction

The Colorado Department of Transportation (CDOT) maintains roadway crossings over streams and rivers where sediment transport and channel alignment changes can affect the structural integrity of bridges. Streambed scour, the mobilization and degradation of bed material, is the leading cause of bridge failure in the United States (Murillo, 1987; Butch, 1991). Structural stability during and immediately after peak streamflow can be assessed by measuring streambed scour; however, placing personnel or boats in the water during high-streamflow events using traditional methods can be difficult, hazardous, and time consuming (Henneberg, 2018). Flooding and associated streambed scour from the September 2013 flood in eastern Colorado highlights the importance of real-time monitoring. The flooding caused major damage and road closures at structures adjacent to or spanning streams and rivers, limiting access to entire municipalities. About 486 miles of State roadways were affected; 39 roadways were temporarily closed; and 120 State bridges were damaged (CDOT, 2015c).

The U.S. Geological Survey (USGS), in a joint effort with CDOT, installed real-time scour monitoring instrumentation at two bridges in 2016 and 2017 to measure streambed elevations in real-time (Henneberg, 2018). The instrumentation included acoustic echosounder depth sensors (herein after referred to as “depth sensor”) mounted to the bridge substructure units with rigid conduit and fittings. Although functional, the rigid mounting configuration took several days at each site to install, which limits the instrumentation to long-term deployments at previously determined sites. Hydrologic events, which result in scouring streamflow, do not occur at every bridge, every year, and instrumenting all scour-vulnerable bridges in Colorado would be cost-prohibitive. To address this limitation, the USGS, in cooperation with CDOT, developed a rapid deployment bridge scour monitoring system (RDBSMS) by refining the previously used sensor technology to allow for greater flexibility in bridge selection and deployment. The RDBSMS can be installed at bridge locations prior to scour-prone runoff periods or storm events based on predictive services such as National Resource Conservation Service Snow Telemetry data (https://go.usa.gov/xzW3D) or National Weather Service (https://www.weather.gov/) weather forecasts. In 2019, the RDBSMSs were installed at two bridges in Colorado, which were jointly selected by CDOT and USGS (fig. 1).

The RDBSMSs were installed prior to the snowmelt runoff period in 2019 (May through September) at selected bridges (CDOT bridge identifications P-01-G and F-05-R) (fig. 1). Both bridges are in western Colorado, with F-05-R spanning the Colorado River near Rifle, Colorado, and P-01-G spanning the San Juan River near the Four Corners area of Colorado. Each bridge was monitored continuously during the snowmelt runoff period, with streambed elevation data being recorded every 15 minutes. Data collected at the sites were transmitted to the Geostationary Operational Environmental Satellite (GOES) every 15 minutes, providing nearly real-time data acquisition, relay, and dissemination.

# Purpose and Scope

This report presents a newly developed implementation strategy to rapidly deploy and monitor real-time bridge scour at select bridges in Colorado. Instrumentation was developed and installed at two bridges in western Colorado to measure streambed elevations in real-time during snowmelt runoff (May through Sept) in 2019. This report summarizes the bridge selection methods; instrumentation design and implementation; and data collection, transmission, and dissemination.

# Methods

This section of the report presents the methods used for bridge identification and selection, the development of the RDBSMS, the installation details at the selected bridges, and quality assurance.

## Bridge Selection Criteria

Bridge selection was done through a joint effort between the USGS and CDOT to assess and rank potential bridge locations based on nine criteria. A bridge scoring matrix was developed and included exclusion and scoring criteria for each bridge. The first three criteria were exclusion factors related to suitability of site location for the instrumentation (water depth and bridge design) and status of CDOT maintenance planning and activities; if the criteria were not met, the bridge was removed from further consideration. The remaining six criteria, which were used as scoring factors, were CDOT regional representation, CDOT scour critical rating, average daily traffic at the bridge, detour length because of bridge closure, cellular signal availability at the bridge, and co-location of the bridge with a USGS streamflow-gaging station. The highest scoring bridge from each CDOT engineering region was selected as a final possible candidate for sensor installation (fig. 2). Right-of-way permit applications were submitted for all five bridges, including details of the proposed hardware installation and traffic control plans. All five sites were also registered in the USGS Station Information Management System so that data collection could begin when needed at each site.

As snowpack accumulated during the winter of 2019, periodic updates of snowpack conditions from Natural Resources Conservation Service Snow Telemetry stations in contributing basins (6-digit hydrologic unit) for each candidate site were provided to the CDOT and USGS team to ascertain which two of the five candidate sites had the highest potential for scouring streamflow conditions during snowmelt runoff period. The two final sites with the highest likelihood of scouring streamflow conditions were selected for the hardware installations. Bridge I-17-EG, located on Fountain Creek near Colorado Springs, Colo., was removed from consideration due to maintenance activities near the bridge. Final selection was made on April 12, 2019, after a Natural Resources Conservation Service (2019) provisional snowpack update through April 11, 2019 (fig. 3), showed that the associated basins for bridges F-05-R and P-01-G had the highest snow water equivalent percentages among the four remaining bridges.

## Instrumentation Development

The RDBSMS uses the same Airmar EchoRange Smart Sensor echosounder (Airmar Technology Corporation, 2017) depth sensor as was successfully deployed at CDOT bridges in 2016 and 2017 (Henneberg, 2018). However, a new two-piece mounting apparatus was developed to facilitate rapid installation of the sensors. A 6-inch (in.) wide by 12-in. tall mounting plate, 3/4 in. thick, was fabricated from a 6061 aluminum plate. The plate is inexpensive to manufacture and can be installed on any flat surface, such as a pier wall or support pile. The plate has holes drilled and tapped to receive a separate depth sensor mount. A mounting plate was installed at each bridge site subunit. The depth sensor mount is also manufactured from a 3/4 in. 6061 aluminum plate and is composed of a flat face which bolts to the mounting plate and a flange to secure the depth sensor. The depth sensor mount is attached to the mounting plate using four 3/8 in.-16 cap head hex screws, which are recessed into the flat face. The depth sensor is secured with a stainless-steel nut, which has a threaded fitting welded to the top to connect 3/4 in. electrical conduit fittings. This allows the depth sensor cable to pass directly into a length of conduit (fig. 4). The depth sensor mount was surveyed during the installation using real-time kinematic Global Navigation Satellite System (RTK–GNSS) methods (Rydlund and Densmore, 2012), so that the elevation of the sensor was known prior to being attached.

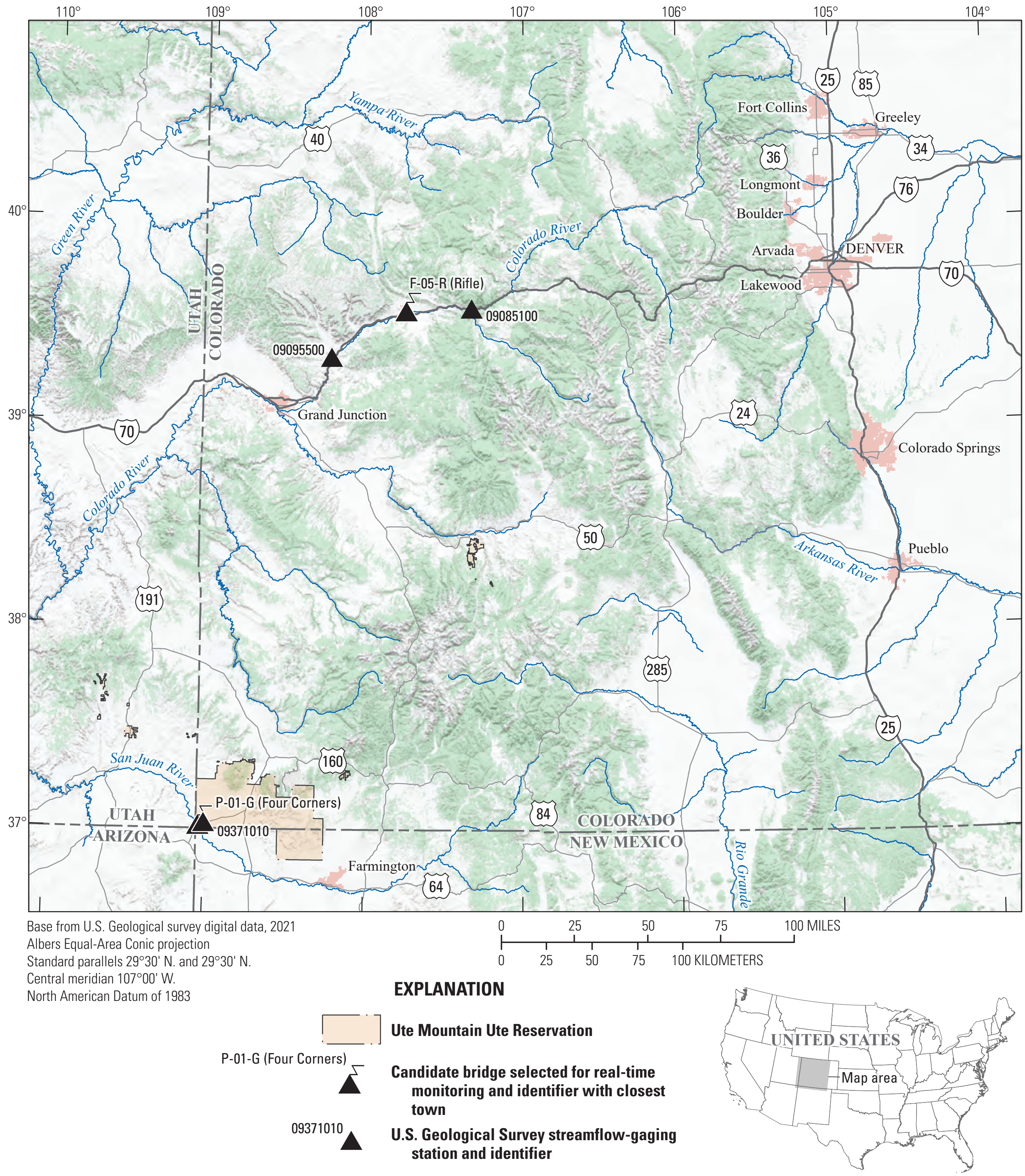



**Figure 1.** Map showing the locations of the bridges in western Colorado selected for the rapid deployment bridge scour monitoring system installation.

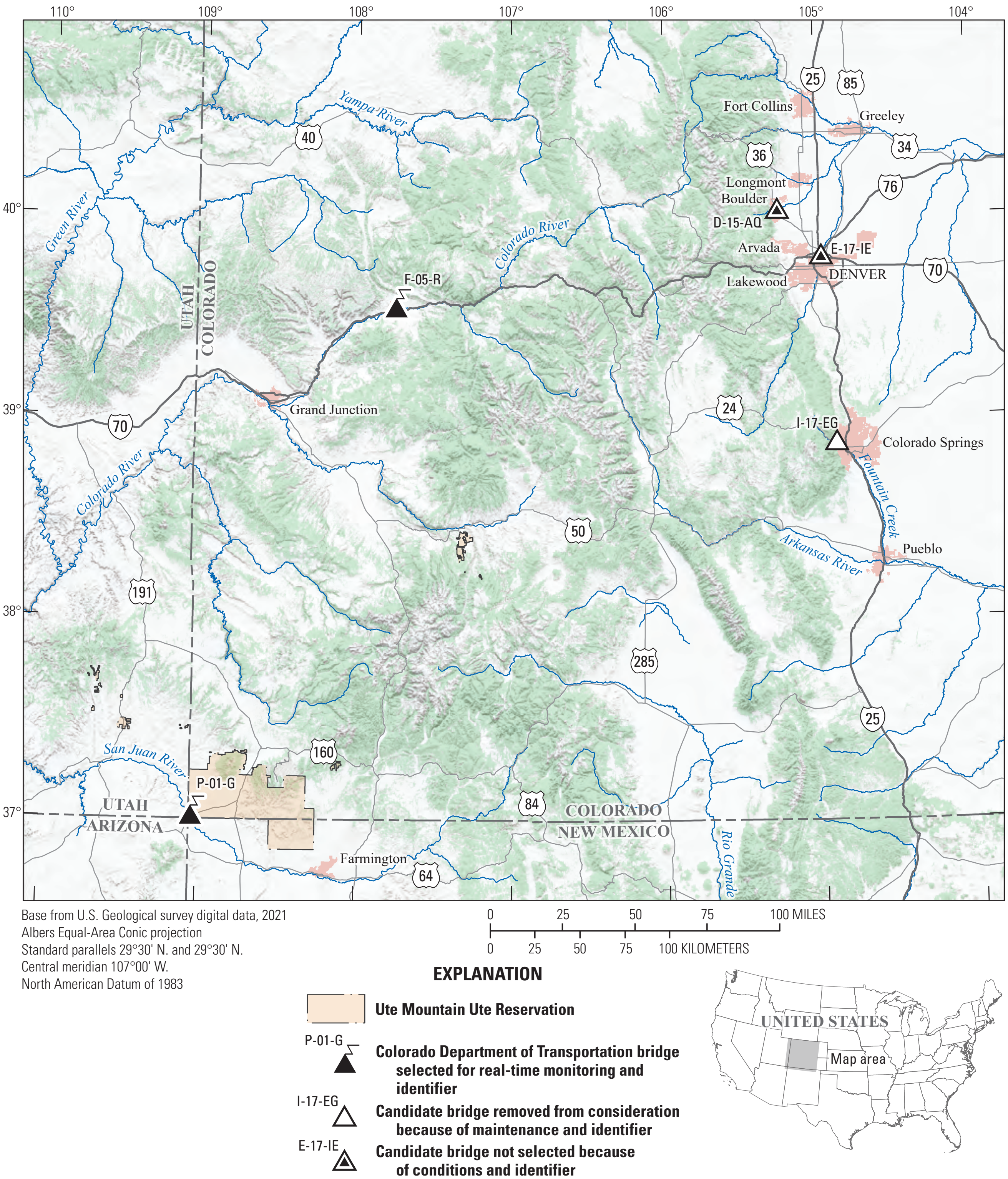
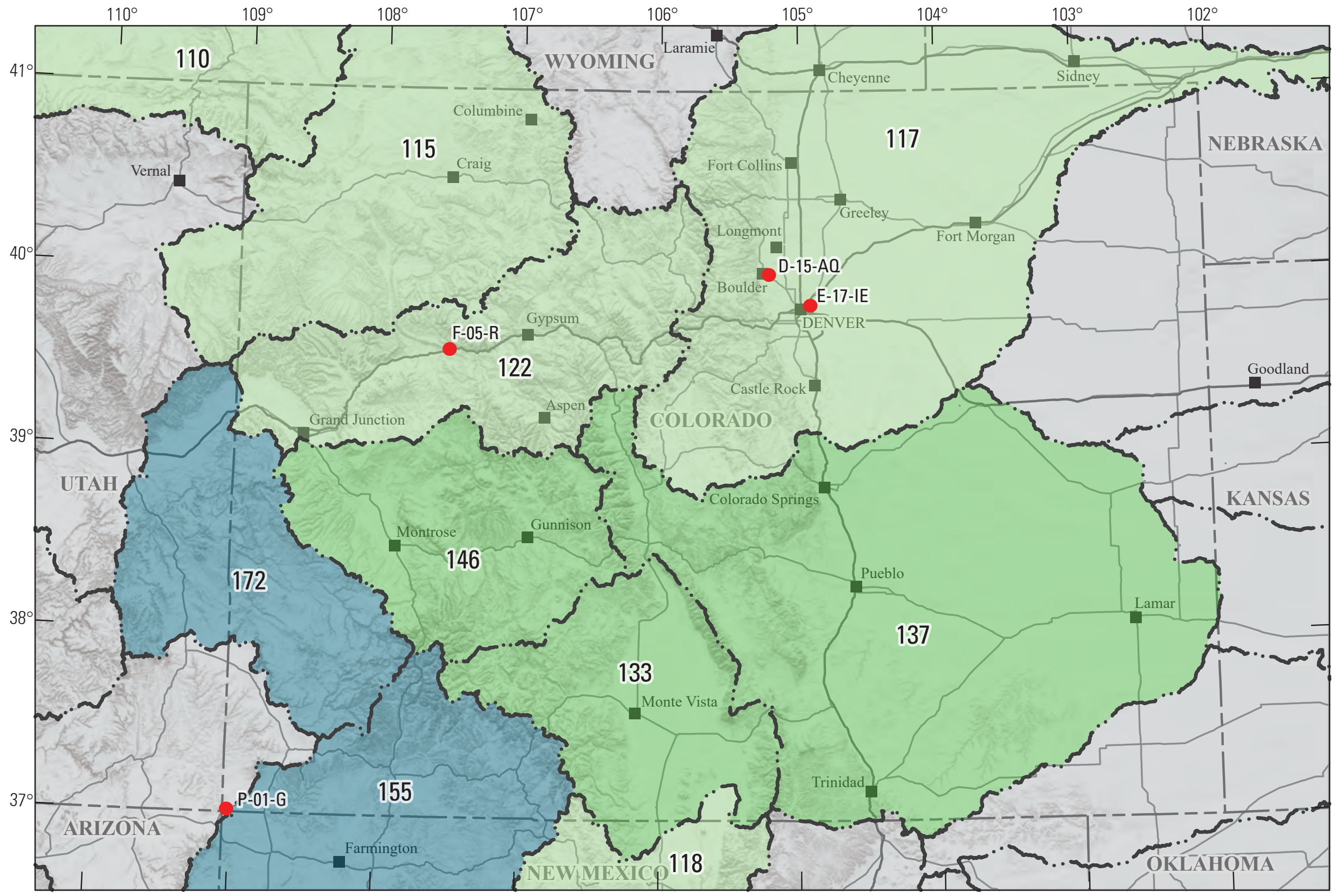



**Figure 2.** Map showing the locations of the final candidate bridges evaluated for this study.




Base from U.S. Geological survey digital data, 2021
Albers Equal-Area Conic projection
Standard parallels 29°30' N. and 29°30' N.
Central meridian 105°30' W.
North American Datum of 1983

0 25 50 75 100 125 MILES
0 25 50 75 100 125 KILOMETERS

**EXPLANATION**

**Percent of Natural Resources Conservation Service 1981–2010 Median snow water equivalent, in percent**

151 to 175
126 to 150
100 to 125
No basin value

**Basin (6-Digit Hydrologic Unit Code)**

P-01-G **Colorado Department of Transportation bridge and identifier**

118 **Snow water equivalent, percent of 1981–2010 median value for basin**

**Figure 3.** Map showing the Natural Resources Conservation Service median snowpack update from April 11, 2019. Provisional data from Natural Resources Conservation Service (2019).

Acoustic echosounder (depth sensor), echosounder (depth sensor) mount, and mounting plate

Echosounder (depth sensor) mount

Mounting plate

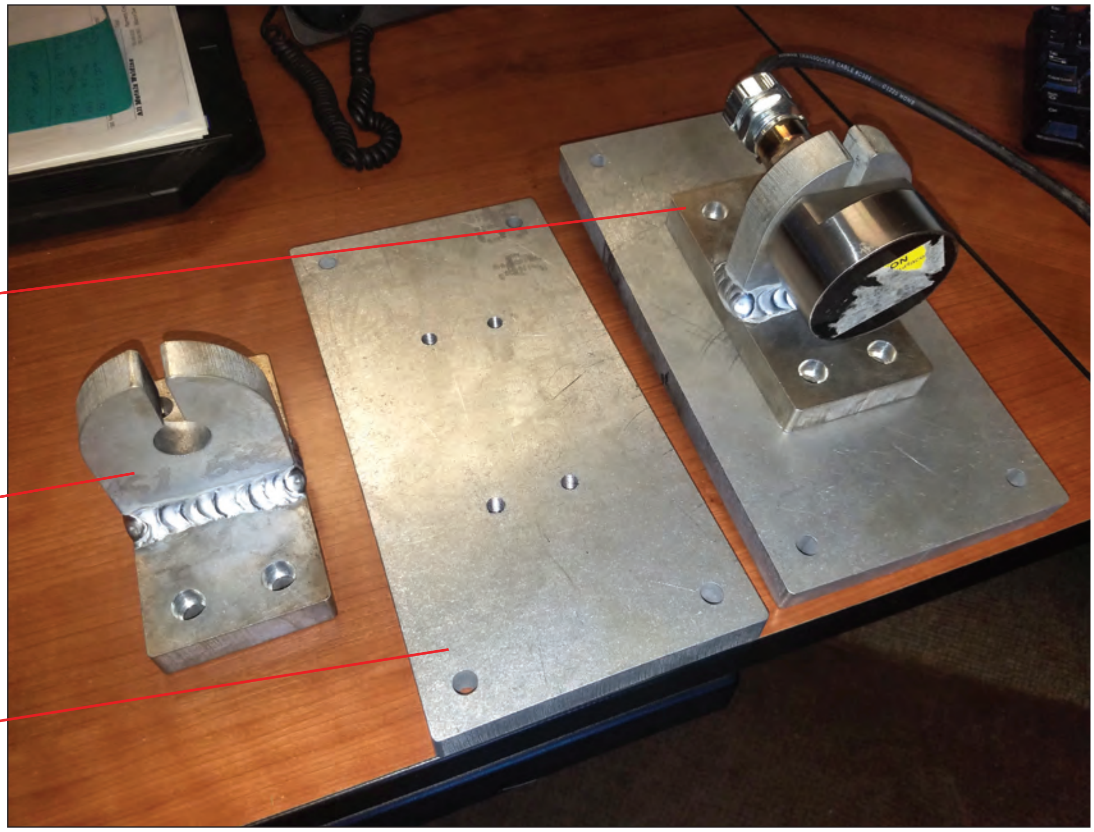


**Figure 4.** Photograph of acoustic depth sensor, depth sensor mount, and mounting plate.

The depth sensor cable is routed through flexible conduit to a small (16 in. x16 in. x8 in.) electrical enclosure. Two preinstalled clamps were used to install the electrical enclosure over a standard H-beam, which is frequently used to secure bridge guide rails. Telemetry equipment includes a data collection platform (DCP), National Marine Electronics Association-0183 to Serial Digital Interface at 1,200 Baud protocol converter, solar charge regulator, and 18 amp-hour battery. The DCP was placed on a 15-minute self-timed GOES radio assignment, which provides near real-time data relay from the bridge site. The DCP was programmed to measure the depth sensor every 15 minutes, with each 15-minute reading being composed of an average of 10 instantaneous values, measured one per second. If the depth sensor was mounted at an angle, the DCP processed the incoming data to determine the vertical component of the measured value using a trigonometric conversion. The calculated vertical height was relayed via GOES to the National Water Information System (NWIS) database website for data storage and dissemination (https://doi.org/10.5066/F7P55KJN). Data relayed from the sites were disseminated on the NWIS database website and were available in the USGS WaterAlert service (https://maps.waterdata.usgs.gov/mapper/wateralert/). The WaterAlert service allows any end user to define alarm thresholds and notification parameters for specific sites of interest.

## Bridge F-05-R

Bridge F-05-R carries Colorado State Highway 13 over the Colorado River at milepost 0.108 near the town of Rifle, in western Colorado. It is a 5-span bridge built in 1976 with reinforced concrete piers and abutments. Upstream from the bridge, the Colorado River has a drainage area of 6,720 square miles ($mi^2$). The natural hydrology of the Upper Colorado River Basin has been considerably altered by water development, which includes numerous reservoirs and diversions (Apodaca and others, 1996). The closest USGS streamflow-gaging stations to the bridge are (1) USGS site number 09085100 (Colorado River below Glenwood Springs, Colo.), which is located upstream from the bridge and has a drainage area of 6,014 ($mi^2$), and (2) USGS site number 09095500 (Colorado River near Cameo, Colo.), which is located downstream from the bridge and has a drainage area of 7,986 ($mi^2$) (fig. 1). Streamflow data used from USGS streamflow-gaging stations are available on the NWIS database website (https://doi.org/10.5066/F7P55KJN) and were processed using standardized USGS techniques and methods as described in Turnipseed and Sauer (2010) and Rantz and others (1982).

The F-05-R bridge subunits (piers and abutments) are skewed 25 degrees to the roadway to align them with the Colorado River. However, recent changes to river alignment with the bridge subunits exacerbate scour forces along the upstream right bank, right abutment, and piers 4 and 5 (CDOT, 2015a). A review of historical satellite photographs indicates that the embankment containing a gravel and (or) borrow pit adjacent to the upstream right riverbank (when oriented looking downstream) was overtopped by the Colorado River at some time between 1993 and 2002. The Colorado River subsequently rerouted itself through the inundated gravel pit, changing the course of the river and alignment with the bridge (fig. 5). The bridge is not aligned with the main thread of the river, and in its current configuration, the approach flow has an angle of attack of up to 30 degrees (CDOT, 2015a).

Pier 4, located mid-channel, is the subunit most directly affected by the river alignment change. Pier 4 is now subject to an attack angle of approximately 30 degrees, resulting in scour conditions around the upstream nose and along the right side of the pier (CDOT, 2015a). Because of these conditions, the team elected to place instrumentation on the upstream nose of pier 4 to monitor scour conditions in real-time.

Installation was completed using prefabricated enclosures and mounts, which minimized onsite fabrication and installation times. The mounting plate, depth sensor mount, and depth sensor were installed on the left side of the pier wall, approximately 5 feet (ft) downstream from the nose. This placed the depth sensor out of direct flow, in the shadow of the pier, to protect the sensor from debris and damage. The depth sensor was mounted at an elevation of 5,302.52 ft above North American Vertical Datum of 1988 (NAVD 88), as determined by optical levels and RTK-GNSS methods following the procedures described in Kenney (2010) and Rydlund and Densmore (2012). The elevated mount keeps the depth sensor out of water until the streamflow exceeds about 10,000 cubic feet per second ($ft^3/s$), which reduces fouling and debris accumulation during low-flow conditions. Because this location requires a boat to access the sensor, reducing the potential for fouling is prudent to minimize boat work and the hazards associated therewith. The depth sensor was oriented at a 30-degree angle from nadir (vertical oriented downward) and aimed upstream so the acoustic footprint would measure the streambed elevation directly upstream from the pier nose (fig. 6). Sounding with a wading rod indicated this was the deepest location around the pier and was likely the most susceptible to further scour based on the angle of attack. The depth sensor cabling was run up the pier wall to the instrument enclosure mounted on the bridge guide rail from a boat-mounted work platform used to access the pier. Installation of the instrumentation and enclosure on the guide rail took approximately 3 hours with two personnel.

## Bridge P-01-G

Bridge P-01-G carries U.S. Highway 160 over the San Juan River at milepost 0.251 about 35 miles southwest of Cortez, Colo., near the Four Corners area (the junction of the States of Arizona, Colorado, New Mexico, and Utah), on lands of the Ute Mountain Ute Tribe in southwest Colorado. It is a five-span bridge with reinforced concrete piers and abutments and was built in 1961. Upstream from the bridge, the San Juan River has a drainage area of 14,600 $mi^2$. The San Juan River at the bridge is regulated by Navajo Dam. Prior to 1963 when Navajo Dam became operational, streamflows in the San Juan River generally were characterized by peak flows during the April through July snowmelt period and much lower streamflows during the remainder of the year, except during storms. Between 1963 and 1992, Navajo Dam was operated in a manner that maximized water storage and delivery for irrigation purposes, as well as providing flood control, recreation, and water for domestic and industrial uses. This generally resulted in a year-round stabilization of flows in the San Juan River, and the reservoir served to average out the sharp differences between peak flows and low flows. Since 1992, the Bureau of Reclamation has changed the operational management of Navajo Dam to recreate pre-dam peak-flow conditions during the snowmelt runoff period to encourage spawning and recovery of the endangered Colorado pike minnow and razorback sucker (Thomas and others, 1998). The closest USGS streamflow-gaging station to the bridge is USGS site number 09371010 (San Juan River near Four Corners, Colo.), which is located approximately 0.35 miles upstream from the bridge (fig. 1). Streamflow and water-quality data used from USGS streamflow-gaging stations are available on the NWIS database website (https://doi.org/10.5066/F7P55KJN) and were processed using standardized USGS techniques and methods as described in Turnipseed and Sauer (2010), Rantz and others (1982), and Wagner and others (2006).

A partially tree-covered island under bridge P-01-G splits the San Juan River into two channels at the structure: the southwest channel along the left and the northeast channel along the right bank. The southwest channel is well-aligned with the bridge and has vegetated banks. The left overbank of the southwest channel consists of a rock cliff with a similar elevation as the road deck and is parallel to the abutment face. The cliff, channel alignment, and vegetated bank increase the horizontal stability of the southwest channel. The northeast channel is 20 degrees out of line with the bridge opening. Channel alignment has shifted to the northeast on the upstream side of the bridge, creating a scour hole at the upstream end of the right abutment, and exposing riprap (CDOT, 2015b). The scour hole also redirects the river towards the right side of pier 5, causing a misalignment with the pier (fig. 7).

The abutments and piers are supported by driven H-piles. Piers 2, 4, and 5 have hexagonal concrete pier caps with a length of 10 ft and 4 in. along the major axis. Pier 3 utilizes a rectangular concrete pier cap with a length of 15 ft and a width of 7 ft. The San Juan River is a perennial river that flows from southeast to northwest under P-01-G. The bridge is well-aligned to the streamflow of the river and has an approximate angle of attack of 0—20 degrees (CDOT, 2015b).

Pier 4, located on the left bank of the northeast channel, was the subunit most directly affected by the river alignment change. Pier 4 is now subject to an attack angle of

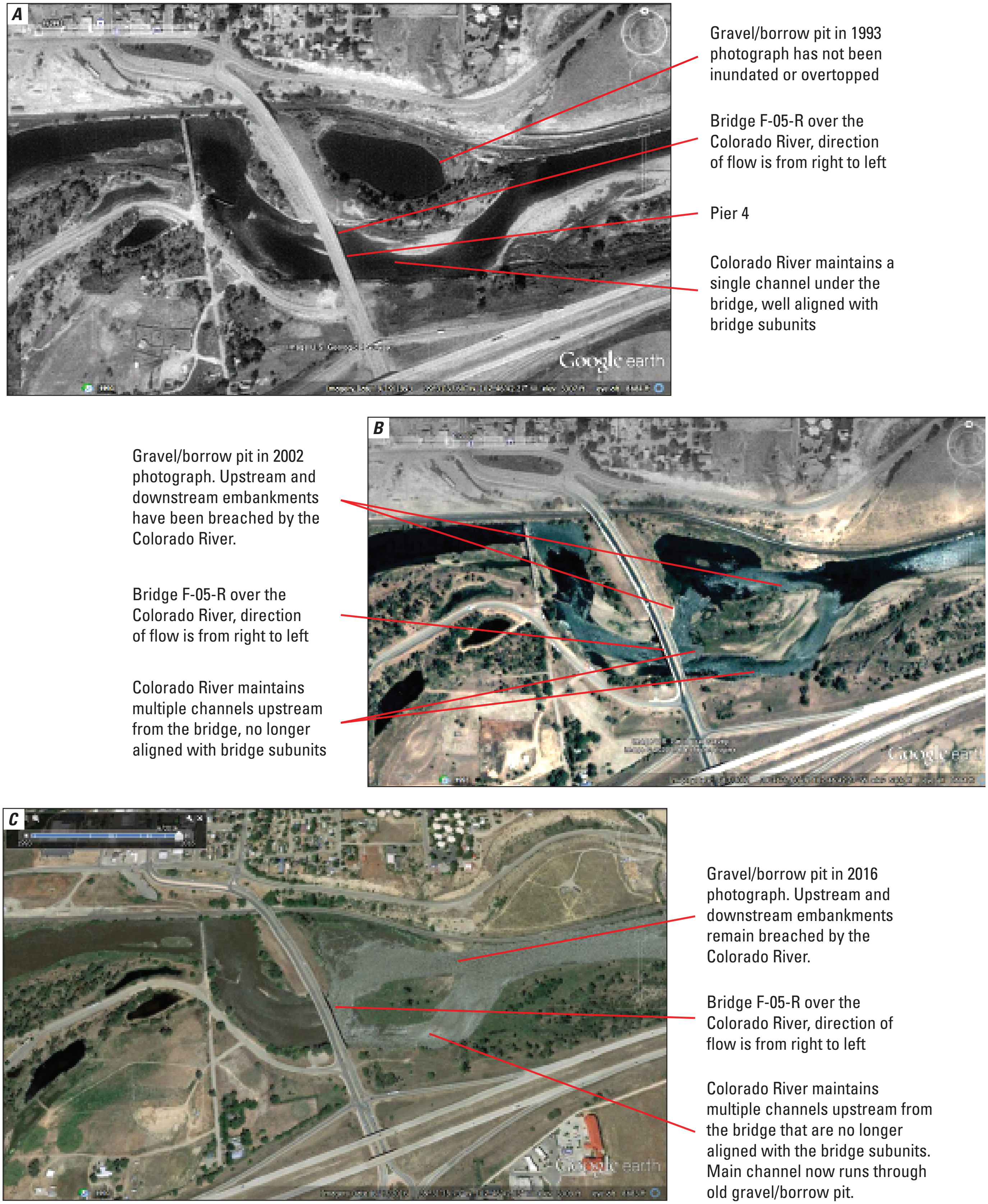



**Figure 5.** Satellite photographs of bridge F-05-R from *A*, 1993, *B*, 2002, and *C*, 2016 that illustrate channel alignment changes to the Colorado River near Rifle, Colorado. Base map data from Google, 2016 and U.S. Geological Survey,1993, 2002.

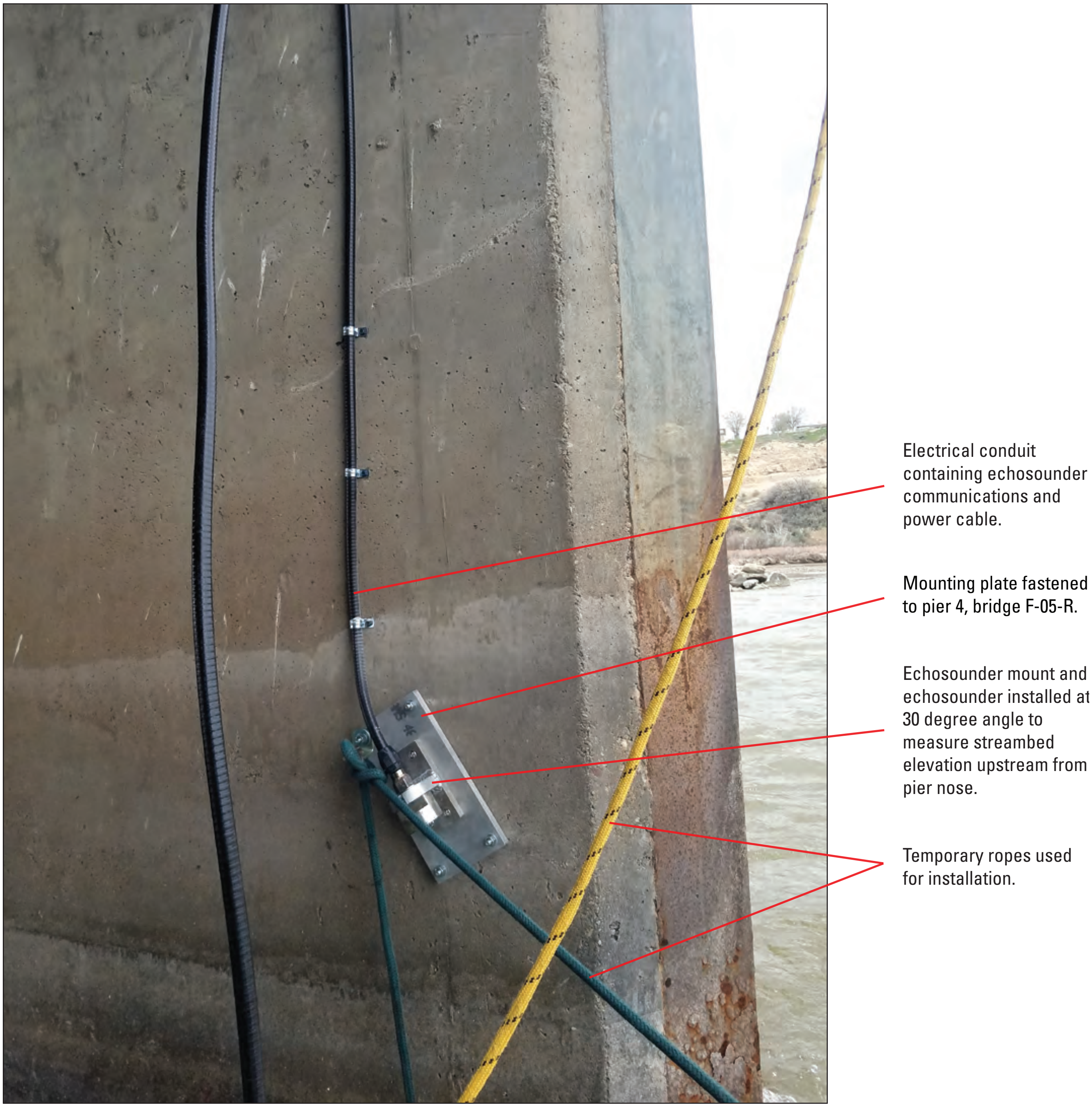



**Figure 6.** Photograph of the depth sensor and mounting plate installed on the upstream, left side of pier 4 on Colorado Department of Transportation bridge F-05-R.

approximately 20 degrees, resulting in scour conditions along the right side of the pier (CDOT, 2015b). Because of these conditions, the team elected to place instrumentation on the right side of pier 4 to monitor scour conditions in real-time.

Installation was completed during low flow using prefabricated enclosures and mounts, which minimized onsite fabrication and installation times. The mounting plate, depth sensor mount, and depth sensor were installed on the right side of the pier wall, approximately 20 ft downstream from the nose. This pier is constructed of two main columns supported by a pile cap, founded on driven piles, with a concrete wall between the columns (CDOT, 2015b). The depth sensor was mounted at an elevation of 4,613.89 ft, as determined by optical levels and RTK-GNSS methods following the procedures described in Kenney (2010) and Rydlund and Densmore (2012). The mounted elevation keeps the depth sensor out of water until

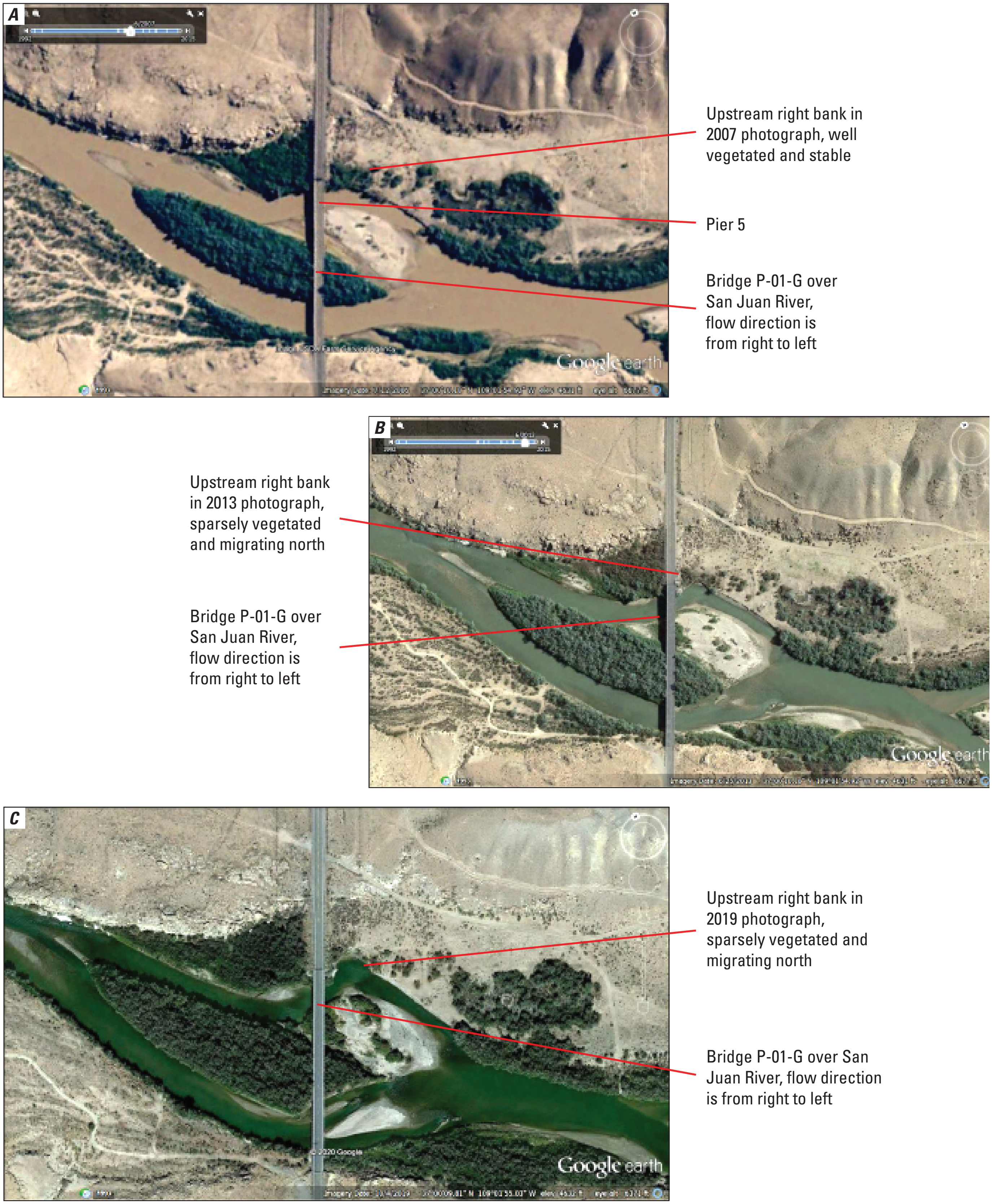



**Figure 7.** Satellite photographs of bridge P-01-G from *A*, 2007, *B*, 2013, and *C,* 2019, illustrating channel alignment changes to the San Juan River near the Four Corners area of Colorado. Base map data from USDA Farm Service Agency, 2007, and Google, 2013 and 2019.

streamflows reach approximately 3,500 ft$^3$/s to reduce fouling and debris accumulation during low-flow conditions. The depth sensor was oriented vertically so that the acoustic footprint would measure the streambed elevation under the pier wall between the two supporting columns. Sounding with a wading rod indicated this was the deepest location around the pier and was likely the most susceptible to scour based on the angle of attack (fig. 8). The depth sensor cabling was run up the pier wall, to the instrument enclosure mounted on the bridge guide rail. Installation of all on-pier hardware required use of a boat-mounted work platform to access the pier. Installation of the instrumentation and enclosure on the guide rail took approximately 3 hours with two personnel (fig. 8).

Telemetry equipment for P-01-G consisted of a DCP, National Marine Electronics Association 0183 to Serial Digital Interface at 1,200 Baud protocol converter, solar charge regulator, and 18 amp-hour battery. The DCP was placed on a 15-minute self-timed GOES radio assignment, which provides near real-time data relay from the bridge site. The DCP was programmed to measure the depth sensor every 15 minutes, with each 15-minute reading composed of an average of 10 instantaneous values, measured once per second. The measured depth was relayed using GOES for data storage and dissemination. Data relayed from GOES were disseminated on the NWIS database and were available in the WaterAlert service (https://maps.waterdata.usgs.gov/mapper/wateralert/). The WaterAlert system allows any end user to define alarm thresholds and notification parameters for specific sites of interest.

## Quality Assurance

Temporary reference marks were established and surveyed at each site using RTK-GNSS following the techniques and methods in Rydlund and Densmore (2012). Elevation data were collected with a Trimble R8 GNSS base unit receiver and TDL450H radio and R8 GNSS rover receiver with TSC3 data collector. The RTK–GNSS position precision, as rated by the manufacturer, is 0.033 ft horizontally and 0.066 ft vertically (Trimble, 2003). These data are referenced to Universal Transverse Mercator zone 12 north projection, the North American Datum of 1983 (NAD 83), and the NAVD 88 geoid 2012B model (2017; https://www.ngs.noaa.gov/GEOID/GEOID12B/).

The installed depth sensor mounting plate elevations were surveyed using optical levels following the techniques described in Kenney (2010). Depth measurements were collected at each sensor using an extended wading rod during installation to independently verify the depth sensor depth data. Incoming real-time data were evaluated in the Aquarius Time-Series software (Aquatic Informatics, 2019) used by USGS to process time-series data. Values determined to be erroneous by visual evaluation were censored for the operational periods.

# Rapid Deployment Bridge Scour Monitoring Systems

Real-time streambed elevation data were measured at both locations through the snowmelt runoff period of water year 2019 (approximately May through September). Evaluation of snowpack information prior to snowmelt runoff identified the two study locations as having the highest possibility for sustained high flows, and therefore, the highest likelihood of scour to test the RDBSMS.

## F-05-R

Streamflow at bridge F-05-R increased as snowmelt runoff progressed, creating two distinct high-flow periods. The first period occurred from approximately June 5 through June 25, with a peak streamflow at USGS site number 09085100 of 18,200 ft$^3$/s on June 21, and a subsequent recession to 11,400 ft$^3$/s on June 25 (fig. 9). Streamflow began increasing again on June 27, attaining a peak streamflow of 20,800 ft$^3$/s on July 1 (fig.10), and subsequently receding below 10,600 ft$^3$/s when the water surface dropped below the elevation of the depth sensor on July 18. The 2019 peak streamflow of 20,800 ft$^3$/s represents the 10th highest peak measured at USGS site number 09085100 out of 53 peaks reported since 1967 (USGS, 2020). The difference in streamflow needed to submerge the depth sensor between the beginning and end of the snowmelt runoff period is likely due to channel geometry changes at the bridge.

Streambed elevation beginning June 5, 2019 was 5,293.22 ft, gradually scouring to about 5,292.95 ft as streamflow increased to 11,500 ft$^3$/s. Streambed elevations remained consistent thereafter until June 18, when a sudden scour of about 2 ft occurred at 10:00 a.m. mountain daylight time. The magnitude of scour was measured multiple times, but the streambed elevation returned to about 5,292.90 ft after several hours of fluctuations. A similar scour and subsequent fill occurred later that day. Streamflow measured at USGS site number 09085100 during this was about 16,500 ft$^3$/s (fig. 9). Rip-rap was placed as a scour countermeasure at this pier (CDOT, 2015a). It is possible that the scour and fill measured at the bridge was the result of a large boulder or rip-rap being mobilized and subsequently replaced by streambed mobilization. The changes measured in the elevation data are consistent with the rip-rap size class.

During the period from June 19 through June 21, streambed elevation gradually increased to about 5,293.20 ft, and again remained consistent until June 29, when streambed elevations began to decrease gradually during rising streamflow. On July 1, streamflow exceeded the peak attained during the first snowmelt runoff period and increased to 20,800 ft$^3$/s. As streamflow remained above 16,500 ft$^3$/s during the period from June 29 through July 4, streambed elevations consistently decreased from 5,293.15 ft to 5,292.85 ft, which appears


**Figure 8.** Photograph of the depth sensor, mounting plate, and instrumentation enclosure at Colorado Department of Transportation bridge P-01-G.

consistent with streambed scour (fig. 10). As streamflow decreased below about 17,500 ft$^3$/s, streambed elevations stabilized and remained consistent around 5,292.85 ft for most of the remaining snowmelt runoff period (fig. 10). During the last 2 days of recorded streambed elevation data, an increase in streambed elevation occurred resulting in an ending elevation of 5,293.07 ft, which is within 0.15 ft of the streambed elevation at the beginning of the snowmelt runoff period (USGS, 2020). Sensor performance at F-05-R was excellent, with no missing or erroneous data during the monitoring period.

## P-01-G

The depth sensor at bridge P-01-G was installed at an elevation of 4,613.89 ft to keep the sensor out of the water during lower streamflow, when scour is unlikely to occur. On May 17, 2019, streamflow exceeded 3,500 ft$^3$/s at USGS site number 09371010 (San Juan River at Four Corners, Colo.), and the depth sensor at bridge P-01-G was submerged until streamflow decreased below 3,500 ft$^3$/s on May 19 (USGS, 2020). No valid data were recorded during this period. Streamflow again increased to more than 3,500 ft$^3$/s, submerging the depth sensor on June 3, but no valid data were recorded until June 10 (fig. 11). Streamflow at USGS site number 09371010 remained above the 3,500 ft$^3$/s threshold until July 13, when the water surface dropped below the depth sensor (USGS, 2020). USGS site number 09371010 is located approximately 1,000 ft upstream from bridge P-01-G, with no tributary inflows between and is co-located with the bridge for the purposes of this report (fig. 1).

Streamflow at bridge P-01-G began increasing because of releases from Navajo Dam on June 3 and reached approximately 10,500 ft$^3$/s on June 11. Streamflow began decreasing on June 15, to approximately 5,000 ft$^3$/s on June 17 (fig. 11). Streamflow ranged from approximately 3,500 to 6,500 ft$^3$/s from June 17 to July 13, when streamflow decreased below 3,500 ft$^3$/s and the depth sensor was no longer submerged (USGS, 2020). Streambed elevation data were measured from June 10 to July 13. USGS site number 09371010 also measures and records turbidity data. During the initial time period when the depth sensor was submerged (May 17 through May 19), turbidity values were consistently more than 250 Formazin Nephelometric Units (FNU) (USGS, 2020). As streamflow increased again in June, turbidity increased above 250 FNU, but streamflow was too low to inundate the depth sensor until June 3. The turbidity sensor malfunctioned from June 3 through June 6, during which time streamflow increased from approximately 3,000 to 7,000 ft$^3$/s, and the depth sensor was submerged. As streamflow continued to increase, turbidity began to decrease, and the depth sensor

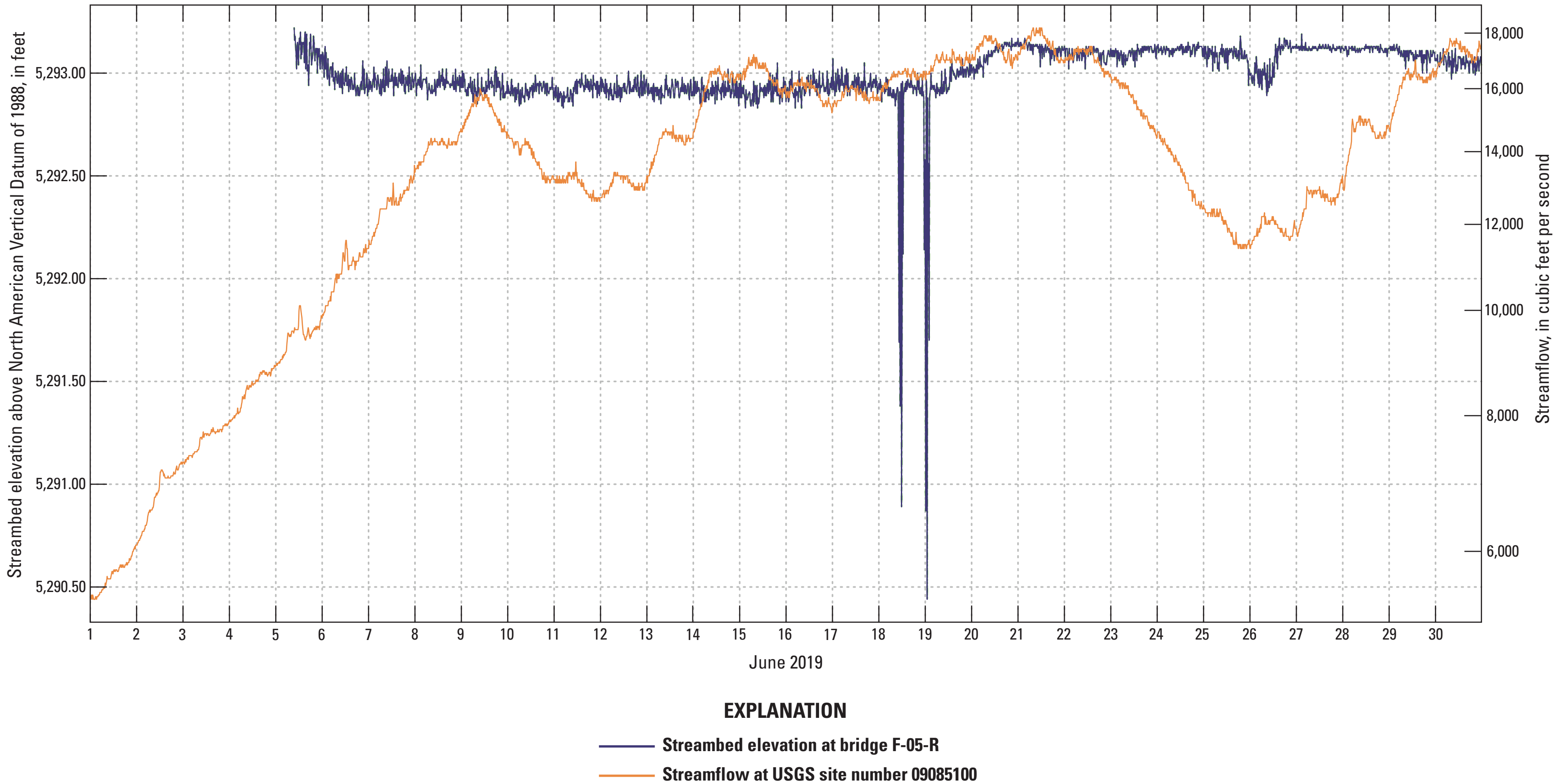



**Figure 9.** Graph showing streamflow and streambed elevation during June 2019, at U.S. Geological Survey site number 09085100 (Colorado River below Glenwood Springs, Colorado) and bridge F-05-R.

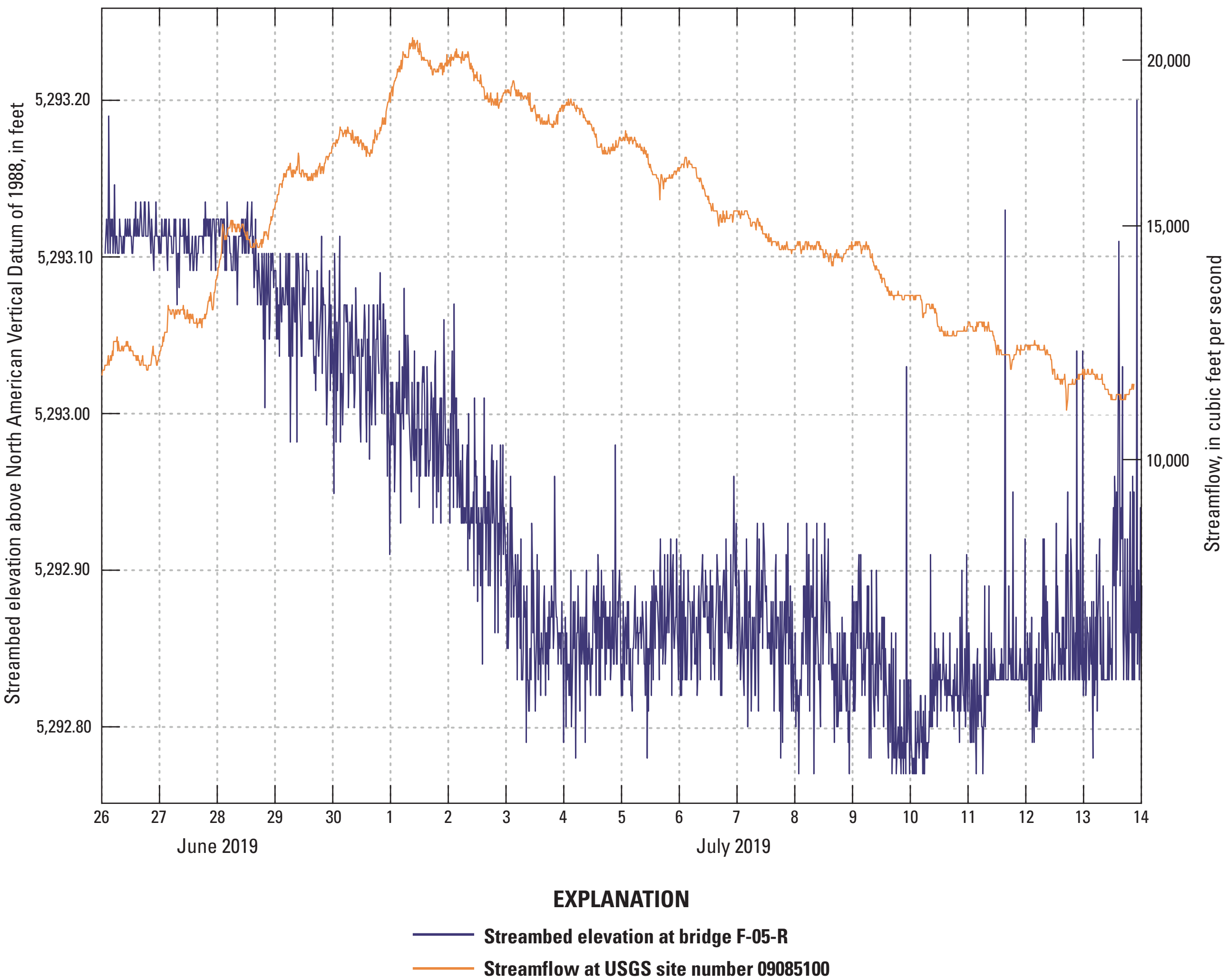


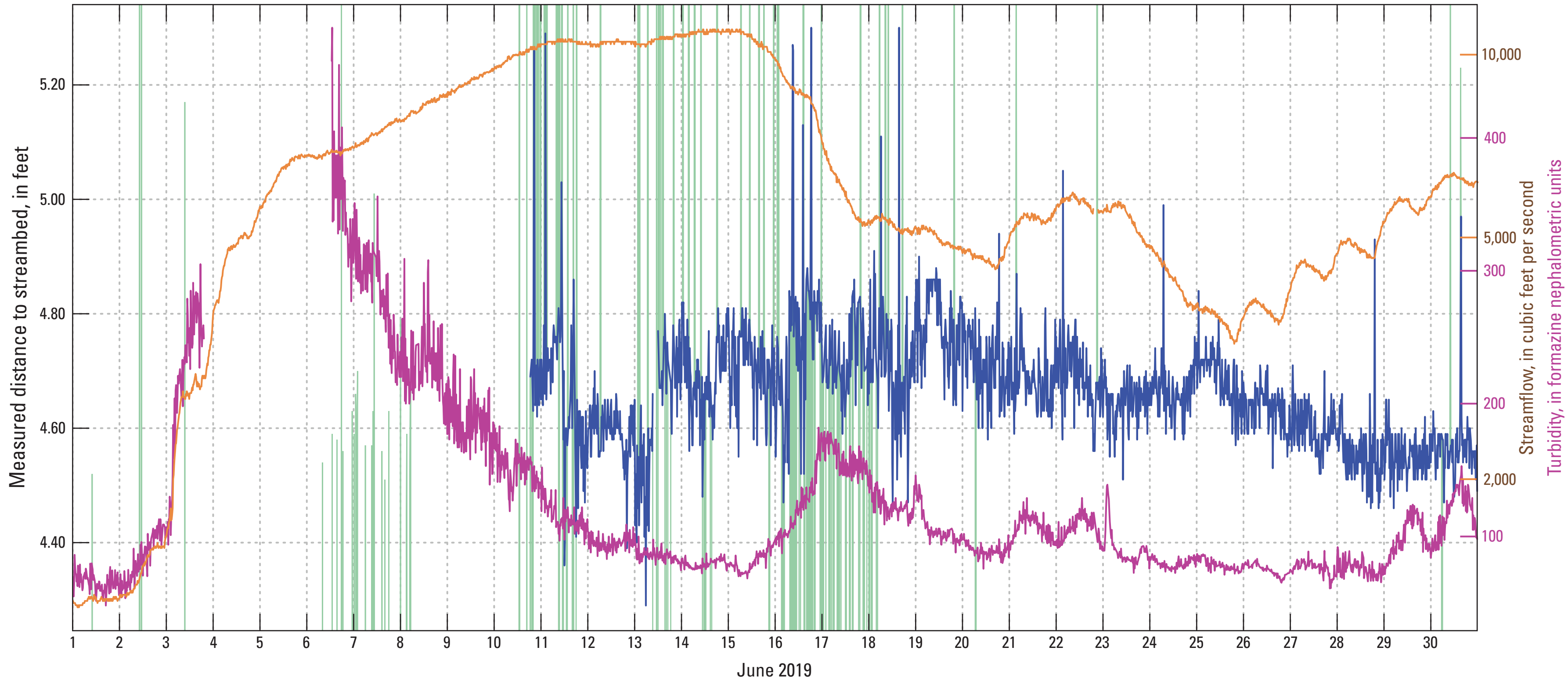

**Figure 10.** Graph showing streamflow and streambed elevation from June 26 to July 14, 2019, at U.S. Geological Survey site number 09085100 (Colorado River below Glenwood Springs, Colorado) and bridge F-05-R.

started measuring streambed data. The depth sensor began measuring valid data on June 10, when turbidity values had decreased to approximately 150 FNU and streamflow was approximately 10,500 ft$^3$/s (fig. 11). The depth sensor continued to measure streambed data until it was no longer submerged on July 13, including some brief periods of time with turbidity values exceeding 150 FNU (USGS, 2020).

Streambed elevations measured during the snowmelt runoff period ranged from 4,608.59 ft to 4,609.68 ft, a 1.09 ft maximum difference in elevation (USGS, 2020). The lowest streambed elevation values were a result of very short duration scour events. It is unclear what caused the scour events, but the values recorded by the depth sensors appear reasonable and do not appear to be erroneous. Sand channels often exhibit highly mobile streambeds, so these values were retained and may be attributed to such geomorphic processes. Measured streambed elevations gradually increased over the entire period, with a beginning elevation of approximately 4,609.20 ft and ending elevation of 4,609.44 ft. Sensor performance at P-01-G was good for most of the period, with about a week of missing and erroneous data during periods of high turbidity.

## Application Lessons and Future Deployments

The depth sensors used for this project and for previous work (Henneberg, 2018) have enabled scour monitoring in Colorado under a variety of environmental conditions. Sensor performance can be affected by both the environment in which they are installed and the conditions in which they operate. Characterizing performance under these varying environmental conditions may provide useful information regarding how the depth sensors will function in similar environmental conditions during future deployments.




**EXPLANATION**

- Measured distance from sensor to streambed at bridge P-01-G
- Erroneous measured distance from sensor to streambed at bridge P-01-G
- Streamflow at USGS site number 09371010
- Turbidity

**Figure 11.** Graph showing measured distance from sensor to streambed, erroneous measured distance from sensor to streambed, streamflow, and turbidity during June 2019, at U.S. Geological Survey site number 09371010 (San Juan River at Four Corners, Colo.) and bridge P-01-G. Because erroneous data cannot be presented in units of streambed elevation, measured distance from sensor to streambed is used here to identify the conditions and time frames when the sensor was not functioning properly.

Because of recurring issues with debris accumulation on and under sensors during previous deployments (Henneberg, 2018), the deployments at F-05-R and P-01-G were both designed to install the depth sensor above the water level during lower flows and non-runoff periods. As a result, there were no issues with debris accumulation or fouling of any kind on either of the sensors at the installations at F-05-R and P-01-G during this study. Additionally, the design of the rapid deployment mounting apparatus allows the depth sensor to be installed closer to the pier wall, with the cable conduit tight to the wall, which reduces the potential for debris to become lodged on the infrastructure. The angled installation at F-05-R also projects the acoustic footprint beyond potential debris piles submerged on the upstream nose of the pier. If debris is a recurring problem at a bridge, employing this type of installation may prove useful.

Geomorphic conditions were also different at F-05-R, P-01-G, and bridges monitored during previous studies. F-05-R is located on a cobble dominated streambed with a steep gradient at the bridge. P-01-G is located on a sand dominated streambed with a low gradient at the bridge. Because of the differing conditions, sand-sized sediment transport tends to be greater in the San Juan River at P-01-G than at F-05-R or at sites studied previously (Henneberg, 2018). Suspended material or sand-bed channels may limit monitoring locations where depth sensors can function reliably. Turbidity is often used to estimate suspended sediment concentrations through regression techniques. However, the relationship between turbidity and suspended sediment can become unreliable when the suspended sediment is dominated by sand-sized particles (Rasmussen and others, 2009). Higher turbidity values at P-01-G during rising streamflow at this site coincide with the period when the depth sensor was submerged but unable to measure valid distance-to-streambed data (fig. 11). The inability of the depth sensor to reliably measure streambed elevations during periods of increased turbidity in sand-dominated conditions may be due to (1) entrainment and movement of sand-sized particles during rising streamflow, resulting in attenuation or scatter of acoustic energy used by the depth sensor to resolve the distance to the streambed; or (2) the suspended sands and moving bedload near the streambed weakening the return signal. Acoustic attenuation increases linearly with sediment concentration and has a complex, multimodal relation with particle-size distribution (Landers and others, 2016); as such, the reliability of measurements depends on the concentration and size of particles. This installation is the first time these depth sensors have been used in a sand-channel system in Colorado. Further study using acoustic suspended sediment methods or suspended sediment sampling may identify suspended sediment conditions when these sensors will not function reliably.

Suspended sediment did not appear to be an issue at F-05-R. The hardware installation and operating conditions at F-05-R were both conducive to successful data collection during the runoff period. No erroneous or missing data were observed at F-05-R. A depth sensor installed at bridges with similar hydrologic and environmental conditions would be likely to perform well.

Both systems were successfully deployed and produced reliable data, demonstrating that both the technology and the installation methods can work in two different riverine environments. Pre-installation of mounting plates would make the installation process faster at flood-prone bridges. Having flood-prone bridges preconfigured and several RDBSMS units ready to deploy could allow for rapid-deploy bridge scour monitoring during floods such as those that occurred in 2013.

# Summary

The U.S. Geological Survey, in cooperation with the Colorado Department of Transportation, installed and operated real-time scour monitoring instrumentation at two bridges in Colorado in 2016 and 2017 to measure streambed elevations in real-time. The instrumentation included acoustic echo-sounder depth sensors mounted to the bridge substructure units with rigid conduit and fittings. Although functional, the rigid mounting configuration took several days to install at each site, which limits the instrumentation to long-term deployments at previously determined sites. To address this limitation and allow for greater flexibility in bridge selection, a rapid deployment bridge scour monitoring system (RDBSMS) was developed by the U.S. Geological Survey in cooperation with the Colorado Department of Transportation.

In 2019, RDBSMSs were installed at two bridges in Colorado, which were selected by using specific scoring criteria to rank candidate bridges and the potential for high streamflow based on accumulated snowpack. A matrix was developed to rank candidate bridges based on scoring criteria, which included depth, foundation type, average daily traffic, detour route, and scour critical condition. Colorado Department of Transportation bridges F-05-R and P-01-G were selected as the final candidate bridges for installation and testing of the RDBSMS.

Bridge F-05-R carries Colorado Highway 13 over the Colorado River near the town of Rifle, Colorado. Because of misalignment of the pier wall with respect to the river, pier number 4 was instrumented on the left side (looking downstream) to monitor scour conditions. Bridge P-01-G carries U.S. Roue 160 over the San Juan River near the Four Corners area, Colo. Because of misalignment of the pier wall with respect to the river, pier number 4 was instrumented on the right side (looking downstream) to monitor scour conditions The RDBSMSs were installed at both bridges in approximately three hours per site.

Scour conditions at both bridges were monitored during the snowmelt runoff period in 2019 using the installed RDBSMSs. Although no major scour events occurred at either structure, minor scour and fill were measured at each site, showing a successful proof of concept. Sensor performance at F-05-R was excellent, with no missing or erroneous data. Sensor performance at P-01-G was good for most of the period, with about a week of missing and erroneous data during periods of high turbidity.

Both systems were successfully deployed and produced reliable data, demonstrating that both the technology and the installation methods can work in two different riverine environments. Pre-installation of mounting plates would make the installation process faster at flood-prone bridges. Having flood-prone bridges preconfigured and several RDBSMS units ready to deploy could allow for rapid-deploy bridge scour monitoring during floods such as those that occurred in 2013.

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