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Landslide, Channel, and Road Culvert Sediment sources at Hollister Hills State Recreational Vehicle Area 2018 Report

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Executive Summary

Faculty and students at CSU Monterey Bay have been performing environmental monitoring at Hollister Hills State Recreational Vehicle Area (HHSVRA) since 2011. The overarching goal of the study has been to assess major non-point sediment sources and their potential contribution to the sediment load of Bird Creek. This report summarizes the cumulative data for the sediment processes involved with landslides, Bird Creek channel, and Cienega Road culverts up to fall 2018. As expected, the intense winter rains of 2017 produced the most significant geomorphic changes of any year of the study.

Landslides showed significant movement, with some survey pegs moving several meters, or being lost through burial beneath local mud flows. Slide-related gullies in Hudner Creek likely delivered over 3000 tonnes of sediment to Bird Creek in 2017. While the slides were active, there was great diversity in the distances moved, kinds of slope failure processes, and activity of slide-related gullies.

Bird Creek remained in steady-state equilibrium, neither aggrading nor degrading through winter 2016. In winter 2017, three of the nine cross sections showed significant sand storage in the channel and floodplain. Sand is not common in Bird Creek because of the trapping efficiency of sediment basins on most tributaries. We believe that sand came from a small landslide located approximately 90 m upstream from the measured cross sections. Future work will determine whether the sediment pulse remains stored in place through vegetation or moves farther downstream to the rest of the cross sections.

Two culverts beneath Cienega Road are chronic sources of sediment to Bird Creek. Deep ravines, gullies and landslides associated with the culverts are especially active in high rainfall years, such as 2017. Cienega Road is currently threatened by one gully head, and another is growing closer each winter with intense rains.

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1 Introduction

Resource managers of California State Vehicular Recreation Areas are working to understand the sources and fates of nonpoint-source sediment in the watersheds they occupy. Quantifying the sediment budget for even small watersheds is problematic because the sources and processes vary significantly through space and time. Hollister Hills State Vehicular Recreation Area (HHSVRA) lies mainly in the Bird Creek watershed (Fig. 1). A six-year study of sediment sources and sediment transport processes summarized the relative importance of several sediment sources in the Bird Creek watershed (Smith et al. 2016). The study included sediment sources directly caused by trail erosion as well as physical processes involving the Bird Creek stream channel, county road culverts, and upland landslides that were identified as important factors to monitor (Fig. 2; Smith et al. 2016). The current report focuses on recent surveys of those features in and near the Hudner Ranch area of HHSVRA.

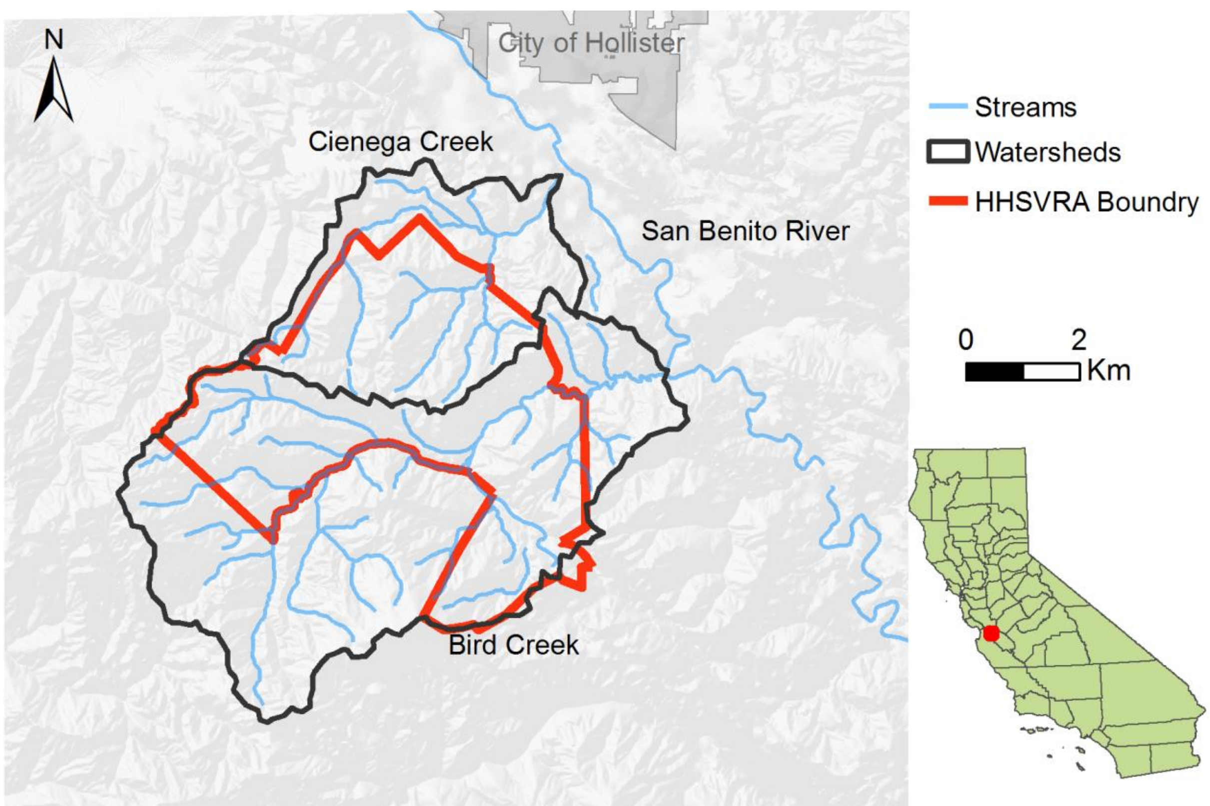

Figure 1. Hollister Hills State Vehicular Recreation Area is found northeast of Salinas in San Benito County, California.

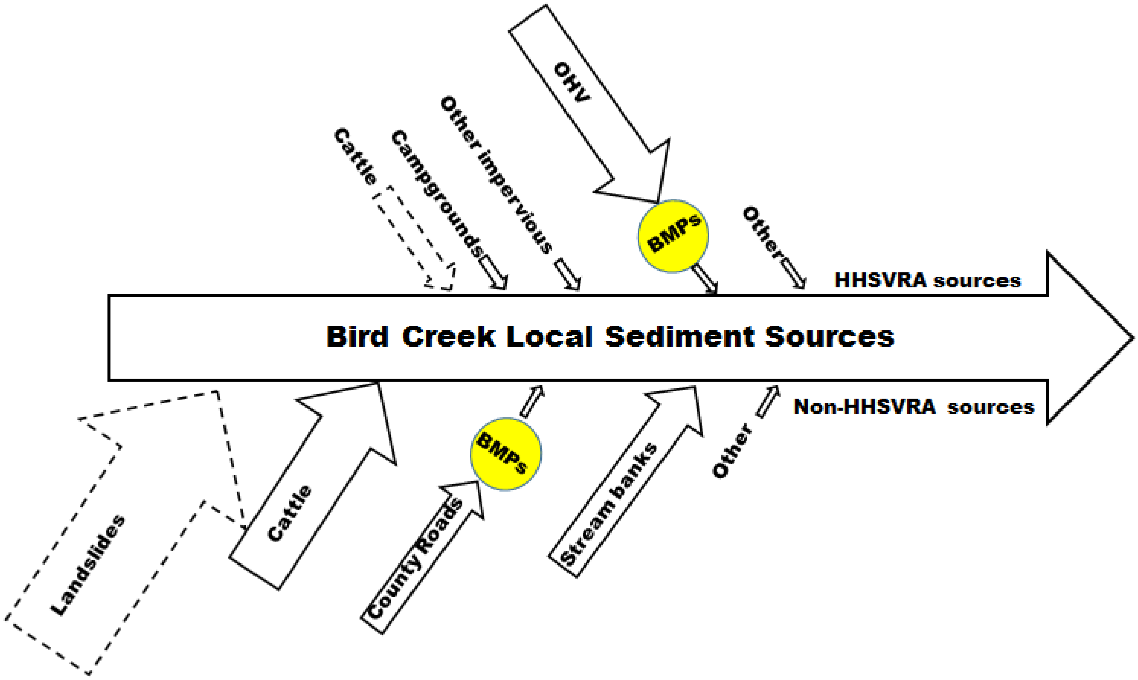

Figure 2. Bird Creek sediment sources (Smith et al. 2016). Arrows are qualitatively scaled to indicate interpreted relative volumetric importance. Upper sources are those related to State Park land. Lower sources are from other portions of the Bird Creek watershed. Dashed arrows indicate the source is unimportant in a typical year, but that might contribute either sporadically or on a longer time frame. Best management practices (BMPs) are shown to decrease the impact of those sources mainly located upstream of sediment retention basins.

1.1 Geologic Setting

The Hudner Ranch area of the HHSVRA is located northeast of the San Andreas Fault where it is underlain by fine-grained Miocene and Pliocene marine and non-marine sedimentary rocks (Fig. 3; Harden et al. 2001; Wagner et al. 2002; Graymer et al. 2006). These rocks produce clay-rich soils (NRCS 2011). The clay-rich soils and rocks abut a long reach of the San Andreas Fault where they have been shown to produce innumerable large, slow-moving landslides (Scheingross et al. 2012). Similarly, abundant landslides are also present in the Hudner Ranch area and surrounding properties (Majmundar 1994; Harden et al. 2001; Smith et al. 2016).

1.2 Landslides

Creep, landslides, and debris flows are gravity-driven colluvial processes that move rock and soil downslope (Dikau et al. 1996). Landslides can be a major source of excess sediment in rivers if they are hydraulically connected to a river channel (Davies and Korup 2006). Smith et al. (2016) summarized the importance of landslides in the overall sediment budget within the study area and described the multistep process responsible for delivering sediment to Bird Creek from two large landslide complexes (Colluvial Creek and Hudner Landslide) in Hudner Ranch. These landslide complexes are the focus of the current report.

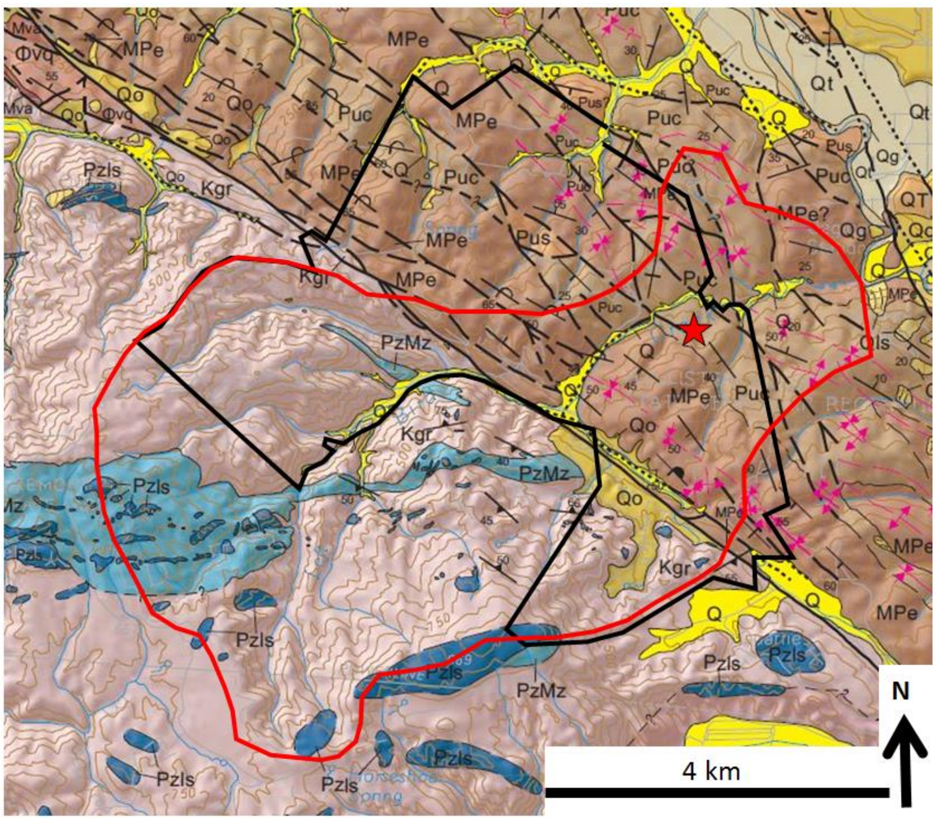

Figure 3. Geologic units within the HHSVRA boundary (black polygon) and Bird Creek watershed (red polygon). Units include Paleozoic limestone (Pzls) and marble (PzMz), Cretaceous granite (Kg), Miocene/Pliocene shallow marine sandstone (MPe), Pliocene continental sandstone (Pus) and mudstone (Puc), and various Quaternary alluvial deposits (Qx) (Wagner et al. 2002). Major northwest trending fault is the San Andreas Fault system. Red star is Hudner Ranch area of HHSVRA.

In general, slope failure changes the local gradient of the valley in which it occurs, and gully systems develop that move sediment from the toe of a slide to Bird Creek during periods of heavy rain (Smith et al. 2016). That is the general case in the Colluvial Creek slide system (Fig. 4). In the Hudner Creek slide system (Fig. 5), the slide body intersects a small tributary to Bird Creek (Hudner Creek). The slide body dammed Hudner Creek, which ponded water and forced sediment to aggrade behind the slide body. A gully has cut a ravine through the slide body and is harvesting the trapped wetland sediment.

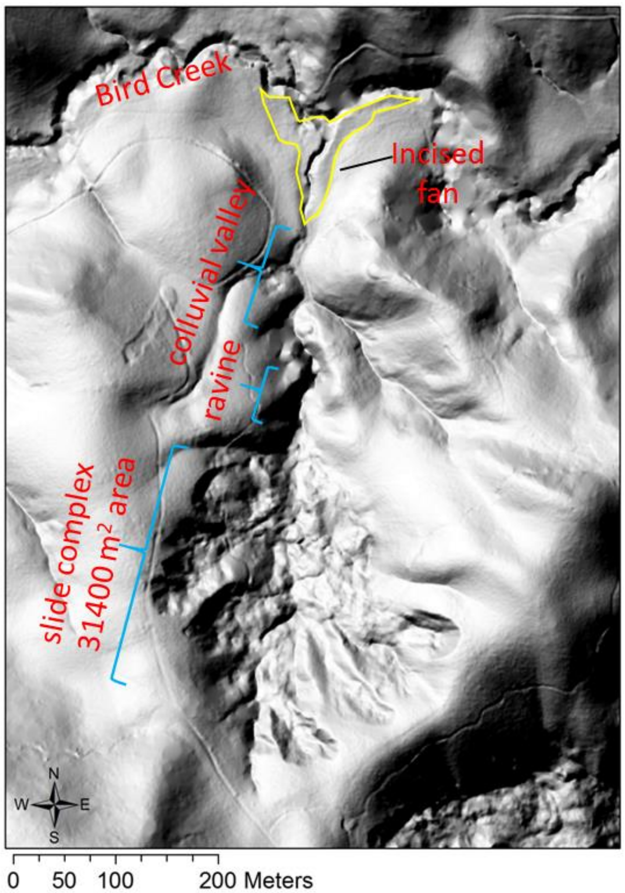

Figure 4. Key geomorphic elements of the Colluvial Creek landslide system. Background is hillshade from 2011 LiDAR-based DEM (1 m/pixel).

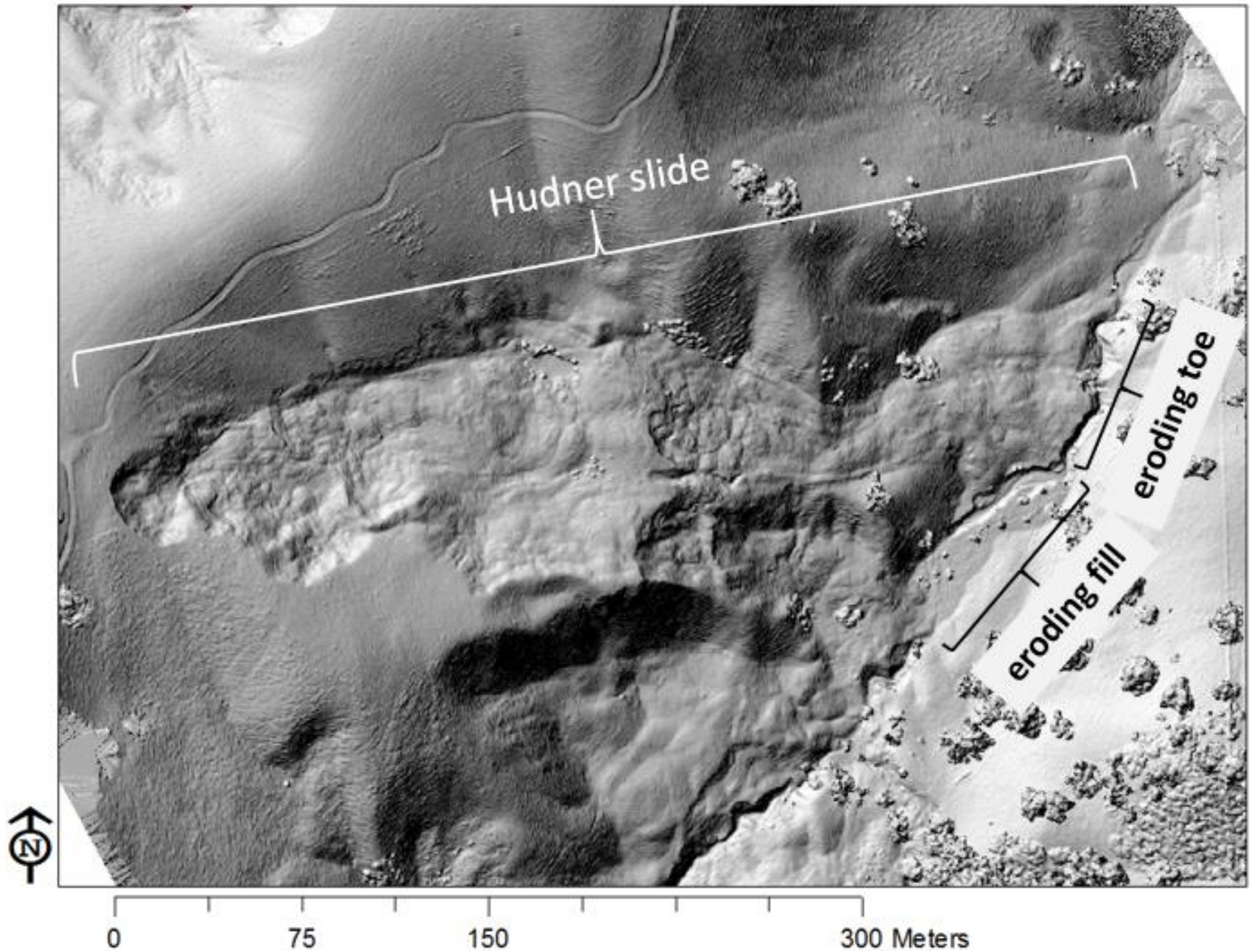

Figure 5. Key geomorphic elements of the Hudner landslide system plotted on hillshade of 4 cm/pixel DSM derived from May 2018 photogrammetry.

Figure 6. Oblique photo showing field relations between slide elements and valley sediment transport system.

1.3 Bird Creek Cross Sections

Stream channels and their adjacent floodplains can be net sources or sinks for sediment. Streams in steady-state equilibrium with watershed conditions tend to transport supplied sediment without net storage or degradation. Annual stream cross section surveys can reveal changes in watershed conditions. Changes in sediment supply can produce degradation, aggradation or avulsion. A series of cross sections have been monitored in the Hudner Ranch reach of Bird Creek since 2011 because the reach receives virtually all runoff generated from the HHSVRA. Additionally, given relatively high flows, the site has the potential to experience the highest bank erosion rates in the park. Furthermore, the channel should be the most responsive to watershed conditions, by exhibiting aggradation in the context of excess bedload, or incision because of excess runoff. This report analyzes the annual cross section changes that have occurred between 2011 and 2018.

1.4 Cienega Road Culverts

Roads that cross small creeks and minor waterways are commonly protected from erosion by culverts that allow stormwater runoff to pass beneath the road bed (CDOT 2014). Culverts focus water energy by confining flow, like water leaving a hose, commonly exacerbating erosion downstream (Nyssen et al. 2002). Armoring and energy dissipators are typically installed to prevent erosion (CDOT 2014), but ineffective measures can allow significant erosion and sediment transport to occur.

Cienega Road crosses the clay-rich soils northeast of the San Andreas Fault where it crosses from Cienega Creek watershed to Bird Creek watershed. A study of road drainage in this region indicates that poorly engineered culverts and drainage should be monitored as potential nonpoint-sources of sediment in Bird Creek (Smith et al. 2016).

1.5 Precipitation

Rain and storm runoff are the driving forces for geomorphic change on slopes and in streams. The average and median rainfall during seven years of monitoring were 14.11 and 10.75 inches, respectively (Table 1; Fig. 7). The rainfall has ranged from severe drought in 2013 and 2014 to extremely wet in 2017, in keeping with regional conditions in central coastal California.

Table 1. Hollister Hills SVRA precipitation data obtained from Western Weather Group (2018).

Water Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	**Total**
2011	0.89	2.29	4.15	1.81	4.07	4.57	0.20	1.11	0.37	0.00	0.00	0.00	**19.46**
2012	0.83	1.96	0.11	2.28	0.62	2.62	2.18	0.03	0.06	0.03	0.00	0.00	**10.72**
2013	0.27	2.54	4.35	0.98	0.75	0.60	0.21	0.00	0.00	0.00	0.00	0.08	**9.78**
2014	0.11	0.28	0.34	0.20	2.72	1.56	0.76	0.00	0.00	0.00	0.00	0.08	**6.05**
2015	1.05	0.51	5.23	0.00	1.26	0.17	1.14	1.24	0.00	0.02	0.06	0.08	**10.76**
2016	0.18	3.42	2.97	5.67	0.88	5.23	0.87	0.08	0.00	0.00	0.00	0.00	**19.30**
2017	2.76	1.53	2.20	9.70	6.27	1.91	1.55	0.06	0.06	0.00	0.00	0.05	**26.09**
2018	0.23	1.43	0.29	2.48	0.27	4.62	1.43	0.00	0.00	0.00	0.00	0.00	**10.75**
Monthly Average	**0.79**	**1.75**	**2.46**	**2.89**	**2.11**	**2.66**	**1.04**	**0.32**	**0.06**	**0.01**	**0.01**	**0.04**	

Annual Average **14.11**

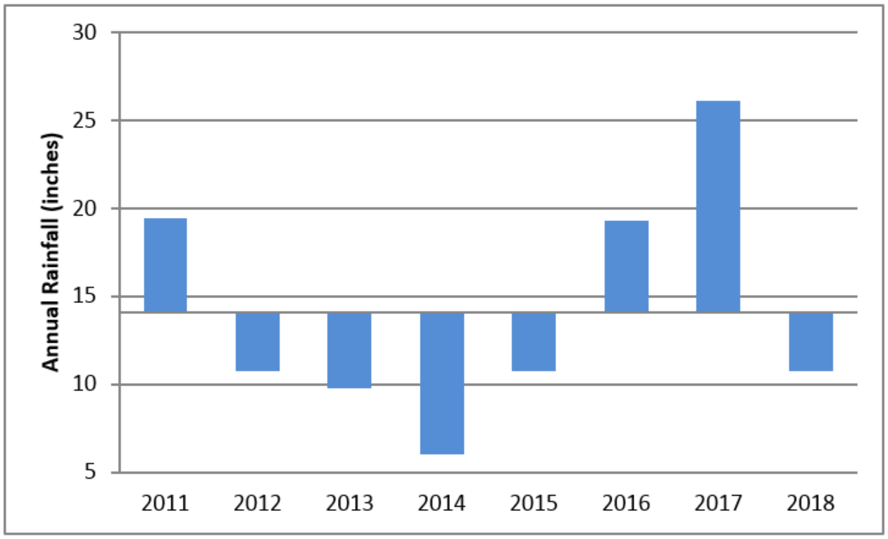

Figure 7: Annual precipitation at Hollister Hills SVRA. Values shown with respect to the mean value of 14.11 inches.

1.6 Goals

The overarching aim of our long-term study is to understand spatial and temporal patterns in sediment production and transport in the Bird Creek watershed (Fig. 2; Smith et al. 2016). The current report adds new survey data to more accurately quantify landslide process rates, Bird Creek sediment processing, and gully erosion along Cienega Road.

2 Methods

Figure 8 shows the general locations of the current surveys.

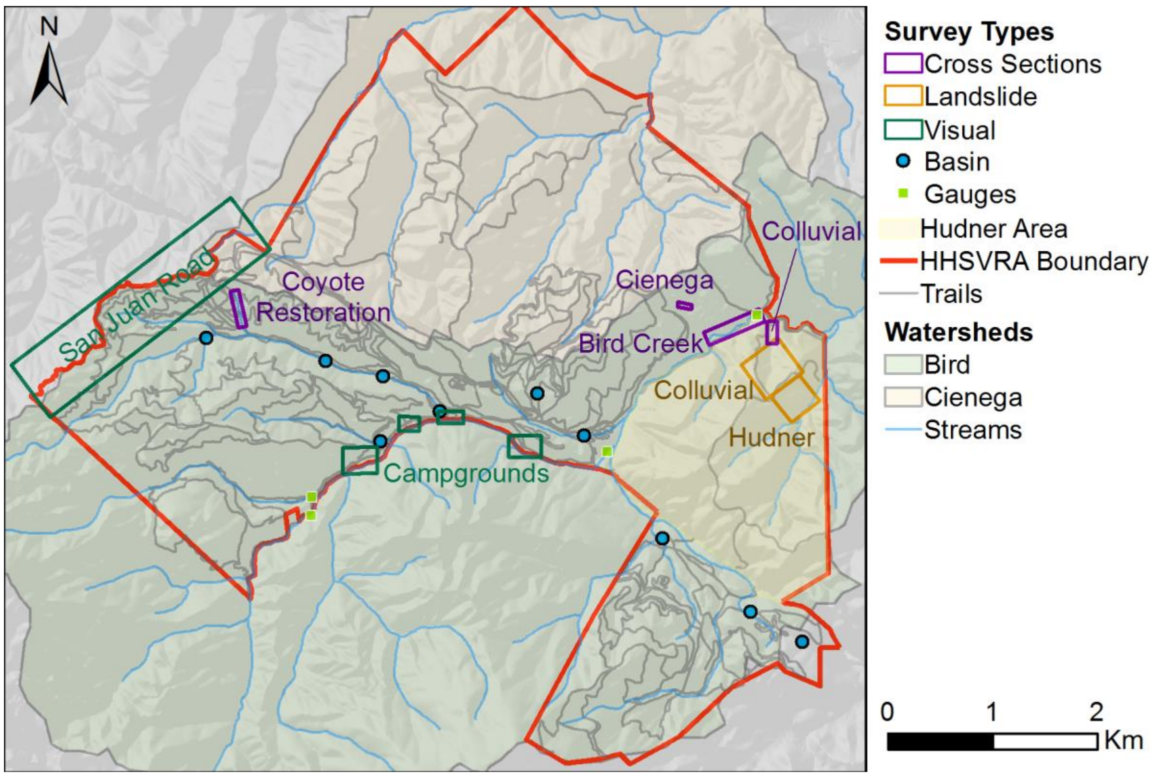

Figure 8. Spatial distribution of all HHSVRA monitoring sites and study types. Current study focuses on landslides at Colluvial and Hudner cross sections along Bird Creek, and culverts along Cienega Road.

2.1 Landslides and Colluvial Processes

Five landslides in Colluvial Creek, and one complex landslide in Hudner Creek watershed (Figs. 4 and 5) were monitored for movement by resurveying a series of iron rods driven into the slide bodies. In the Colluvial Creek slides, four pegs were placed in a line across the heads of several landslides in 2012, whereas six rows of iron rods were placed across the Hudner slide at various locations along the length of the slide body in 2016. Rods were also placed outside the slide body to estimate the creep rates of hillslopes not directly on a landslide. Landslide movement was monitored with repeated RTK GPS surveys to measure the 3-D change of rod position in each slide. Both landslide complexes were also surveyed using small unmanned aerial system (sUAS) photogrammetry in 2018. Slide motion and subsequent sediment transport from gully activity (e.g., Fig. 6) were assessed in each slide. Other colluvial processes located elsewhere in the park are qualitatively described in this report.

2.2 Channel Cross Sections

Nine benchmarked cross sections have been surveyed at least annually between 2011 and 2018 using the methods of Harrelson et al. (1994; Fig. 9). The cross sections were analyzed for aggradation, degradation and bank erosion. Since grain size is an indicator of watershed conditions, Wolman pebble counts (Harrelson et al. 1994) were analyzed at each cross section to assess changes in grain size through time. Gravel-sized particles are present in Bird Creek unless there has been an influx of fine material generated by local cattle impacts (Smith et al. 2016), bank erosion, or other sources.

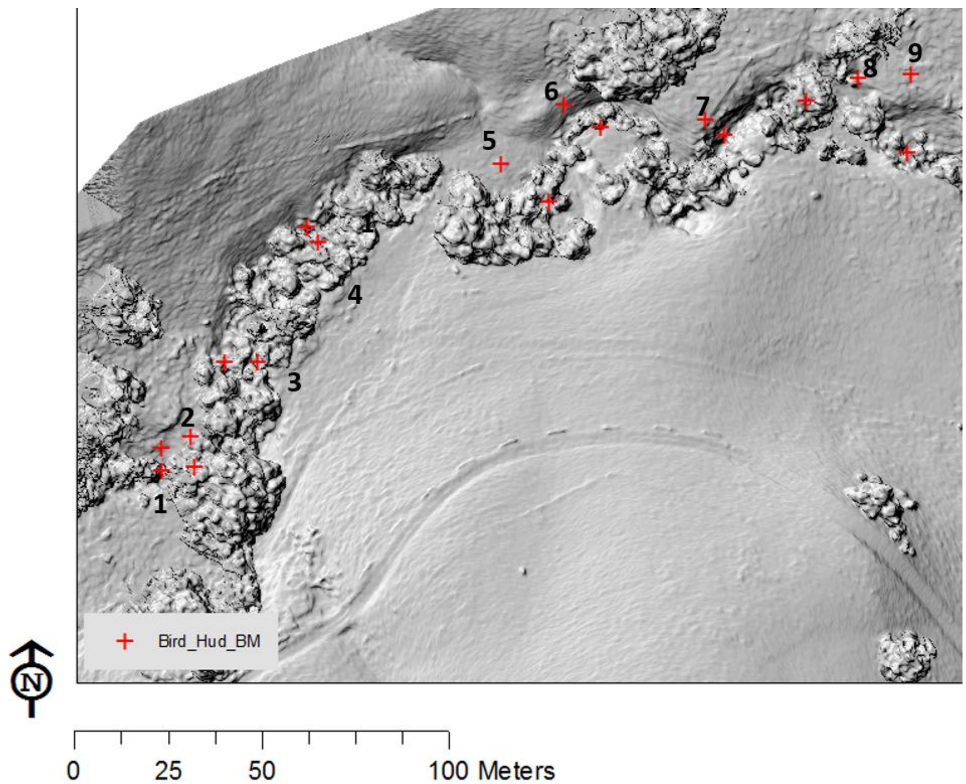

Figure 9. Nine benchmarked cross sections on Bird Creek resurveyed annually to assess channel and bank processes. Map background is hillshade of a 5 cm/pixel DSM derived from May 2018 photogrammetry.

2.3 County Road Culverts

The Cienega Road culverts (Fig. 8) and associated gullies were visually inspected and photographed using low altitude photogrammetry. Erosional features of 103 acres of HHSVRA land along Cienega Road were captured by photogrammetry from 514 overlapping photographs shot at 80 m altitude using a 4K camera mounted on a Phantom 4 sUAS. Photos had 80% forward overlap and 70% side overlap Eight ground control points (GCPs) were used to georeference the data during processing. GCPs were surveyed using RTK GPS corrected in OPUS. Photogrammetry was processed using Pix4D software and analyzed in ESRI ArcMap. The 3D GCP location root mean square error was 14 mm. The resulting DSM and orthophoto have 29 mm pixels for fine resolution of surface features (Fig. 22). Additional data include oblique sUAS aerial views of the landscape and ground-based photography.

3 Results

3.1 Landslides and Colluvial Processes

Two landslide complexes have been monitored in detail to determine on what time scale, and through what processes, they contribute sediment to Bird Creek.

3.1.1 Colluvial Creek Slide

The Colluvial Creek slide complex includes several individual slump features, a colluvial and alluvial system that historically transported sediment to a sediment fan, and a gully that has incised the fan (Fig. 4). Five of the slumps were monitored for motion since January 2012 (Fig. 10, Table 2). Slide 1 shows the typical movement history where only a few centimeters of motion occurred in any given year until the heavy rains of 2017. In 2017 slide 1 moved 50 cm. The slide again slowed during a more typical rain year in 2018 (Fig. 11; Table 2). Slide 3 moved over 5 m in 2017, which was the largest displacement measured in the Colluvial Creek slide system (Fig. 12; Table 2). Like the other slides, slide 3 returned to a few centimeters of movement in 2018 (Fig. 12). The intense rains of 2017 triggered movement on all the slides monitored in the Colluvial Creek system (Fig. 13).

Table 2. Three-dimensional slip magnitude of five landslides in the Colluvial Creek slide complex. Differences in slide peg position measured from 2016 to 2018. Blank spaces are years when specific slides were not measured.

Colluvial Creek Slide Average Slide Movement Since 2012 (m)

slide	Apr-12	Oct-12	Oct-13	Jul-16	Oct-17	Nov-18
1	0.01	0.10	0.19	0.31	0.80	0.89
2	0.02	0.11	0.30	0.56	0.93	1.00
3	0.20	0.24		0.53	5.90	5.95
4	0.05		0.17	0.33	0.52	0.61
5	0.01		0.27	0.57	0.92	1.01

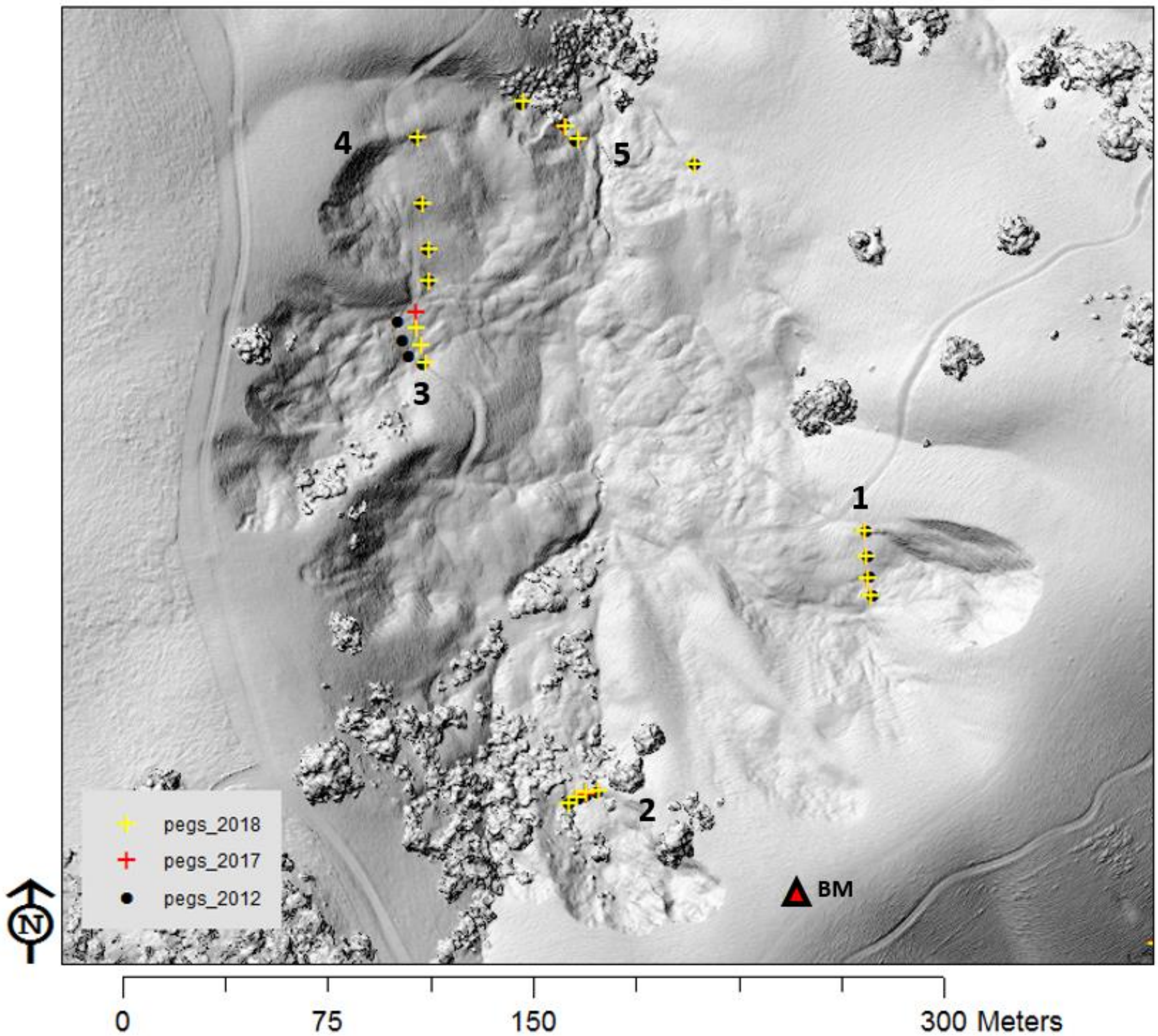

Figure 10. Twenty iron rods installed in the Colluvial Creek Slide in 2012 (black dots) were resurveyed six times. The initial positions, 2017 (red cross) and 2018 (Yellow cross) positions are plotted. Pegs are in clusters of four in each slide area. Background is hillshade from 5/2/2018 low altitude photogrammetry.

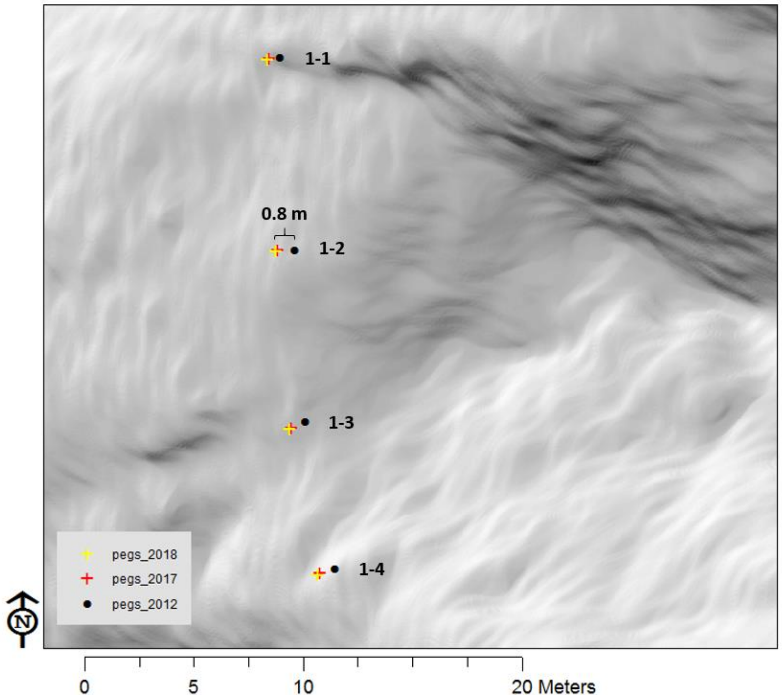

Figure 11. Close view of pegs in head of Colluvial Creek Slide number 1 (Fig. 10 for context). Background is hillshade from 5/2/2018 low altitude photogrammetry.

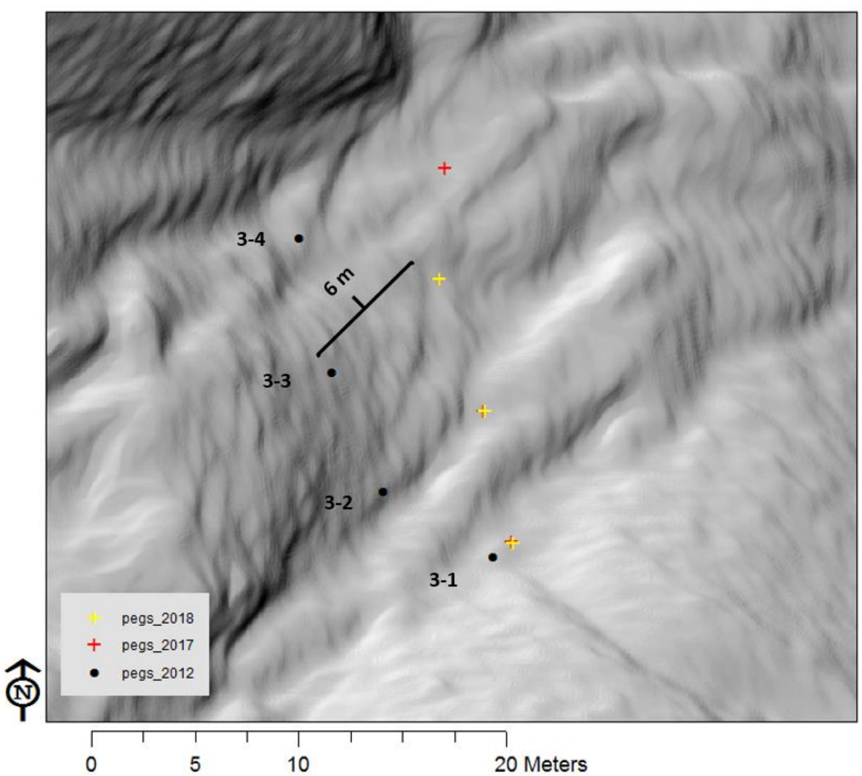

Figure 12. Close view of pegs in head of Colluvial Creek Slide number 3 (Fig. 10 for context). Background is hillshade from 5/2/2018 low altitude photogrammetry.

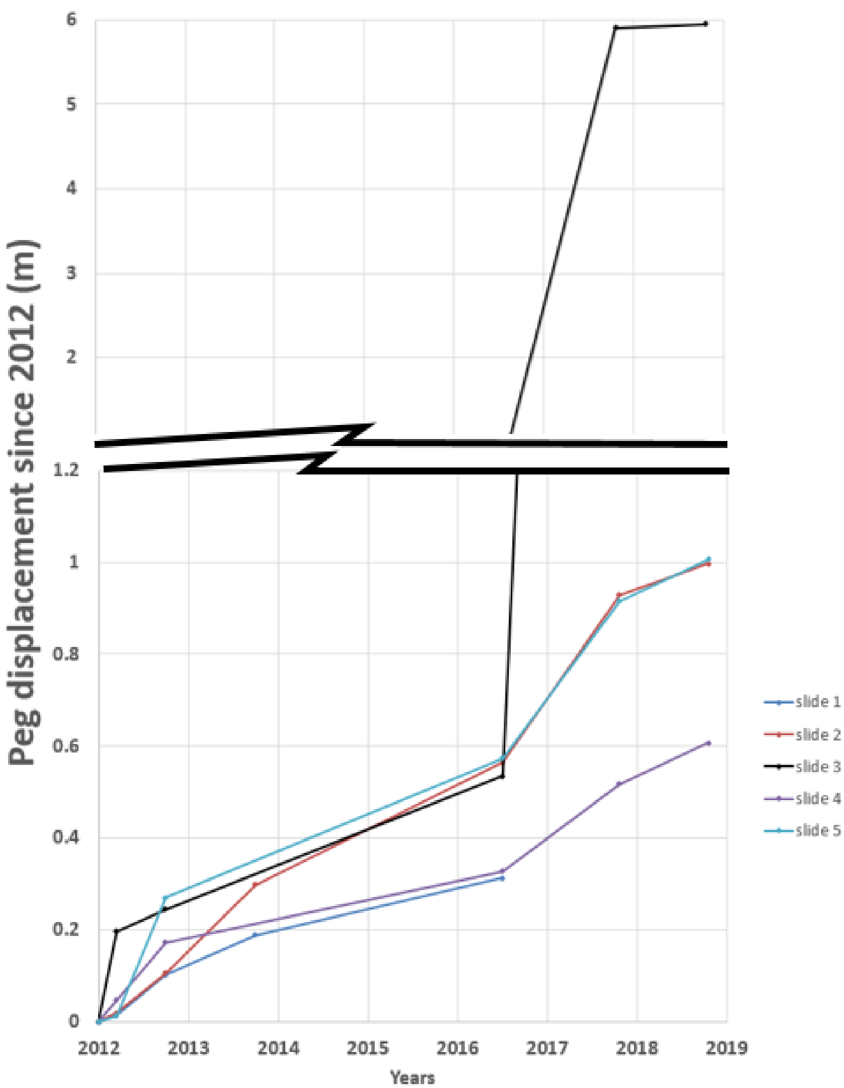

Figure 13. Slide displacement history of Colluvial Creek Slide. Note scale change to accommodate large displacement of Slide 3 in winter 2017.

The individual slides of Colluvial Creek coalesce into a single slide body that fills the axis of the Colluvial Creek valley (Fig. 10). Active gullies erode the slide body and move sediment toward Bird Creek. Two gullies are visible in Figure 10. One is located directly west of the number 5 in Figure 10; the other is a similar feature located 100 m up-valley (south). Recently eroded banks and fresh knickpoints in the gully bottoms indicate the gullies have been recently active. However, visual inspection and repeat benchmarked cross sections of the valley downstream of the gullies (Fig. 14) have not produced evidence of active transport or storage of new material in the valley segment between the gullies and Bird Creek since 2012 (Fig. 15). Evidence of minor erosion in the gully incising the sediment fan show that the gully occasionally transports water, but geomorphic changes have typically been smaller than between-survey precision on cross sections (Fig. 15). Cross section 4 was positioned only a few centimeters up-valley of the gully head shown in Figure 14 in 2012 but has not captured any topographic incision (Fig. 15). The cross section would have captured active head cutting if the gully had extended just a few centimeters.

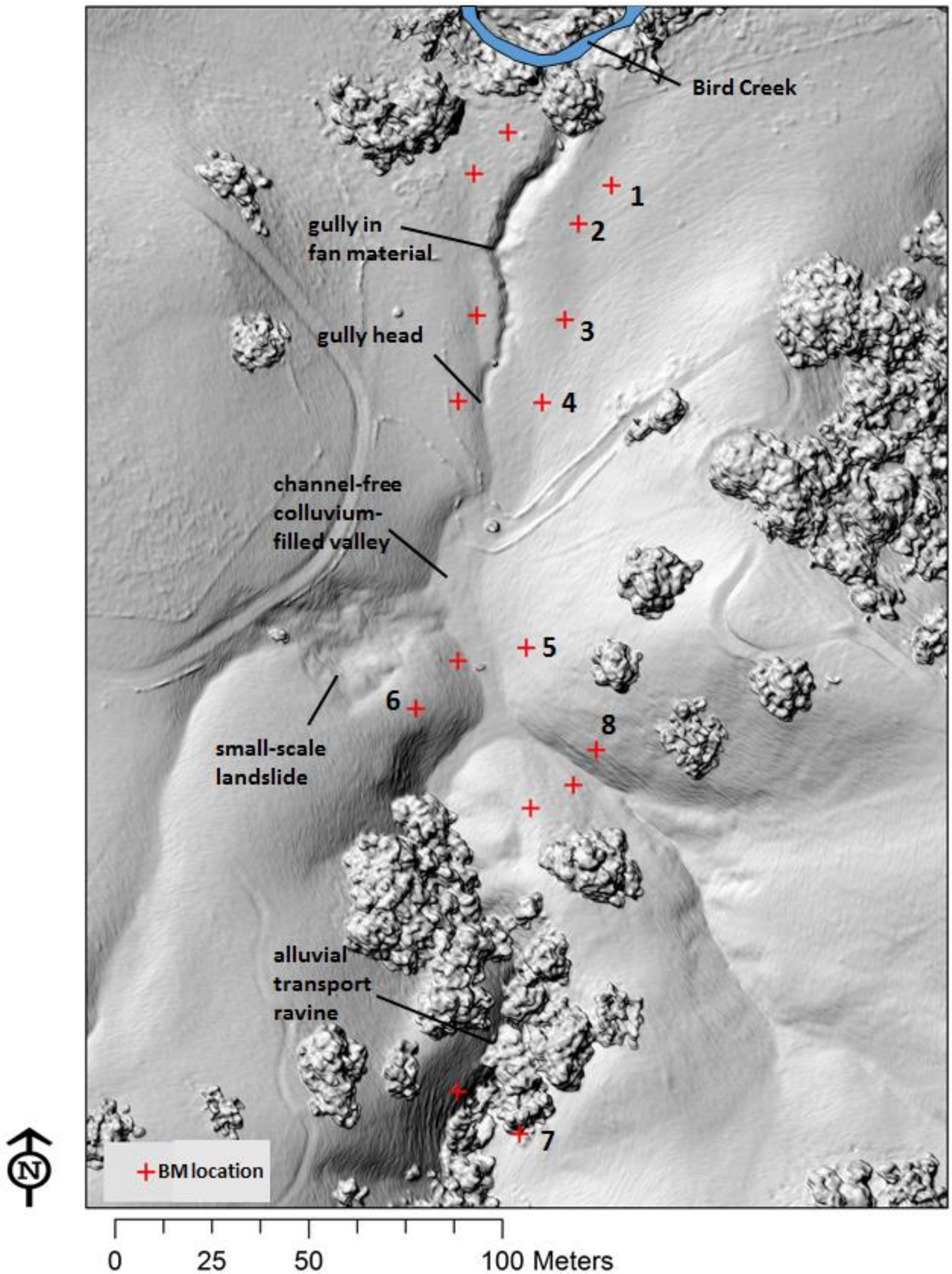

Figure 14. Benchmark locations for Colluvial Creek cross sections shown in Figure 15. Background is hillshade from 5/2/2018 low-attitude photogrammetry.

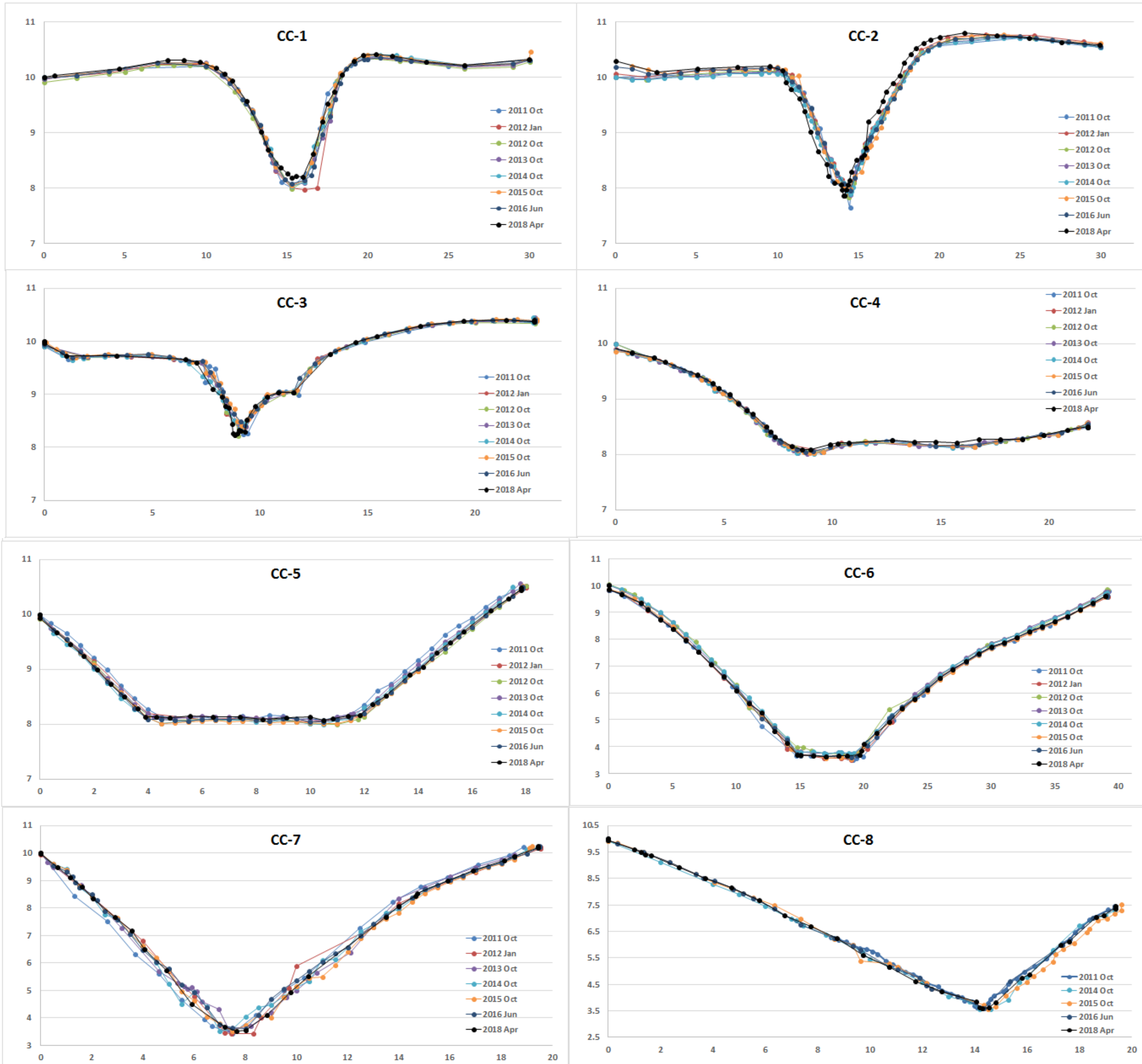

Figure 15. Time-series cross sections of Colluvial Creek. Horizontal axes are distance (m) from left benchmark. Vertical axes are elevation in meters relative to 10 m assigned to left benchmark. See Figure 14 for locations.

3.1.2 Hudner Slide

The Hudner Creek Valley contains numerous large landslides that terminate in the valley axis. One example is the "Hudner Slide" we have monitored since 2016. It is a large complex slide with a variety of processes including coherent slumping and earth flow. Like the Colluvial Slide system, small gullies erode the slide body, locally transporting sediment in flowing water. The slide toe blocked the valley axis, and a large gully has since cut up-valley through the slide toe, trapping sediment (Figs. 5 and 6). Twenty pegs placed in rows in the slide captured slide motion between 2016 and 2018 (Table 3; Fig. 16).

Table 3: Three-dimensional slip vector magnitudes of the Hudner Slide pegs measured from 2016 to 2018. "Average Slide" includes the pegs in the Hudner slide body; "Average Control" includes the pegs located in more stable ground outside the slide body (grey cells). Peg 4-1 was located in a tributary slide, adjacent to the main slide. See Figure 16 for peg locations. Blank entries indicate pegs that were present in 2016 that were likely buried beyond the reach of a metal detector in 2018.

Hudner Slide Peg Movement (m)

	Peg	3D
	0-2	
	1-1	0.65
	1-3	2.74
	1-4	
	1-5	6.76
	1-6	0.03
	2-1	
	2-2	3.79
	2-3	0.33
	3-1	
	3-2	0.90
	3-3	1.34
	3-4	0.04
	4-1	0.39
	4-2	0.79
	4-3	0.88
	4-4	0.17
	5-2	2.64
	5-3	0.35
	5-4	0.05
Average Slide		1.77
Average Control		0.08

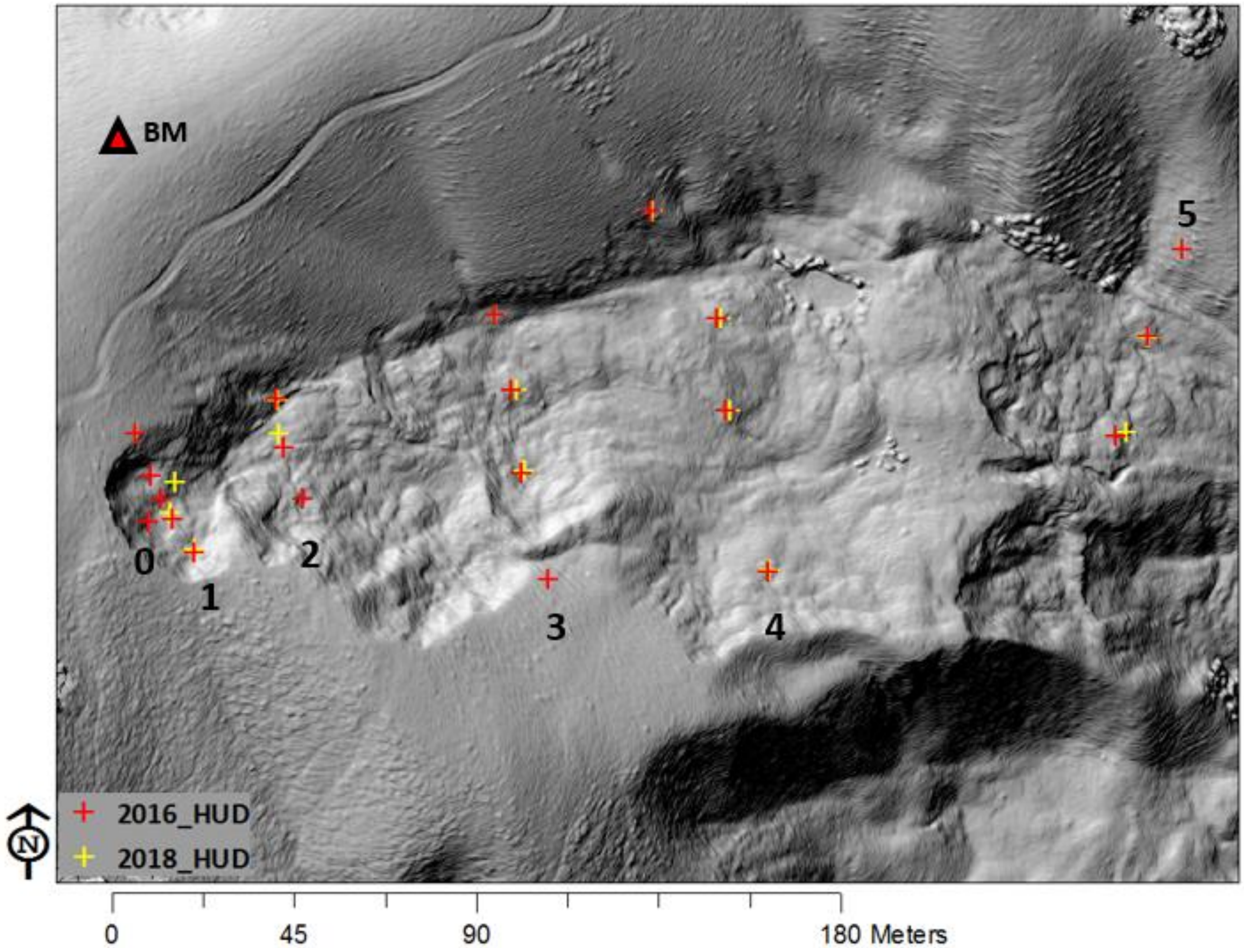

Figure 16. Twenty iron rods installed in the Hudner Slide in 2016 (red crosses) were resurveyed in 2018 (yellow crosses). Pegs are arranged in rows 0 through 5. Pegs are numbered sequentially from south to north in each row. Background is hillshade from 5/2/2018 low-altitude photogrammetry.

Figure 17 shows the expected behavior of a line of pegs when a coherent slide body has moved downslope; more movement occurs in the main slide body (pegs 3-2 and 3-3) than on adjacent hillslopes (pegs 3-1, 3-4). Movement on the adjacent hillslopes can be attributed to typical background colluvial processes. Movement beyond that rate in the slide body is attributable to motion of the slide.

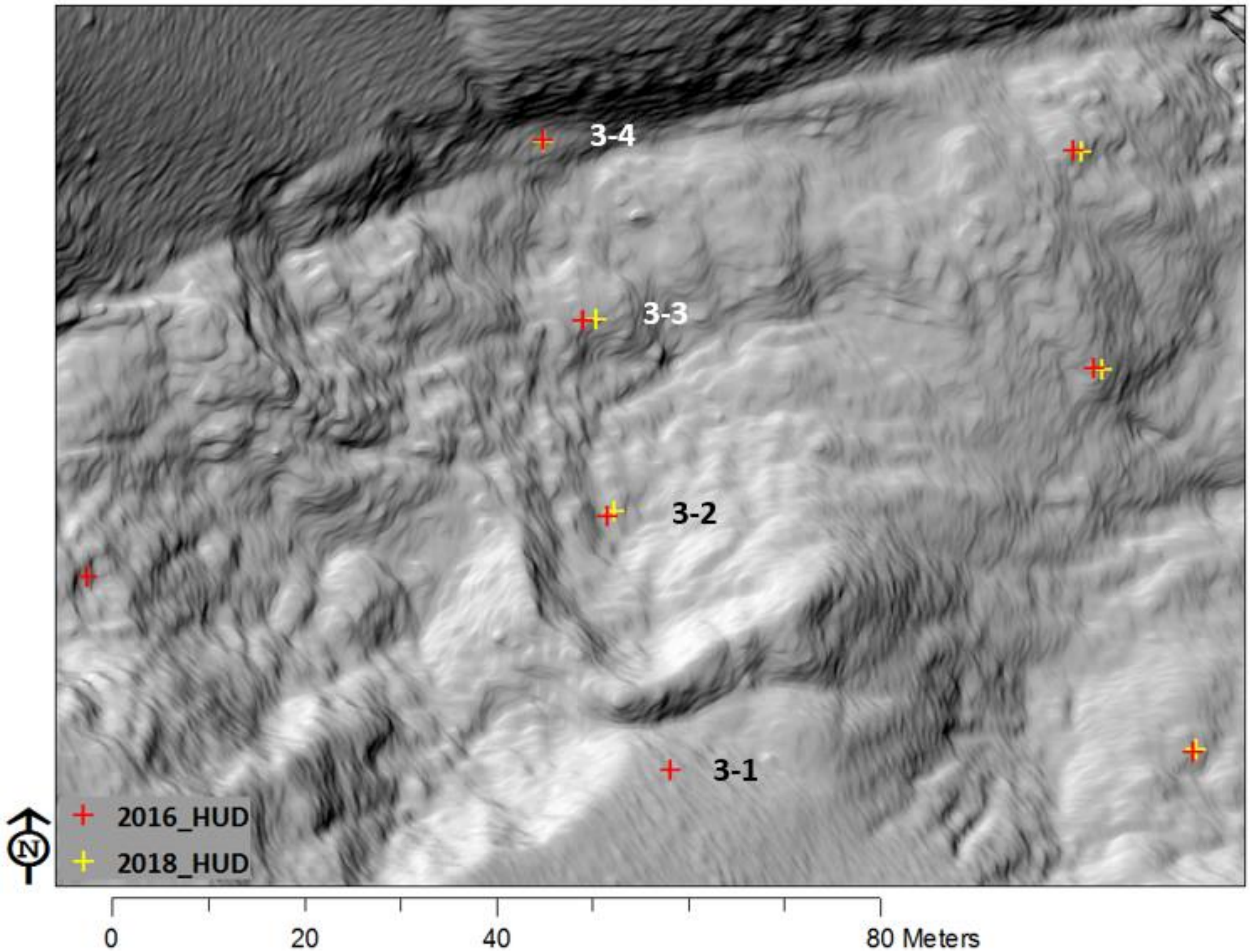

Figure 17. Third row of pegs in Hudner Slide installed in 2016 (red crosses) were resurveyed in 2018 (yellow crosses). Peg 3-1 was missing in 2018. Locations in Figure 16. Background is hillshade from 5/2/2018 low altitude photogrammetry.

The slide pegs placed in the hillslope adjacent to the slide (e.g., 3-1 and 3-4) are considered “experimental controls” in that they approximate expected motion of the ground if a landslide event were not triggered. Slide pegs moved an average of 1.77 m, in excess of the control pegs which moved just 0.08 m on average (Table 3). Peg motion in rows 3 and 4 are compatible with downslope motion of a single coherent slide body (Figs. 16 and 17). However, other peg movement indicates that slide motion was highly variable through space (Table 3; Fig. 16), leaving the average slide motion value less indicative of true overall sediment transport rates in landslide processes. The highly variable peg movement, including significant lateral (rather than directly downslope motion) indicates that the slide locally moved as an incoherent earthflow rather than as a coherent slide.

Visual observations indicate recent gully activity within the slide body. For example, a gully is visible as a crease in the hillshade directly southwest of the southern peg of row 5 (Fig. 16). Such gullying is an efficient way to transport slide material farther downslope toward Bird Creek via Hudner Creek.

More frequent measurements in the Colluvial Slide system show that intense rain in winter 2017 drove most of the motion between 2016 and 2018. The same is likely true of the Hudner Slide as well.

The multiphase sediment transport process active in Hudner Slide includes gullying that liberates slide-related sediment from the slide toe and sediment trapped upstream of the slide toe (Smith et al. 2016; Figs. 6 and 18). Sediment released to Bird Creek through this gully system alone during the winter of 2017 is estimated at approximately 1100 m^3 (1460 yd^3), based upon 55 m of headward gully growth and a typical cross-sectional area of 20 m^2 (Fig. 19). That volume represents approximately 2950 tonne (2900 ton) assuming an alluvium density of 2590 kg/m^3, which is the value calculated for sediment deposited in an "alluvial meadow" (Dumikh 2014). The volume and mass reported here are minimum contributions of sediment to Bird Creek from Hudner Creek because there are similar active gully systems located farther up the Hudner Creek valley.

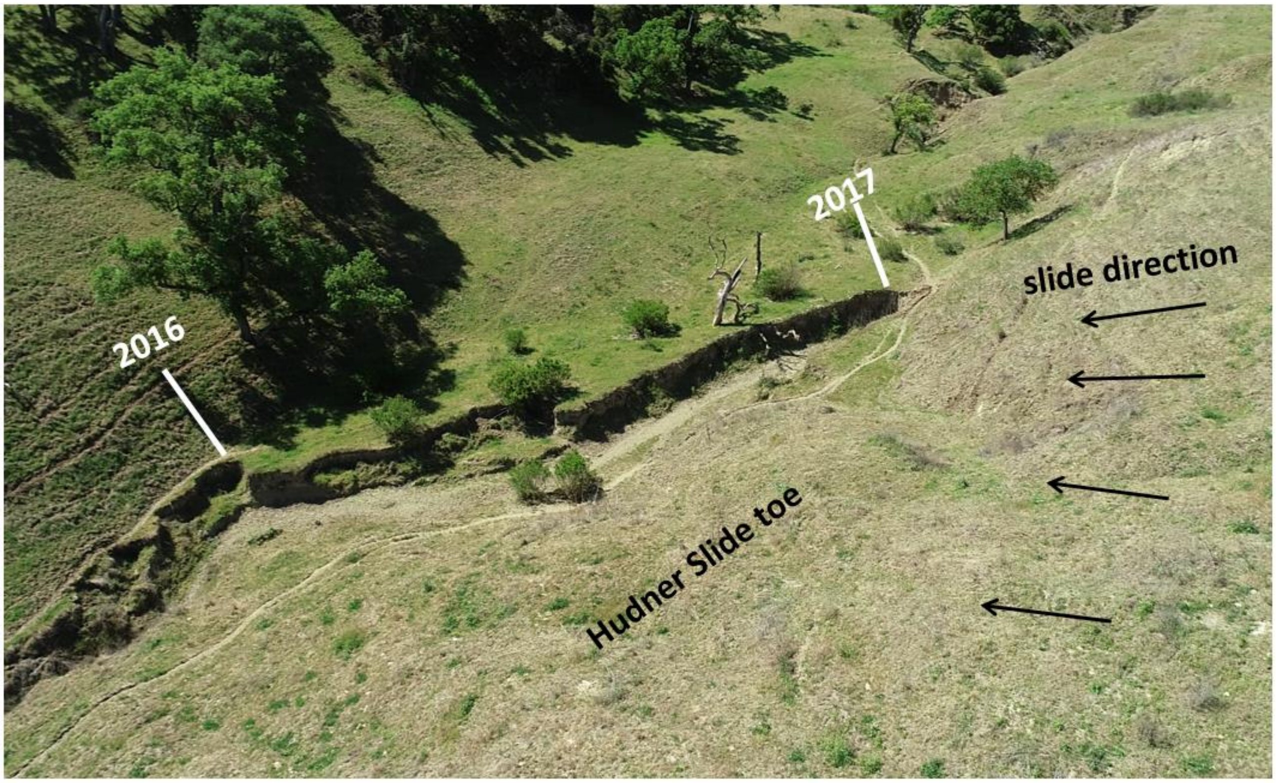

Figure 18. Low-altitude oblique aerial photograph (5/2/18) of Hudner Creek gully incising toe and trapped alluvium at base of Hudner Slide. Dates are locations of gully head in 2016 and 2017.

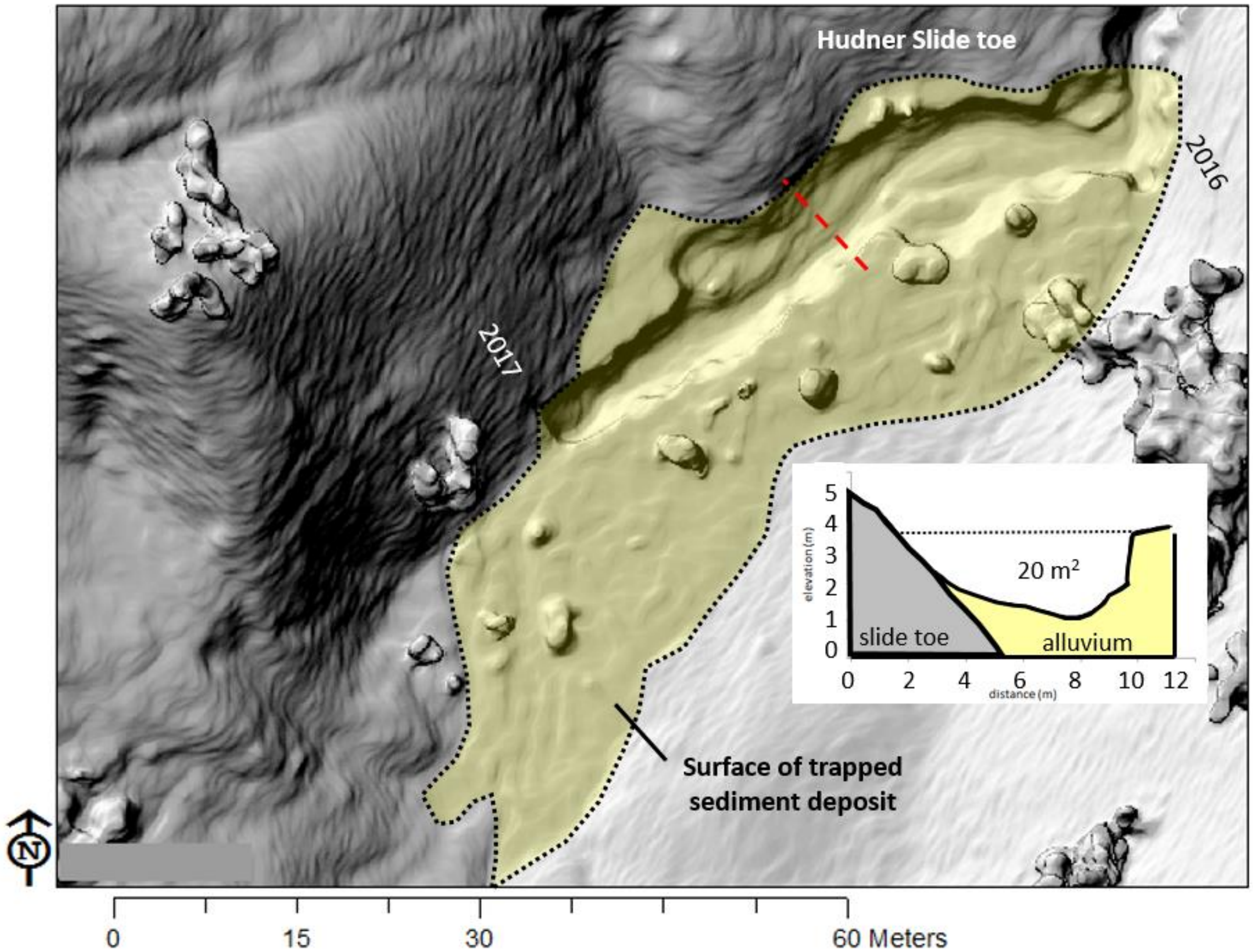

Figure 19. Hillshade shows gully at toe of Hudner Slide (5/2/18). Red dashed line is position of cross section inset. Cross section dimensions in meters. Dates are locations of gully head in 2016 and 2017.

3.1.3 Other Slope Failure Features

In concert with the Colluvial and Hudner slides, intense rains of 2017 triggered colluvial processes throughout the region. We noted a moderate slump generated by bank erosion in Bird Creek with an estimated volume of 300 m^3 (614 yd^3; Fig. 20). Using a common density for colluvium (1500 kg/m^3) the slide liberated 450 tonne (408 ton) of mud and sand. Unlike the larger monitored slides described above, this slide delivered all material directly to the Bird Creek channel.

Figure 20: Slide feature that delivered material to Bird Creek in winter 2017. Photo 1/25/17.

Landslide complexes were activated elsewhere in the HHSVRA, including along Cienega Road in the Cienega Creek watershed. Aerial photogrammetry captured the Cienega Slide complex in fall 2017 as a baseline for analysis in future years.

3.2 Bird Creek Cross Sections

Nine benchmarked cross sections of Bird Creek at the Hudner area (Fig. 9) were surveyed approximately annually since fall 2011 to capture major geomorphic changes that would indicate whether the creek is storing, sourcing, or transporting sediment (Fig 21). Natural streams gradually shift their positions, and temporarily store and erode sediment in small amounts as they transport the varying annual sediment load. Between 2011 and 2016, and between 2017 and 2018, all transects were either unchanging or varied in magnitudes typical of natural stream adjustment to annual sediment load. Some between-survey variability is assignable to survey precision as well.

High magnitude storm runoff events generate high shear stress, and sometimes high sediment loads from the watershed, which can impact stream morphology. The extreme rain events of winter 2017 provided such a test of channel stability and function. All transects maintained their pre-2017 geometry except for transects 3, 4, and 5 (Figs. 9

and 21). The reach of river that starts between transects 2 and 3 and ends between 5 and 6 experienced varying amounts of significant aggradation of sand-sized bed material in 2017. We estimate the volume of sand and small gravel stored in the channel to be approximately 320 m^3 (420 yd^3) by averaging the change in cross sectional areas between adjacent cross sections and multiplying by the distance between cross sections. That volume is the same order of magnitude estimated to have been input directly to the channel in 2017 by a small landslide located just 90 m upstream of transect 1 (Fig. 20). The channel is relatively straight and narrow between the slide and transects 1 and 2. Therefore, interruption of sediment transport is unlikely in this reach. A 90-degree left bend in the Bird Creek channel just after transect 2 apparently slowed the flow enough to trigger a pattern of aggradation in the reach just downstream, measured in transects 3 to 5. The volume of sediment deposited gradually tapered downstream until the 300 m^3 of sand from the slide was exhausted just downstream of transect 5.

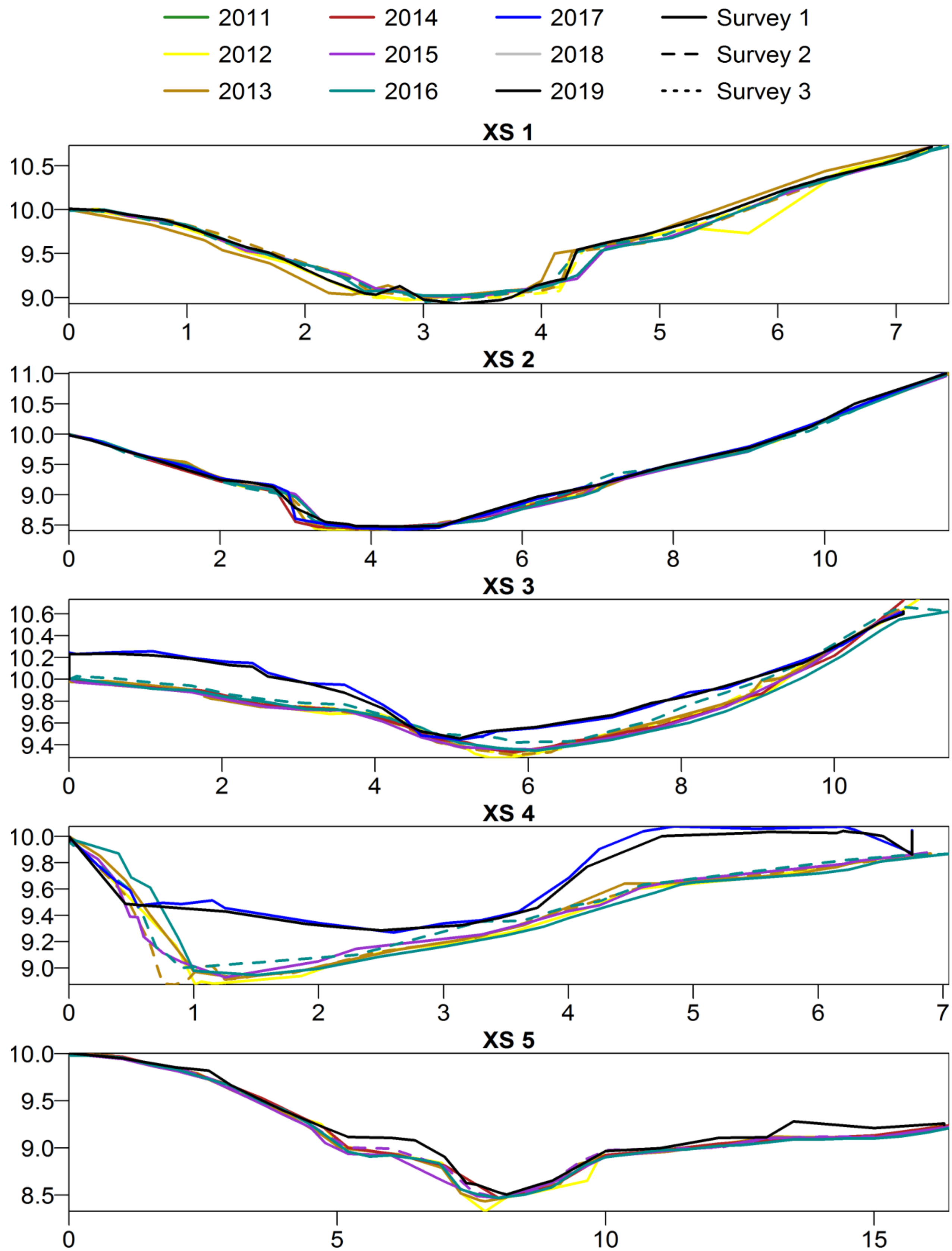

Figure 21.: Time-series benchmarked cross sections in Bird Creek in the Hudner area. Dashed lines are used for years with multiple surveys. See Figure 9 for locations.

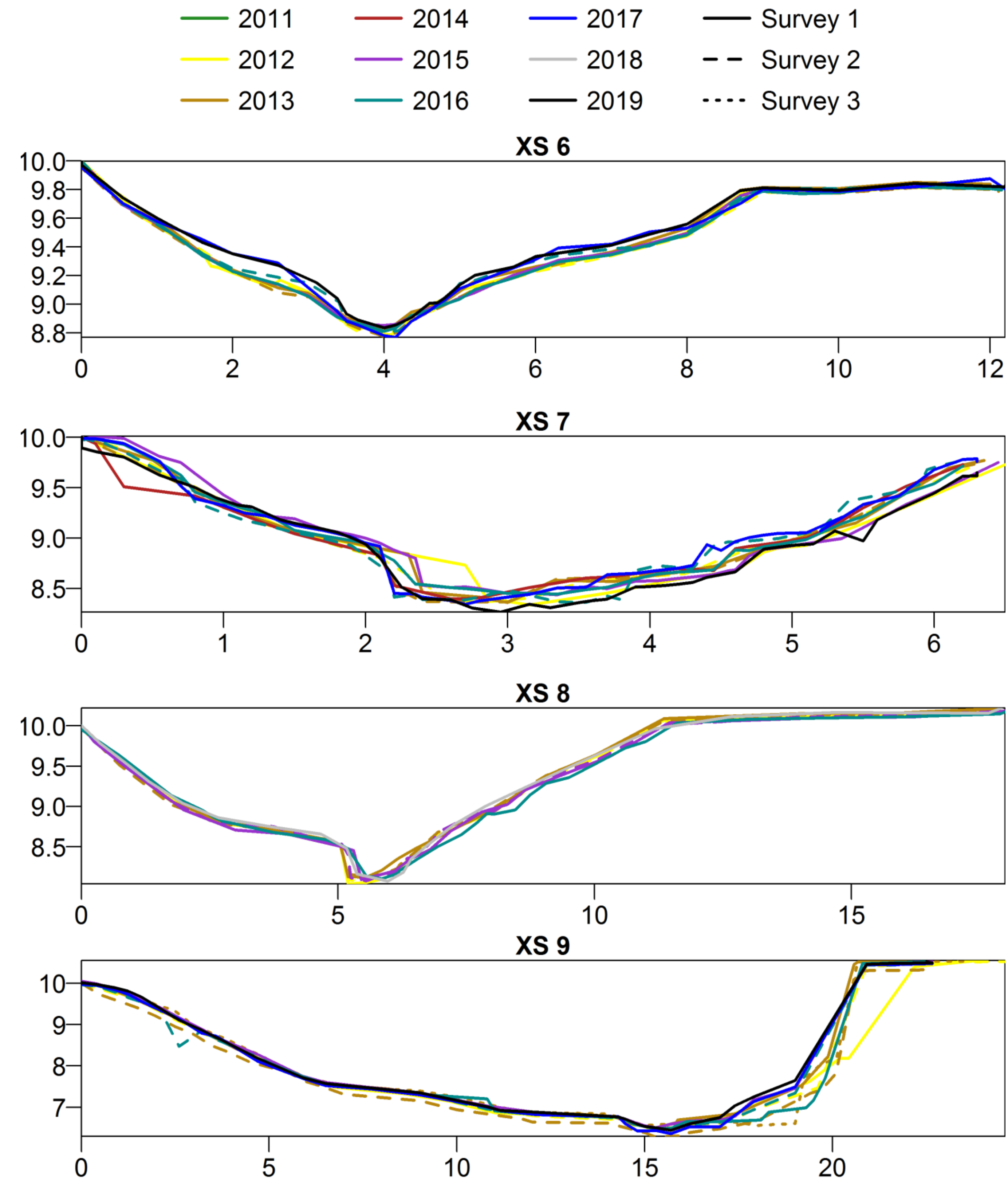

Figure 21 cont. Time-series benchmarked cross sections in Bird Creek in the Hudner area. Dashed lines are used for years with multiple surveys. See Figure 9 for locations.

3.3 County Road Culverts

Drainage networks grow from budding of new side channels and headward growth of those new channels through up-slope erosion. This natural process is considered a hazard when the resulting erosional features intersect roads or other infrastructure. These processes are accelerated by intense rainfall or flow modifications that force local high erosion rates, and can be associated with slope failure features. Specific erosion rates and slip rates are not well documented. This report discusses some of the road-related erosional features and geomorphic changes observed along Cienega Road.

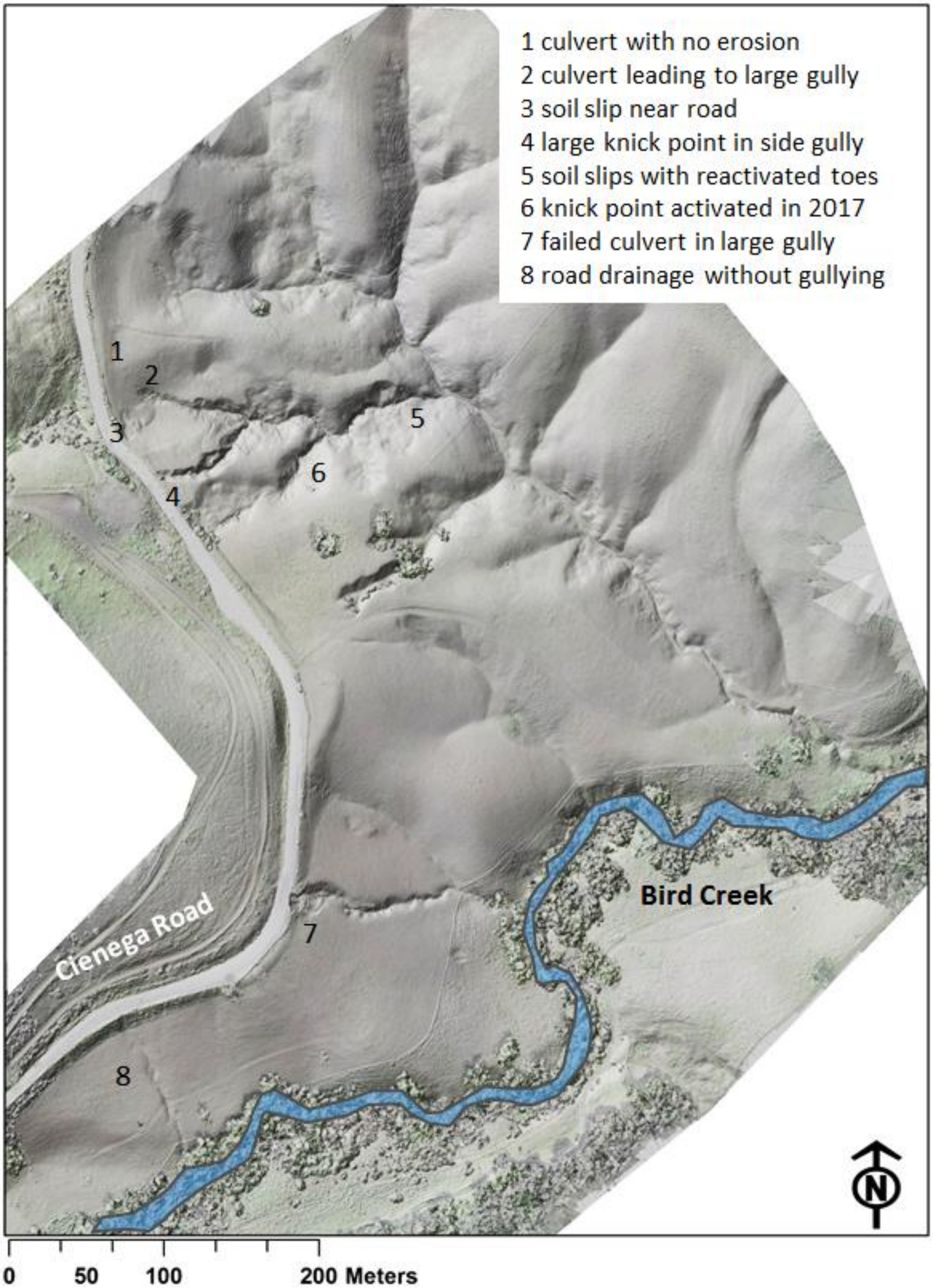

Figure 22. Culverts and erosional features along Cienega Road. Image is blended hillshade and orthophoto.

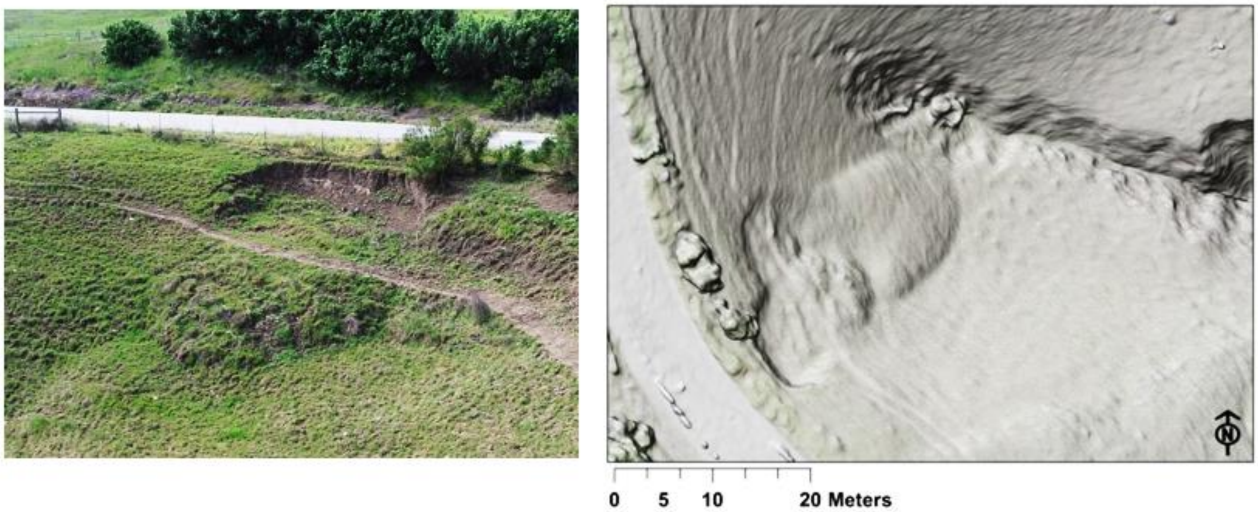

Figure 23. Oblique aerial photograph and hillshade from spring 2018 show soil slip that was reactivated in winter 2017. Location shown in Figure 22, feature number 3. Culvert labeled number "2" in Figure 22 is visible in hillshade, 5 m north of soil slip toe.

The culvert labeled "2" in Figure 22 is the source of water that has produced a large gully and ravine system that includes the features labeled "4", "5", and "6" in Figure 22. Feature four is a tributary gully that has cut several meters downward in response to base-level drop in the main valley fed by this culvert. The head of that tributary gully is deep, and is growing close to the Cienega Road (Figs. 24-27). Cross section transects through the high-resolution DSM shows that gully depth increases rapidly down gradient (Fig. 25). Steep walls with bare soil indicate the tributary is a chronic and significant source of sediment (Figs. 26 and 27).

Figure 24. Oblique aerial photograph from sUAS showing active gully near Cienega Road. Feature is labeled "4" in Figure 22. Hillshade of feature is Figure 25. Ground-based photo is Figure 26.

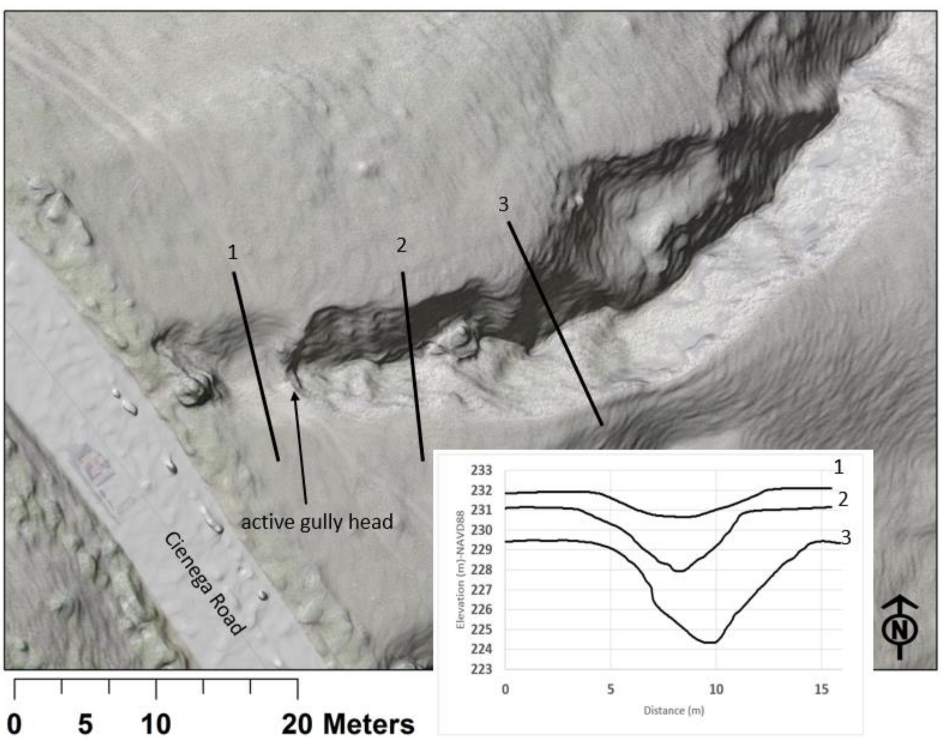

Figure 25. Hillshade showing active gully feature near Cienega Road. Location shown in Figure 22, feature number four.

Figure 26. Gullies related to culvert drainage erosion. Right gully with surveyors terminates at the culvert labeled “2” in Figure 22. Broken white culvert pipe visible in thalweg is also visible in Figure 24. Left gully is feature number four in Figure 22, also shown in Figures 24 and 25. Image from Smith et al. (2016).

Figure 27. Close-up of gully walls seen in Figure 26. Image from Smith et al. (2016).

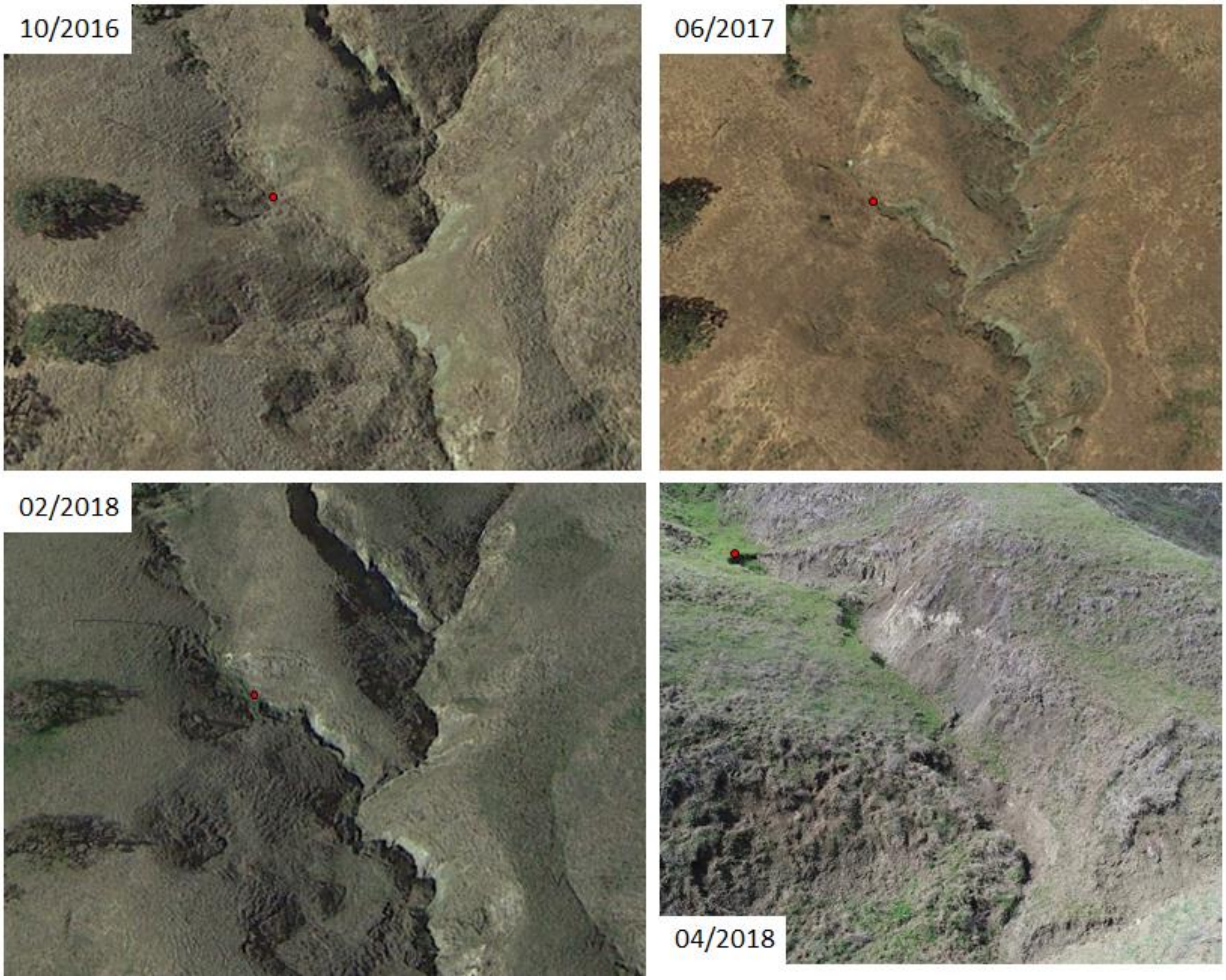

Figure 28. Time series images from Google Earth showing gully formed in 2017. Lower right image is oblique aerial view from sUAS. View is up-gradient. Red dot in all images is the location of the gully head in 2018. Gully is feature six in Figure 22.

The feature labeled “6” in Figure 22 is the second tributary to the main drainage below Culvert two. Serial images indicate this tributary experienced significant new erosion in winter 2017. A new gully grew headward 31 m up the drainage (Fig. 28). It is not visible in fall 2016 aerial imagery but appears for the first time in spring 2017 (Figure 28). The gully is generally between 0.5 m and 2 m deep, and is 2 m to 3 m wide. It is not a threat to Cienega Road but will likely remain a new chronic source of sediment in high rainfall years.

Innumerable small soil slip features are located along the walls of the main gully below culvert two (Fig. 29). Visual observations indicate the toes of many slips were reactivated in winter 2017. One of those is labeled in Figure 29. Reactivation of gullies in the tributaries and reactivation of slide toes is evidence that the main gully downcut in Winter 2017, lowering local base level for adjacent hill slopes. The system generated significant sediment that was transported to Bird Creek in winter 2017 (Fig. 30).

Figure 29. Down gradient view showing unstable slopes in gully system below culvert labeled "2" in Figure 22. Image is oblique aerial view from sUAS. Scene depicts feature five in Figure 22.

Figure 30. Upgradient view of sediment in ravine bottom downstream of Cienega Road gullies. Photograph from 1/25/2017.

The feature labeled "7" in Figure 22 is a road culvert that has accelerated erosion downslope from Cienega road (Fig. 31). The head of the resulting gully is eroding the edge of Cienega Road, and will pose a continued threat to the road in high-intensity rains. Sediment eroded from the gully bottom and walls can reach Bird Creek along a well-established channel (Fig. 22). While this gully appears to have been active in recent years, it is not a new feature. The feature is visible in aerial images from 1976, but it does not appear to impose a threat to the road at that time. Images from 1996 show the head eroding into the roadway.

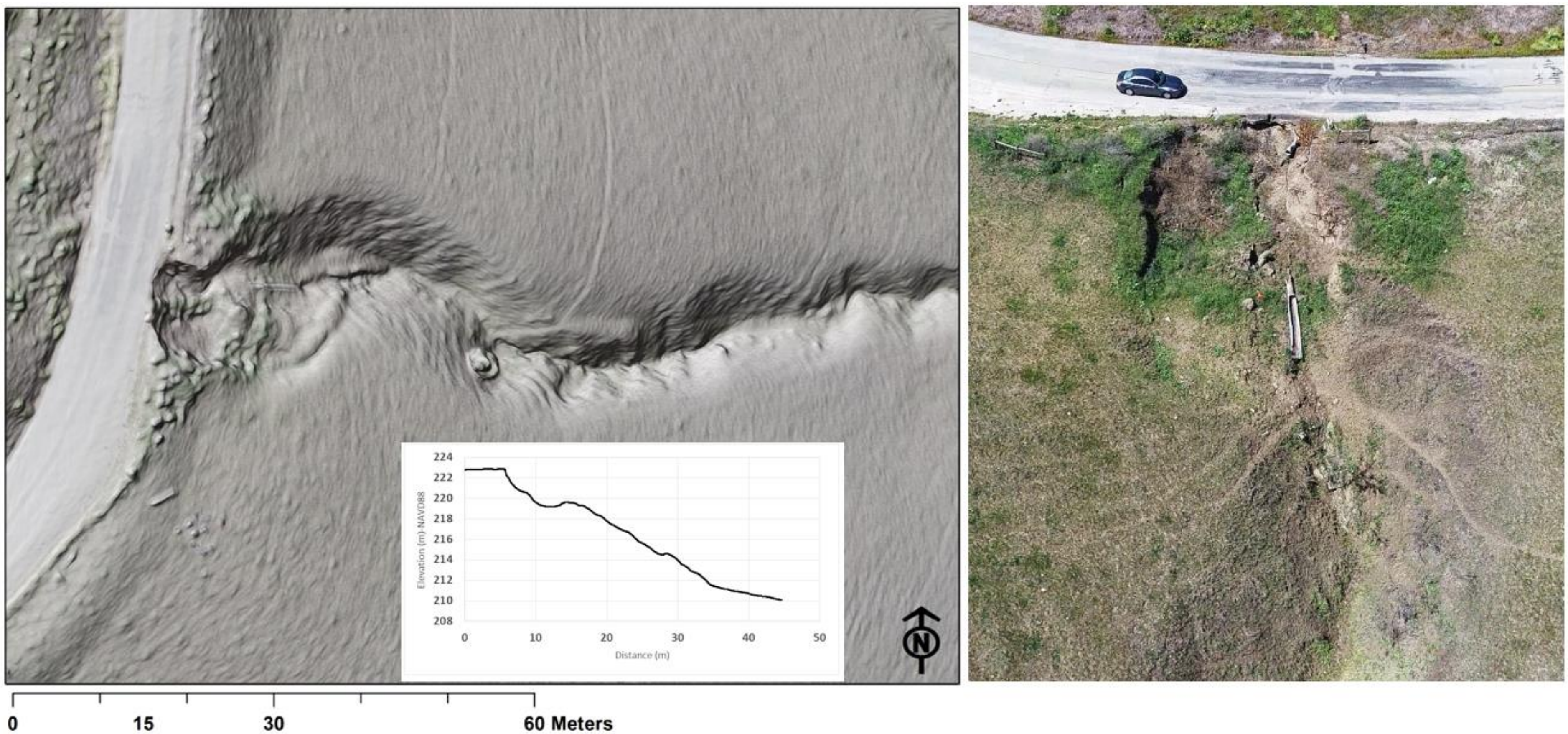

Figure 31. Hillshade and oblique sUAS aerial photograph of culvert-generated gully labeled “7” in Figure 22. Inset image is longitudinal profile of the upper reach of the gully, starting from the road surface.

4 Summary

Smith et al. (2016) provided an inventory of sediment sources in the Bird Creek watershed (Fig. 2). Here we improved our understanding of the respective roles of landslides, streams, and county roads in sediment supply and transport to Bird Creek.

1) Surveys of pegs driven into large landslides show that landslides generally move each year at a creeping rate commensurate with colluvial slopes that are not cut by landslides. Winters with intense rainfall generate higher slip rates.
2) Landslide surveys in Colluvial Creek show that heavy winter rains do not impact landslides equally. Although individual landslides in the same watershed might appear to be similar, some have event-driven slip rates that are over 10 times higher than others (Figs. 10 and 15).
3) Landslide surveys in Hudner Creek show that individual parts of large landslides can have radically different slip rates and material response to high rainfall events. Some parts of the complex slide moved as a coherent slide body, while other parts liquefied into mudflows.
4) A conceptual model described by Smith et al. (2016) describes how sediment from landslides eventually reaches Bird Creek through a multistep process involving sediment storage and gullying. The gullying part of the process is highly variable in time and space. Recent gullying in Colluvial Creek has included only minor work in the middle of the slide body (Fig. 10), and there is no geomorphic evidence of sediment transport downstream of the slide (Figs. 14 and 15). In contrast, gullying in Hudner Slide includes both small gullies in the slide body (Fig. 16) and gullies that cross the slide toes. The toe gullies became active in winter 2017, releasing over 3000 tonnes of sediment to Bird Creek (Figs. 18 and 19).
5) Bird Creek channel has been in steady-state equilibrium since our studies began in 2011 (Fig. 21). In 2017, a small landslide located upstream of the cross sections produced significant sand deposits in the channel and banks of the creek. Future surveys will trace the fate of these deposits to determine whether the sediment is processed further downstream, or becomes locked into the creek by riparian vegetation.
6) Erosion at the downstream end of some culverts has the potential to destabilize the local landscape (Figs. 24 and 31). The resulting gullies are a chronic source of sediment for Bird Creek. Associated gullies and landslides are more active in years with intense rainfall, as expected.

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