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Six Year Summary of Watershed Studies at Hollister Hills State Recreational Vehicle Area: Fall 2010 to Fall 2016

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Executive Summary

Off-highway vehicle (OHV) use and the attendant environmental impacts are managed in California by State Recreational Vehicle Areas. In 2010, Hollister Hills State Recreational Vehicle Area (HHSVRA) commissioned a 6-year study of erosion and sediment transport processes to improve resource stewardship practices. The study focused on Bird Creek, which drains most of the park.

This report summarizes data and qualitative observations from the following Bird Creek watershed sediment sources: OHV use, stream channels, county roads, cattle, campgrounds and other impervious areas, and landslides. Stream gages assess the sediment transport from the watershed. We also estimate the sediment trapping efficiency of sediment retention basins located in the subwatersheds. We create a sediment budget by loosely extrapolating the trail erosion and sediment retention data to the entire HHSVRA property (within the Bird Creek watershed).

Using poorly-constrained assumptions (described in the text), OHV use erodes approximately 20,800 tonnes/yr of sediment, and sediment basins retain approximately 10,800 tonnes/yr. The other sources of sediment are very small in comparison, but stream bank erosion, cattle impacts, campgrounds, and some county road impacts are located downstream of sediment basins, and contribute to directly to Bird Creek. On the other hand, nearly all of the OHV erosion and much of the county road impacts are located upstream of sediment basins, so they contribute almost no sediment directly to Bird Creek. We have measured the sediment leaving the watershed each year. A typical value of sediment transport is 180 tonnes/yr. Although OHV erosion apparently outpaces sediment retention, the sediment basins trap 100% of the bedload and a very high proportion of the suspended sediment load, as evidenced by the low sediment load at the gage. We interpret this disparity between eroded and trapped sediment to mean that either 1) a large proportion of the eroded sediment is building up as slope-mantling colluvium, 2) the time length of our study is insufficient for a balance of erosion and trapping to be realized, or 3) the extrapolation assumptions are incorrect.

Bird Creek contributes to the San Benito River. The San Benito is listed as impaired by excess suspended sediment. The proposed future target for annual suspended load in the watershed is 93,460 tonnes. Based on proportional drainage areas, Bird Creek is currently far below its target share of 2060 tonnes/yr.

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1 Introduction

The California Off-Highway Vehicle (OHV) Recreation program started in 1971 when the Chappie-Z'Berg Off-Highway Motor Vehicle Law was signed as part of a state-wide effort to reduce OHV impacts (Bedrossian and Reynolds 2007a). The law ensured stewardship of the land through maintenance and oversight while providing ample designated riding areas for enthusiasts (Bedrossian and Reynolds 2007a). The resulting State Vehicular Recreation Areas (SVRAs) are managed by the Off-Highway Motor Vehicle Recreation (OHMVR) Division of California State Parks, which was established by the OHMVR Act of 2003 to foster "education, conservation, and enforcement efforts that balance OHV recreation impacts with programs that conserve and protect natural resources" (California State Parks 2009).

Early studies documented significant erosion impacts of OHV use both in unregulated wilderness (Wilshire 1983) and within the SVRA system (Griggs and Walsh 1981). In response to these studies, ideas about best management practices (BMPs) began to emerge (Tuttle and Griggs 1987).

Soil conservation standards and guidelines for OHV use in California were published in 1991 (and updated in 2006) in response to a 1987 mandate (Bedrossian and Reynolds 2007a and 2007b). The standards require maintenance of OHV areas and trails, use of an erosion hazard rating system, and annual monitoring that would allow for "feasible rehabilitation by resource managers" (Bedrossian and Reynolds 2007a). The updated soil conservation standards stimulated SVRAs managers to improve and expand BMPs and restoration efforts. In particular, they aimed to reduce soil loss and eliminate off-site sediment transport. While there is an encyclopedic inventory of the volumes written about OHV impacts (Ouren et al. 2007), there is scant literature on the appropriate methods for documenting the improvements that result from BMP implementation and environmental restoration efforts.

This report is a six-year study of watershed processes, focusing on sediment erosion, transport, and management within the Bird Creek watershed portion of the Hollister Hills SVRA (HHSVRA). The HHSVRA is located near Hollister, CA (Fig. 1). Park environmental scientists contracted the Watershed Geology Lab at California State University Monterey Bay to provide a variety of watershed studies focused on evaluating sediment sources, sediment BMPs, and the net impact on local waterways. The monitoring work spanned from Fall 2010 to Fall 2016.

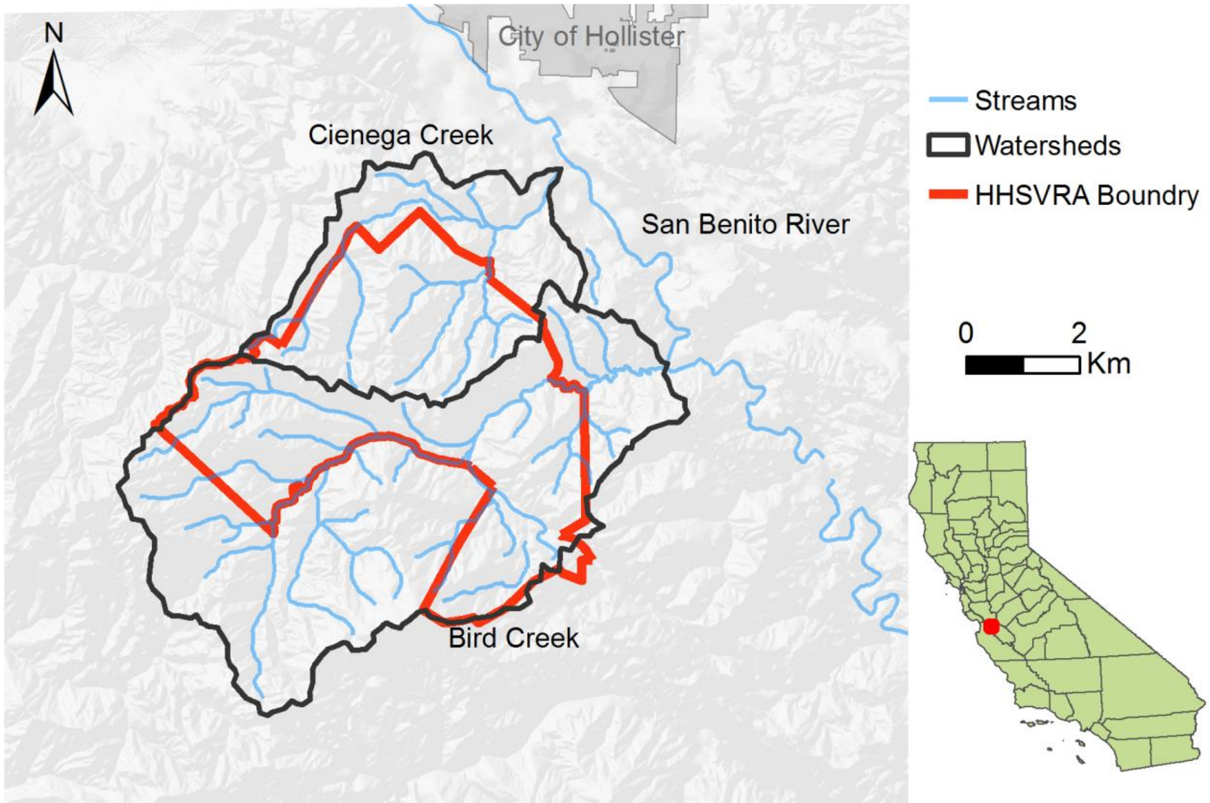


Figure 1. Hollister Hills State Vehicular Recreation Area is found northeast of Salinas in San Benito County, California.

Runoff from the HHSVRA enters the San Benito River via Bird Creek and Cienega Creek (Fig. 1). The San Benito River is 303(d) listed for suspended sediment (RWQCB 2006). While the relative importance of individual suspended sediment sources in the San Benito watershed is not well established, the range of possible sources includes a variety of agricultural activities, timber harvesting, grazing upon pasture and range lands, urban and rural residential development, paved and unpaved roads, farm animal and livestock, off-highway recreational vehicle areas, uncontrolled off-highway trails, sand and gravel mining, various other hydro-modifying activities, and natural erosion and landslides (Figs. 2 and 3; RWQCB 2005). Total maximum daily loads (TMDLs) have been assigned to various activities in the watershed, with a goal for the entire San Benito Watershed to not exceed 93,460 tonnes/yr by approximately 2050 (RWQCB 2005). One goal of this study is to explore the sediment budget of Bird Creek and the HHSVRA within the context of the broader San Benito watershed sediment problem.

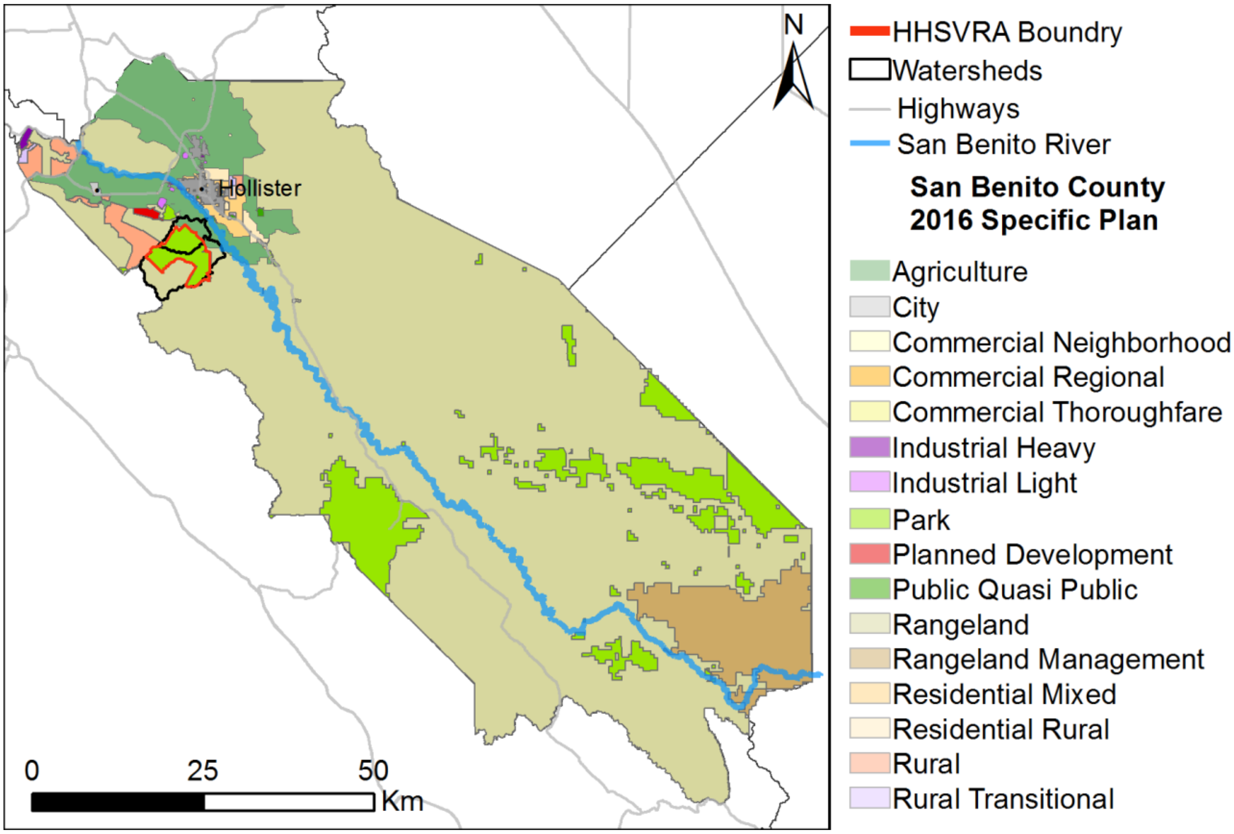


Figure 2. San Benito County 2016 Specific Plan. Data from San Benito Count 2016.

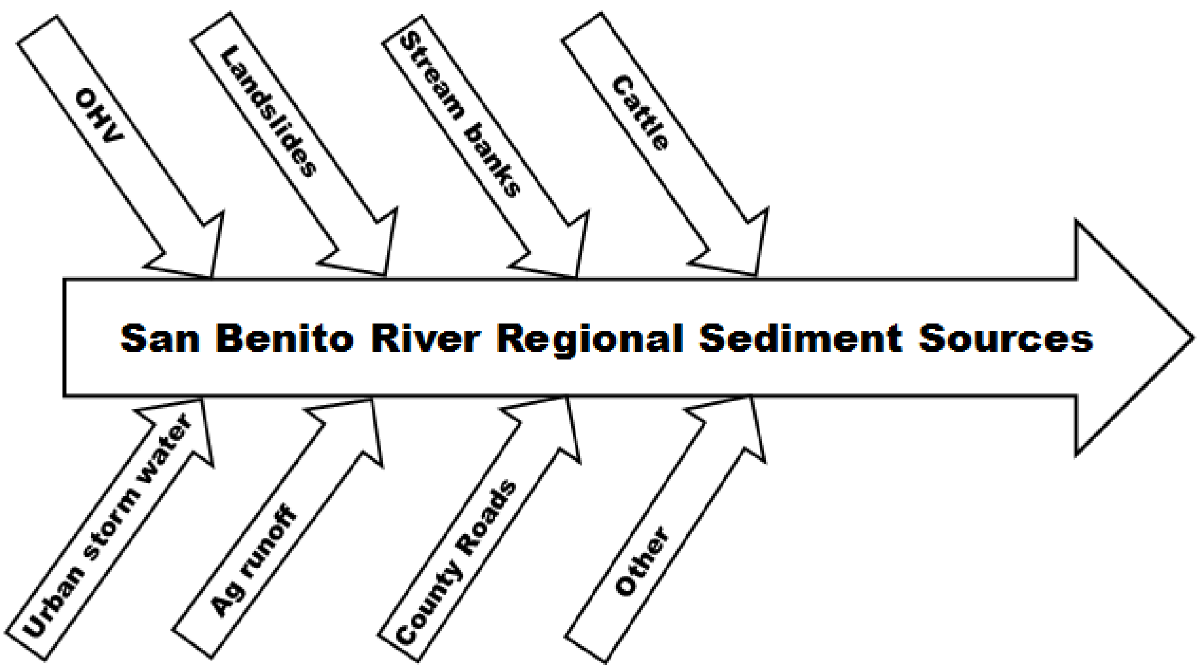


Figure 3. There are many sediment sources in the San Benito River watershed.

1.1 Geologic Setting

The San Andreas Fault bisects the park into two regions with contrasting substrate and soils (Fig. 4 and 5). The northeastern portion of the park is underlain by fine-grained Miocene and Pliocene marine and non-marine sedimentary rocks (Harden et al. 2001; Wagner et al. 2002; Graymer et al. 2006) that produce clay-rich soils (NRCS 2011). Our experience indicates that the clay-rich soils are prone to slope failure and deep erosion in wet weather. The southwestern portion of the park is underlain by pervasively fractured Cretaceous granite and older dolomitic marble that produce well drained granular soils (Harden et al. 2001; Wagner et al. 2002; Graymer et al. 2006; NRCS 2011). These soils are typically less erodible than the clay-rich soils in wet weather, but can form significant gullies on steeper slopes.

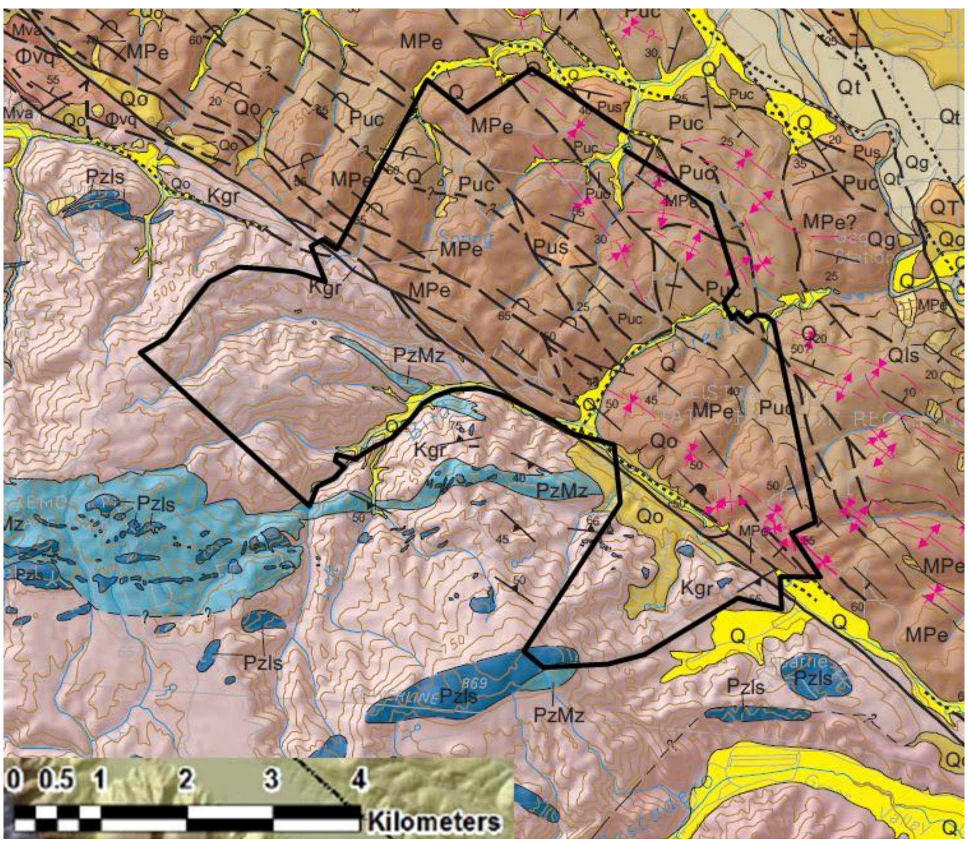


Figure 4. Geologic units within the HHSVRA boundary (black line) include Paleozoic limestone (Pzls) and marble (PzMz), Cretaceous granite (Kg), Miocene/Pliocene shallow marine sandstone (MPe), Pliocene continental sandstone (Pus) and mudstone (Puc), and various Quaternary alluvial deposits (Qx). From Wagner et al. (2002).

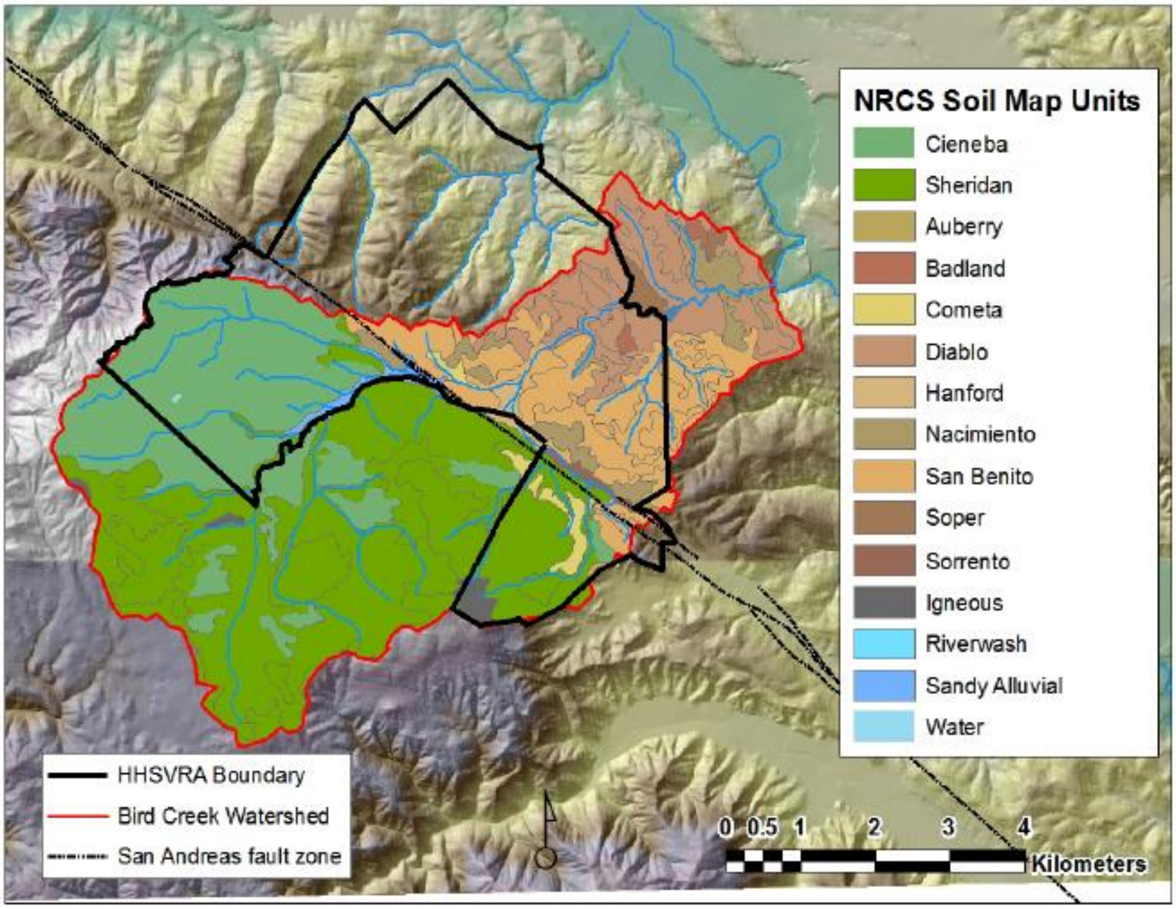


Figure 5. Soil map of Hollister Hills State Vehicular Recreation Area and the Bird Creek watershed. Note the change is soil type from the northeastern to the southwestern side of the San Andreas Fault.

1.2 Goals

The specific goals of our work has been to:

- estimate the amount of sediment transported by Bird Creek,
- create an inventory of sediment sources within the watershed,
- generally assess the relative importance of each sediment source, and
- explore the general efficacy of sediment control measures at HHSVRA.

The general approach for this work is to gage the Bird Creek for water and sediment discharge and to monitor a range of potential sediment sources at least once, and annually in some cases. Most of the data were collected and analyzed by paid student research assistants, but in some cases classes of students would study specific topics in greater detail as part of a class project. This report summarizes all the results, including class projects that had sufficient quality control.

1.3 Hydrology

Bird Creek responds to a Mediterranean climate in which most of the precipitation falls between October and April. The average annual precipitation for Bird Creek is 419 mm (16.5 in), ranging from 397 mm (15.6 in) in the lower watershed to 491 mm (19.3 in) at the ridge tops (Prism 2004). The rainfall in Central California is characterized by rare, high-magnitude rain events (such as El Niño winters), which can have dramatic and lasting impacts on landscapes and infrastructure.

Small streams in Central California often have a “flashy” hydrograph, in which short term large flow events account for a large portion of annual stream discharge. Most stormflows can be expected to last less than 24 hours, although multiple rain events within a short period of time may lead to longer lasting (and relatively higher) flows. Similarly, rain events late in the season will generate larger runoff events, as a wet antecedent moisture condition will not allow soils to absorb as much of the rainfall. Hot and dry summers typically lead to ephemeral streamflow in the regional waterways, including Bird Creek. Ephemeral streams typically have a period of baseflow between late spring and the start of the next rainy season. Baseflow is the condition when all streamflow originates from gradually declining groundwater reserves, which were recharged during the rainy season. This behavior is present in Bird Creek except in two short reaches that have nearly perennial flow because of locally active springs. During the recent drought years, even the spring-fed stream reaches went dry as the water table dropped below the stream channel elevation.

1.4 Sediment Transport

Sediment transport within the park mainly starts when either natural colluvial processes or human impacts (OHV use, cattle, etc.) dislodge sediment from a hillslope where it can advance downslope under the influence of gravity, flowing water, or both. Once sediment reaches a 1^{st}-order channel, it moves as either bedload or suspended load along the channel network. Bedload is classified as the portion of sediment that moves on, or near, the stream bed by rolling, sliding, or skipping. Suspended sediment is the portion of fine particles, which is transported within the water column, suspended above the bed by water turbulence (Leopold et al. 1964). We assessed both bedload and suspended load transport rates in Bird Creek.

1.5 Sediment Sources

Sediment sources that we assessed in the past six years include: off highway vehicle use, campgrounds, stream bank and channel erosion, cattle, county road culverts, other impervious surfaces, and colluvial processes such as landslides (Fig. 6).

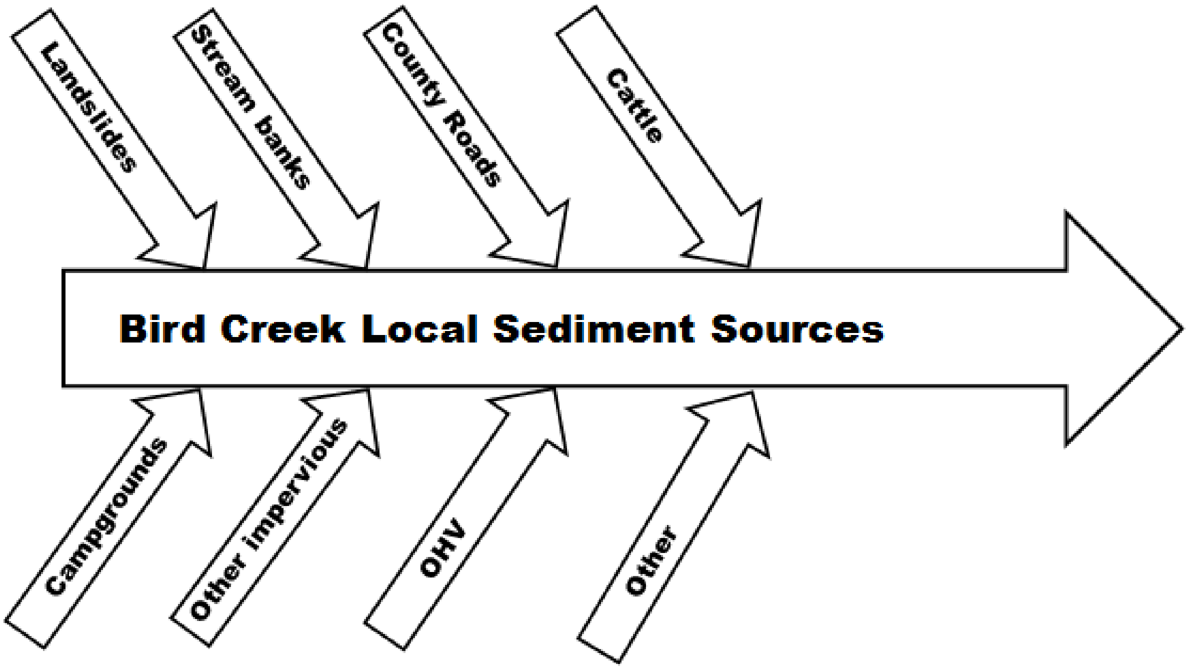


Figure 6. Potential sediment sources in the Bird Creek watershed.

HHSVRA comprises over approximately 150 miles of dirt trails for 4-wheel drive, ATV, and motorcycle recreation. Past studies have shown that even though unpaved trails may only take up a small percentage of a watershed they contribute a disproportionate amount of sediment runoff (Turton et al. 2009).

Campgrounds, staging areas, and roads that are only indirectly related to OHV activities were explicitly called out as commonly overlooked sediment sources in OHV parks (Bedrossian and Reynolds 2007b). HHSVRA contains seven campgrounds with compacted dirt areas. Compacted dirt in the campgrounds, staging areas, and near administrative and maintenance buildings can acts as an impervious cover causing runoff to flow into adjacent streams. Likewise, county roads unrelated to the park are present in the watershed. San Juan Canyon Road bounds the park on the northwest and Cienega Road crosses the park lower in the watershed, near the park entrance. These roads are impervious surfaces that concentrate runoff onto park property. The roads also employ a great number of culverts that further concentrate flow into jets that can erode the down-gradient slopes. Impervious surfaces and culverts inevitably lead to an increase in surface runoff, slope destabilization, and sediment load (Montgomery 1994, Luce and Wemple 2001).

Stream channels and banks naturally transport, store, and release sediment to reach equilibrium with watershed conditions (Wynn and Mostaghimi 2006). Steam systems that have been destabilized by chronic excess runoff can become long-term sources of non-point source sediment as they undergo a well-documented cycle of incision and re-equilibration (Harvey and Watson 1986; Hawley et al. 2012). Sediment contributions from these sources can be quantified with bank pin and cross section studies (Harrelson et al. 1994). Stream banks along Bird Creek vary greatly in height and material strength. For example, a marked change in geology occurs across the San Andreas Fault (Fig. 4). West of the fault, in the granitic part of the watershed, the soil along Bird Creek is sandy alluvial loam. East of the fault, where the watershed is underlain by weaker sedimentary rocks, the Creek runs through diablo clay and gravelly loam (NRCS Website). Clay, having low bulk density, is not only a suspended sediment component but also prone to subaerial erosion (Prosser et al. 2000, GEOL 460 2012). Bedrossian and Reynlods (2007b) note the key role that geologic substrate plays in local OHV erosion impacts. Given the geologic complexity, a large number of monitoring sites would be required to fully assess the contribution of channel processes to Bird Creek.

HHSVRA grazes cattle during certain times of the year on the Hudner Ranch area to reduce the amount of invasive perennials and grass species (CDPR 2012). Cattle are agents of geomorphic change, trampling and reshaping the landscape with their hooves. While upland grazing compacts and disturbs the soil, the greatest water quality impacts occur when cattle have access to the streambanks and channel (Trimble and Mendel 1995). Grazing is restricted to certain times and areas in the HHSVRA, and riparian areas are fenced to keep cattle out of the channel.

Colluvial processes (e.g., creep, landslides, debris flows) are the main natural mechanism by which soil and rock move down from hillslopes to waterways. Landslides are defined as the downward and outward movement of a mass of rock, earth, or debris under the influence of gravity (Dikau et al. 1996). Scheingross et al. (2012) recognized that much of the substrate along the San Andreas Fault near near the HHSVRA is susceptible to slow landsliding (earthflow) processes that are prevalent along regions with fine-grained sediment, steep slopes, and a lack of high-magnitude earthquakes (Fig. 7). These conditions prevail in the Bird Creek watershed, east of the san Andreas Fault. Landslides can be a major source of excess sediment in rivers if they are hydraulically connected to a river channel (Davies and Korup 2006). While landslides are abundant in the HHSVRA, it is unclear if they are volumetrically important to the annual sediment load of Bird Creek, or if they are active on a much longer (geologic) time frame that is of less interest to resource managers.

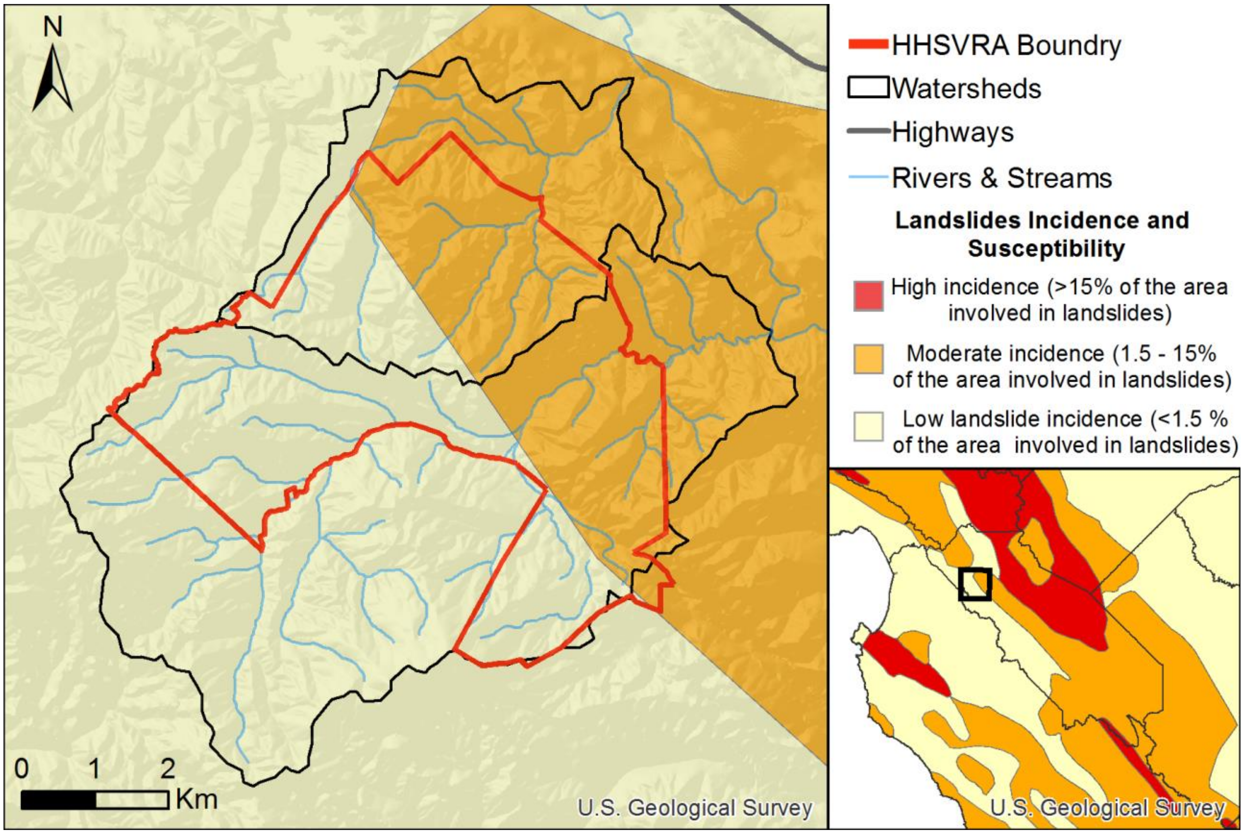


Figure 7. Landslides susceptibility within San Benito County and HHSVRA. Data from USGS 2016.

1.6 Best Management Practices

HHSVRA best management practices (BMPs) include trapping eroded sediment in 25 retention basins located throughout the park. Sediment is removed from the basins on a multi-year time frame as part of long-term sediment management. These basins were constructed in the Bird Creek tributaries many years ago to retain sediment eroded by OHV use. Traditionally, the sediment volume retained by the basins was crudely estimated by the number of "truckloads" that were excavated from time to time. We began more detailed sediment volume estimates during our study. Many basins were scheduled for cleanout in Fall 2012. This cleanout cycle was targeted to initiate a long-term program for more precise accounting of sediment retention. Other best management practices (BMPs) employed by the park include fostering narrowing trails, outsloping the constructed trails, planting native plants on hillslopes, and decommissioning and restoring trails that are deemed to be unsustainable or that pose extreme erosion hazards (Fig. 8). These practices have been ongoing for decades at HHSVRA.

Figure 8. Example of BMP that includes trail narrowing, outsloping, and planting. Decommissioned part of trail has rocked drainage and native plantings. Vegetation is sparse because it was recently planted on the newly graded slope.

Another best management practice is gully stabilization. A 20% grade segment of Coyote Trail (granitic soils) became gullied when tire tracks concentrated runoff (Fig. 9).

Figure 9. View down Coyote Trail restoration project. A) Before decommissioning, circa 2009. B) After grading and placement of rock berms, but before revegetation in July 2011.

To reduce erosion, the gully was filled and the slope was graded. Twenty-seven rock berms were installed across the channel to protect the slope from future gullying (Fig. 9). We monitored the restoration site from 2012 to 2016.

2 Methods

A variety of methods are described below. Some have changed over the years by updating instruments and technology. More detailed methods can be found in the past reports. Table 1 is a timeline indicating when various data sets were collected. Figure 10 is a map showing where most studies are located.

Table 1. Timeline of HHSVRA study type and year.

Study		Year					
		2011	2012	2013	2014	2015	2016
Precipitation							
	Radio Ridge		X	X	X	X	X
	Grand Prix 1		X	X	X	X	X
Gauges	Qw & Qsus						
	Nature	X	X	X	X	X	X
	Hudner	X	X	X	X	X	X
Bedload							
	Nature	X					
	Hudner	X					
Bank pins							
	Bird Creek	X	X		X	X	X
Landslide Pegs							
	Colluvial Landslides	X	X	X	X		X
	Hudner Landslides						
Trails			X	X	X	X	X
Sediment Basins							
	Gilmore		X	X			
	Grand Prix 1		X	X	X	X	X
	Grand Prix 2						
	Lodge					X	
	Office		X				X
	Scandia			X			X
	Super Hill			X			X
	Sycamore						
	Whoopdeedoo		X				
	Woodwardia		X				X
Cross Sections							
	Bird Creek	X	X	X	X	X	X
	Colluvial Creek	X	X	X	X		X
	Coyote		X		X	X	X
	Cienega Culverts			X			X
	Colluvial Landslide						X
Misc							
	Campgrounds		X				
	Cattle Impact		X				

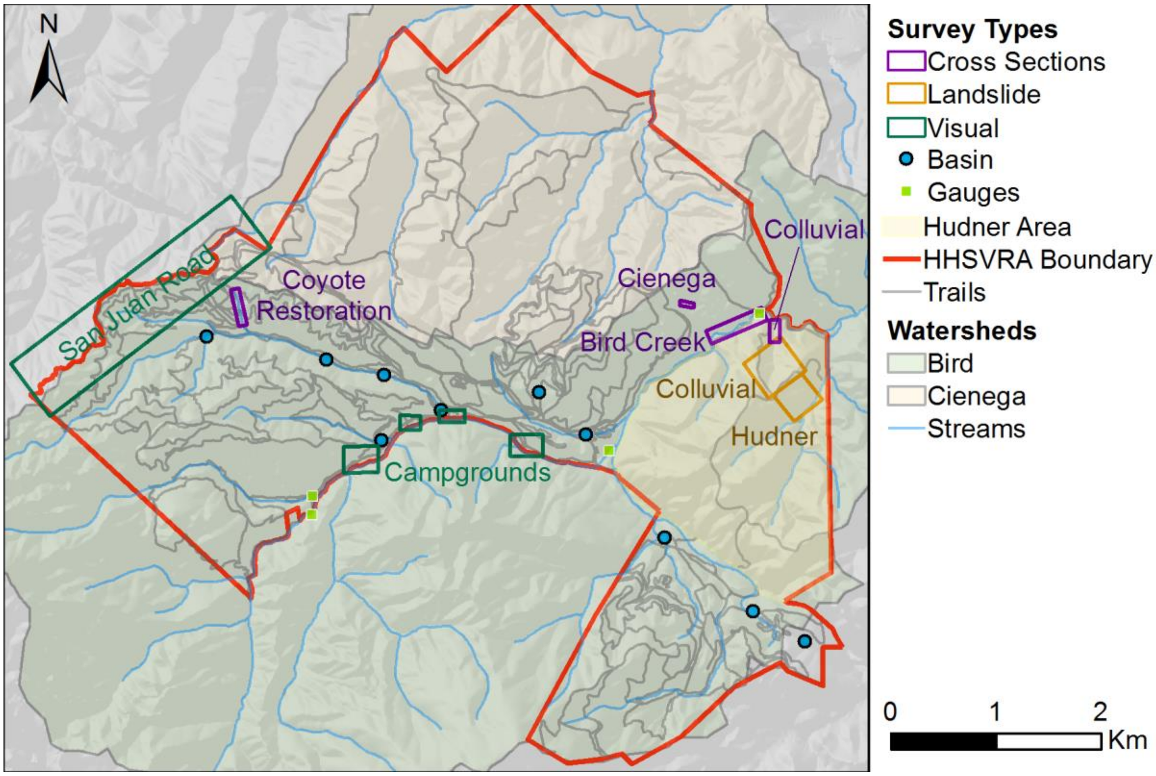


Figure 10. Spatial distribution of all HHSVRA monitoring sites and type of study.

2.1 Hydrology

2.1.1 Precipitation

Local precipitation was monitored from 2011 - 2016 through Western Weather Group's web-based platform. Hourly data were collected from HHSVRA meteorological stations at Radio Ridge and the Gran Prix Track (WesternWeather 2016).

2.1.2 Streamflow

In 2010, gaging sites were established in areas with adequate accessibility and hydraulic control (Fig. 11). Streamflow was continuously measured through a combination of several gaging instruments in four streams. The equipment deployed at each stream is described below.

- Hudner and Nature- In 2010, the Hudner and Nature gages included telemetered YSI multi-parameter water quality sondes to record water pressure, temperature, dissolved oxygen, turbidity, and Ph. These units were replaced in fall 2015 with DTS-12 digital turbidity sensors and SDI pressure transducers that are telemetered by GOES satellite. At both sites there is a backup vented LevelTroll pressure transducer.

- Ranger- In 2010, a vented Level Troll transducer was installed near the park entrance to record stage.
- Hidden Springs – A non-vented Level Troll transducer and paired Barotroll transducer were installed near the mouth of Hidden Springs Creek to record stage.

Data were recorded at 15 minute intervals at Hudner Creek, Nature Area, Ranger Bridge, and Hidden Springs. For each stream, gauge parameters were converted to discharge parameters using event-based measurements and a rating curve developed from many measurements.

Through the year, event-based flow measurements were taken in a wide range of flow conditions near the gauge sites using a Flowtracker Acoustic Doppler meter. We modified the U.S. Geological Survey guidelines to account for narrower cross-sectional widths of the streams (Nolan and Shields 2000).

When flow was below the Flowtracker's detection limit a portable three-inch Parshall flume was used to measure the flow.

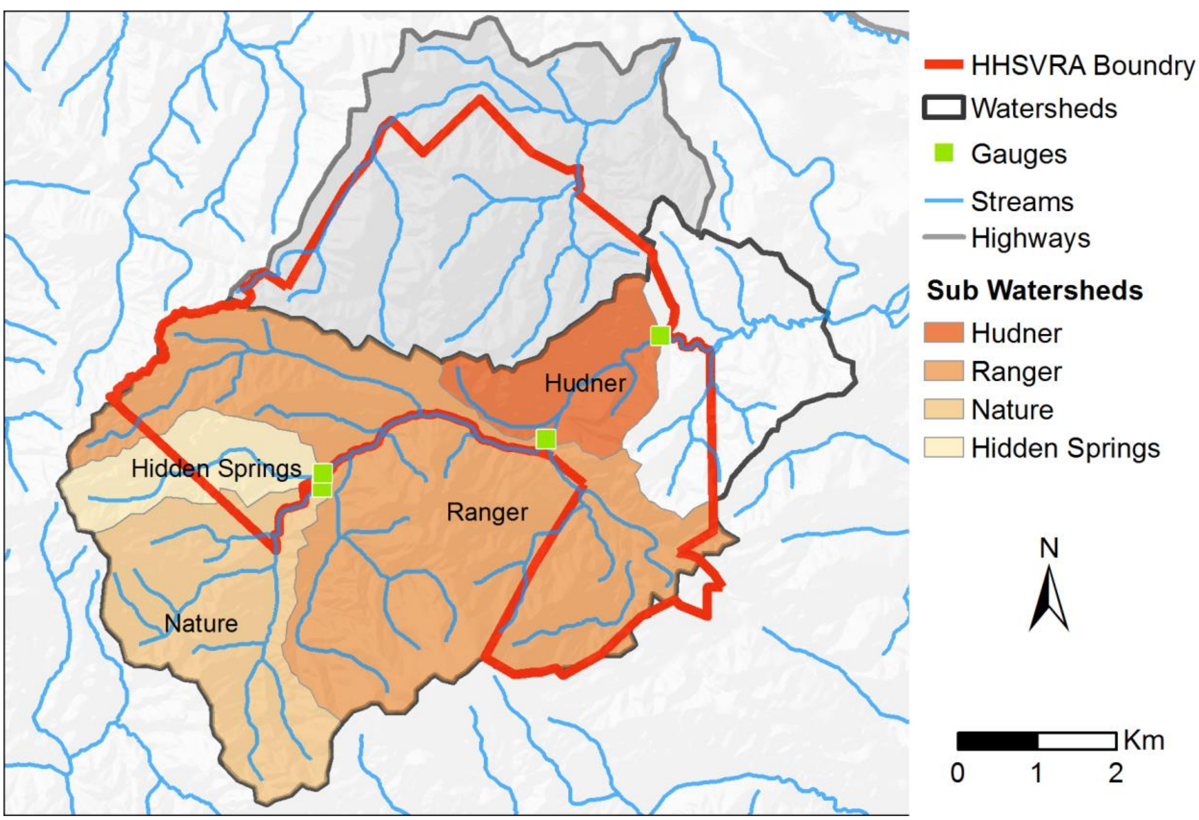


Figure 11. Gaging sites located within HHSVRA and the Bird Creek Watershed.

2.2 Sediment Transport

Sediment transport rates were determined using a 3-inch Helley-Smith for bedload and a DH-48 depth-integrated sampler for suspended load at the same time that water discharge measurements were taken at Nature and Hudner gages (see section 2.1.2). In water year 2011, the pressure gage record was rated for suspended and bedload sediment discharge using event-based sediment transport measurements. Following the 2011 Water Year, bedload was no longer measured because it was virtually absent in 2011 (Nicol et al. 2011). Following 2011, a 15-minute time series of turbidity was rated for suspended sediment concentration to create a time series of suspended sediment transport rate (Minella et al. 2008; Wass et al. 1997).

The Nature gage is located near the upstream boundary of the HHSVRA, and Hudner gage is located near the downstream boundary of the park. Subtracting the Nature sediment yield from the Hudner sediment yield gives an approximation of the sediment entering Bird Creek from all sources along the length of the HHSVRA. The above-below experimental design is complicated by the presence of non-state lands bordering the creek as well. Ranger gage was established to aid in flood frequency analysis. Hidden Springs is the only Bird Creek tributary that does not have a sediment retention basin. The gage was established to help determine if Hidden Springs Creek should have a basin.

2.3 Sediment Sources

2.3.1 Off Highway Vehicle Use

In 2013 we began measuring annual trail erosion at 18 sites throughout the park. Trail sites were chosen in collaboration with HHSVRA natural resource managers based upon soil type, trail use, and trail condition. Trail use types include off road vehicle (4x4), all-terrain vehicle (ATV), and single-track (motorcycle). Trail condition was determined by park environmental scientists based upon visual inspection (HHSVRA 2012). Trail condition rating includes red, yellow, and green for highly eroded, moderately eroded and no erosion respectively (Fig. 12). Two benchmarks (BM) were established at each monitoring site for annual reproducibility. 2013 & 2014 surveys were conducted using a Trimble s6 Robotic Total Station with surface scanning capability. DEM's were then created using ArcGIS.

In 2015 survey methods were upgraded to structure from motion (SfM) photogrammetry. SfM photogrammetry is the process of capturing overlapping aerial images and then using software to create georeferenced orthophotos and DEMs. More detailed information on photogrammetry can be found in Chow et al. 2015. 2015 and 2016 surveys were conducted using a 3" Nikon Total Station to georeference the aerial photos shot with a Hero 3+ GoPro. The orthophotos and DEMs were created in Agisoft Photoscan.

Annual trail erosion was analyzed in ArcGIS using *Raster Calculator* to subtract consecutive annual DEM's and determine average change in elevation. The *Cut and Fill* tool was also used to determine total volume of eroded or deposited sediment.

The total volume of sediment eroded from the study sites was generalized into a single value of erosion, normalized by trail length. That value was extrapolated to the total length of trails in the park to estimate the annual volume of OHV derived erosion. The volume was converted to mass using an assumed average substrate bulk density of 2 tonnes/m^3.

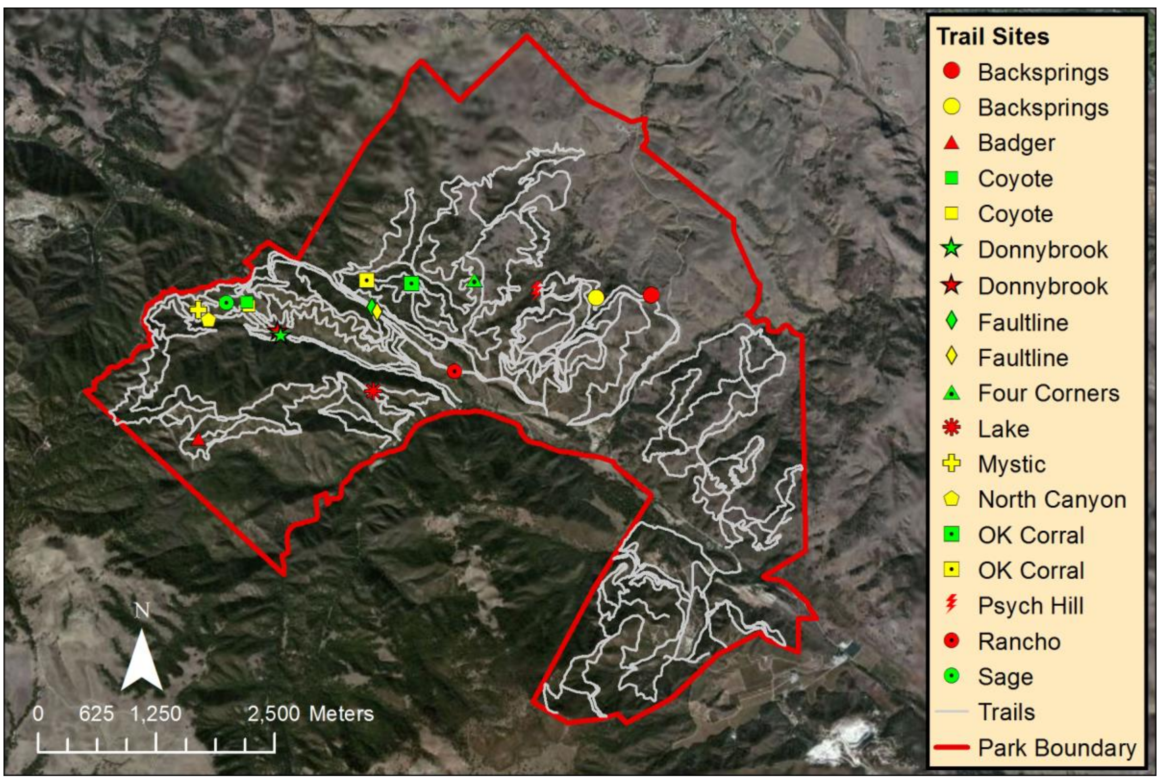


Figure 12. Trail erosion site locations within Hollister Hills State Vehicular Recreation Area, Hollister, CA. Color of symbol represents rating index classification as red, yellow, or green.

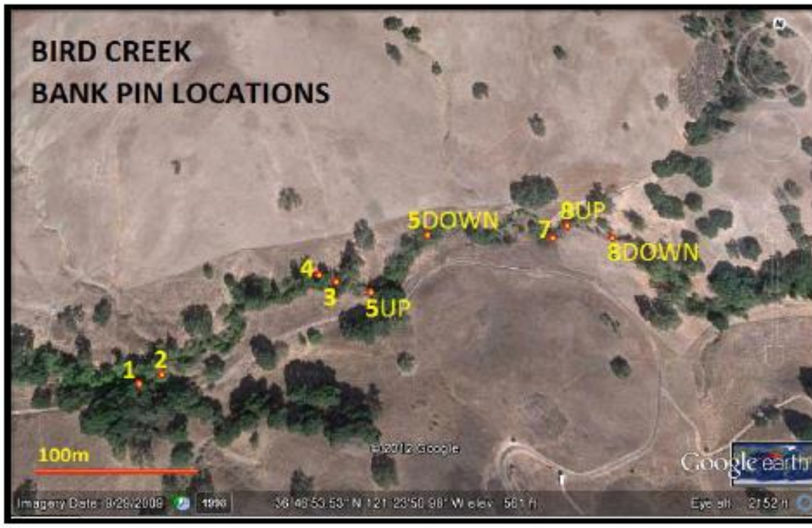
2.3.2 Campgrounds

Assessment of unpaved recreational areas included field reconnaissance, GPS data collection, GIS map production, and literature review. Four campsites were mapped using a Trimble GeoExplorer 2008 GPS unit. Presence or absence of sediment erosion and transport was mapped and photo documented. Sediment pathway maps were developed for a subset of recreational areas (GEOL 460 2012).

2.3.3 Stream Bank and Channel Erosion

Stream channels and banks were monitored in the Hudner Ranch reach of Bird Creek because it has the largest watershed drainage area, while still located within the HHSVRA boundary. Given the relatively higher flows, the site has the potential to experience the highest bank erosion rates in the park. Also, the channel should be the most responsive to watershed conditions, such as exhibiting aggradation in the context of excess bedload, or incising because of excess runoff.

Bank pins were installed at 8 locations along the Hudner Ranch reach of Bird Creek in March 2011 to estimate the contribution of bank erosion to Bird Creek (Fig. 13). This study only extrapolates the results to the reach of Bird Creek that has similar morphology and geology to the reaches with bank pins. The extrapolation includes 2800 m of stream located between the downstream boundary of the HHSVRA and the San Andreas Fault, where the watershed geology and topography significantly change. Pin sets 5 and 8 have upstream and downstream sets. Each bank pin set consists of 2 to 3 rebar stakes inserted into the channel bank. Bank pin exposure was measured to the closest millimeter using a metric scale. Total volume of stream bank erosion was calculated by multiplying the average pin exposure, the 2800 m stream length, and the estimated average bank height (1.2 m). That product was multiplied by two to account for the two stream banks. The mass of eroded material was estimated by multiplying the volume of eroded material by the stream bank soil density (0.980 tonnes/m^3) measured in the CSUMB lab from many field samples (GEOL 460 2012).



PIN #	UTM Coordinates Zone 10N
1	0642814E 4071710N
2	0642815E 4071715N
3	0642933E 4071797N
4	0642932E 4071809N
5 UP	0642961E 4071801N
5 DOWN	0642961E 4071801N
7	0643099E 4071887N
8 UP	0643112E 4071889N
8 DOWN	0643112E 4071889N

Figure 13. Bank pins located along Bird Creek plotted in Google Earth (GEOL 460 2012).

Aggradation and degradation were monitored in the Hudner Ranch reach by establishing nine benchmarked cross sections that were surveyed in each of the 6 years of the study (Fig. 14). Several other cross sections were monitored for shorter periods upstream of those cross sections, and in granitic soils located west of the San Andreas Fault near Walnut Camp.

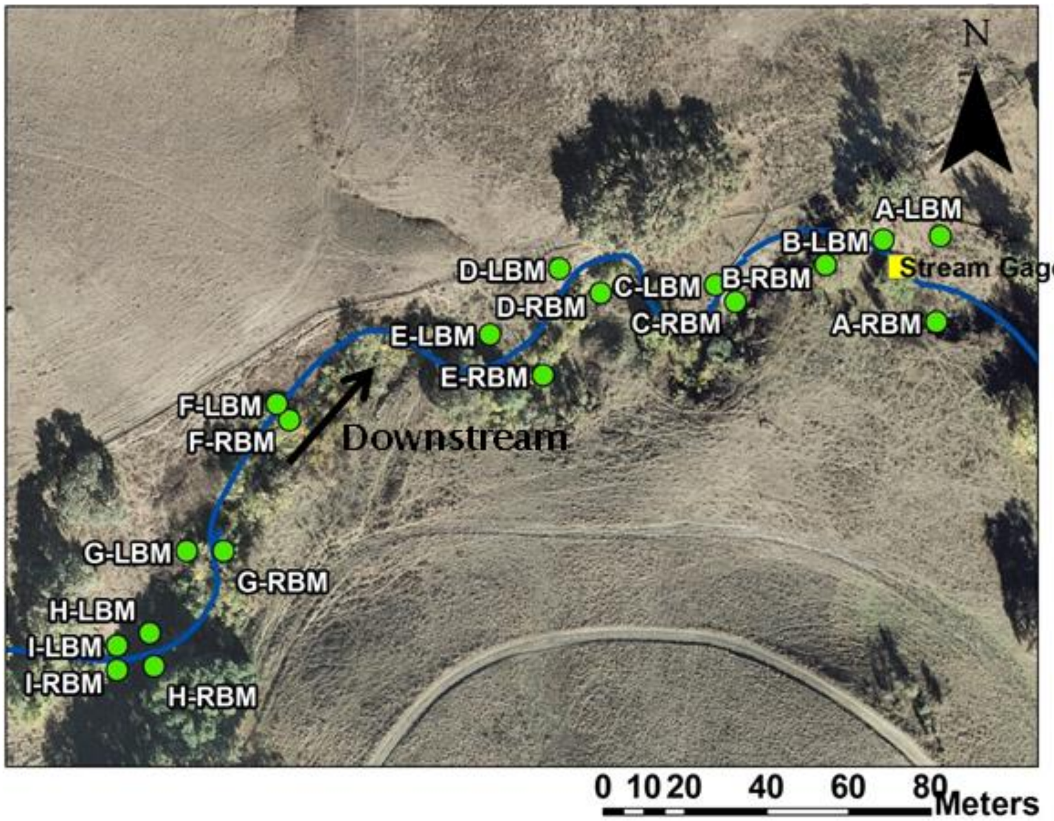


Figure 14. Nine benchmarked cross sections (A-I from downstream to upstream) were resurveyed annually to assess channel and bank processes.

2.3.4 Cattle

Upland cattle impacts were not directly assessed. The impacts of riparian cattle access were documented during creek walks and in a study comparing impacted and unimpacted reaches of Bird Creek within the Hudner Ranch area. The comparative study collected photographic and channel substrate data in 2012 in a location where cattle had access the creek, and a reach immediately upstream that had no cattle access (GEOL 460 2012).

2.3.5 County Road Culverts

The California Department of Transportation (CDOT) installs many different types of road drainage systems (CDOT 2014). Two such drainage features found in HHSVRA are asphalt berm confined spillway and runoff management culverts off Cienega Road and San Juan Canyon Road (Fig. 10, GEOL 460 2014). There are also areas with uncontrolled runoff.

Every point of runoff discharge from San Juan Grade Road to the HHSVRA hillslopes was evaluated for erosion hazard. In addition to visual inspection of the drainage structures for stability, and the hillslopes for erosion, the peak runoff (Q peak) for the 25 year storm was calculated for each runoff diversion point using the rational method (CDOT 2014).

$$Q\ Peak = CIA$$

The rational method takes into consideration the runoff coefficient "*C*" the rainfall intensity "*I*" and the drainage area "*A*".

Drainage area was calculated from GIS of LiDAR-derived digital elevation models. The runoff coefficient "*C*" was a composite value obtained from a Runoff Coefficient table that integrates slope, soil type and land use. Typical slope was between 2-6% as calculated from the elevation change and distance between each upper watershed and diversion. Soil type in this area is classified as shallow soils over nearly impervious material which is shown on the table as soil type "D". In our assessment, it was found that the watersheds consisted of multiple land uses. Primarily, these land uses were asphalt roadway and open space forests. Weighted runoff coefficient was determined by the following equation:

$$C_{weighted} = \frac{((C_{asphalt})(A_{asphalt})) + ((C_{open\ forest})(A_{open\ forest}))}{(A_{asphalt}) + (A_{open\ forest})}$$

Asphalt area was calculated by multiplying road length of each watershed by the average road width measured in the field (18.5 ft). This area was then subtracted from the total watershed area to give us open forest area. This process was completed for each watershed. Rainfall intensity "*I*" represents the rate (in/hr) of rainfall. For our study, intensity was obtained from the California Department of Water Resources (CDWR) gauge: Hollister 9 ENE. We used the 25-year recurrence interval, which corresponds to 1.04 in/hr. We then assigned the Q peak values red, yellow and green colors to signify high, moderate or low Q peak values.

The Cienega Road culverts and associated gullies were visually described, and one was selected for long-term study using benchmarked cross sections to assess the general erosion rate. Four benchmarked transects was established immediately downstream of a culvert off Cienega road. Transects were spaced approximately every 40 meters; they were surveyed in 2014 and 2016 using a metric tape for distance and autolevel for elevations. Tape distance and elevations were recorded at every major break in slope to create a cross-sectional profile. The 2014 and 2016 cross sections were plotted and compared to assess geomorphic change.

2.3.6 Landslides and Colluvial Processes

Landslides were identified by visual reconnaissance in the watershed and through aerial photography. General sediment transport processes were evaluated by inspection, and several landslides were selected for longer-term study to determine if they were active, and to estimate the current rates of motion and sediment contribution to Bird Creek. Five landslides in Colluvial Creek, and one landslide in Hudner Creek watershed were monitored for movement by resurveying a series of iron rods driven into the slide bodies (Fig. 10). In the Colluvial Creek slides, four pegs were placed in a line across the hummocky terrain of each landslide, near the slide head. In contrast, we drove many rows of iron rods into the slide in Hudner Creek. Rods were also placed outside the slide body as a control. Landslide movement was monitored by repeat RTK GPS surveys to measure the 3-D change of rod position. Anecdotal evidence of landslide activity was collected from park environmental scientists.

Both intense rainfall and seismicity are known to trigger slope failure. A review of rainfall intensity and seismicity was done to assess whether any typical landslide triggering events had occurred in the recent past, or during our study.

2.4 Best Management Practices

2.4.1 Sediment Retention Basins

One measure of effective sediment management at HHSVRA is the volume of sediment trapped by retention basins. The park staff chose a subset of basins within the park to study between 2012 and 2016 (Fig. 15). Basins were chosen based on excavation status and whether or not they were dry enough to survey. We surveyed the basins a Real-Time Kinetic (RTK) Global Position System (GPS) system and permanent benchmarks for local referencing. In dense trees, where GPS signal was not reliable, we used a Nikon 3 arc-second total station.

Elevation points taken with RTK GPS or total station were used to make a digital elevation model (DEM) using the natural neighbor interpolation tool in ArcMap (v. 10.1). Following winter runoff, we resurveyed several basins in different years using the same methodology. Net aggradation and degradation of sediment was determined in ArcGIS. We used the *Cut and Fill* tool to extrapolate how much sediment aggraded in the system by inputting the earlier DEM as the “before” raster and the most recent DEM as the “after” DEM.

When sediment volume was too thin to quantify with standard survey methods, sediment accumulation was estimated by multiplying the average thickness of the new deposit (measured by penetration with a calibrated rod) by the area of the deposit (Teaby et al. 2013b).

Sediment volumes trapped in the study basins were stratified by watershed substrate, normalized by contributing drainage area, and extrapolated to the unmeasured basins in the watershed. The total volume was converted to mass using an assumed density of 1.63 tonnes/m^3.

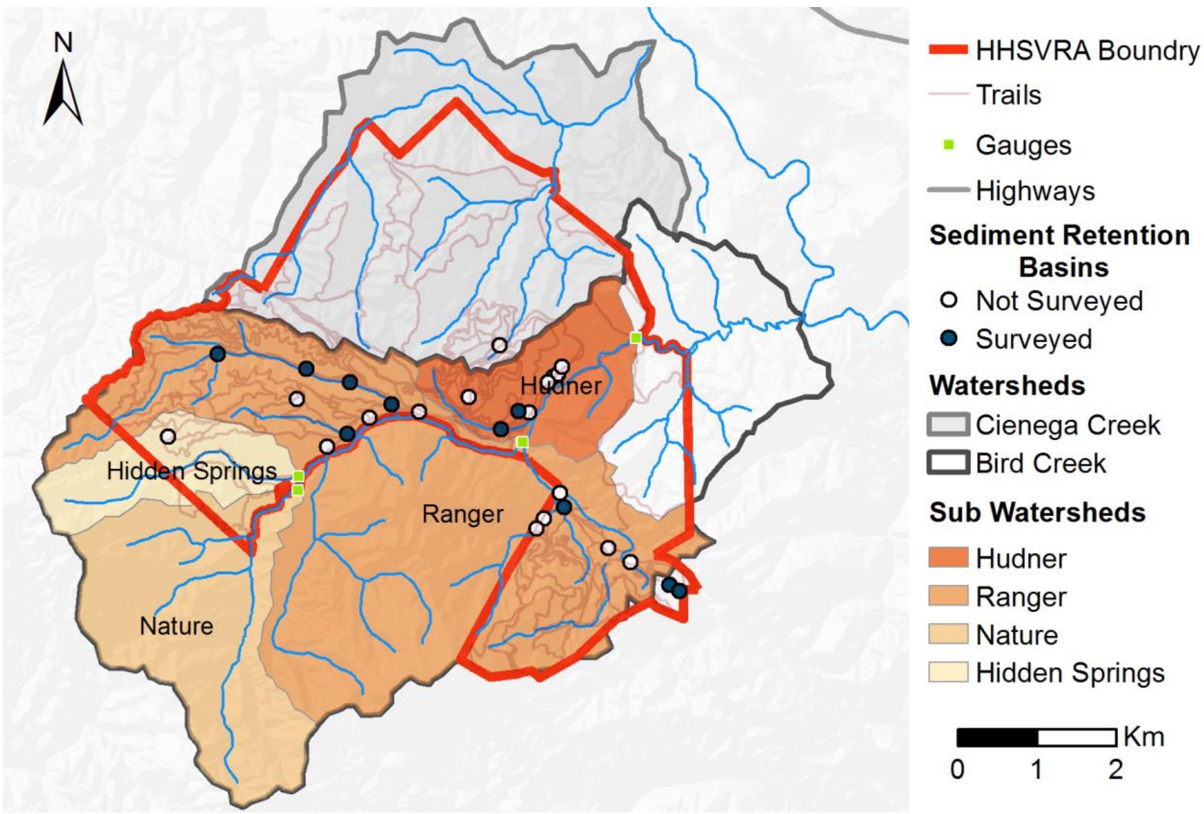


Figure 15. Sub-watershed and HHSVRA sediment retention basins located within the Bird Creek watershed.

2.4.2 Coyote Trail Erosion Control

The Coyote Trail erosion control project was monitored for general effectiveness and stability. Each berm and intervening slope facet was periodically visually inspected and photographed for signs of renewed erosion and geomorphic stability. Six berms were selected for further study. Six benchmarked cross sections were established at each of the 6 berms for a total 36 transects that are periodically resurveyed to monitor project success. Surveys are conducted with autolevel and metric tape. The site was also periodically photographed to evaluate vegetative recovery.

3 Results

3.1 Hydrology

3.1.1 Precipitation

During the study, Radio Ridge had the highest average annual precipitation at 11.82 inches while GP 1 had 10.47 inches (Table 2 and 3). The rain gages have similar rain records because they are closely spaced: 2.8 km away from each other and approximately 100 m elevation difference. The spatial variability in rainfall is driven by the highly variable topography and the HHSVRA location in the rain shadow of Fremont peak, the tallest peak of the Gabilan Range. The presence of steep-walled deep canyons might also drive variability by funneling wind. The majority of the rain occurs from October to April or May, while the remaining months are typically dry. In the State-wide drought water years of 2013 to 2015, the watershed vegetation dried, exposing the clay soils to the sun earlier than usual (Fig. 16).

Table 2. Precipitation record (2012-2016) for Radio Ridge located in Hollister, California. Data from Western Weather Group (2016).

HHSVRA Precipitation Record for Radio Ridge, Hollister California (2012-2016)
Values are inches

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	0.2	1.11	0.37	0	0	0	**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**
Monthly Average	**0.49**	**1.74**	**2.60**	**1.83**	**1.25**	**2.04**	**1.03**	**0.27**	**0.01**	**0.01**	**0.01**	**0.05**	

Annual Average 11.32

Table 3. Precipitation record (2012 - 2016) for Grand Prix 1 weather station, Hollister, California. Data from Western Weather Group (2016). In 2014 the logger cut out intermittently between November and December causing lower precipitation measurements than for those months.

HHSVRA Precipitation Record for Grand Prix 1 (GP 1), Hollister California (2012-2016)
Values are inches

Water Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
2011	0.81	2.21	4.28	1.71	4.27	4.02	0.21	1.1	0.32	0	0.01	0	**18.94**
2012	0.83	1.78	0.12	2.40	0.71	2.48	2.28	0.03	0.06	0.02	0.00	0.00	**10.71**
2013	0.41	0.09	2.83	1.14	0.77	0.72	0.23	0.00	0.02	0.00	0.00	0.06	**6.27**
2014	0.20	0.34	0.38	0.18	2.53	1.69	0.51	0.00	0.00	0.00	0.00	0.08	**5.91**
2015	1.44	0.50	5.42	0.00	1.22	0.17	1.21	1.37	0.00	0.01	0.07	0.05	**11.46**
2016	0.15	3.22	2.86	5.44	0.82	4.53	0.92	0.06	0.01	0.00	0.00	0.00	**18.01**
Monthly Average	**0.61**	**1.19**	**2.32**	**1.83**	**1.21**	**1.92**	**1.03**	**0.29**	**0.02**	**0.01**	**0.01**	**0.04**	

Annual Average 10.47

Figure 16. In March, the HHSVRA grazing hills are typically green and full of wildflowers. In March 2013, prematurely dry south-facing hills were juxtaposed against more typical spring vegetation, including grasses and lupines, preserved for a few weeks longer on the north-facing slopes.

3.1.2 Streamflow

Water discharge was gaged at Nature and Hudner areas of the HHSVRA (Fig. 17 and 18). Variability in flow correlates directly with rainfall. The soils are very dry at the end of each water year, so the first several rainfall events infiltrate without producing surface runoff. Stream flow and winter base flow only occurs after several storms have saturated the soils. In the drought years, the clay soils developed exceptionally deep polygonal cracks, locally up to 0.4 m deep. The resulting macroporosity infiltrated nearly all the precipitation, leaving little for runoff in bird Creek (Fig. 19). Base flow typically ended at Nature in April, but continued throughout the year at Hudner when there was enough groundwater to serve the spring located upstream from the gage. In water years 2013 and 2014, Bird Creek did not have continuous flow between the Nature and Hudner gages, and it connected only briefly in water year 2015. On average, peak discharge at the Hudner gage was approximately three times the magnitude of peak discharge at Nature.

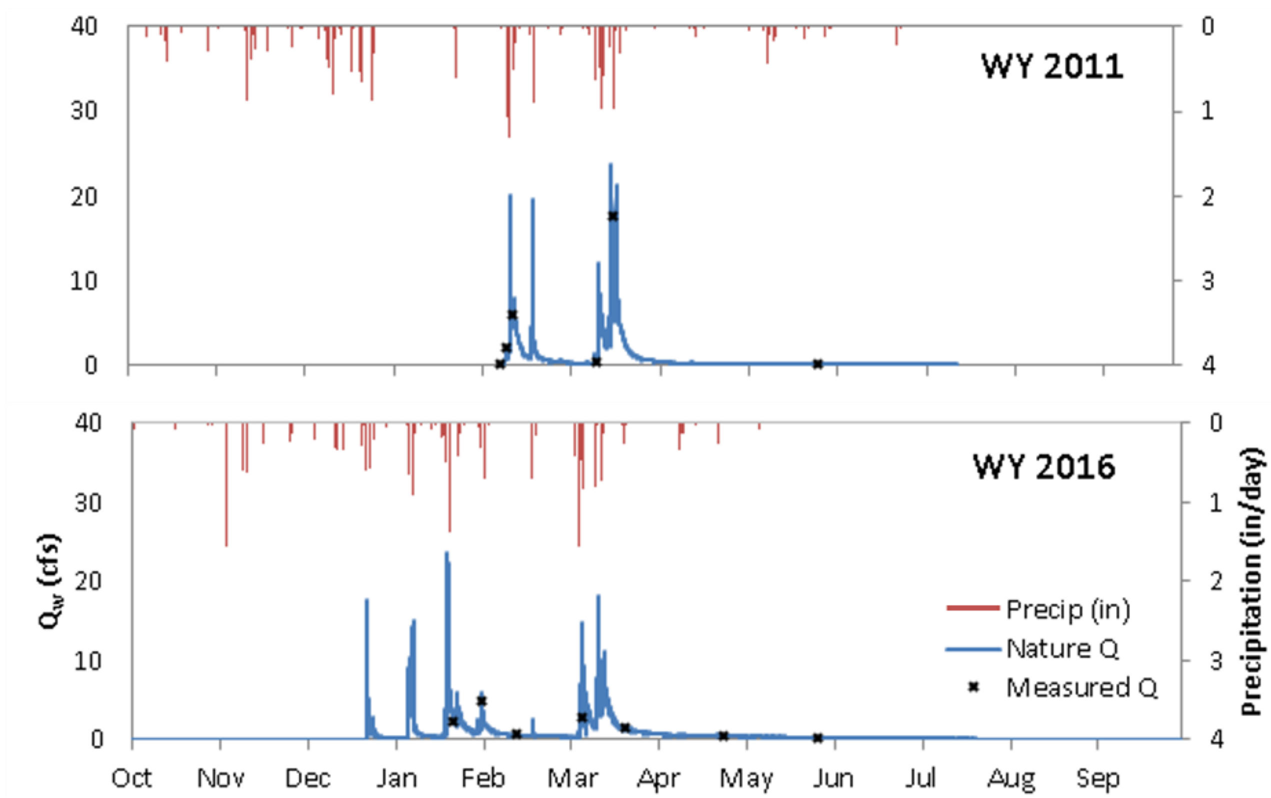


Figure 17. Rainfall at the Radio Ridge gage is plotted with stream discharge measured at the Nature gage (Fig. 11). The gage was installed in February of 2011, so early runoff events were not captured in that water year. Nature gage showed insignificant flow in water years 2012 to 2015.

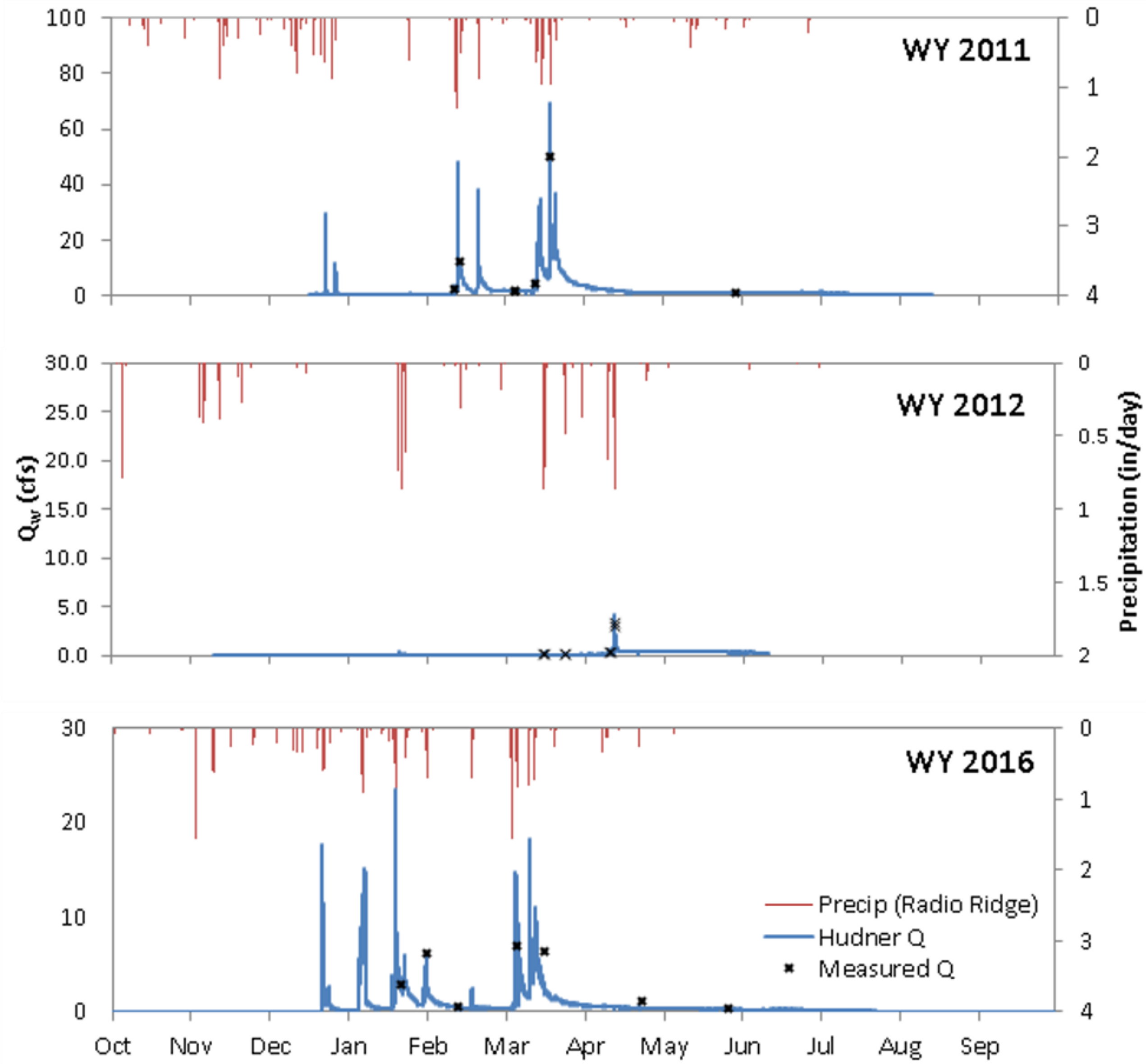


Figure 18. Rainfall at the Radio Ridge gage is plotted with stream discharge measured at the Hudner gage (Fig. 11). The Hudner gage showed insignificant flow in water years 2013 to 2015.

Figure 19. Deep, polygonal cracks form during the dry months. In 2013, the cracks formed prematurely in March. View west toward Cienega Road.

3.2 Sediment Transport

3.2.1 Bed Load

Bed load was sampled in the 2011 Water Year at Nature and Hudner gage locations (Fig. 20). Total mass of bedload passing Nature and Hudner gage locations was approximately 21 kg and 176 kg respectively (Table 4). Bedload was not sampled in subsequent years because the transport volume was an insignificant proportion of the total load. Apparently, sediment basins employed in the region are very efficient bedload traps.

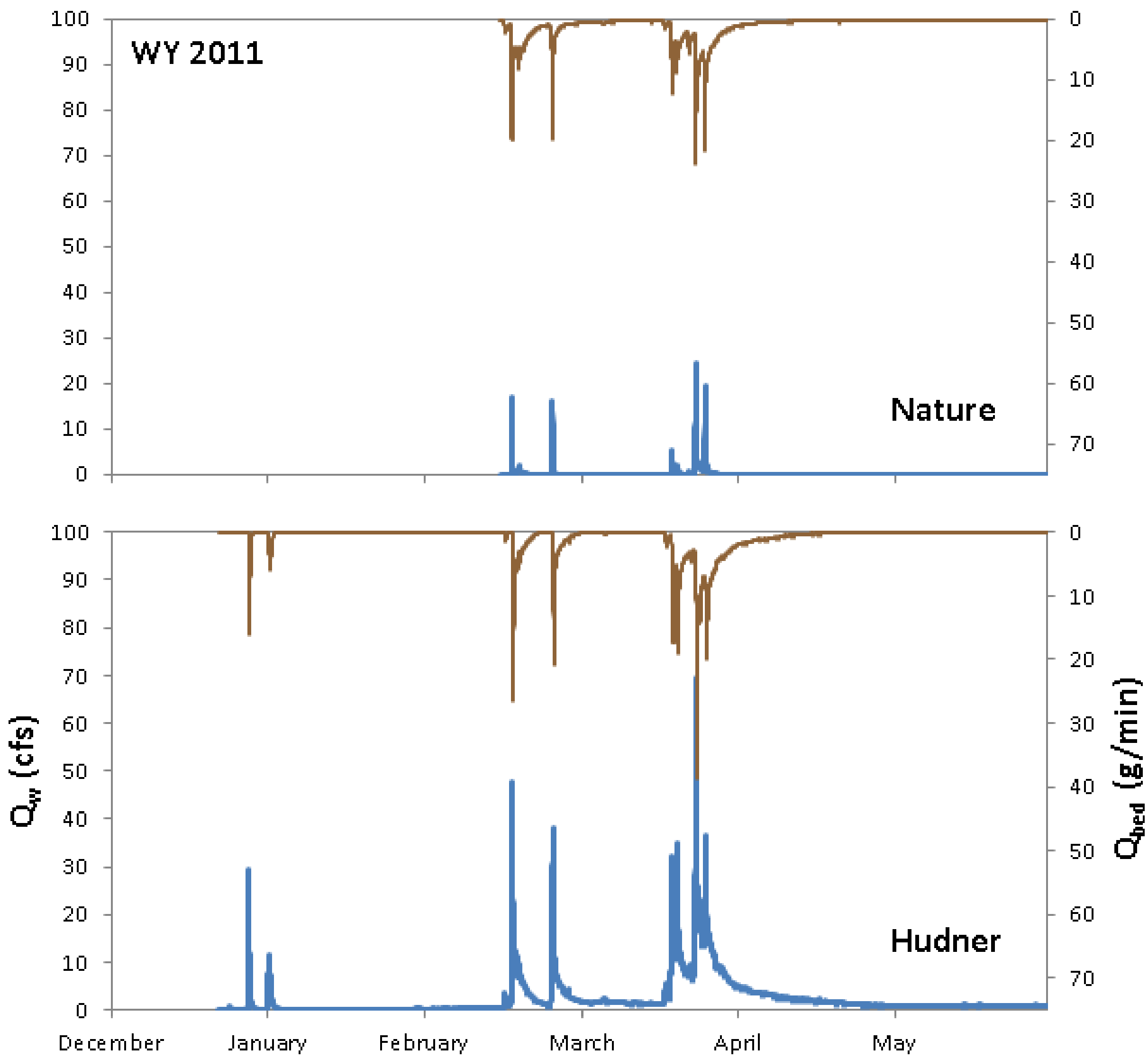


Figure 20. Bedload and water discharge for WY 2011.

Table 4. Bedload values for WY 2011.

	Gaged Period	Threshold for bedload movement	Peak Q_{bed}	Total Bedload	
	mm/dd/yyyy	cfs	g min^{-1}	kg	tonnes
Nature Area	2/15/2011 - 10/1/2011	2.17	24	21	0.02
Hudner	12/23/2010 - 10/1/2011	1.84	38	176	0.18

3.2.2 Suspended Load

The Nature gage was rated for suspended sediment transport for WY 2011 and 2016 (Fig. 21). There was insufficient flow for rating in the intervening drought years. Peaks in suspended sediment transport correspond to storm runoff peaks in WY 2011. In WY 2016, three storms in March produced runoff peaks of approximately 20 cfs, but the flows remained relatively clear of suspended sediment (Fig. 21). Apparently the earlier storms accessed all the loose, readily transported sediment that was available. Perhaps the previous drought years interrupted the gradual flow of colluvial material toward the channel network, leaving a deficit in the first post-drought rainy year.

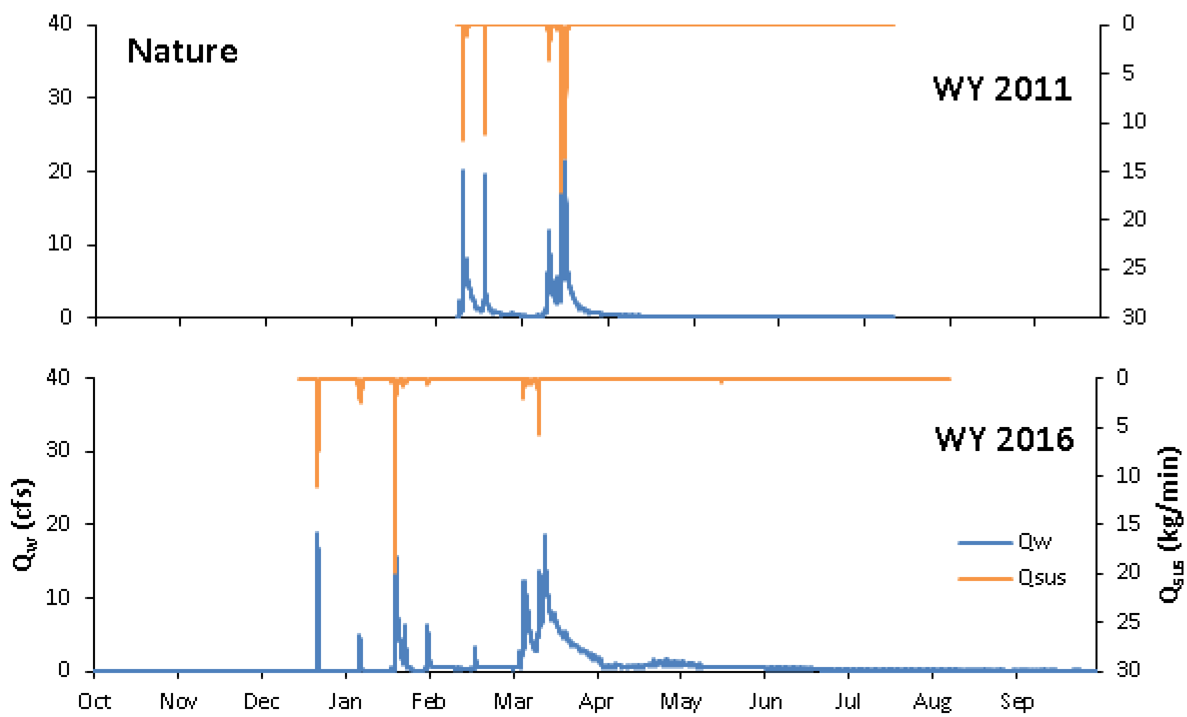


Figure 21. Gaging records for water discharge (blue) and suspended sediment discharge (orange) at Nature gage.

The Hudner gage was rated for suspended sediment in WY 2011, 2012, and 2016 (Fig. 22). There was no measurable sediment transport in WY 2013 and 2014. Low rainfall and runoff conditions of WY 2012 resulted in virtually no suspended sediment transport as indicated by visual inspection of the creeks and turbidity readings from the Hudner gage sonde (Fig. 22).

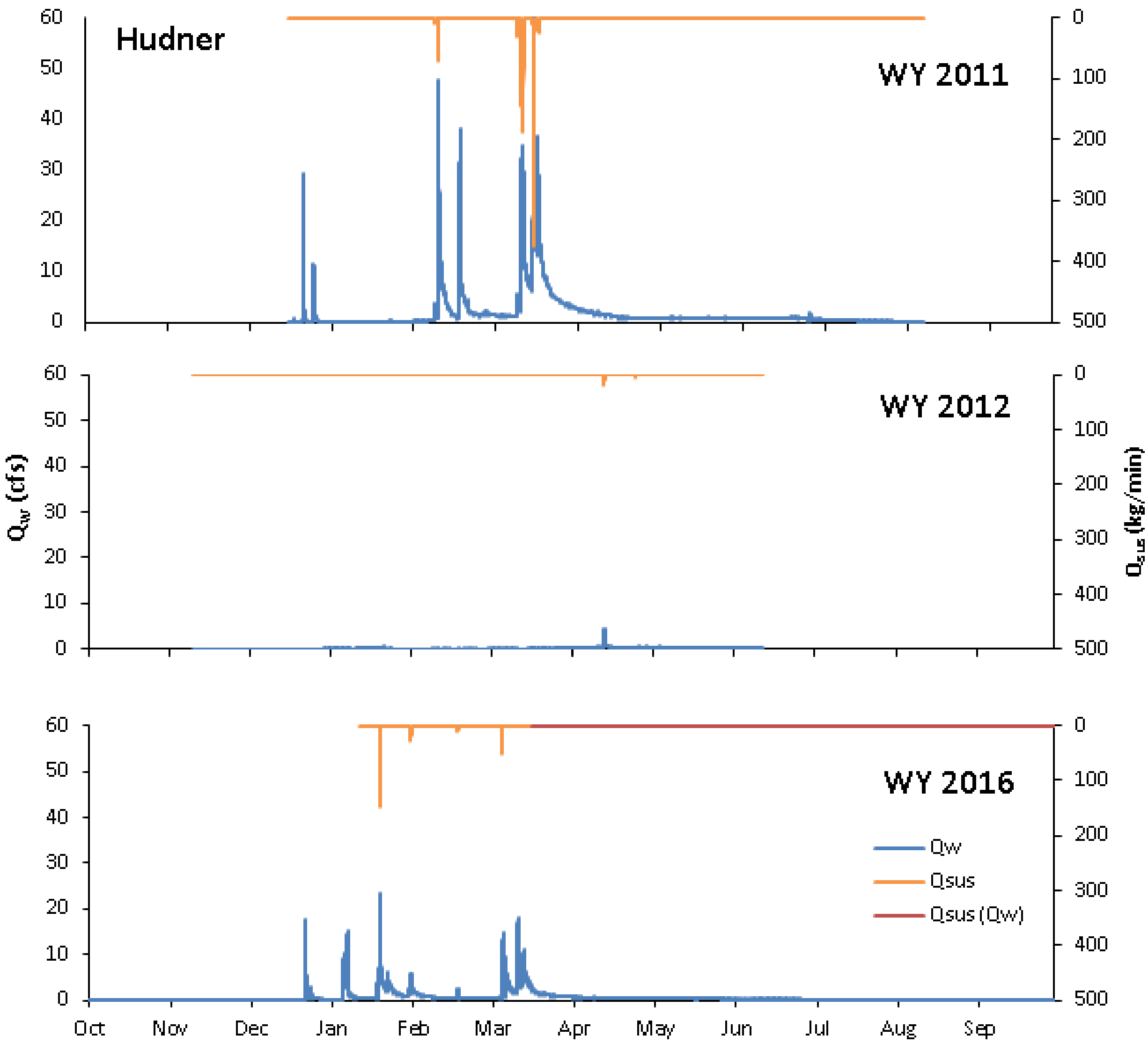


Figure 22. Gaging records for water discharge (blue) and suspended sediment discharge (orange) at Hudner gage. The record starts late in WY 2016 because the gage was not operating. The red line indicates when the suspended sediment was no longer rated using turbidity.

Table 5. Summary of suspended sediment yield through time.

Water Year	Rainfall (in)	Gaged Period Nature	Hudner	Qsus (tonnes) Nature	Hudner	Diff	Yield (tonnes/km^2) Nature	Hudner	Diff
2011	19.46	2/15/11-10/1/11	12/13/10-10/1/2011	12	183	171	1.0	4.8	3.8
2012	10.72	-	11/9/11-6/12/12	-	11	-	-	0.3	-
2013	9.78	Insufficient Flow							
2014	6.05	Insufficient Flow							
2015	10.76	Insufficient Flow							
2016	19.30	12/15/15-8/8/16	1/11/16-10/2/16	17	67	50	1.4	1.7	0.4

3.3 Sediment Sources

3.3.1 Off Highway Vehicle Use

Trail erosion was assessed by subtracting precise DEMs surveyed at 18 sites throughout the park (Teaby et al. 2013a; Silveus et al. 2014, Chow et al. 2015; Chow et al. 2016). Sites were categorized by use designation, soil type and a three-level, visually assessed, erosion potential (red, yellow, green; HHSVRA 2012).

Average annual trail erosion values show that "red" trails have the highest average erosion (Fig. 23). Figure 24 indicates that trails on granite soils southwest of the San Andreas Fault have a higher erosion rate than trails on clay soils located northeast of San Andreas Fault. During the study period, green and yellow trails typically had 0.02 m of erosion each year (Fig. 23). Water year 2016 produced the highest erosion rates because it had the highest rainfall of the trail erosion study period.

Avg Elev Δ	Green	Yellow	Red
2013-2014	-0.02	-0.03	-0.02
2014-2015	-0.02	-0.02	-0.03
2015-2016	-0.02	-0.01	-0.10
2013-2016	-0.02	-0.02	-0.05

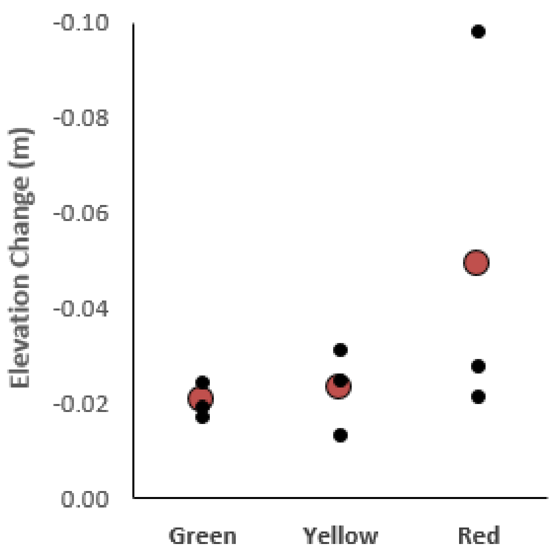


Figure 23. Average elevation change ("Avg Elev Δ," m) for each year separated by site condition. Black dots indicate annual average erosion. The larger, red dots indicate total average erosion between 2013-2016. Positive numbers indicate deposition and negative numbers indicate erosion (Chow et al. 2016).

Avg Elev Δ	Clay	Granite
2013-2014	-0.02	-0.03
2014-2015	-0.02	-0.03
2015-2016	-0.04	-0.05
2013-2016	-0.02	-0.04

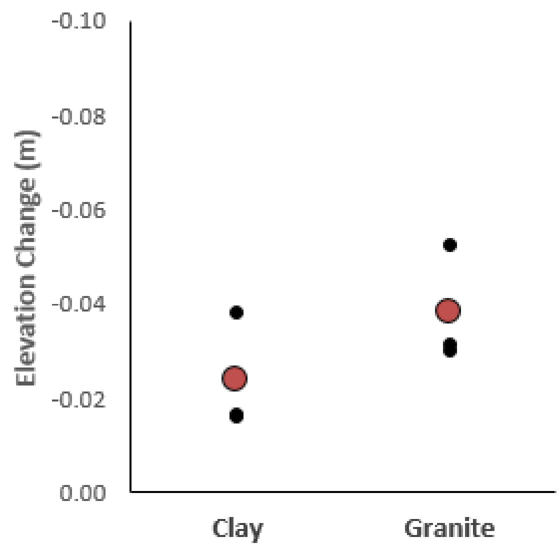


Figure 24. Average elevation change ("Avg Elev Δ," m) for each year separated by soil type. Black dots indicate annual average erosion. The larger, red dots indicate total average erosion between 2013-2016.Positive numbers indicate deposition and negative numbers indicate erosion (Chow et al. 2016).

The trail erosion study has shown that little trail erosion occurs in dry years, and that the erosion is highly variable. Continuing the study in average and greater than average precipitation years will improve the accuracy of the long-term sediment yield calculations. Using the very poorly constrained grand average erosion rate for the colored trail classification, we can obtain a very rough estimate of the OHV erosion volume in Bird Creek through extrapolation. We determined the volume of erosion per meter of trail length in the subset of trails for which red, yellow, and green assessments had been made, and then extrapolated that average result (0.075 m^3/m/yr) to the unassessed trails in Bird Creek. For the extrapolation, we make three assumptions:

1) The unassessed trails have the same relative abundance of red, yellow and green trails as the assessed trails.
2) The erosion rates measured in WY 2016 represent a reasonable average annual value, given that the region received approximately average precipitation.
3) The trail erosion material includes both bedrock and loose sandy soil, so we use a density of 2 tonnes/m^3 to convert volume to mass. This density value is a compromise between loose sand (1.6 tonnes/m^3) and quartzo-feldspathic bedrock (2.65 tonnes/m^3).

All three assumptions may be poor, and we do not have much erosion data, especially for red trails from WY 2016 (Chow et al. 2016). Given those parameters, the annual Bird Creek trail erosion value is loosely 20,800 tonnes/yr.

Local evidence from Hidden Springs watershed indicates that our extrapolation method provides a gross overestimate, at least locally. The trail erosion in Hidden Springs watershed is estimated to be 820 m^3 (1640 tonnes)/yr, based upon the extrapolated trail erosion values. Hidden Springs is the only Bird Creek tributary in the park that does not have a sediment basin near its mouth, but Tule Lake traps a portion of the runoff from trails located high in the watershed. Hidden Springs has a very steep channel with steep canyon walls, so there should be a very short lag time between peri-channel erosion events and sediment transport into Bird Creek. Direct visual monitoring during almost all peak runoff events during the past 6 years absolutely precludes a high sediment transport rate (bedload or suspended load) from the mouth of Hidden Springs (but see description of non-OHV sourced sediment in next section). In summary, either our extrapolated trail erosion estimates for the Bird Creek watershed are too high, net long-term sediment storage of eroded material is occurring on colluvial slopes, Tule Lake traps nearly all the Hidden Springs sediment, or the balance of erosion volume and channel transport volume is achieved over longer time frames longer than 6 years.

3.3.1.1 Bedload from Hidden Springs

We visually assessed the input of storm runoff and sediment from all major tributaries during WY 2011 to determine which tributaries to study in more detail. The Tributaries were all impounded behind large sediment basins, and generated no runoff or sediment to the Bird Creek channel. The one exception is Hidden Springs, which is the only major tributary lacking a retention basin near its mouth. Despite not having a sediment basin, Hidden Springs carried no bedload and virtually no suspended load as observed during peak runoff events during the year, and the Bird Creek channel showed no change in bed grain size above and below the confluence with Hidden Springs.

During the peak flow of Winter 2012, Hidden Springs began transporting coarse sand and small gravel as bedload on top of the boulder armor layer that was previously exposed. Field investigation indicated that the gravel was sourced in a small rill that had no obvious relationship to OHV use (Fig. 25).

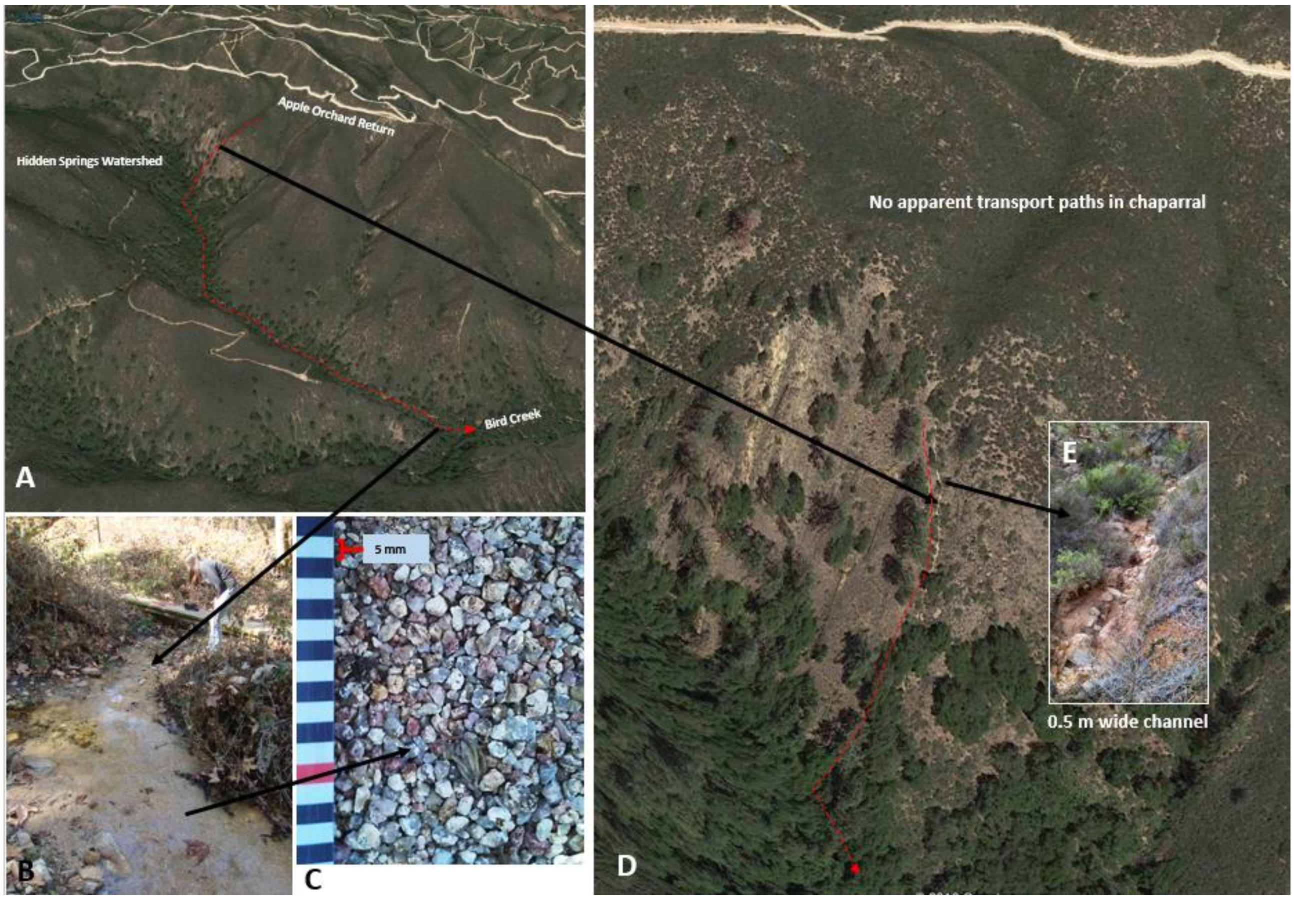


Figure 25: Gravel pathways in Hidden Springs watershed. A) Broad view of lower Hidden Springs watershed, downstream of Tule sediment basin. Red line indicates pathway of small gravel that started flowing in 2012. B) Small gravel in Hidden Spring Creek. C) Closeup showing uniform grain size of new sediment. D) Thin white line next to red is rill that transports, and perhaps sources the gravel. E) Close up of rill indicating the size in relation to typical scrubland vegetation.

Despite the presence of OHV trails above the rill, there was no indication that the rill was hydraulically connected to the roads (Fig. 25). Our conclusion is that the downcutting and headcutting rill might be the main source of fine gravel sediment. The rill will probably not deepen into a gully because bedrock is locally exposed, indicating that the regolith is very thin. Future sediment rates could increase if the rill head eventually advances upslope where it could access the sidecast road prism fill of the Apple Orchard Return trail (Fig. 25).

3.3.2 Campgrounds

A CSUMB student study in 2012 evaluated runoff pathways from campgrounds and parking lots located along the banks of Bird Creek. Madrone and Bee campgrounds featured frequently disturbed landscaped with rolling terrain, heavy vehicular traffic, and deeply incised channels. Lodge and Walnut campgrounds featured gentle slopes and long winding channels leading to Bird Creek (Fig. 26 – 28, GEOL 460 2012).

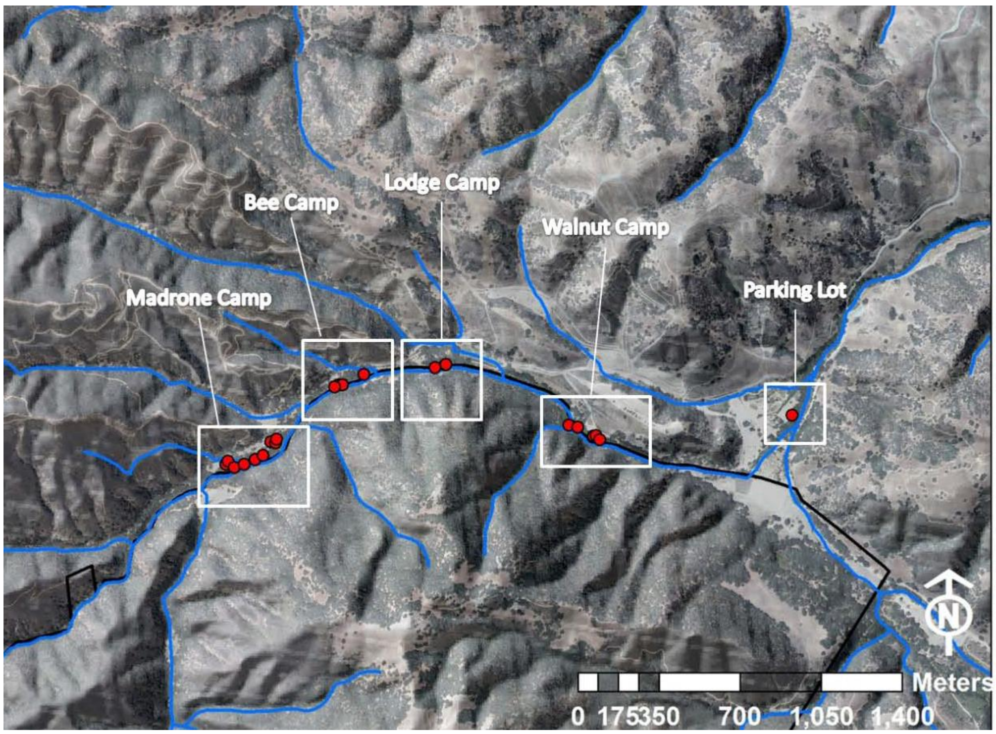


Figure 26. Location of Drainage pathways relative to Lower Ranch Campgrounds and parking lots at HHSVRA (GEOL 460 2012).

Figure 27. Rill channel pathways at Madrone (MC) and Bee Camp (BC) (GEOL 460 2012).

Figure 28. Rill channel pathways at Lodge (LC) and Walnut Camp (WC) (GEOL 460 2012).

Following the 2012 report, HHSVRA initiated significant upgrades to the campground grading and substrates, and has continued to evaluate related runoff problems. Planned studies include the use of silt fence traps to better locate and quantify remaining runoff problems from impervious surfaces near the campgrounds, administrative buildings and other outbuildings.

3.3.3 Stream Bank and Channel Erosion

Bank pin exposure was used to calculate volume and mass of sediment eroded from Bird Creek stream banks in 2011, 2012, 2014, 2015, and 2016 (Table 6). The resulting masses are highly variable from year to year. In particular, as the study moved forward, several bank pins gradually became covered by colluvium slumped from the upper bank that was not removed in subsequent droughty years. So, the number of bank pins used to determine erosion rates changed through time. The reduction in bank pin number also reduced the diversity of bank sites that were used in the average, so errors in extrapolated values likely increased as well. The WY 2011 rate may have been higher than the rest because it followed a year with relatively high rainfall in the state. That high runoff might have washed colluvial deposits away from the lower bank, leaving the banks ripe for a year with high pin exposure. The annual average rate of bank erosion measured on just the 2800 m of Bird Creek between the San Andreas Fault and the park boundary was 65 tonnes. This value underestimates the total contribution of bank erosion to Bird Creek because there are 10's of kilometers of stream channel located upstream of the fault that were not assessed. Given the results of cross section surveys provided below, there is no recent chronic channel incision events that would have led to the measured bank erosion. Therefore, the bank erosion is probably typical of the region, rather than being driven by excess runoff from the park, or other runoff sources.

Table 6. Volume and mass of bank pin erosion in Bird Creek.

2011	2012	2013	2014	2015	2016		
0.028	0.007	--	0.022	0.001	0.001	m	Average pin exposure
200	50	70	70	8	9	m^3	Total volume of stream bank erosion
180	50	70	70	8	9	tonnes	Total mass of stream bank erosion

Average mass of bank erosion	65 tonnes

Benchmarked cross sections of Bird Creek at the Hudner area were surveyed approximately annually to capture major geomorphic changes that would indicate whether the creek is storing, sourcing, or just transporting sediment (Fig. 29; Appendix A). Serial cross sections surveyed for six years indicate that Bird Creek transported the sediment supplied to it without net aggradation or degradation of the channel. This behavior indicates that Bird Creek is in a state of steady-state equilibrium with the sediment supply from the watershed as measured over a 6-year period (e.g., Ritter et al. 2011). While local cattle-derived fine sediment locally covered the channel bottom with a few centimeters of fine sediment, the material washed through the system once stream discharge renewed, leaving no lasting geomorphic changes.

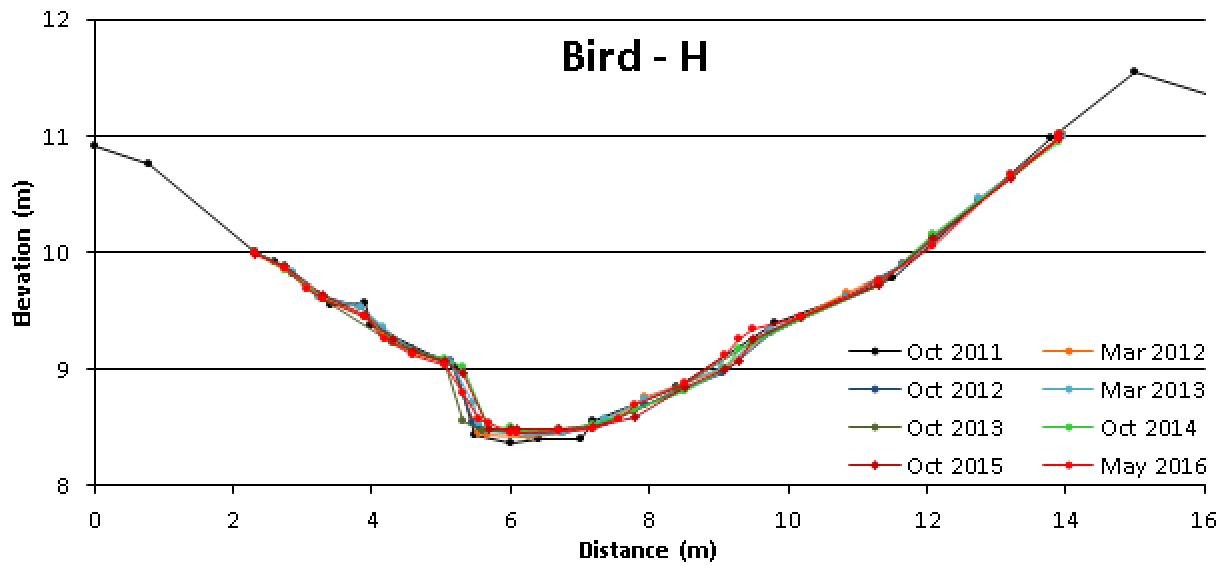


Figure 29: Cross section H shows the typical history of all the cross section locations in the Hudner reach of Bird Creek. Other cross sections are in Appendix A.

Benchmarked cross sections were also measured from time to time on Bird Creek near Walnut Camp (Fig. 10). This reach is located in the granitic soils, rather than the clay soils of Hudner. Cross sections did not change significantly during the study period, and a minor knick point at that site did not significantly erode, so we interpret steady-state equilibrium to be in effect there on the time-frame of the study as well (GEOL 460 2012).

3.3.4 Cattle

Direct cattle impacts on the banks and bed of Bird Creek include sporadic, rare access when riparian cattle fencing within the HHSVRA is accidentally breached by cattle. A comparative study of one such incident indicated that the cattle hooves sheared fine-grained sediment in the stream banks, leaving a several cm thick veneer of mud blanketing the previously gravelly channel bottom (Fig. 30; GEOL 460 2012). Drought years followed that accidental breach, and the mud veneer was present over 350 m of channel until runoff of WY 2015 washed it downstream.

Figure 30. Hoof prints are visible in the mud in Bird Creek following an accidental breach of riparian fencing in 2012.

The HHSVRA property line splits Bird Creek along much of its length southwest of the San Andreas Fault (Fig 11). However, the park fence is located high on the stream bank within the park property, leaving the stream channel and riparian areas open to neighboring properties. Along this reach, neighboring cattle enjoy unimpeded access to the riparian zone and channel invert (Fig. 31). Sheared stream banks and manure are a chronic problem along this reach (Fig. 32).

Figure 31. Upstream view of Bird Creek in March 2012, downstream of Walnut Camp. Cattle impact from neighboring property is indicated by sheared muddy stream banks.

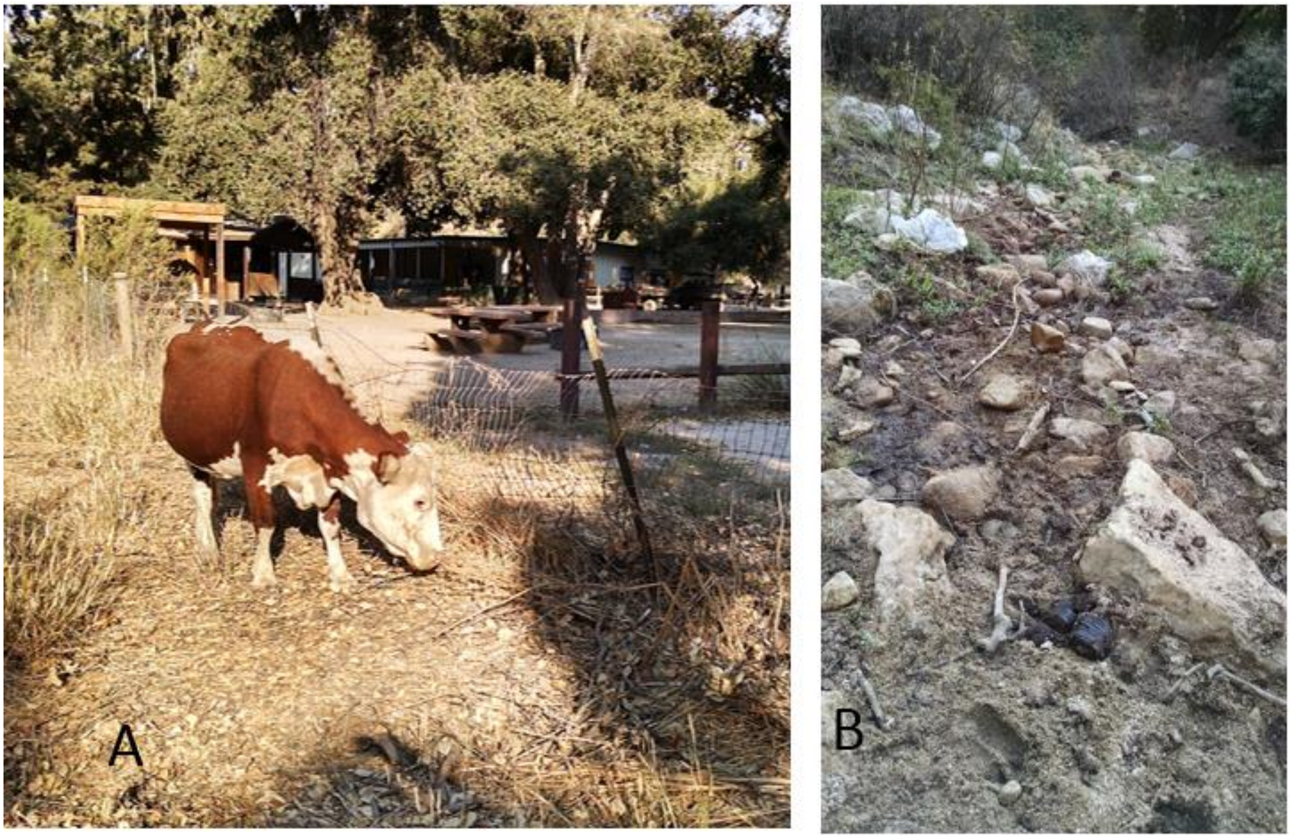


Figure 32. A) Cow in riparian terrace adjacent to park fence at Faultline Store. B) Manure in Bird Creek channel at same location as figure A.

Cattle grazing downstream of the park also includes continuous, unimpeded access to Bird Creek in the clayey soils east of the San Andrea Fault. During intense rains, the cattle trails likely contribute muddy water mixed with manure to the Bird Creek flow that contributes to the San Benito River. Similar cattle impacts are likely pervasive in the San Benito River watershed, given the proportion of land intended for that use on similar fragile soils (Fig. 2).

In summary, we do not have a numerical measurement of the cattle-generated sediment, but it is clearly a chronic source that could be better controlled, especially on neighboring properties and property downstream of the park.

3.3.5 County Road Culverts

Two county roads contribute impervious area runoff to the HHSVRA via a variety of drainage control structures and from uncontrolled runoff. San Juan Grade Road borders the park and Bird Creek watershed divide along the western edge of the park (Fig. 10). Cienega Road bisects HHSVRA land as it crossed from the Cienega watershed to the Bird Creek watershed close to the eastern edge of the park (Fig. 10).

3.3.5.1 San Juan Grade Road Drainage

Visual inspection of oblique aerial photography indicates that hydraulic flow concentration below road-draining culverts erodes HHSVRA hillslopes below San Juan Grade Road, producing a long-term chronic sediment source for Bird Creek (Fig. 33). A review of 1979 USDA aerial photographs indicate that the sediment pathways have been active and visible from the air since at least that time.

Figure 33. Oblique aerial photograph of hillslope erosion concentrated below a subset of culverts along San Benito County's San Juan Grade Road. White arrows point to vertical runoff paths delivering hydraulically concentrated culvert flow onto the HHSVRA slopes. Google Earth image from 2015.

Bedrock material underlying san Juan Grade Road is the same as all the rock located west of the San Andreas Fault in the Bird Creek watershed; it is pervasively fractured, deeply-weathered granitic rock that generally produces small gravel (Fig. 34). The small gravel is either transported directly to channels, or stored on colluvial slopes. The bedrock does not produce much suspended sediment.

We made a qualitative evaluation of erosion hazard of the culverts draining San Juan Grade Road (Table 7; Fig. 35). Eleven of the 25 culverts were in either fair or poor condition, two of the culverts showed erosion near the culvert exit from the limited perspective of the top of the slope, and ten culverts had high enough modeled peak flows to transport gravel down the steep hill slopes (Table 7). While only two of the culverts had erosive features visible from the road, many of them are chronically generating erosive runoff on the hillslopes below the road (Fig. 35)

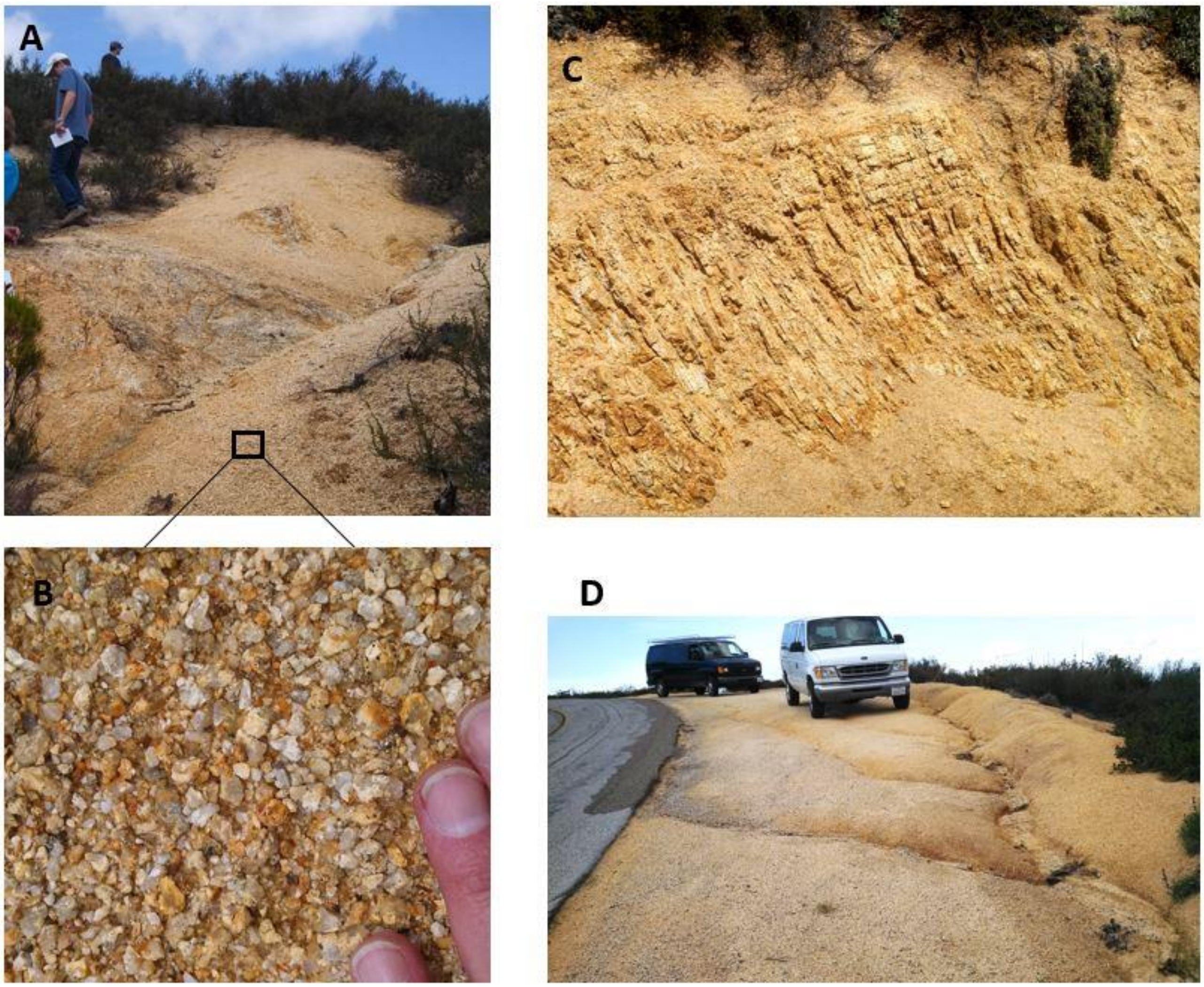


Figure 34. Source material west of the San Andreas Fault is granule and small pebble-sized quartz and feldspar derived from highly weathered bedrock. A) Bedrock outcrop of granitic material. B) close up of bedrock surface showing granule-sized crystals that are easily scraped from the outcrop by hand. C) Bedrock fractures shown in road cut are pervasive throughout the watershed. The fracturing and weathering produces only small diameter gravel for transport down the watershed drainage network. D) Unprotected shoulders are a chronic source of small gravel. Photos from spring 2013 near San Juan Grade Road.

Table 7. Stormwater Diversion Attributes. Diversion number (Div#) is in the order 1 to 25 from high elevation (SW) to lower elevation (NE) in Figure 35. Colors in the table correspond to qualitative erosion hazard based upon modeled peak discharge values (25 yr, 1.04 in/hr storm). Colors are the same in Figure 35.

Diversion Number	Diversion Type	Armored	Diversion Condition	Visible Erosion	Watershed Area (ft^2)	Peak Discharge (cfs)
1	Natural (no man made diversion)	No	N/A	No	31677	0.57
2	Natural (no man made diversion)	No	fair(fresh)	No	5565	0.10
3	Natural (no man made diversion)	No	good	No	16162	0.20
4	Natural (no man made diversion)	No	N/A	No	6816	0.09
5	Asphalt Berm Confined Spillway+Sluice	No	fair	No	6860	0.08
6	Asphalt Berm Confined Spillway	No	fair	No	3777	0.05
7	Asphalt Berm Confined Spillway	Yes	good	No	8370	0.08
8	Culvert	Yes	fair	Yes	30064	0.35
9	Asphalt Berm Confined Spillway+Sluice	No	good	No	11418	0.12
10	Asphalt Berm Confined Spillway+Sluice	Yes	poor	No	10682	0.12
11	Asphalt Berm Confined Spillway+Sluice	No	fair	No	8701	0.10
12	Decommissioned Diversion	No	poor	Yes	18982	0.22
13	Asphalt Berm Confined Spillway	No	N/A	No	3099	0.05
14	Asphalt Berm Confined Spillway	No	fair	No	1643	0.03
15	Asphalt Berm Confined Spillway	Yes	good	No	5122	0.06
16	Asphalt Berm Confined Spillway	No	good	No	4081	0.06
17	Asphalt Berm Confined Spillway+Sluice	Yes	fair	No	11007	0.14
18	Natural (no man made diversion)	N/A	N/A	No	2838	0.05
19	Natural (no man made diversion)	No	fair	No	13526	0.18
20	Natural (no man made diversion)	No	N/A	No	14033	0.24
21	Sluice	No	N/A	N/A	45365	0.45
22	Top of Culvert	Yes	fair	No	32721	0.39
23	Natural (no man made diversion)	No	good	No	17042	0.18
24	Natural (no man made diversion)	No	good	No	4450	0.07
25	Natural (no man made diversion)	No	good	No	6115	0.06

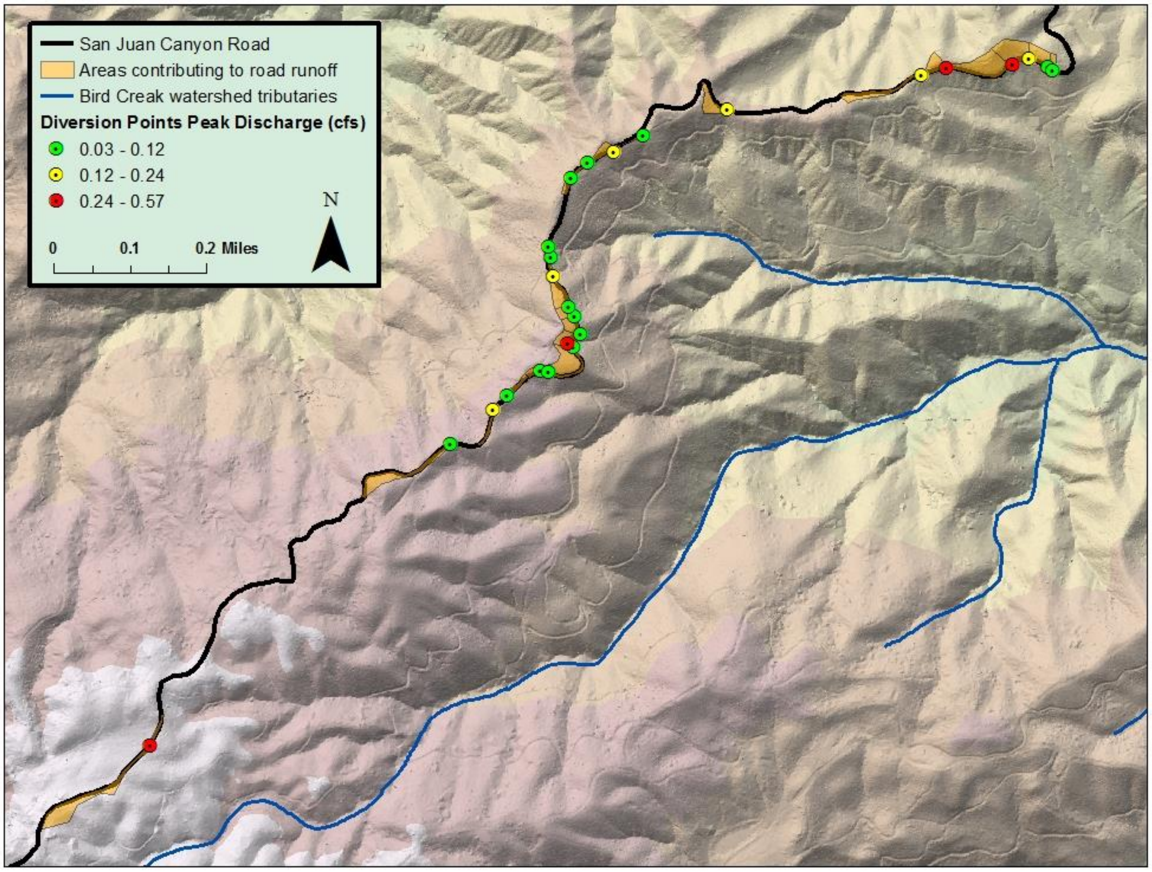


Figure 35. Peak Discharge (Q Peak) of diversions relating to relative areas contributing to San Juan Canyon Road runoff derived by rational method model. See attributes in Table 7. Culverts are numbered in order with descending elevation in Table 7, so culvert #1 is the southwestern red dot.

3.3.5.2 Cienega Road Drainage

Cienega Road crosses the clay-rich soils east of the San Andreas Fault, except where it lies directly upon the fault south of the park entrance, so the erosion style and erosion products are very different. The eroding bedrock comprises terrestrial and marine mudstone that weathers to expansive clay (Fig. 19), and the material transported from the site is nearly all suspended load material with a small fraction of sand.

Cienega Road culverts are associated with gullies within both the Cienega and Bird watersheds. We selected one gully within the Bird watershed for long-term monitoring (Gully A in Fig. 36; GEOL 460 2014).

Figure 36. Oblique aerial photograph of hillslope erosion concentrated below culverts along San Benito County's Cienega Road. Black arrows point to gullies below culverts. Gully A has benchmarked cross sections for long-term monitoring. White arrow points to a gully that developed as result of incision of culvert-related gully. Google Earth image from 2015.

Gully A is deeply incised in the ambient rolling hills, and exhibits steep, bare walls, indicative of recent incision and widening (Fig. 37). Despite the appearance of recent activity, serial cross sections spanning from 2013 to 2016 showed that the gully was stable during that time, despite the average rainfall in WY 2016. Apparently, erosion of the clayey soils results from rarer, high-magnitude events.

The HHSVRA land located downstream of Cienega Road and north of Bird Creek are used for seasonal grazing rather than OHV. The gullies and natural ravines in this part of the watershed do not have sediment basins. Suspended sediment is either captured along natural, narrow, low gradient terraces that border Bird Creek, or directly enters the Bird Creek channel.

Figure 37. Cienega Gully A: Downstream view of a portion of the gully labeled A in Figure 36. Arrows point to recently eroded gully sides with a range of heights.

A steep-walled gully (Fig. 36, white arrow) is a tributary to Gully A. It also exhibits steep bare walls of fine material indicating that it has experienced recent erosion (Fig. 38). The tall bare walls indicate that it too is a chronic source of fine sediment to Bird Creek, when rainfall rates exceed the threshold for active vertical and lateral erosion. The tributary gully (white arrow in Fig. 36) is not visible in a 1979 USDA aerial photograph, indicating that it budded from the main gully after that year.

Figure 38. A tributary to Gully A is a volumetrically important source of fine sediment in Bird Creek.

3.3.6 Landslides and Colluvial Processes

The fine-grained bedrock east of the San Andreas Fault is very unstable on moderate to high slopes (Fig. 39). It fails in slow earthflows and more rapid colluvial processes throughout the San Benito watershed where the substrate persists for 100's of square kilometers (Sheingross et al. 2012). Many landslides, with a wide range of ages are visible in a single view (Fig. 40). These slope failure features are part of the natural sediment transport system rather than related to OHV use. We selected two landslide systems (Colluvial Creek and Hudner Slide) to study in detail. We tried to determine the slope failure mechanisms and rates, and to assess whether the colluvial products are reaching Bird Creek on a time frame of interest to resource managers and the TMDL regulatory process.

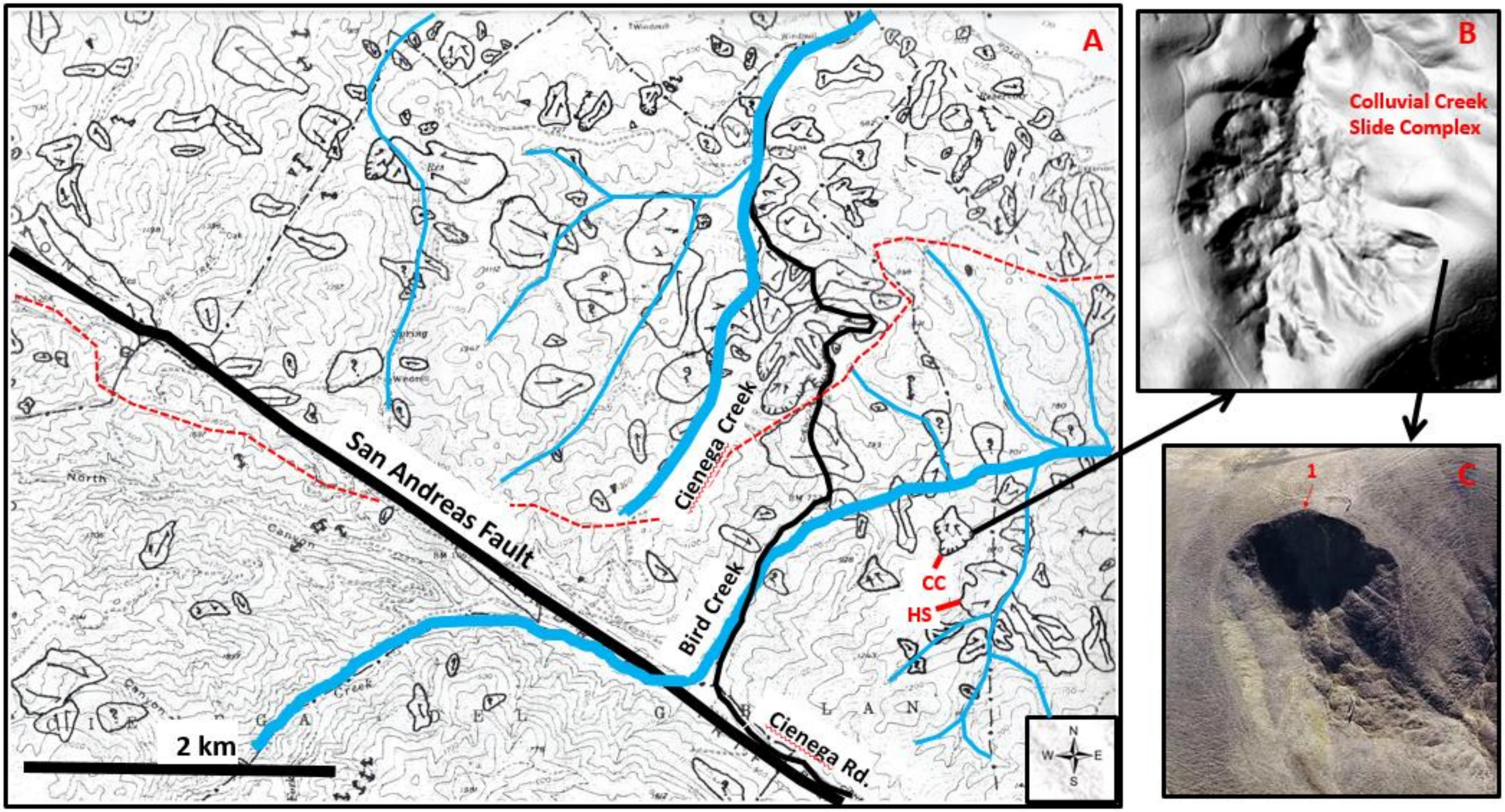


Figure 39. A) Landslide map showing approximately 80 slope failure features in the clay soils of the Bird Creek and Cienega Creek watersheds. Landslides are enclosed areas with arrows showing earthflow direction. Red dotted line is ridge dividing Bird Creek from Cienega Creek. CC is location of Colluvial Creek landslide complex. HS is Hudner slide. Modified excerpt from 1993 draft of Majmunder (1994). B) DEM of Colluvial Creek slide complex. C) Individual slump unit within the Colluvial Creek slide complex.

Figure 40. Low altitude oblique aerial view of unstable slopes in study area (foreground) and in the region, beyond. Red arrows point to a subset of slope failure features (typically "slumps") present in the region. Numbered arrows correspond to the numbered features in Figure 46. HS is headwall of Hudner Slide. OS is an example of a geomorphically "older" slide.

3.3.6.1 Colluvial Creek Slide Complex

Colluvial Creek is a small tributary to Bird creek located downstream of the Hudner stream gage and Hudner cross section reach (Fig. 10). The upper watershed is ringed with slumps (Figs. 41) and the lower watershed is a low-gradient colluvial valley and small, incised canyon-mouth fan (Fig. 42). The transition is a steep-walled, V-shaped ravine (Fig. 41).

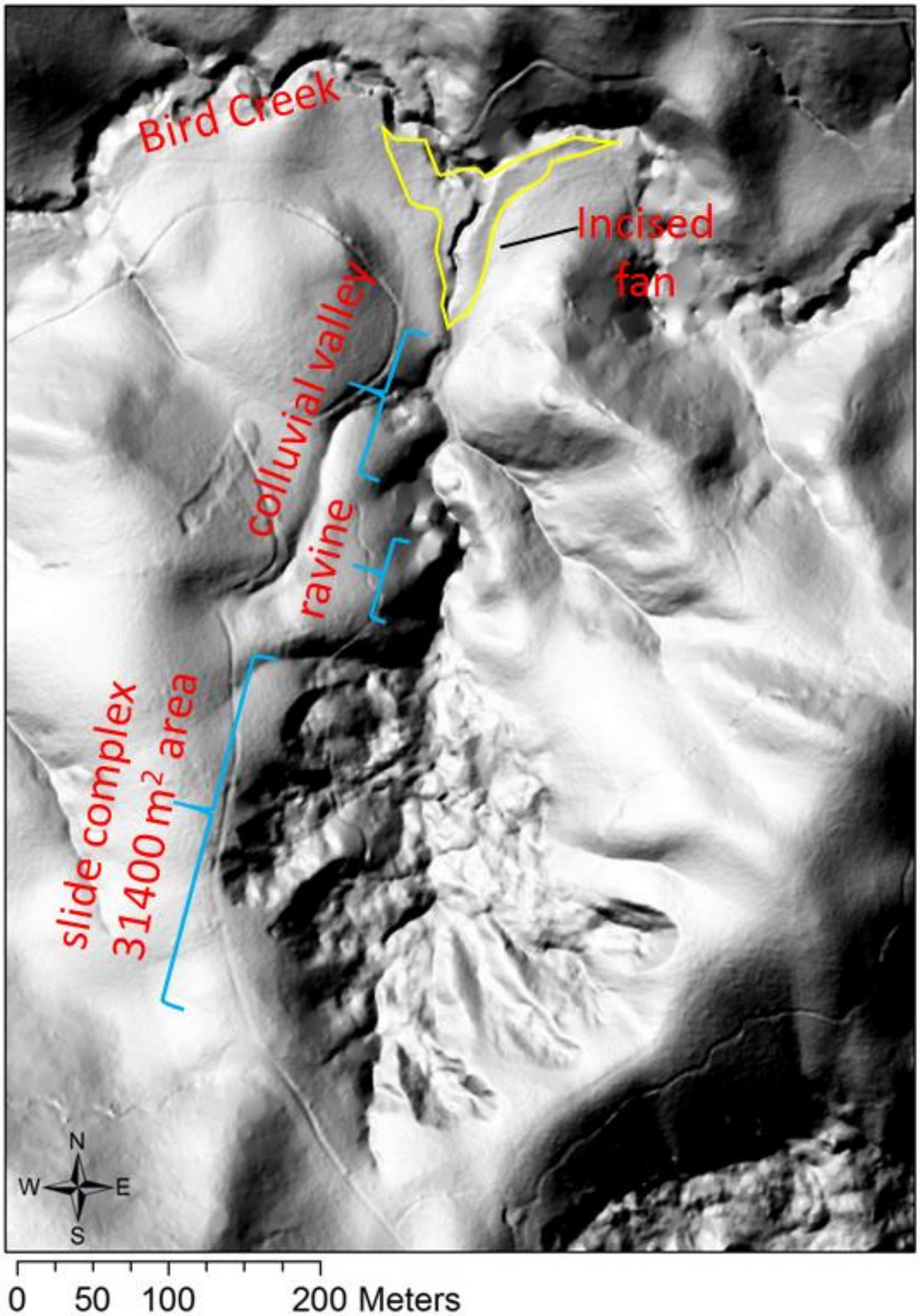


Figure 41. Key geomorphic elements of the Colluvial Creek landslide system. Location in Figure 39.

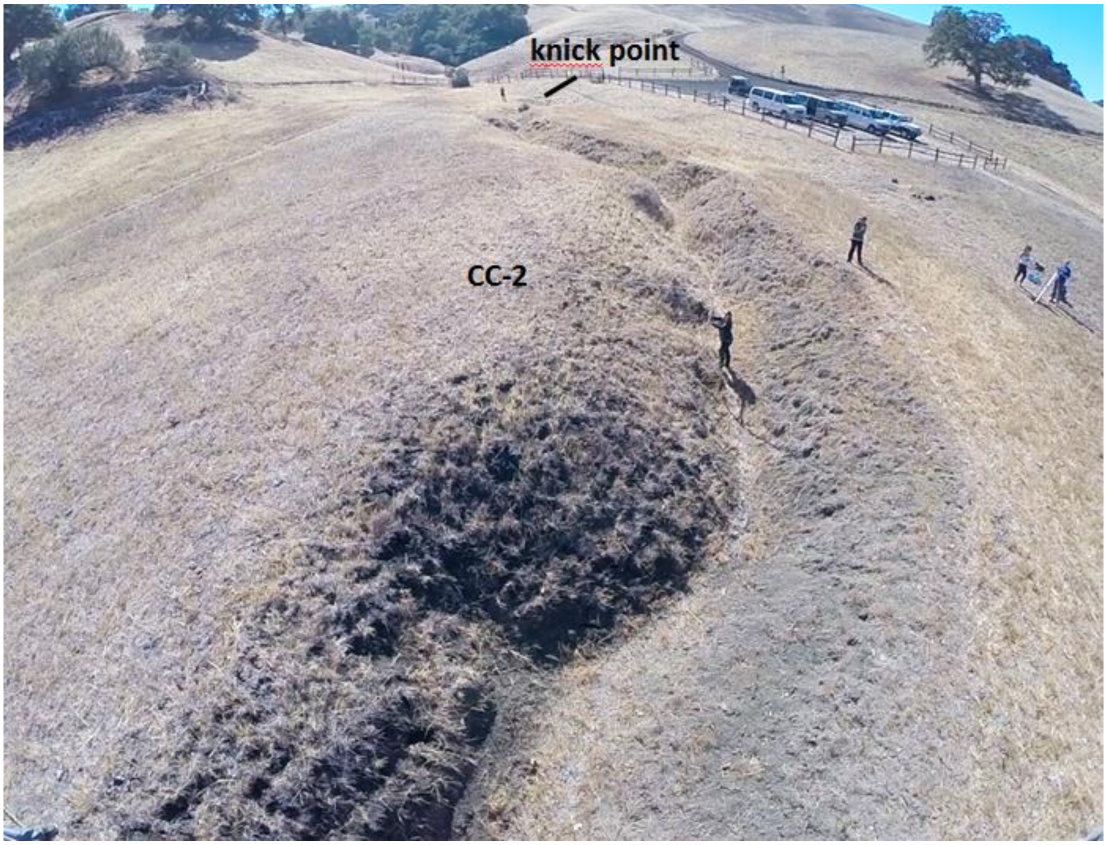


Figure 42. Oblique wide-angle view of incised canyon-mouth fan. View is up gradient from near Bird Creek. The knick point is the transition to the unchannelized valley. CC-2 is location of cross section CC-2 (Appendix).

The general processes occurring in each part of the system can be deduced by reconnaissance level investigation, and with reference to geological cross sections (Fig. 43). In general,

1) earthflows in the upper watershed transport material downward until it is impeded where the watershed narrows (approximate location of "ravine" in Figure 41);
2) the slide material is then reworked via knick points that hydraulically connect the slide body to the ravine where material is transported by dilute alluvial flow down the steep ravine;
3) when the transported material reaches the break in slope at the mouth of the ravine, the dilute flows become less competent as they spread out to fill the wider space of the unchannelized valley bottom, and the material is deposited in a laterally confined fan emanating from the ravine; and
4) the aggrading valley fill is then gradually reworked directly to Bird Creek via a second knick point that is eroding the fan, leaving a steep-sided" V"-shaped gully.

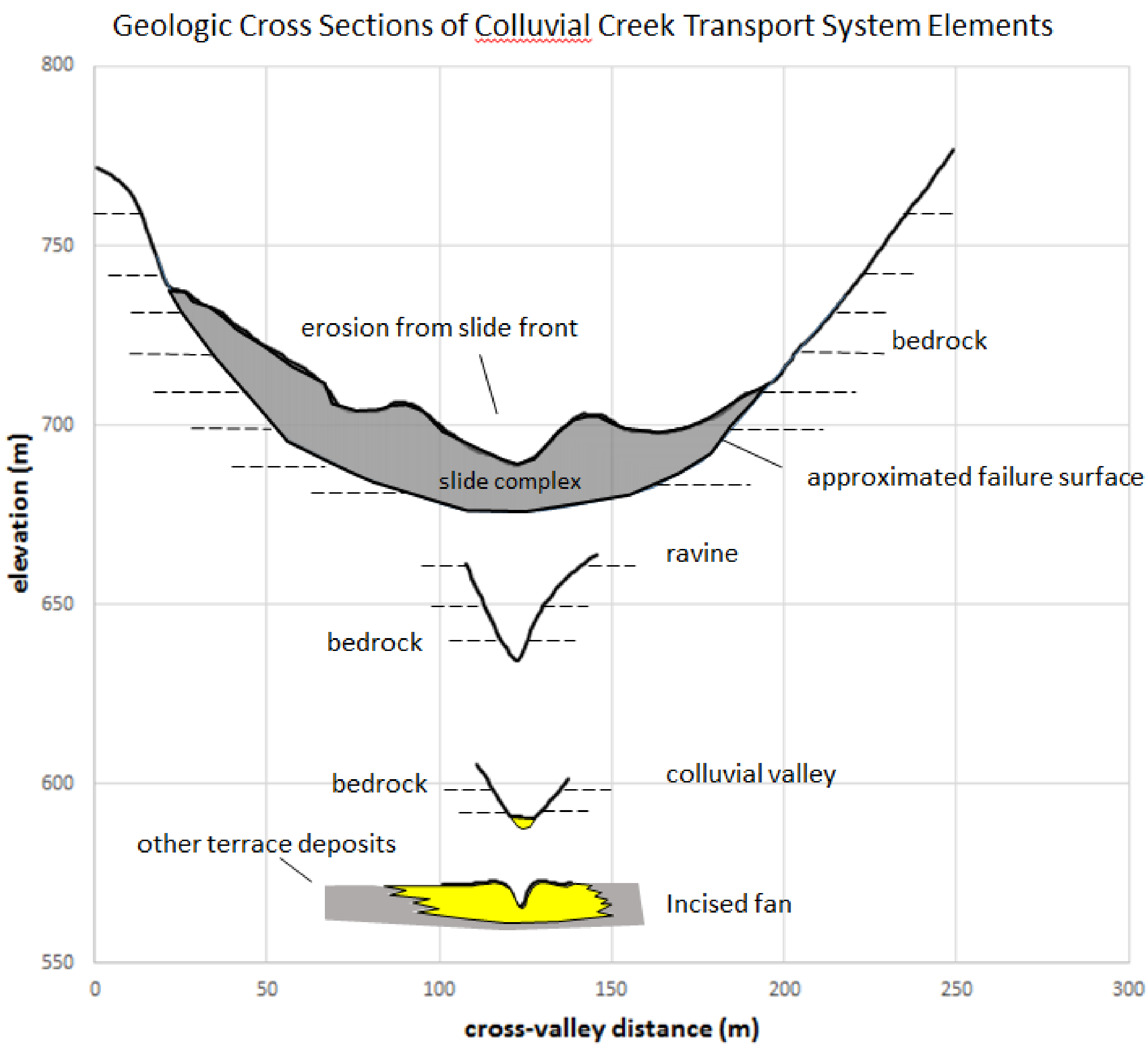


Figure 43. Properly-scaled geologic cross sections illustrating components of the Colluvial Creek sediment transport system. View is down valley. Long term storage (grey) occurs in the slide complex; no sediment is stored in the steep-gradient ravine; a small volume of alluvial fill (yellow) is stored beneath the unchannelized colluvial valley bottom; and moderate-term material storage and transport occurs in the incised fan. Surface profiles from LiDAR-derived, 1m pixel DEM. Figure 41 shows map-view spatial distribution of features.

Adding complexity to the process is the recognition that separate parts of the system do not operate synchronously, and not at the same rate. The mass (M) of material in the slide complex can be estimated as:

$$M = (\rho_s)(V) = (\rho_s)(A)(T),$$

where ρ_s is the density of the mudstone slide body (estimated at 2.07 tonnes/m^3), V is the volume (m^3), and A and T are estimates of the slide complex area and average thickness respectively. The area is approximately 31400 m^2 (Fig. 41), and the average thickness is somewhere between 10 m to 20 m (Fig. 44). Therefore the slide complex embodies between 650,000 tonnes and 1,300,000 tonnes of regolith that is progressing downslope to Bird Creek.

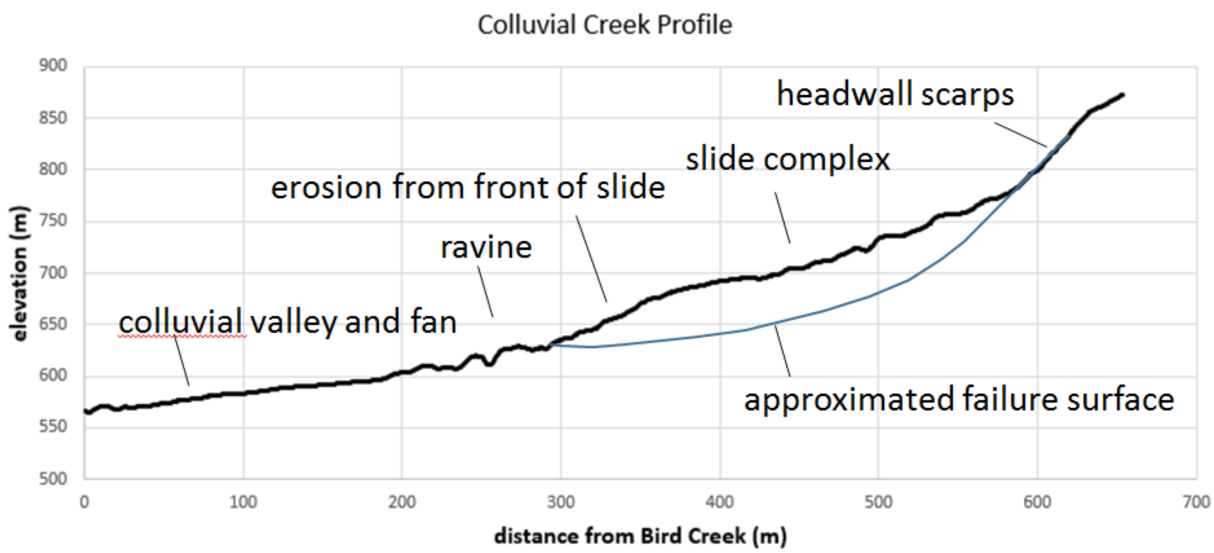


Figure 44. Longitudinal profile through LiDAR-based DEM of Colluvial Creek landslide system. Bird Creek is located 10 m down gradient of the plotted profile.

Comparison between 1979 and 2010 aerial photographs reveals that slope failure features are growing in number and size, while some are inactive and aging (Fig. 45).

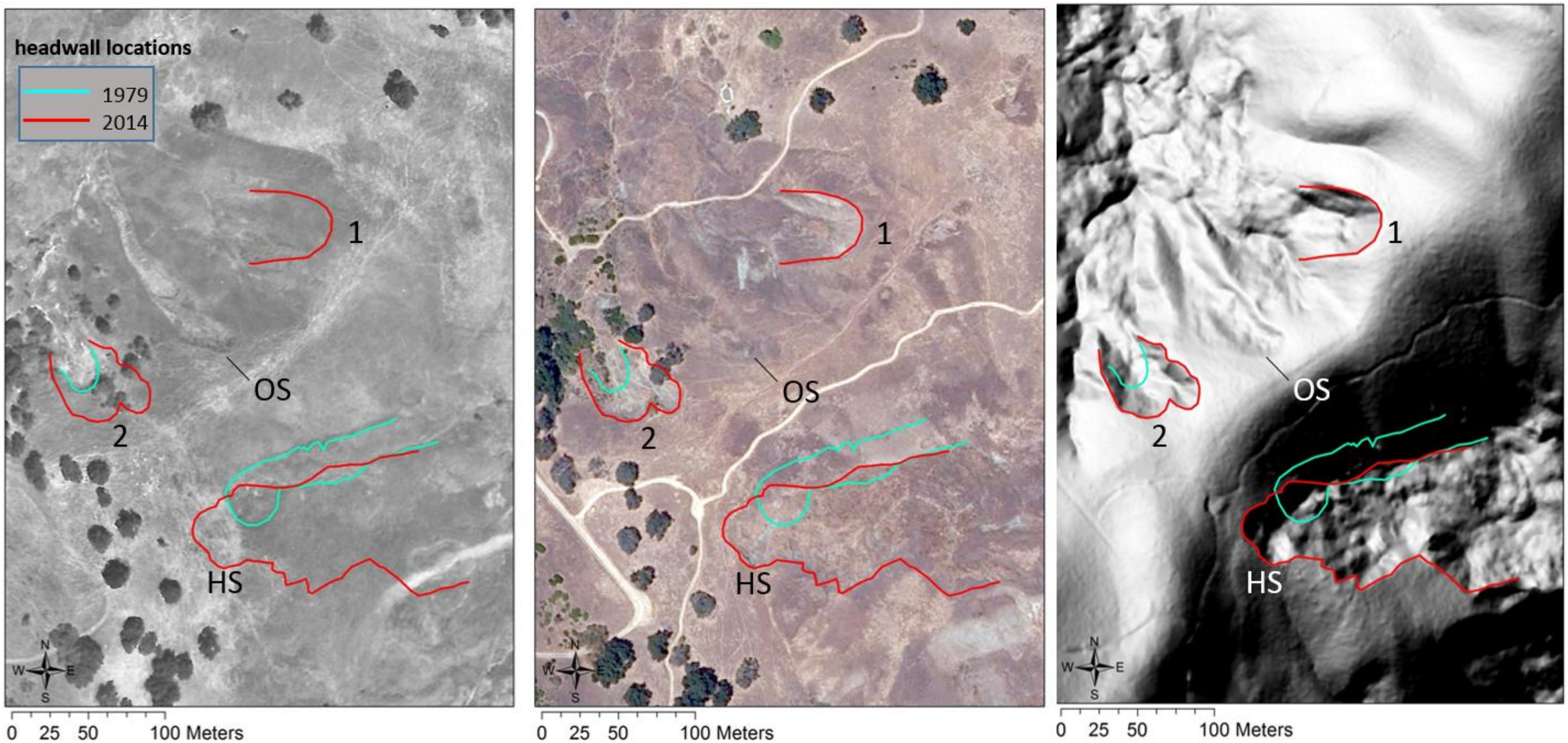


Figure 45. Left aerial photograph is from 1979. Center photograph is from 2010. Right image is a hillshade from 2010 liDAR data. The headwall scarp of slide 1 in Colluvial Creek is not present in 1979. The slide labeled OS appears youthful (sharp outlines) in 1979 and has not advanced upslope or enlarged in the 2010, however, the slide feature has now aged, as seen in Figure 40. Slide 2 of Colluvial Creek has enlarged and advanced as much as 40 m upslope. Hudner Slide (HS) has greatly expanded from the narrow earthflow in 1979 to a broad and complex slope failure seen in the 2010 hillshade. Hudner Slide is described further in the next section of the report.

Iron rods driven into 5 areas of the Colluvial Creek slide complex indicate that the slide body is active, even during drought years (Fig. 46).

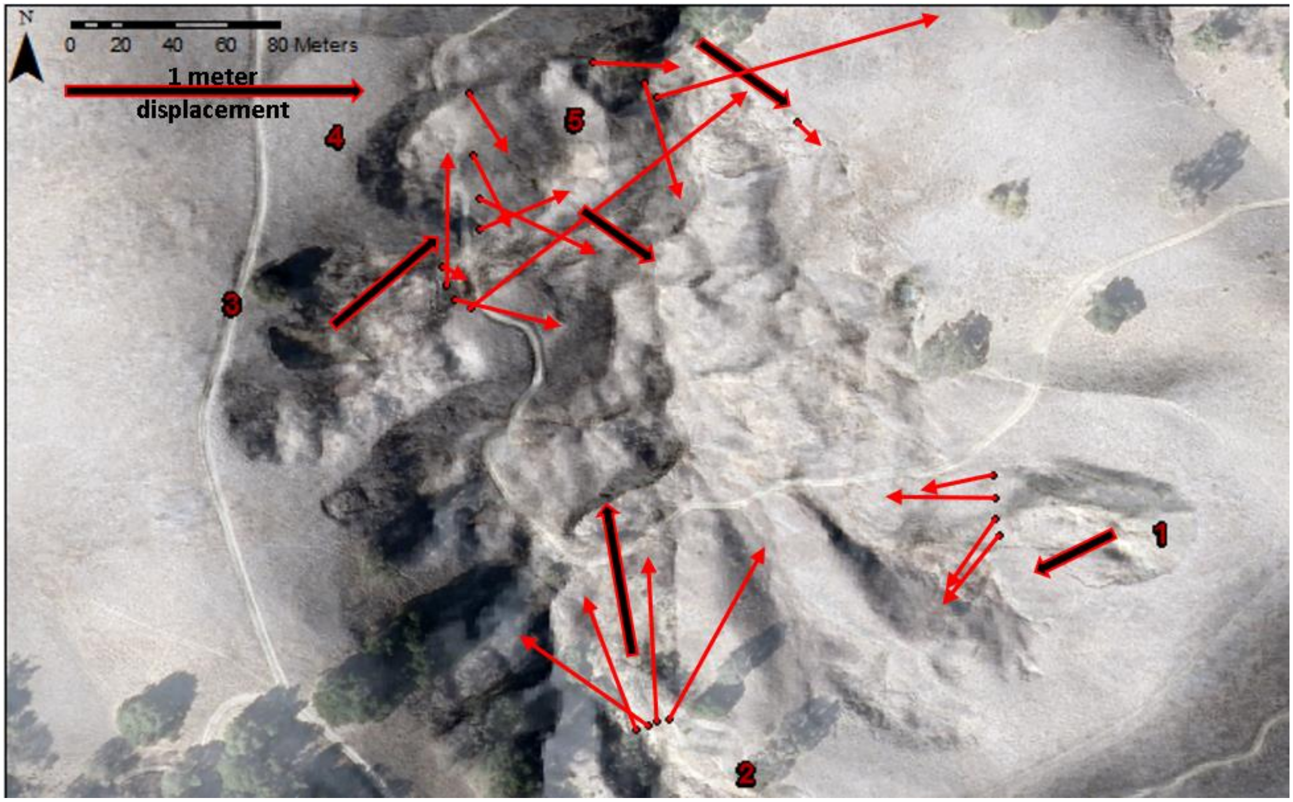


Figure 46. Colluvial Creek landslide pin movement between January 2012 and July 2016. Thinner vectors are individual iron rods. Thicker vectors are pin averages for each surveyed slide.

Given the 4.5 year span of the record, the "1 m" slip magnitude arrow scale can be considered as a "rate" scale of approximately 0.2 m/yr, which is the typical velocity for earthflows in this region, as measured by interferometric synthetic aperture radar (Scheingross et al. 2012). The velocities in Colluvial Creek are somewhat less than that average (Fig. 46), perhaps because of the drought conditions. The slip vectors near the toe (north end) of the complex may show that the slide is folding back on itself, constrained by the narrow choke point in the watershed. The slides moved faster between 2012 and 2014 and slowed thereafter, likely in response to reduced annual precipitation (Fig. 47).

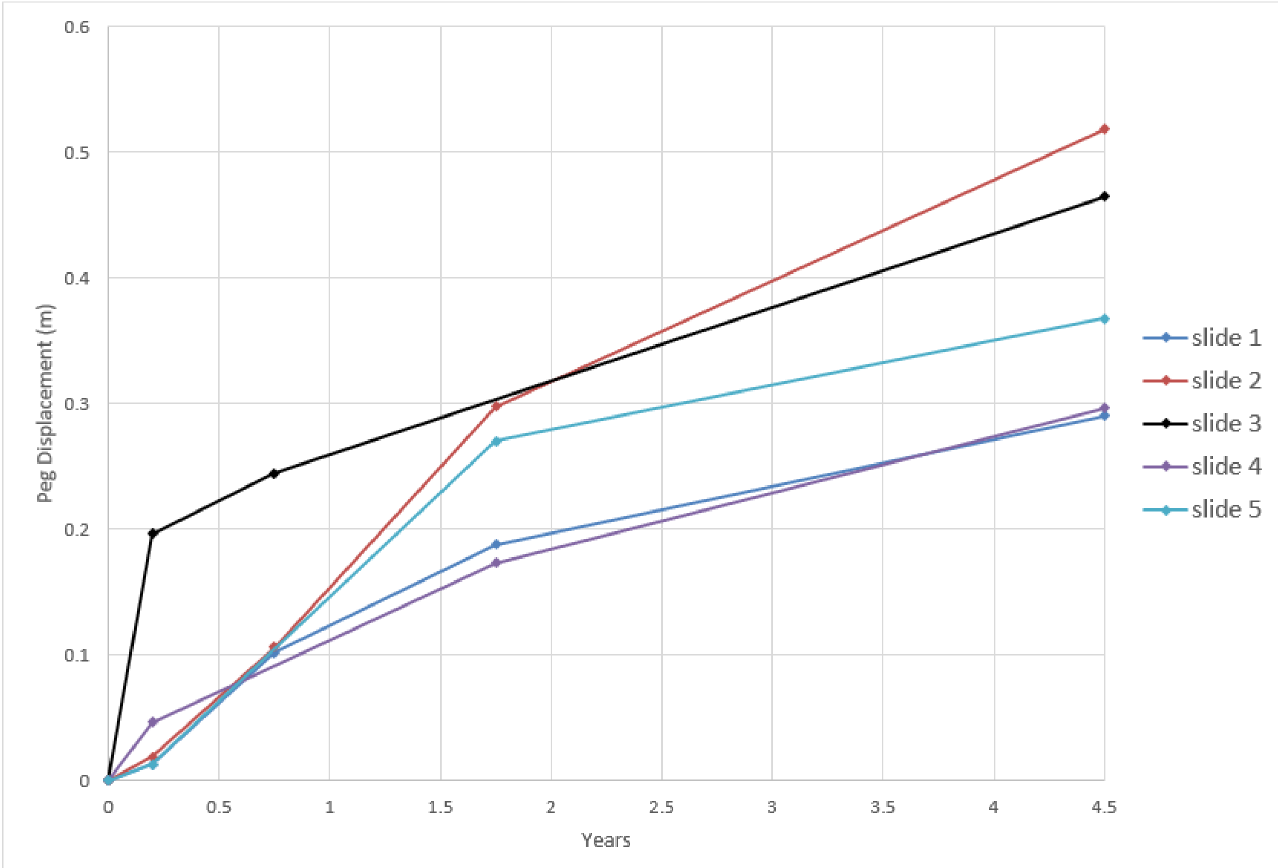


Figure 47. Cumulative slip of the Colluvial Creek landslide pins (site average). Time axis is years since January 2012. See Figure 41 for locations and slip directions.

While the slide complex has been active during the study period, visual inspection and benchmarked cross sections of the ravine (Section CC-7 and CC-8 appendix CC), colluvial valley (Sections CC-5 and CC-6 Appendix CC), fan (CC-4 Appendix CC), and incised fan (Sections CC-1 to CC-3 Appendix CC) indicate that those elements have been relatively inactive. In particular, we have seen no change in the location of the main knick point at the head of the incised fan gully (Fig. 42). However, the age of the fan fill is young (decades), as indicated by buried ranch artifacts now exposed in the gully walls (Fig. 48), and a 1979 USDA aerial photograph of the site indicates that the fan incision is younger than 1979. These processes that transport material from landslide toes toward Bird Creek act on a decadal scale, of interest to resource managers.

Fig 48. Ranch implements, including glass bottles, fluid storage tank, and tires only several decades old are exposed by erosion of the fan fill. Up gradient wide-angle photo view of cross sections CC-1 and CC-2 (Appendix) from near Bird Creek.

3.3.6.2 Hudner Slide Complex

Hudner Creek is a small tributary to Bird creek. The watershed is mostly HHSVRA property, but the mouth joins Bird Creek downstream of the property line (Fig. 10). The upper watershed includes widespread slope failure, like that described in Colluvial Creek. Slide material has filled the valley bottom from both sides (Fig. 49). The Hudner Slide complex includes several superimposed slope failures that head near the divide with Colluvial Creek. The toe of the slide dammed the valley when it became very active sometime after 1979 (Fig. 45), forcing aggradation and the development of a poorly-drained wet meadow (Figs. 49 - 51).

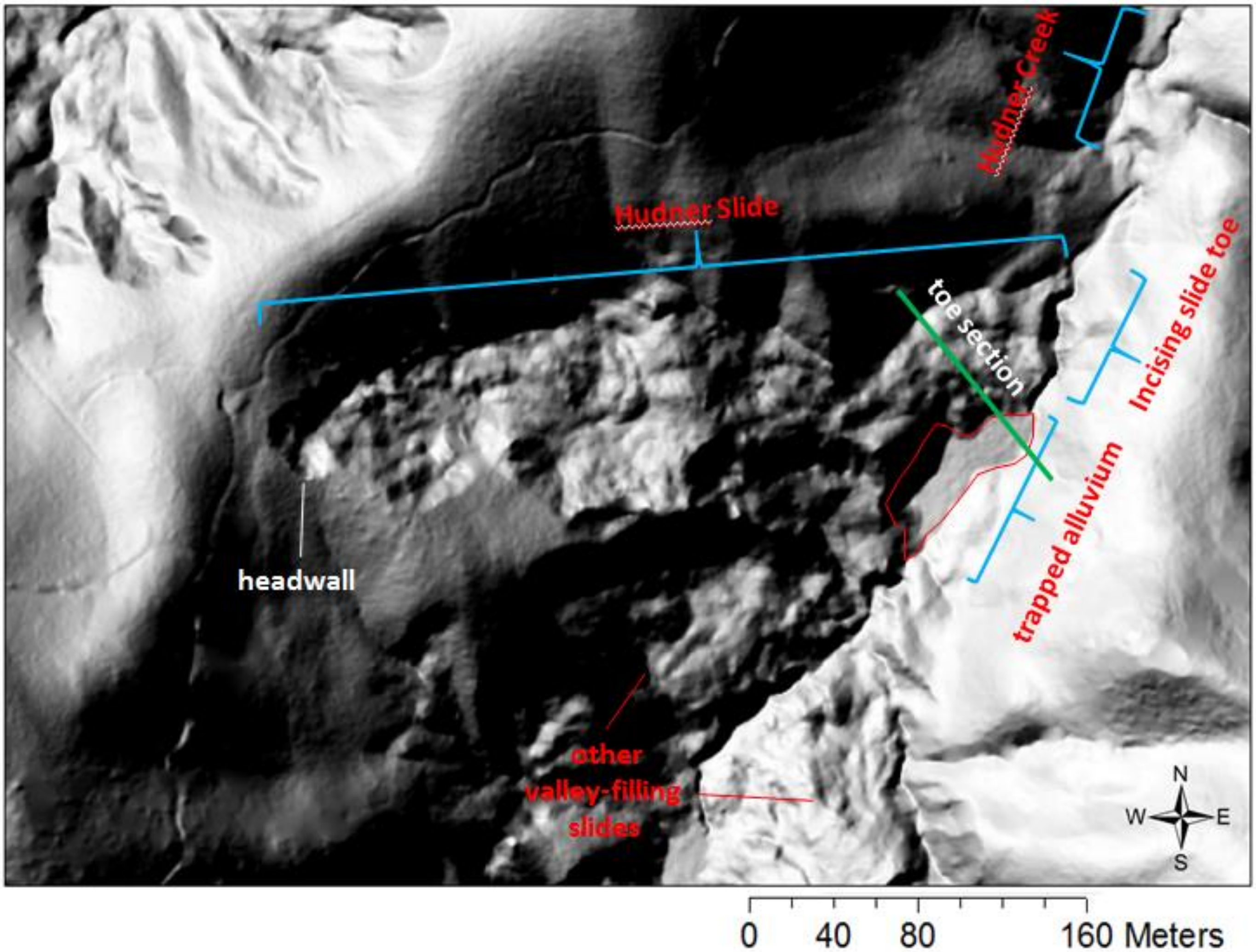


Figure 49. Key geomorphic elements of the Hudner landslide system shown in a 1 m DEM from 2010. Green line is section line for Figure 50.

A deep "V"-shaped ravine has incised the slide toe where it had over steepened the valley floor (Fig. 49). The ravine knick point is currently at the elevation of the trapped meadow, and the meadow will gradually lose sediment, and its meadow habitat character, as incision continues (Fig. 51). The ravine transports slide material and aggraded alluvium to the lower reach of Hudner Creek where it reaches Bird Creek below the park boundary through alluvial processes in wet years.

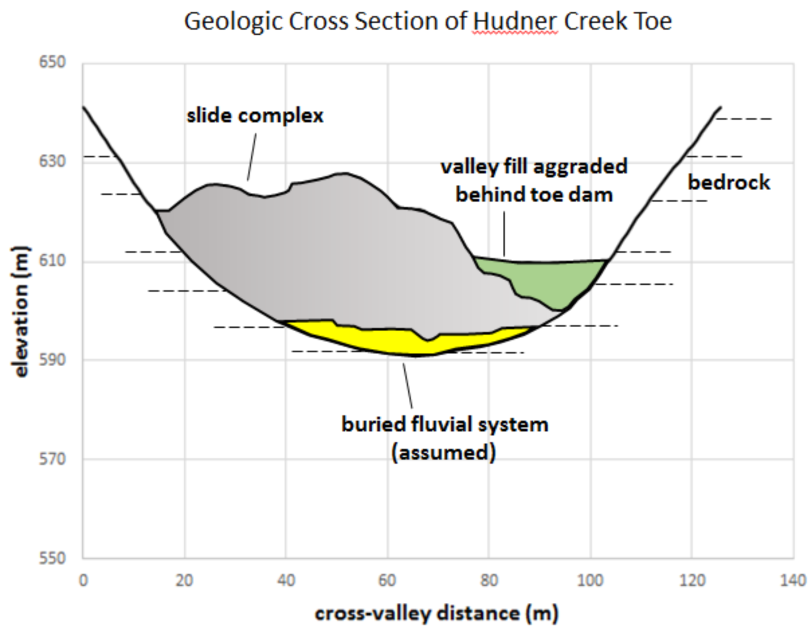


Figure 50. Properly-scaled geologic cross section illustrating components of the Hudner Creek alluvial valley. View is down valley. Long term storage occurs in the slide complex (grey) that buried the Hudner Creek fluvial system (yellow); the slide toe dammed the valley, forcing sediment to aggrade as a ponded, channel-free valley fill (green). Surface profiles from LiDAR-derived 1 m DEM. Figure 49 shows map spatial distribution of features.

Figure 51. Oblique photo showing field relations between slide elements and valley sediment transport system. Meadow sediment filled in behind dam caused by slide toe. The creek eroded through the toe (see ravine) and now has access to transport the sediment trapped behind the toe.

The Hudner Slide was a 25 m wide earthflow identifiable by subtle geomorphic features in 1979 (Fig 45). The slide body had expanded to over 60 wide, and had become more complex by 1998, as seen in Google Earth imagery. The headwall scarp had a very youthful appearance in 2012, indicated by steep to overhanging headwall with vegetation-free soil (Fig. 52). The HHSVRA District Superintendent noted that the fresh scarp appeared in the few months immediately preceding a park-wide aerial photography and LiDAR mission in fall 2010 (personal communication Mr. Matthew Allen). Comparing the 2010 orthophotos with those flown in 2014 indicates that the headwall is still adjusting (Fig. 53). Iron rods driven into several areas of the slide complex body are being monitored for future movement.

Figure 52. Hudner Slide headwall scarp in spring 2012. Lack of vegetation and sharp (locally overhanging) top corner on the headwall scarp indicates that the slide motion is young. Yellow arrow indicates approximately 6 m of displacement. Cattle fence in background is indicated in Figure 53.

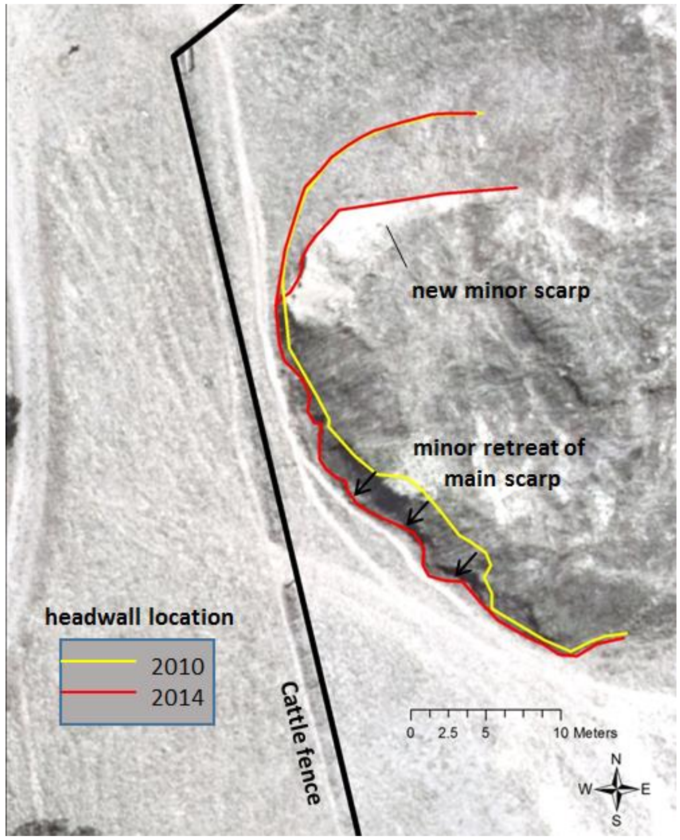


Figure 53. Location of the Hudner Slide headwall scarp has eroded headward approximately 3 m between 2010 and 2014 aerial photos. A new minor scarp formed on the north wall of the scarp during that time.

3.3.7 Landslide Causes

Landslides are commonly triggered by either strong rains that saturate soils, strong transient earthquake accelerations, or both. During the most recent 26 years there were 26 earthquakes above a magnitude of 4.0 within 20 km (12.5 miles) of Colluvial and Hudner Creeks, and only one that exceeded 5.0 (Fig. 54). The majority of the earthquakes occurred on, or within a few km of, the San Andreas Fault. Only 10 earthquakes occurred in the same years as a 10-year 24-hour rainfall event (NOAA). Major earthquakes and storms co-occurred in 1995, 1998, 2001, and 2016 (Table 8). The highest magnitude earthquake occurred within three kilometers of the park during the 1998 El Nino. There were no obvious triggers for the new headwall scarp that evolved sometime near 2010.

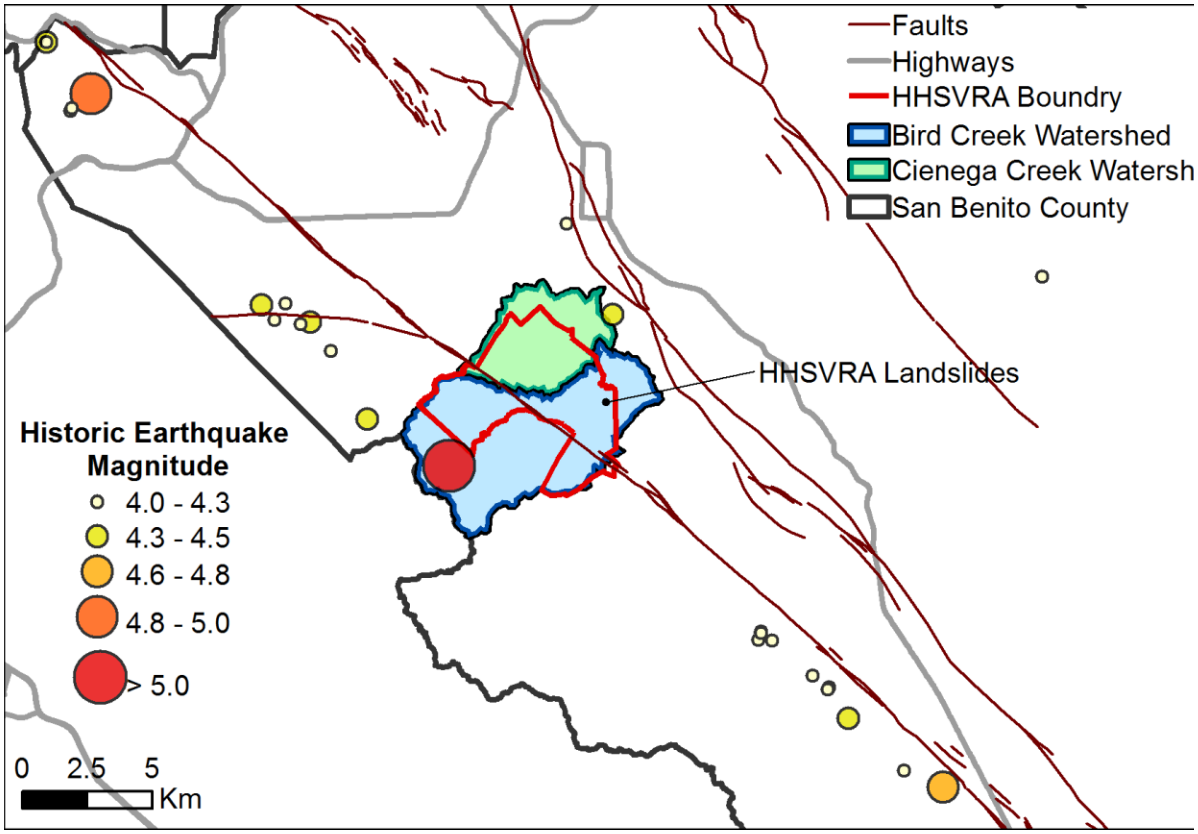


Figure 54. Historic earthquakes from 1990 – 2016 above a magnitude 4.0 and within 20 km of HHSVRA.

Table 8. Rainfall events larger than the 10-year 24-hour threshold and earthquakes greater than 4.0 magnitude within 20 km of HHSVRA between 1990 and 2016.

Year	Rain Events	Earthquake Magnitude		
		4.0 – 4.5	4.6 – 5.0	> 5.0
1990				
1991				
1992				
1993				
1994	1			
1995	1	3		
1996				
1997				
1998		1		1
1999		2		
2000				
2001	3	5	1	
2002				
2003		1		
2004		1		
2005				
2006		1		
2007				
2008		1		
2009		1		
2010		1		
2011		1		
2012				
2013				
2014		1		
2015				
2016	1	1		

A recent study of slope failure features along the San Andreas Fault near the study area suggests that slow-moving earthflows like the features described above are triggered by winter rains saturating slopes underlain by fine-grained rocks along the San Andrea Fault (Sheingross et al. 2012). They further contend that the lack of strong seismicity along the "creeping" segment of the San Andreas Fault keeps the material on the slopes longer, fostering the low-velocity failure processes. The slope features in the study area therefore conform with the regional slope behavior.

3.4 Best Management Practices

3.4.1 Sediment Retention Basins

Physical sediment retention has been a long-term BMP at HHSVRA. Nearly all of the trails in HHSVRA are located upstream of sediment basins that catch sediment eroded from the trails. Some tributaries have more than one basin in series along the length of the channel. The basins are large enough to allow storm runoff to pond. The low energy and large capacity ensures that they capture 100% of the bedload that would have entered Bird Creek. The basins have enough residence time to allow the silt fraction to settle as well. Following the winter runoff season, the basins gradually lose water through infiltration to groundwater and evaporation, leaving the remaining suspended sediment as a thin clay drape.

Basins located in the clay soils receive mostly suspended sediment that is retained as thin silt and clay laminations (Fig. 55), while those in the granitic soils receive mostly sand and small gravel bedload with a smaller proportion of suspended sediment (Fig. 56). We surveyed several basins to determine the volume of retained sediment (Table 9).

Figure 55. Superhill sediment basin receives runoff from clay soils east of the san Andreas Fault. Little bedload is present. Inset is a close-up view of laminated fine-grained deposits. Small color blocks on scale are 0.005 m.

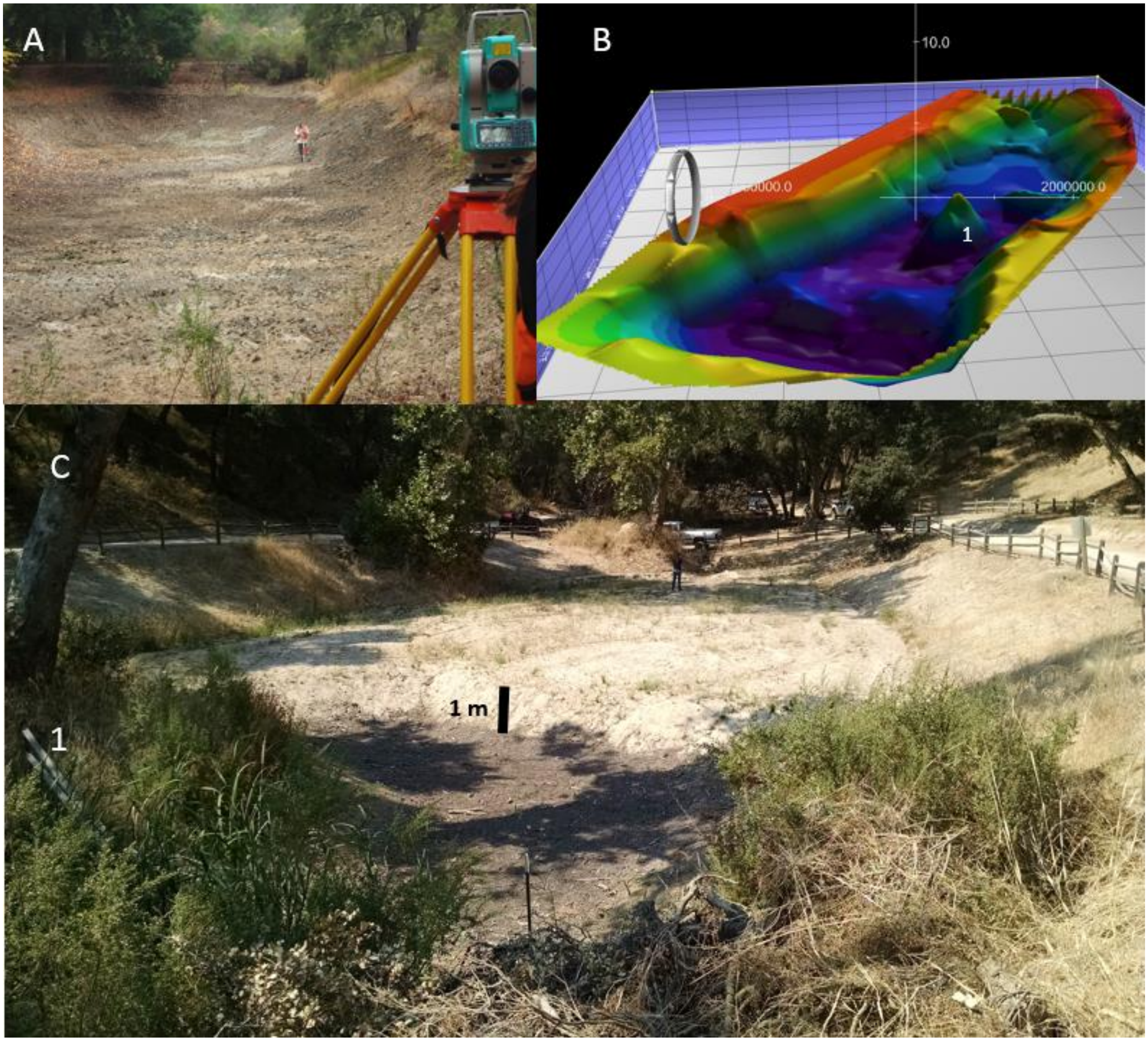


Fig 56. Sediment basin studies include surveying the shape with total station or survey-grade GPS (A), creating digital models (B), and resurveying after sedimentation (C). A) Gilmore Basin after cleanout in 2012. B) DEM of Woodwardia basin after cleanout in 2012. View is upstream. Island is labeled “1.” C) Upstream view of Woodwardia basin in fall 2016 showing a 1 m thick sand deposit. Island is labeled “1.”

Table 9. Volume of sediment retained in a subset of basins of the Bird Creek watershed. Gilmore, GP1 and GP2 are located in the Monster Truck sub-watershed of Bird Creek. An asterisk (*) indicates basin surveys that potentially represented an average water year erosion. Mass value assumes a basin fill bulk density of 1.63 tonnes/m³.

	Year Surveyed				
Basin	Initial	Final	Volume (m^3)	Volume (yd^3)	Mass (Tonnes)
Gilmore	2012	2013	10	13	16
GP1*	2014	2016	13	17	22
GP1	2012	2013	1	1	1
GP2	2014				
Lodge Lake	2015				
Office*	2012	2016	486	635	792
Scandia*	2013	2016	342	447	557
Super Hill*	2013	2016	67	88	109
Sycamore	2012	2013	2	2	2
Whoopdeedoo	2012				
Woodwardia*	2012	2016	39	50	63

The retention values in Table 9 that were last surveyed in 2016 were summarized by substrate (granitic and clay soils) and then normalized to drainage area feeding the basin. That volumetric yield value was then extrapolated to the full set of basins in the HHSVRA. Then the volume was converted to mass using an assumed density of 1.63 tonnes/m³, which would be a combination of silty loam and sand. Using this approach, the total value of retained sediment in the HHSVRA is approximately 10,750 tonnes per year. The retained volumes in Table 9 are well constrained through modern survey methods, however there are considerable uncertainties in both the appropriate average density of basin fill and the relationship between drainage area and fill volume.

3.4.2 Restoration Efforts

Of the many restoration BMPs active at the HHSVRA, we selected the newly constructed Coyote Trail restoration site to monitor because this one appeared to pose the greatest engineering challenge. It was designed to mitigate gully erosion on a very steep, bare slope with coarse granular granitic soils that are naturally prone to gully erosion. The engineering measures included filling and regrading a deeply incised trail system (Fig. 57). Once the steep site was regraded, 27 rip-rap grade control structures were installed to manage future erosion. The site was revegetated with native plants selected for the site conditions.

Visual inspection, ground-based photography, and serial surveys of a subset of the berms indicate that the berms underwent a period of adjustment. The berms trapped sediment until the shallow reservoirs upstream of the berms were filled (Fig. 57). During the first surveys in 2012, many of the berms showed early signs of lateral and vertical failure. Photographs in 2014 show that in some cases the berms are compromised by erosion (Figs. 58 and 60). Revegetation efforts have been successful despite the drought. Reconnaissance and surveys performed in 2016 indicate that the site vegetation is very healthy, but the berm system is still evolving (Appendix A). While the site is generating modest sediment runoff, the sediment is eventually caught in the sediment basins locate down gradient. Future grade-control projects on steep granitic slopes should include closer spaced berms, and deeper keying into the bed and banks.

Figure 57. Berm-1: View up-gradient of a berm in the Coyote Trail gully restoration site in March 2014. The berms trapped sediment until the space behind the berms had filled with sediment.

Figure 58. lateral: View down-gradient of a berm in the Coyote Trail gully restoration site in March 2014. Some berms provided incomplete grade control because of lateral erosion.

Figure 59. undercutting: View up-gradient of a berm in the Coyote Trail gully restoration site in March 2014. While major gullying has been stopped, some berms provided incomplete grade control because of undercutting.

4 Discussion

We studied sediment sources, transport and BMPs at HHSVRA for 6 years. While OHV activity at the park might have been average, rainfall, which drives the sediment transport system, was below average for 4 successive years. The drought limited our ability to interpret long-term average values from this study. WY 2016 had close to average rainfall, so we use that year to make weakly-supported statements about longer-term volume estimates.

The sediment budget for Bird Creek may be stated as,

Inputs – Retention–Outputs = Change in Storage + Error.

The budget can be stated in the following variables,

$$(S_a + S_{nsb}) + S_{nu} - S_{ret} - S_{out} = S_c + S_e$$

S_a is the total mass of anthropogenic sediment sources we estimated
S_{nsb} is the portion of natural sediment supply measured as streambank erosion
S_{nu} is the unmeasured portion of the natural background sediment supply, and
S_{ret} is the mass of sediment retained in the basins
S_{out} is the mass of sediment leaving the system as measured at the Hudner gage
S_c is the unmeasured mass of sediment stored in hillslope colluvium
S_e is the error in the budget.

Rearranging the terms, we sum all the un-estimated values on the right side of the equation to calculate the net residual mass (Table 10):

$$(S_a + S_{nsb}) - S_{ret} - S_{out} = S_c - S_{nu} + S_e.$$

Table 10. Sediment budget for Bird Creek Watershed Above Hudner Gage

Variable	Mass (tonnes)	Context	Assumptions
OHV roads and trails	20800	Extrapolated from sparse erosion data. (At least locally, this value is a gross overestimate of erosion)	Uniform erosion rate 0.075 m^3 /yr /m trail Average substrate bulk density (2 tonnes/m^3)
Stream channels	0	Repeat surveys	High confidence
County Roads	10	San Juan Grade erosion captured by basins. Cienega Road little change in cross sections. Becomes more important in decadal scale budget	Poorly constrained
Cattle	2	Difficult to quantify distributed impacts	Poorly constrained
Campgrounds	<1	Anecdotal observations	Poorly constrained
Landslides	2	Ravine erosion of slide toes is small annual input. Colluvial process are very important in decadal to centennial-scale budgets	Poorly constrained
S_{nsb} (Natural erosion from stream banks)	Measured from 9 to 180	Input from stream bank pins east of San Andreas Fault and no other input from stream channels	Low value. Not extrapolated to total watershed.
($S_a + S_{nsb}$) (Total inputs)	≈21000	Severely underestimates natural input, might overestimate OHV trails	
S_{ret} (Basin retention)	10800	Extrapolated basin capture. Extrapolation based upon drainage area above basin. Basins stratified by granitic or clayey soils.	Extrapolation based upon sparse data. Average bulk density of basin fill is between sand and silty loam (1.63 tonnes/m^3)
S_{out} (Sed leaving system)	180	Hudner gage	Confident to order of magnitude.
($S_c - S_{no} + S_e$) (change in storage – unmeasured natural erosion + Errors)	≈10000	Net residual mass that is either stored on slopes (Sc) or does not exist (errors)	Likely an overestimate because OHV erosion value is likely an overestimate.

The TMDL for the San Benito River watershed sets an eventual goal of 93,460 tonnes/yr of suspended sediment from all sources by the year 2050 (RWQCB 2005). Of course, that is not a value that the Regional Board proposes to directly measure in the main San Benito channel. It is a conceptual goal that can be indirectly monitored through periodic suspended sediment concentration measurements (RWQCB 2005). But, if we simplistically assume that all parts of the San Benito River watershed would contribute equally to that future goal, then Bird Creek upstream from the Hudner gage can be ascribed 2.2% of the load (2060 tonnes), since it occupies approximately that much of the

San Benito watershed. However, the highest annual load Bird Creek produced during our study was only 180 tonnes, in 2011. Apparently sediment management in the HHSVRA is keeping the total watershed yield well below the target value, perhaps by trapping both the anthropogenic and natural suspended sediment loads that are generated within the park boundary.

Figure 60 represents our general understanding of the relative importance of the various sediment sources within the Bird Creek Watershed.

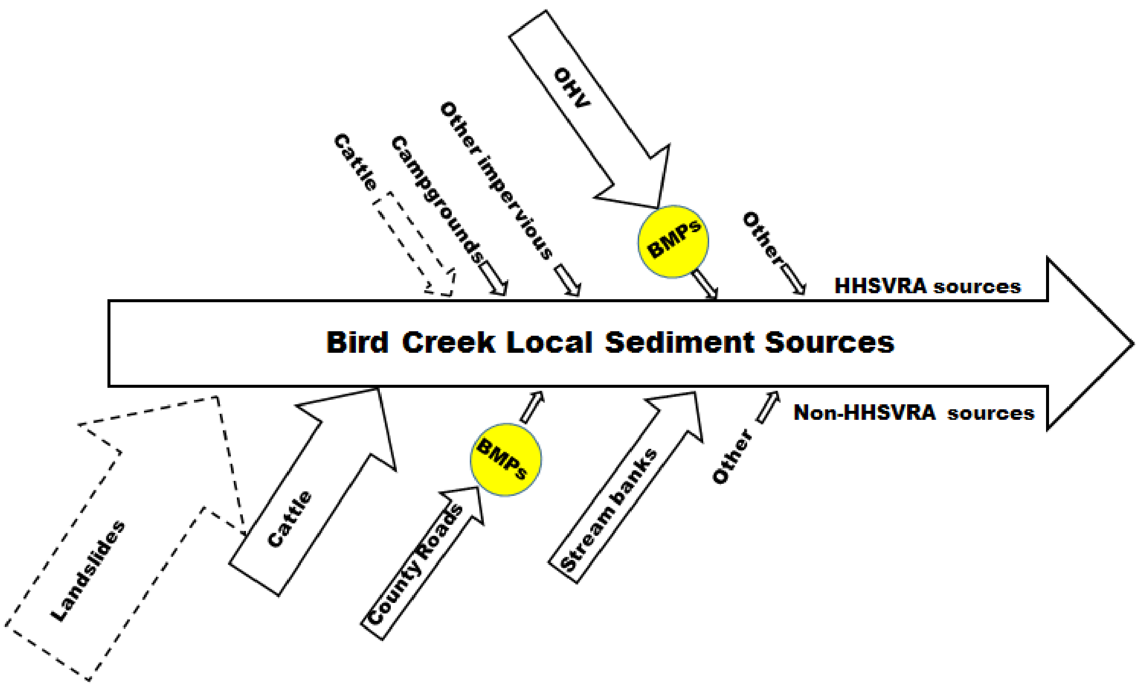


Figure 60. Bird Creek sediment sources. Arrows are qualitatively scaled to indicate our opinion about their relative volumetric importance. Upper sources are those related to State Park land. Lower sources are from other portions of the Bird Creek watershed. Dashed arrows indicate that they are not important in a typical year, but that might contribute either sporadically or on a longer time frame. BMPs are shown to decrease the impact of those sources mainly located upstream of sediment retention basins.

Our understanding of the relative importance of sediment sources will continue to evolve as data sets grow through continued monitoring. In particular, extrapolation of trail erosion rates and sediment basin retention rates should improve through time.

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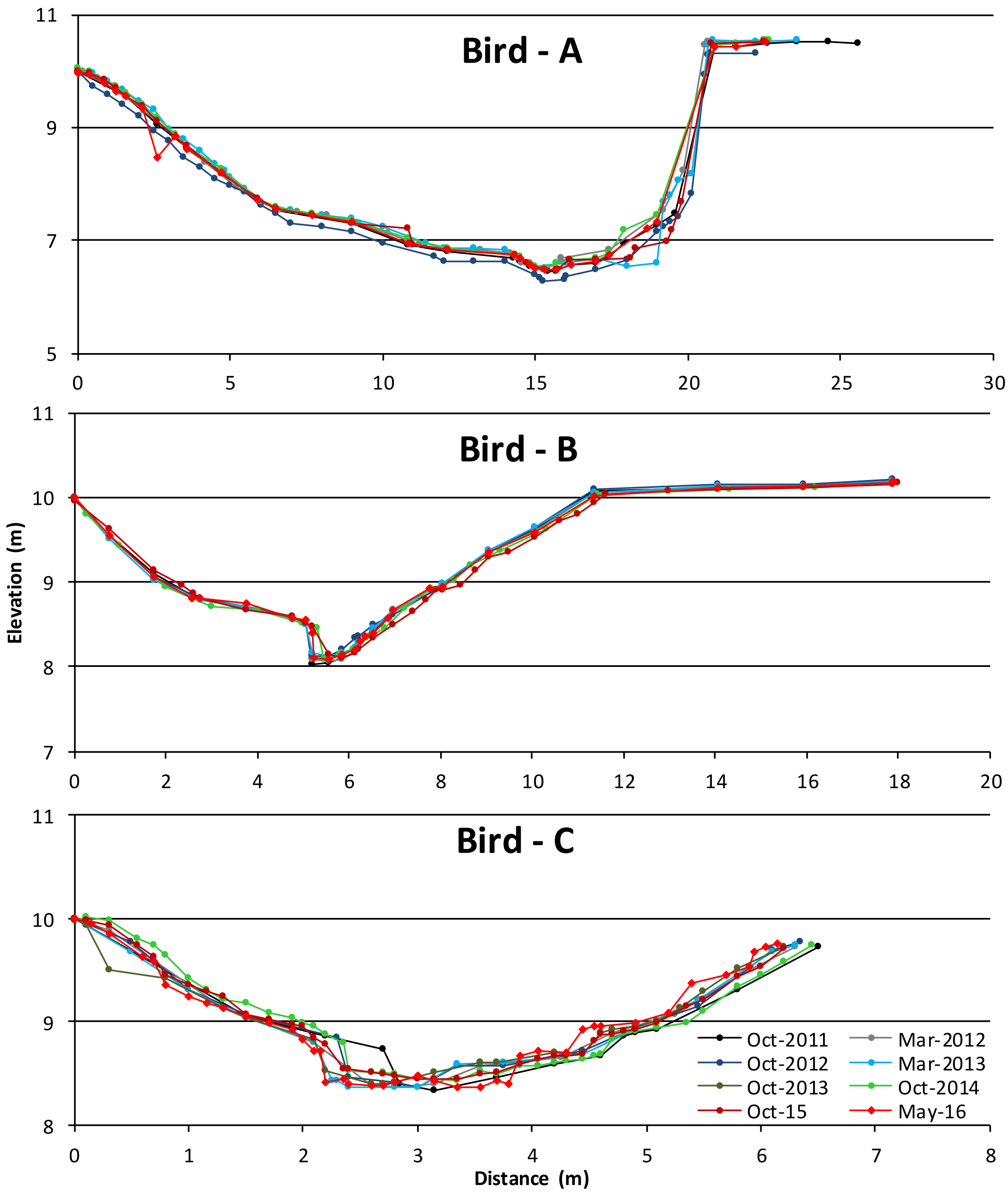
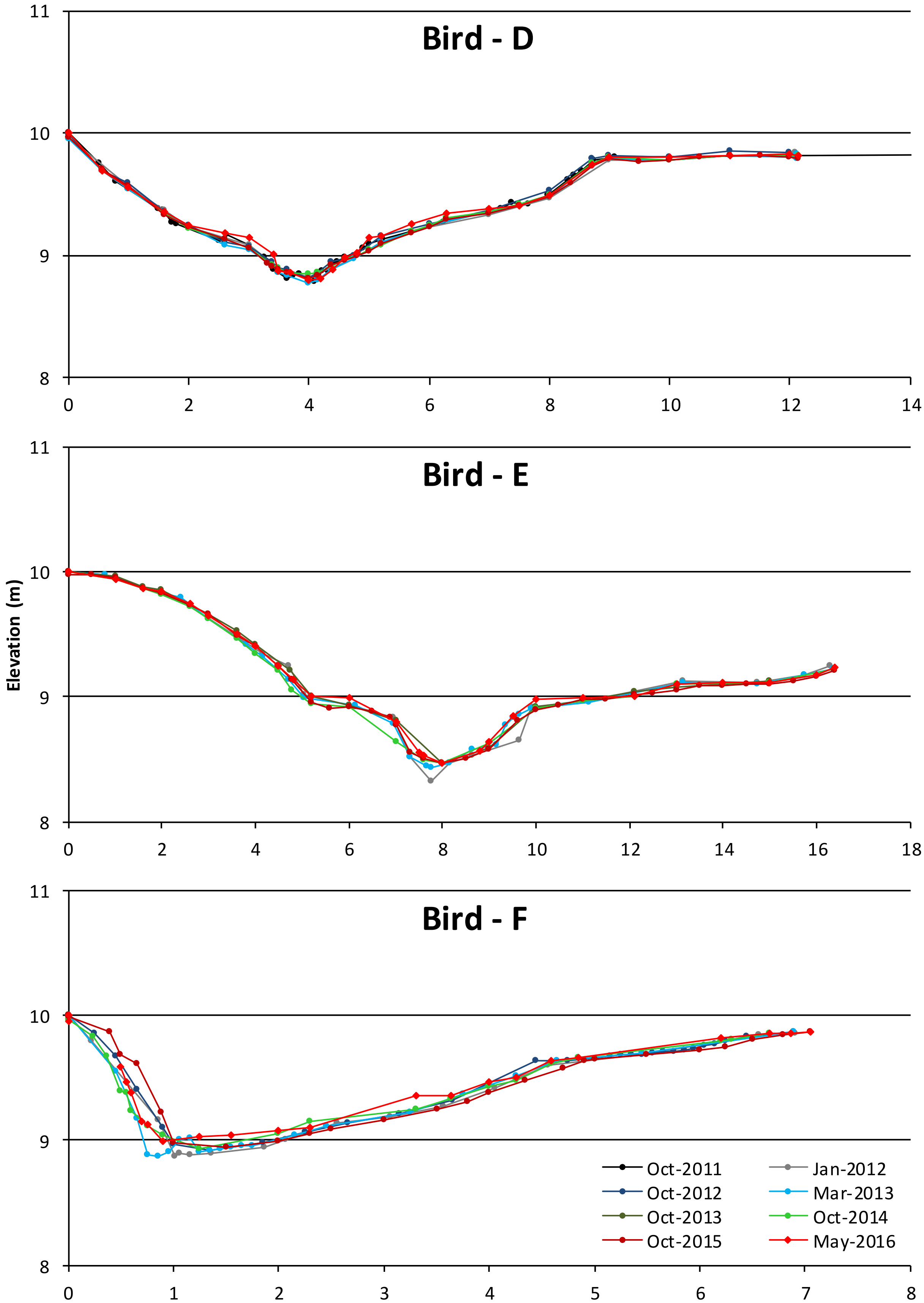
6 Appendix A

Subset of cross sections from the study. "Bird – X" is from Hudner Ranch reach of Bird Creek. "CC-X" is from Colluvial Creek. "CRC-X" is from Cienga Road culvert. "4X" is from Coyote Trail restoration site.





Bird - D
11
10
9
8
0
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4
6
8
10
12
14
Bird - E
Elevation (m)
11
10
9
8
0
2
4
6
8
10
12
14
16
18
Bird - F
11
10
9
8
0
1
2
3
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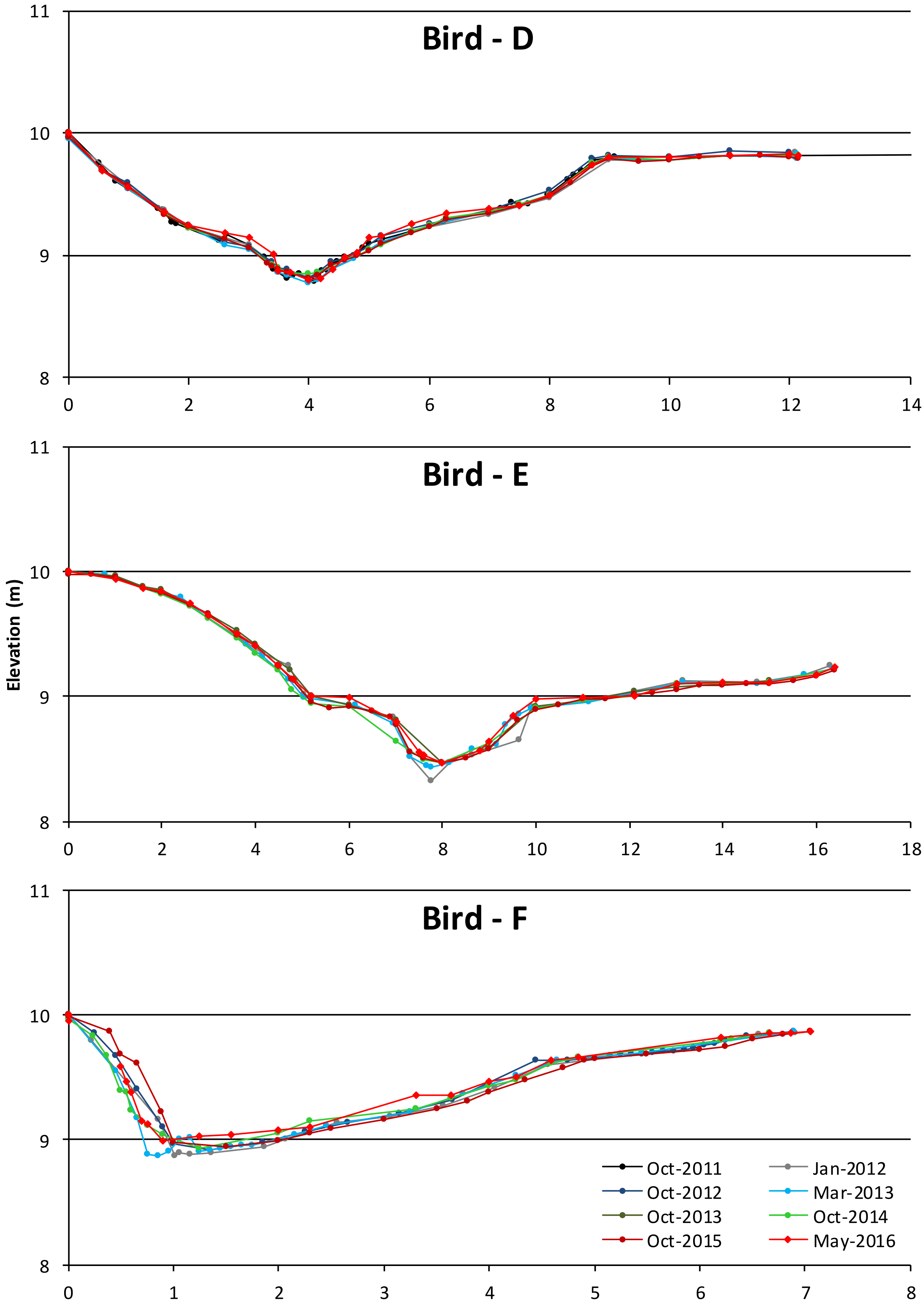
6
7
8
Oct-2011
Jan-2012
Oct-2012
Mar-2013
Oct-2013
Oct-2014
Oct-2015
May-2016


Bird - D
Bird - E
Bird - F
Elevation (m)
Oct-2011
Jan-2012
Oct-2012
Mar-2013
Oct-2013
Oct-2014
Oct-2015
May-2016
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1
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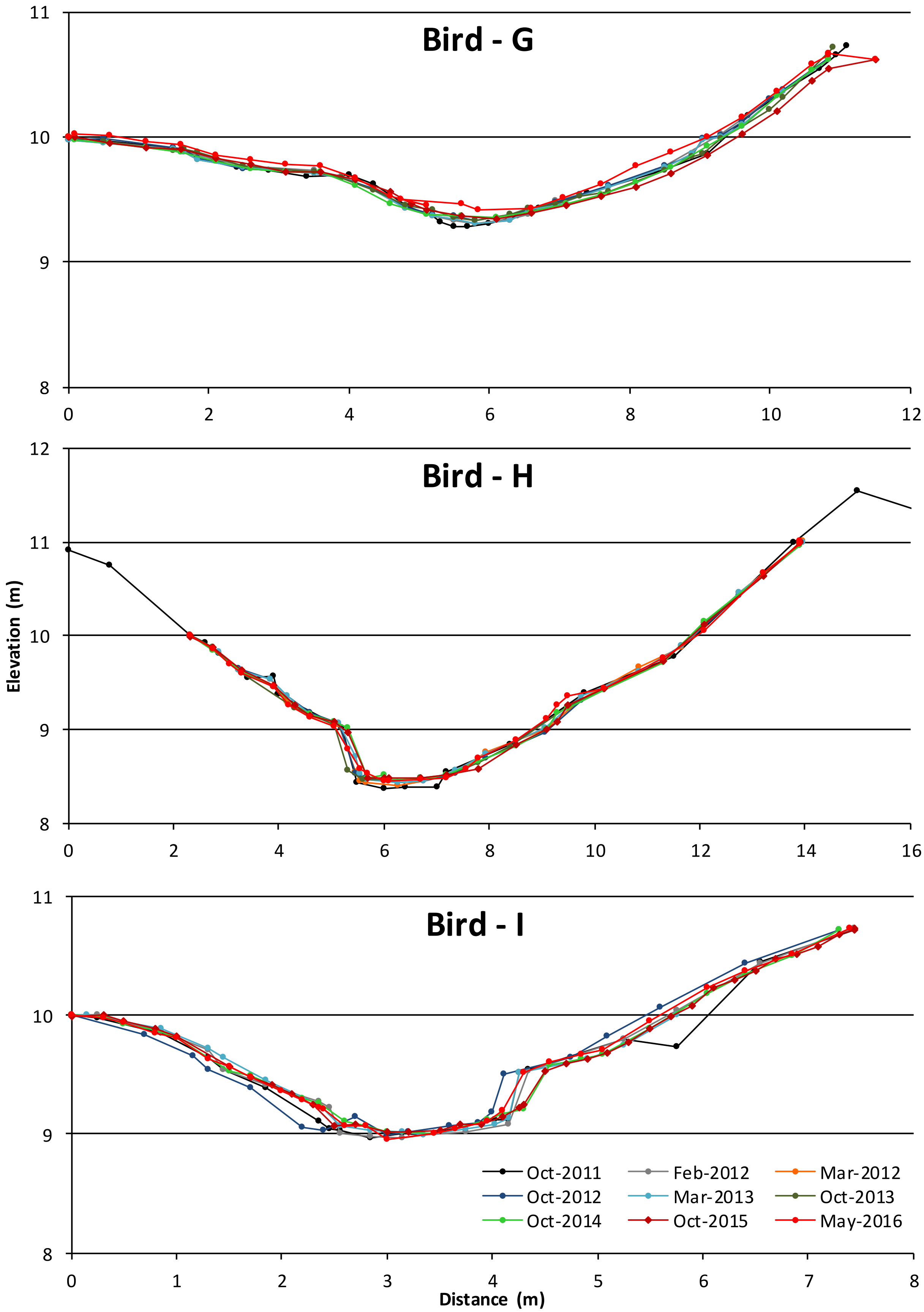

Bird - G
Bird - H
Bird - I
Elevation (m)
Distance (m)
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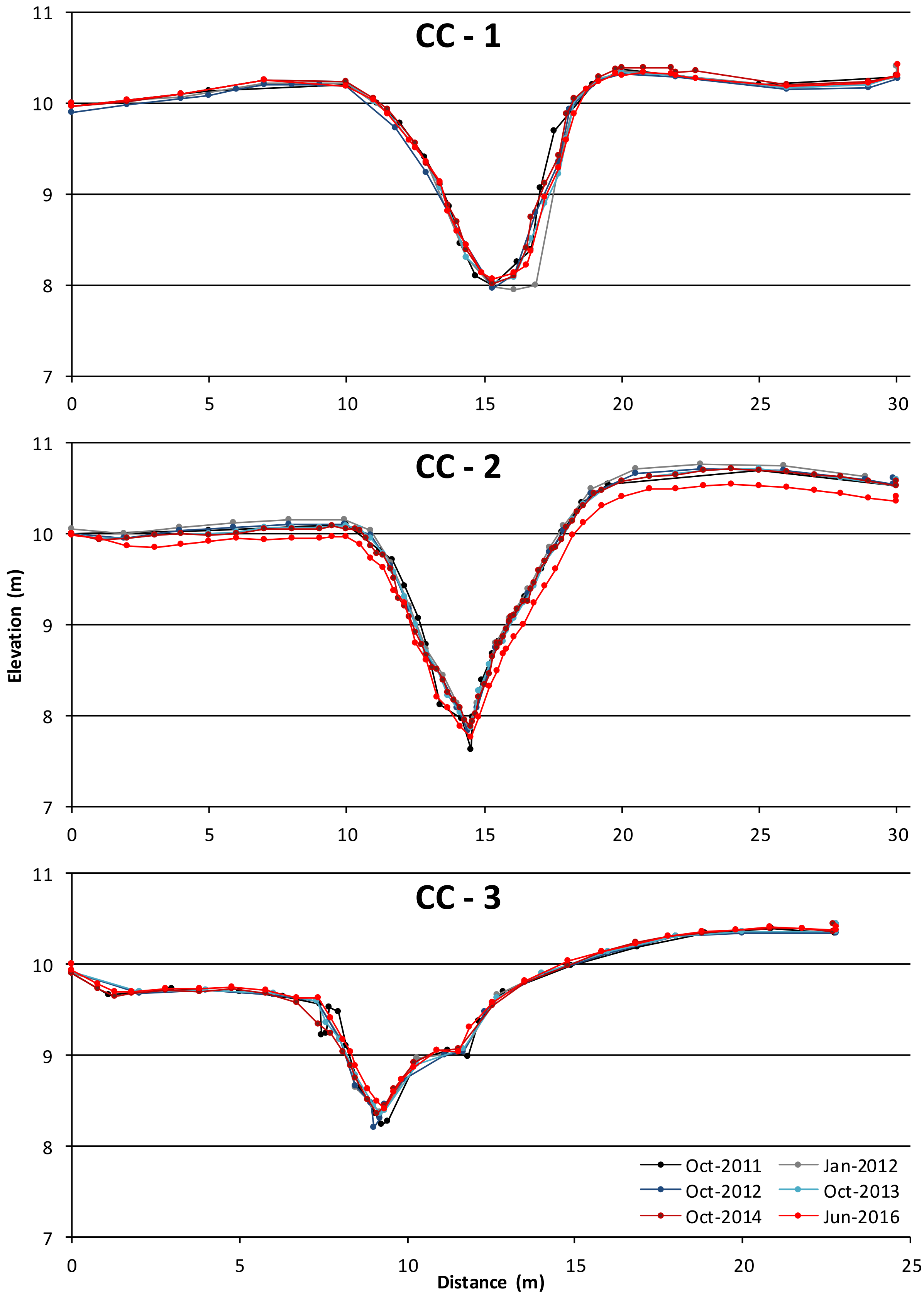
Feb-2012
Mar-2012
Oct-2012
Mar-2013
Oct-2013
Oct-2014
Oct-2015
May-2016


CC - 1
CC - 2
CC - 3
Elevation (m)
Distance (m)
Oct-2011
Jan-2012
Oct-2012
Oct-2013
Oct-2014
Jun-2016
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15
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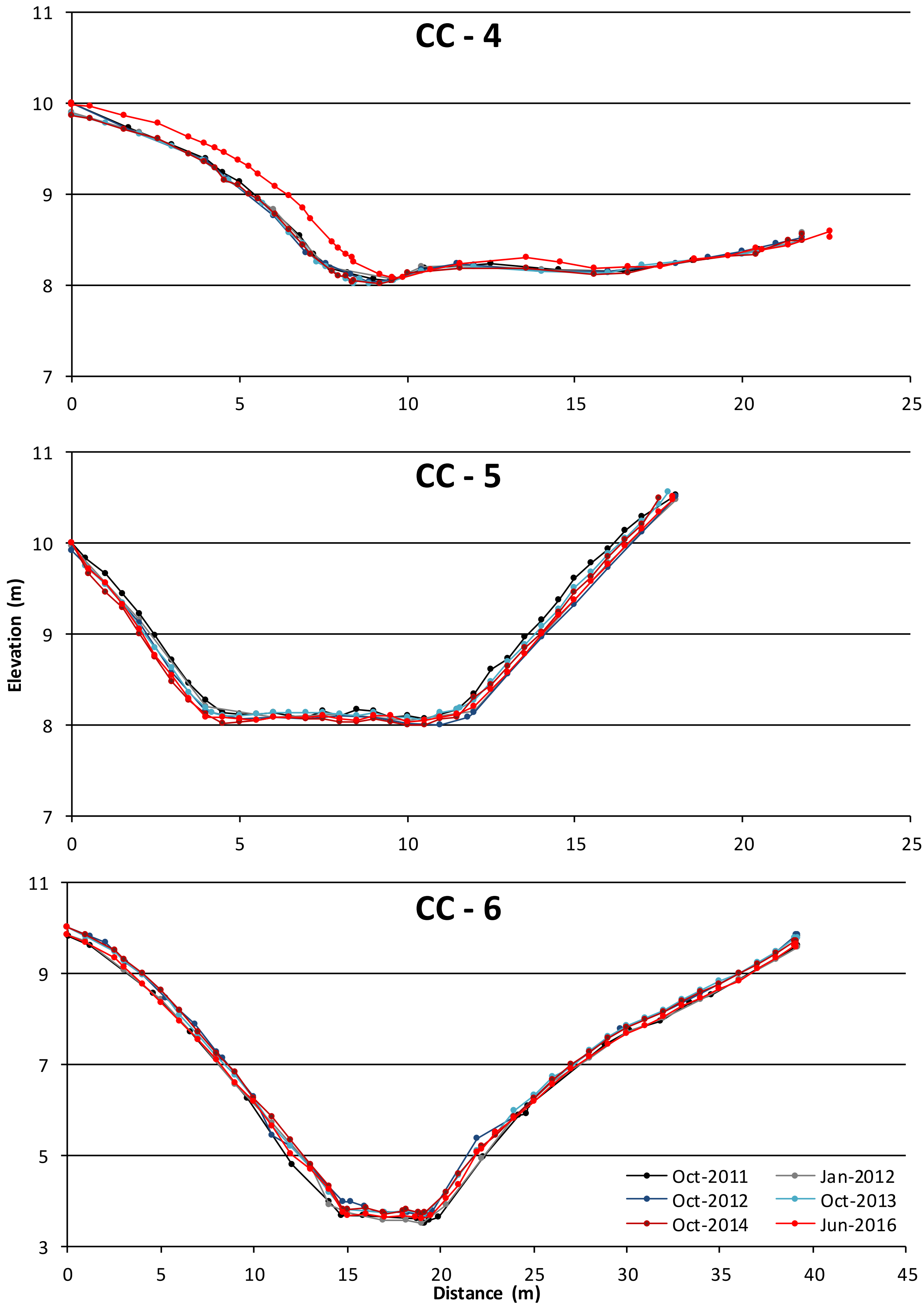
25
30


CC - 4
CC - 5
CC - 6
Elevation (m)
Distance (m)
Oct-2011
Jan-2012
Oct-2012
Oct-2013
Oct-2014
Jun-2016
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35
40
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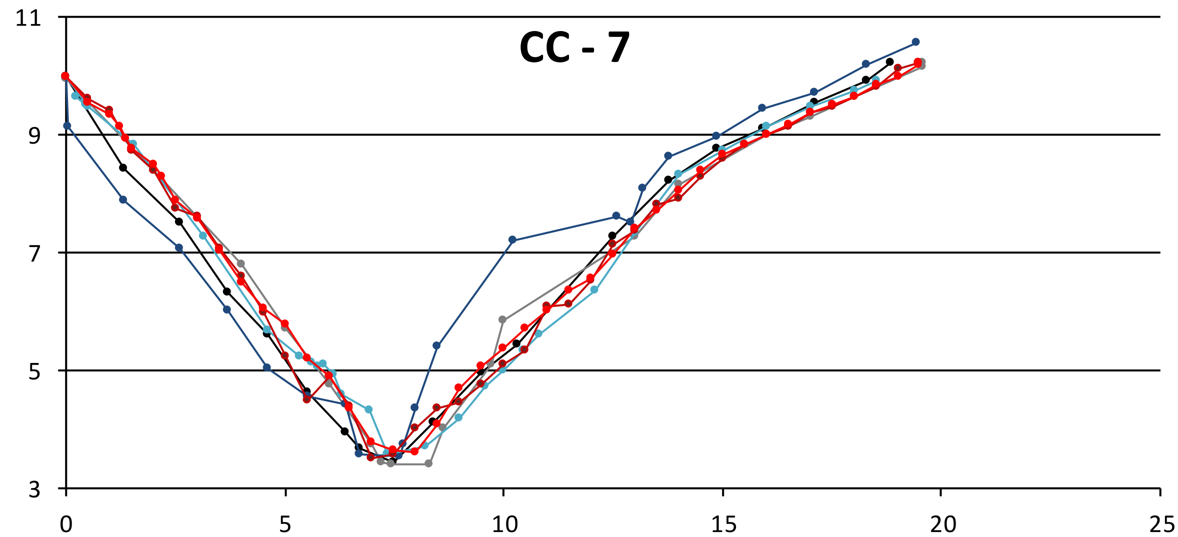

CC - 7
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9
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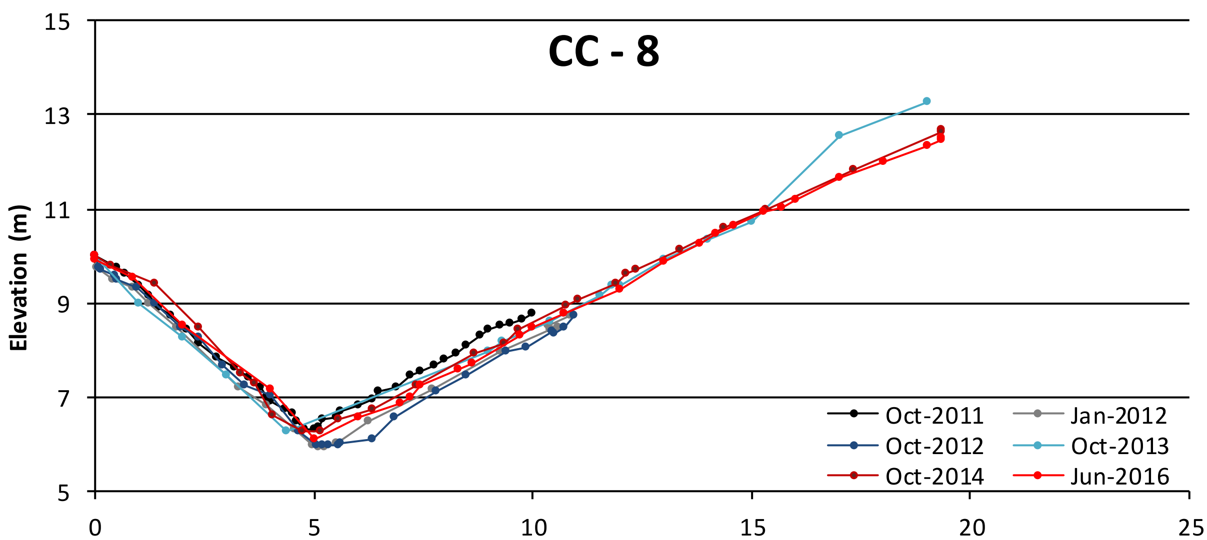

CC - 8
Elevation (m)
15
13
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Oct-2011
Jan-2012
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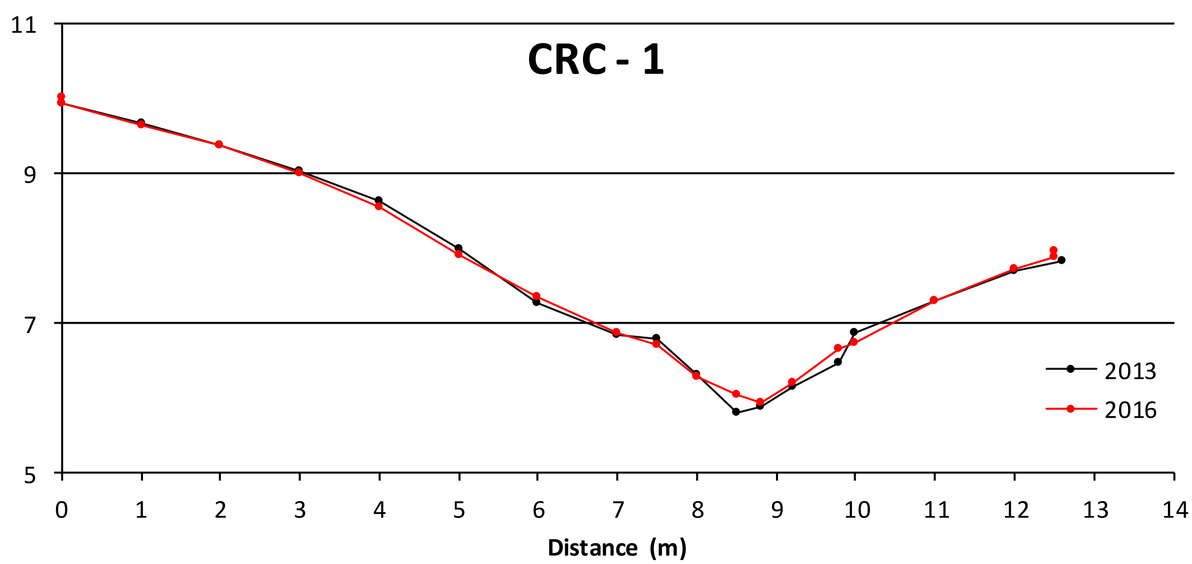
Oct-2013
Oct-2014
Jun-2016



CRC - 1
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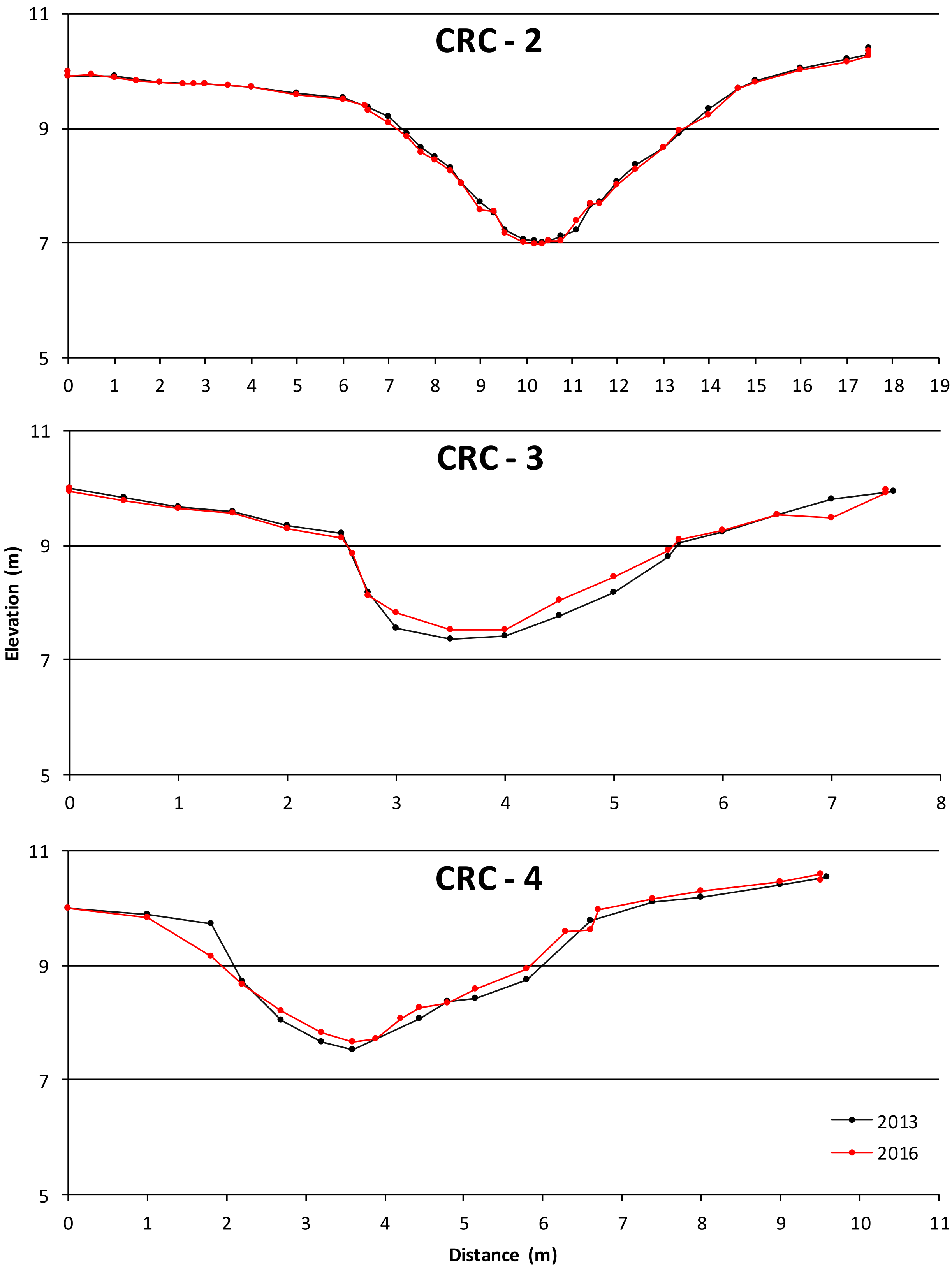
Distance (m)
2013
2016


CRC - 2
CRC - 3
CRC - 4
Elevation (m)
Distance (m)
2013
2016
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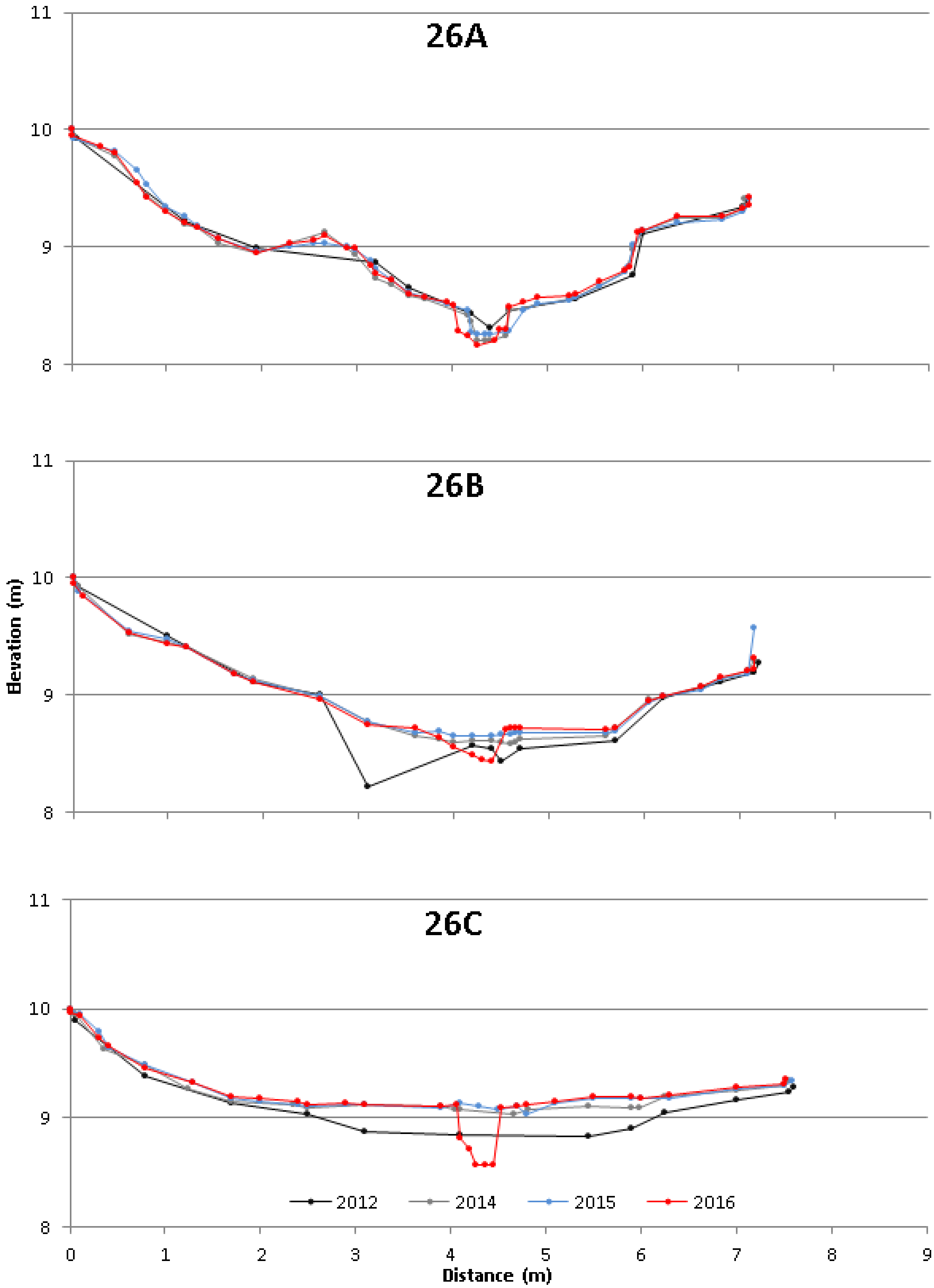
26A
26B
26C
Elevation (m)
Distance (m)
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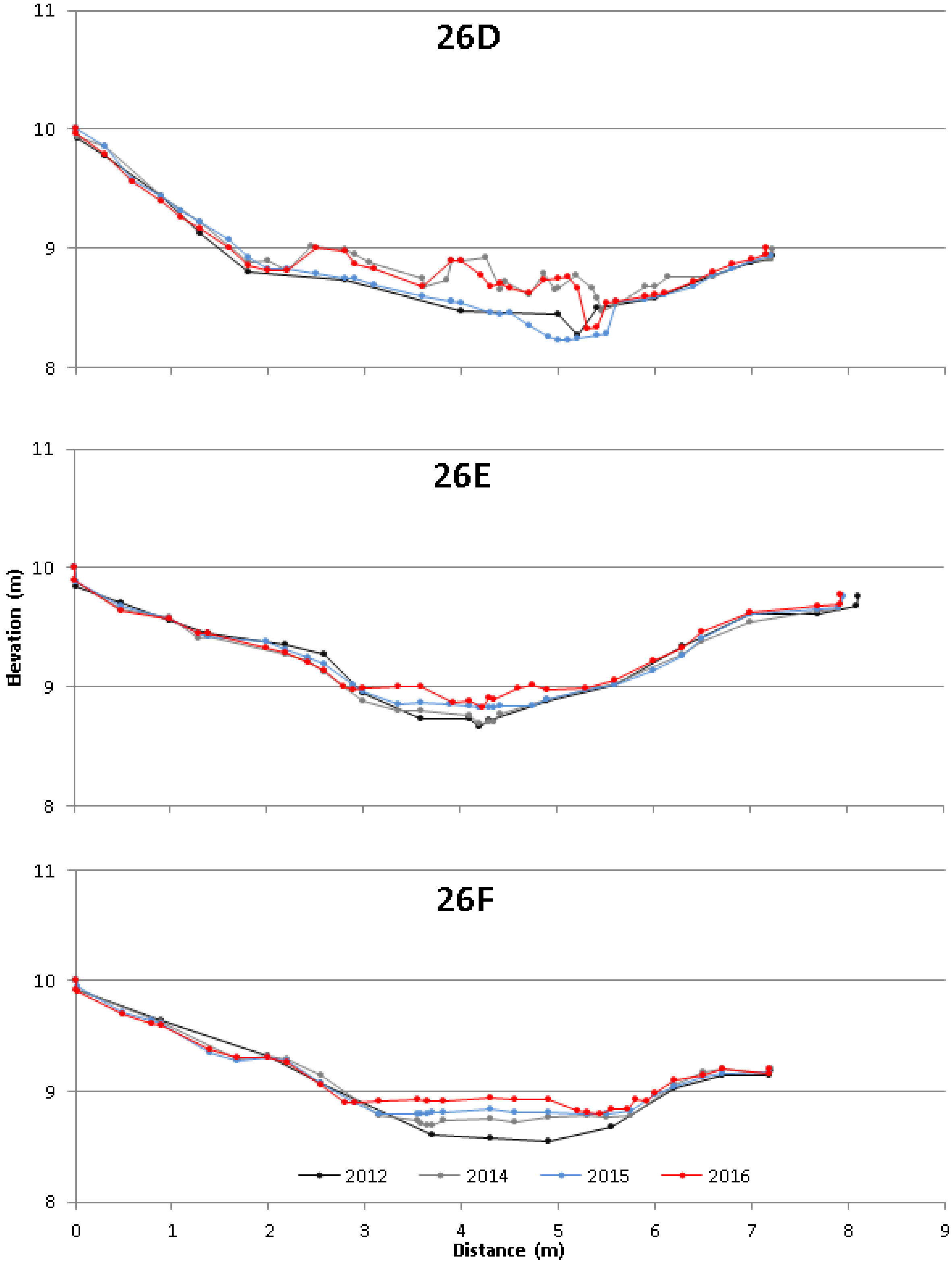
2012
2014
2015
2016


26D
26E
26F
Elevation (m)
Distance (m)
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2014
2015
2016
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7
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