HYDRAULIC MINING SEDIMENTATION IN THE WILLOW CREEK

WATERSHED, YUBA COUNTY, CA.

A Thesis/Project

by

John C. Kelley

Summer 2019

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HYDRAULIC MINING SEDIMENTATION IN THE WILLOW CREEK WATERSHED, YUBA COUNTY, CA.

A Thesis

Presented

to the Faculty of

California State University, Chico

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

in

Geosciences

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by

John C. Kelley

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HYDRAULIC MINING SEDIMENTATION IN THE WILLOW CREEK

WATERSHED, YUBA COUNTY, CA.

by

John C. Kelley

Master of Science in Geosciences

California State University, Chico

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Hydraulic mining is the practice of using high-pressure water to mobilize sediment. In California, historical hydraulic mining mobilized over a billion cubic yards of sediment to work Eocene placer gold deposits in hillsides above modern creek beds of the Western Sierra Nevada Metamorphic Belt. This research utilized sediment mixing ratios to investigate the storage and movement of hydraulic mining sediment (HMS) in the Willow Creek Watershed.

The percentage of white quartz was used in the Bear River watershed to determine the percent of hydraulic mining sediment (HMS) in a deposit (James, 1991). Applying sediment mixing ratios to the Willow Creek Watershed, sediment deposits that contained ≥ 50% rounded white quartz pebbles in the 6-64 mm range were considered to be comprised of 100% HMS, Sediment mixing ratios of the hydraulic mining deposits were divided into populations based on their location within the watershed to determine the longitudinal and lateral movement of HMS in the Willow Creek Watershed.

Hydraulic mining was shown to increase the white quartz percentage of deposits an average of 7.6% over in-situ auriferous gravels in the Willow Creek Watershed. The sediment mixing ratio varied geomorphically and decreased from mine tailing deposits in high terrace samples (n=12, μ=100%) to gravel bar samples (n=12, μ=49.3%) found in the active channel. Results from this study indicate that sediment mixing ratios can be extended throughout the Western Sierra Nevada metamorphic belt wherever historical hydraulic mining occurred to determine the current location and movement of HMS.

CHAPTER I

INTRODUCTION

The Western Sierra Nevada Foothills Metamorphic Belt (Figure 1) is home to one of the great gold mining provinces in California history (Harden, 2004). Gold-rich quartz veins intruded into the metamorphosed rocks of the Sierra Nevada during the late Jurassic and early Cretaceous periods (Dodge and Bateman, 1977; Bierlein et al., 2008). During the Eocene period, these quartz veins were eroded, resulting in the deposition of gold-rich sediment in the north-south trending paleo-river channels of the Sierra Nevada, which were later buried and then uplifted in subsequent tectonic events during the Oligocene and Miocene periods (Harden, 2004; Yeend, 1974). During the California Gold Rush, these gold-bearing Eocene deposits were worked by placer miners using hydraulic mining techniques (Lindgren, 1911; Harden, 2004).

History of Hydraulic Mining in California

Hydraulic mining was developed in California in 1853 to recover gold from the Eocene placer-gold deposits of the Western Sierra Nevada Foothills (Gilbert, 1917). Hydraulic mining was carried out by pressurizing large volumes of water stored in an upstream reservoir, and funneling it into pipes that taper to a 6-9 in. (15.24-22.86 cm) nozzle (commonly referred to as a monitor), and blasting the water at Eocene paleo-river deposits (Gilbert, 1917; Hagwood, 1981). The auriferous gravels were washed into sluice boxes. Sluice boxes were long sloping troughs with a riffle configuration used to separate the gold by density differentiation. Gold would settle in the riffles, where mercury (Hg) was applied to amalgamate with the gold, producing recoverable pieces of a gold-

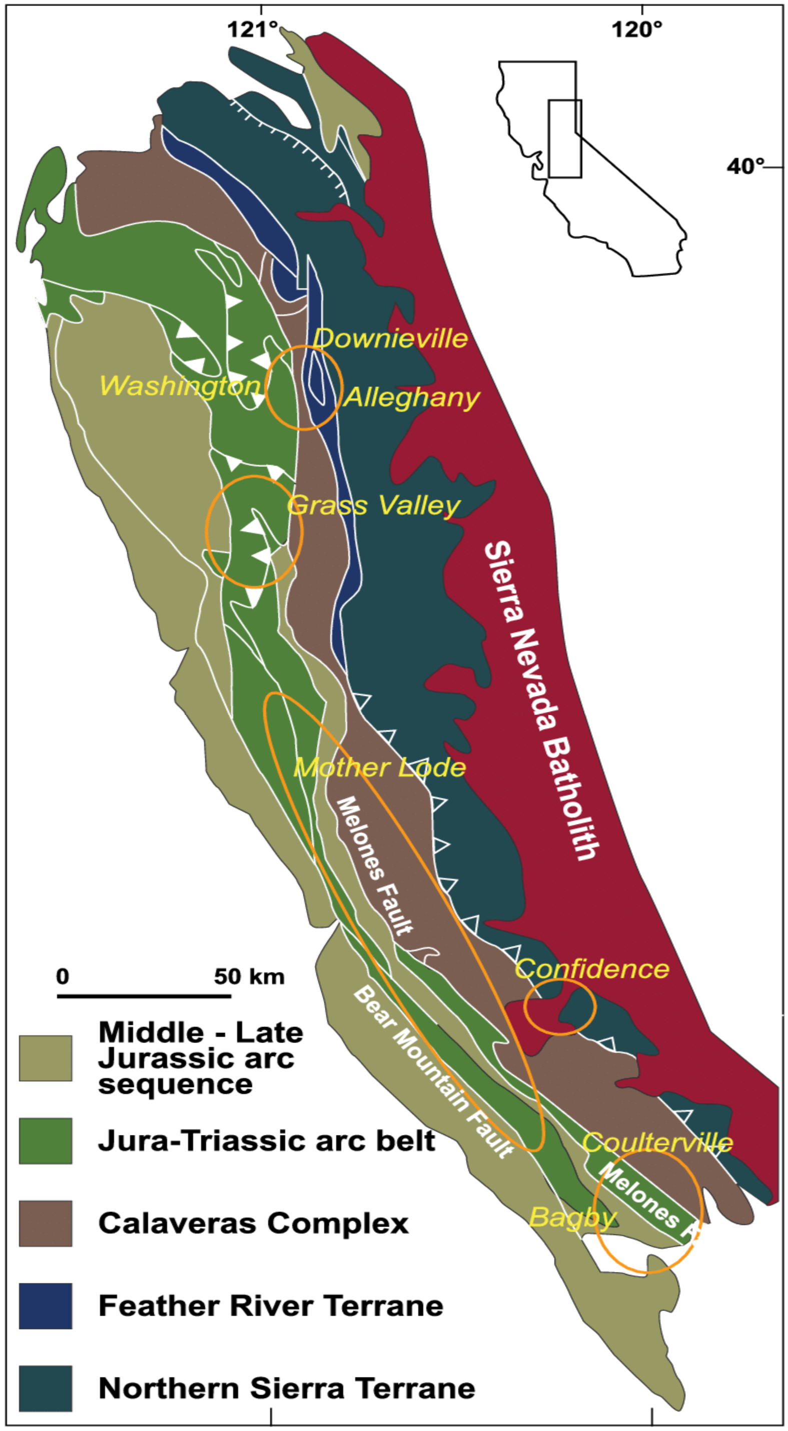


Figure 1. A map of the Western Sierra Nevada Metamorphic belt. The orange ovals indicate gold districts in the area. Figure taken from Marsh et al. (2008)

mercury amalgam. The remaining fine gravels and sands were washed downstream and the process was repeated (Gilbert, 1917; James, 2005).

During the 32-year period of unlicensed hydraulic mining lasting from 1852 to 1884, approximately 1.1 billion cubic meters of sediment were washed downstream of the hydraulic mines (Gilbert, 1917; Ghoshal et al., 2010). This huge volume of sediment disrupted waterways, flooded farmland, and caused damage to communities downstream of the hydraulic mines (Gilbert, 1917). Legal action was brought by impacted downstream parties, and in the 1884 case *Woodruff vs. North Bloomfield Gravel Mining Company,* Judge Lorenzo Sawyer handed down an injunction against all hydraulic mining in the Sierra Nevada region, commonly known as the Sawyer decision (Gilbert, 1917; Ashley et al., 2002; Woodruff vs. North Bloomfield Gravel Mining Company, 1883).

In 1893, under pressure from mining lobbies, the U.S. Congress passed the Caminetti Act (U.S. Congress, 1917). The Caminetti Act once again permitted hydraulic mining to take place in the Sierra Nevada region, as long as hydraulic mining sediment would never reach "navigable waters." An important outcome of the Caminetti Act was the establishment of the California Debris Commission (CDC) (U.S. Congress, 1917; Gilbert, 1917). The CDC issued permits to hydraulic mines that could demonstrate the ability to prevent their hydraulic mining sediments from affecting downstream communities, either by secluding the sediments in a mining pit or constructing debris control dams (DCDs) to restrain the sediment (Gilbert, 1917; James, 2005). The first DCDs were made of wood and brush, and many of these failed. This led the CDC to direct that all DCDs licensed by the CDC be constructed of concrete (James, 2005).

Although the majority of hydraulic mining occurred during the unlicensed period prior to 1884, hydraulic mining continued well into the 20th century after passage of the Caminetti Act (James, 2005; Gilbert, 1917). The final permit for hydraulic mining issued by the CDC was granted in 1954 (Lic. # 1287, 1954; California Debris Commission Archives, n.d.).

Mercury Use in the Sierra Nevada

Since at least the time of the Roman Empire, mercury (Hg) has been used to facilitate the recovery of fine gold particles (Nriagu, 1994). Mercury readily binds with gold to form an amalgam, which can aid in the recovery of gold too fine to be recovered by other means. This amalgam is then heated, vaporizing the mercury and leaving the gold behind for collection (Cordy et al., 2011). Naturally occurring Hg, mined in the Coast Range of California, was brought to the Western Sierra Nevada Foothills Metamorphic Belt region and applied to sluice boxes to amalgamate the gold washed out of Eocene paleo-river deposits (Gilbert, 1917; Hunerlach et al., 1999) as it passed through the sluice. A typical sluice box was seeded with 800 lb (363 kg) of Hg at the beginning of the 6-8-month season. An additional 100 lbs. (45 kg) of Hg would be applied monthly to replenish Hg lost during the sluicing process (Hunerlach et al., 1999). Of the 26 million lbs (11,800,000 kg) of Hg used during the Gold Rush, approximately 10,000,000 lbs. (4,500,000 kg) was lost in the sluicing process and entered the environment in this manner during the mid to late 1800s (Churchill, 1999). Small particles of mercury (called 'floured' mercury) can adsorb onto fine-grained sediments and be carried out of the sluice boxes and downstream. Numerous studies have demonstrated a strong correlation between total suspended sediment and particulate bound mercury in a system (Babiarz and Andren, 1995; Slowey et al., 2005; Forstner, 1982). Mercury use continued through the period of licensed hydraulic mining, and mercury entrained in hydraulic mining sediments continues to be a source of contamination today (Hunerlach et al., 1999; Singer et al., 2016; Fleck et al., 2011).

Health Impacts of Mercury

Elemental mercury (Hg) is relatively non-bioavailable until it is either vaporized and inhaled or converted to methyl mercury (CH_3Hg^+) by sulfur- and iron-reducing bacteria (Domagalski, 2001; Singer et al., 2016). Methylmercury is a neurotoxin that can bio-magnify and bio-accumulate in the food chain and can reach toxic concentrations at higher trophic levels, such as large predatory fish (Slotton et al., 1997). This poses a risk to all forms of life that consume fish contaminated with methylmercury (Lawson and Mason, 1998). The primary exposure pathway to humans is through consumption of contaminated fish (Bernhoft, 2012). Biochemical reactions in humans results in methyl mercury binding to sulfhydryl groups, particularly those in the amino acid cysteine (Simmons-Willis, 2002). Once bound to a cysteine, methylmercury can enter most major organs and cross both the placental and blood-brain barriers (Bernhoft, 2012). With an excretory half-life of 70 days in humans, inorganic mercury can accumulate to toxic levels through regular consumption of contaminated fish (Bernhoft, 2012).[1] At toxic levels in humans, mercury can have severe effects on the central nervous system, with symptoms ranging from tremors and mood swings to paralysis and death (Mergler et al., 2007). The toxic effects of methyl mercury can be even more deleterious

[1] The excretory half-life of methylmercury is slightly longer than elemental mercury, averaging approximately 80 days in an adult (Jo et al., 2015).

for vulnerable populations, such as fetuses and the children, affecting brain development and cognition at levels 5-10 times lower than in adults (Krabbenhoft and Rickert, 1995). Furthermore, since methyl mercury equilibrates between the blood and the body within four days, detecting mercury toxicity in a patient can be difficult, even while they are showing symptoms of the condition (Bernhoft, 2012).

Effects of Debris Control Dams on Salmonids

Currently, there is much interest in dam removal in the Yuba River watershed in order to allow anadromous fish, such as salmon, to return to their historical spawning grounds (Pejchar and Warner, 2001). Today, hundreds of miles of spawning streams in the Yuba River watershed are inaccessible to threatened salmonid populations due to the presence of dams on the Yuba River and its tributaries (Pejchar and Warner, 2001). By preventing naturally flowing allochthonous sediments from moving downstream, dams are depriving salmonid species of the sands and gravels necessary for spawning (Moir and Pasternack, 2010). In many instances, dams also change local channel hydraulics sufficiently to allow the establishment of invasive flora and fauna in the impacted streams (Fencl et al., 2015; Schmidt et al., 1998). The HMS stored behind DCD can present a complication to dam removal due to the presence of mercury. Several studies have shown mercury levels in fish upstream of DCDs are significantly higher than downstream of the DCDs (Slotton et al., 1997; Domagalski, 2001). These results imply that dams, including DCDs, act as sinks for the mercury-laden hydraulic mining sediment (Domagalski, 2001; James, 2005). More recent research suggests DCDs do not stop mercury from moving downstream, and mercury in the water column is available for methylation and bioaccumulation in riparian environments downstream of dams (Moray et al., 2017).

The existing DCDs in the Tahoe and Plumas National Forests need to be assessed to identify the amount of mercury present in the sediments behind the DCDs and to develop methods for the safe removal of mercury-laden sediment. CDC records of DCDs in California are incomplete due to missing data (Hagwood, 1981). While at least 260 different DCDs were licensed in the Plumas and Tahoe National Forests during the period of regulated hydraulic mining (CA Debris Commission Archives, no date), an unknown number of DCDs still exist in the Plumas and Tahoe National Forests. Furthermore, due to concrete deterioration from natural weathering processes, the average life expectancy of a concrete dam is 50 years (Association of State Dame Saftety Officials [ASDSO], 2017). Many of the DCDs in the Yuba River watershed are over 100 years old. For example, historical records indicate the concrete dam located on Horse Valley Creek was completed prior to October 1, 1915, the date that Horse Valley Mining Company applied for the mining license. The CDC required DCDs be completed and inspected, prior to mining (Tucker and Waring, 1917; Hagwood, 1981). These DCDs are in danger of failing, which could result in the release of the mercury-laden sediment stored behind the DCDs into downstream ecosystems. Currently, the Tahoe National Forest Service desires to locate these DCDs, assess their impacts on local water quality and determine the nature of the sediment stored behind the dams (Carol Purchase, United States Forest Service, personal communication, May 22, 2017).

Identifying Hydraulic Mining Sediment

Early in the history of hydraulic mining in California, miners learned that quartz-bearing gravels of the Eocene paleo-channels were a source of gold in stream beds and began mining these gravels using hydraulic techniques (Whitney, 1880; Yeend, 1974). In 1991, Dr. Allan James, then working on a Ph.D. dissertation at the University of California, Davis, realized that a similar association of quartz could be used to identify displaced sediment deposits related to historical hydraulic mining in the Bear River watershed (James, 1991). Through his research, he developed a relationship called a sediment mixing ratio.

In sedimentology sediment mixing ratios are created by determining the distinct lithological and geochemical characteristics of sediment sources and using these traits to determine what percentage of a deposit comes from each sediment source (Andrews and Eberl, 2012). James' sediment mixing ratio correlates the amount of white quartz in a sediment deposit to the percentage of that deposit comprised of hydraulic mining sediment. James suggested that this method of identifying and quantifying hydraulic mining sediment could be extended to other watersheds in the Northern Sierra Nevada (James, 1991). Since historical hydraulic mining sediment has been identified as an ongoing source of mercury contamination (Singer et al., 2016; Howle et al., 2016), James' sediment mixing ratio method could be used to identify sediment deposits in a watershed that may contain hydraulic mine debris and, by association, may also be mercury hotspots in that watershed. The Willow Creek Watershed in Yuba County, CA provides an opportunity to test the application of James' sediment mixing ratio. The Willow Creek Watershed was extensively impacted by hydraulic mining and also contains two DCDs. This research investigated the applicability of using James' sediment mixing ratio in the Willow Creek Watershed in the Western Sierra Nevada Foothills Metamorphic Belt impacted by historical hydraulic mining.

Site Description

The Willow Creek Watershed is located in northern CA in northeastern Yuba County (Figure 2), approximately 2 miles (3.2 km) northeast of the town of Camptonville. Willow Creek flows into New Bullards Bar Reservoir (Figure 2) at 39°28’17.3” North and 121°03’37.9” West, and is part of the North Yuba River Watershed, which is a tributary of the Sacramento River. There are three named

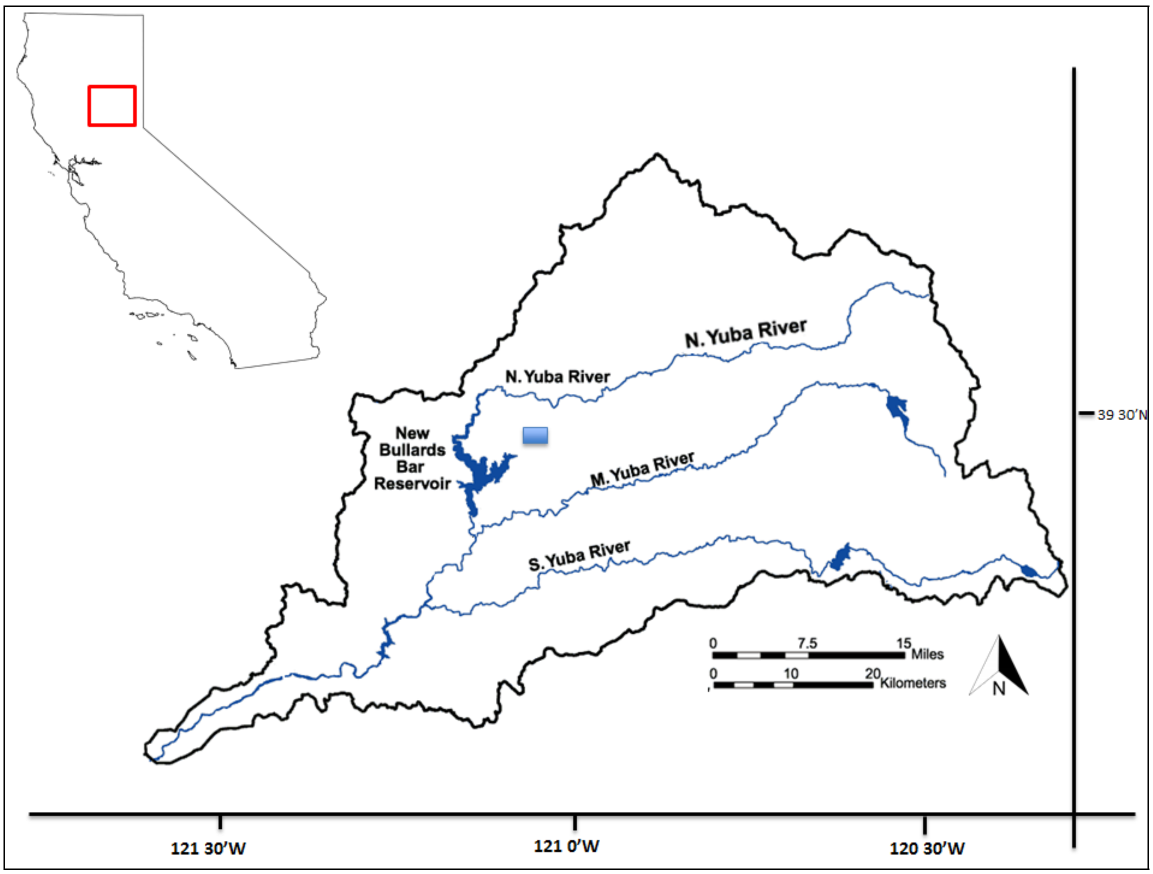


Figure 2. The Yuba River watershed. The rectangle in the CA inset (red) shows the location of the watershed. The blue rectangle between the North and Middle Yuba rivers indicates the Willow Creek Watershed area. New Bullards Bar Reservoir, at 39°28’17.3” North and 121°03’37.9” West, is shown for reference. See Figure 3 for a detailed view of the Willow Creek Watershed. Map modified from Childs et al. (2003).

drainages that comprise the Willow Creek Watershed: Willow Creek, Brandy Creek, and Horse Valley Creek (Figure 3).

Figure 3. A digital elevation map showing the Willow Creek Watershed, delineated in dark blue, as it flows into New Bullards Bar reservoir in the SW corner. The three reaches in the watershed, Willow, Brandy and Horse Valley Creeks, have black labels. The hydraulic mine sites in the watershed have white labels.

Horse Valley Creek is a first-order perennial stream with a 581.5 acre (0.91 sq-mi, 2.35 sq-km) watershed (NHD, 2002; Strahler, 1954). Horse Valley Creek is 6,800 feet (2074 m) in length from its headwaters to its confluence with Brandy Creek.

Brandy Creek is a second-order perennial stream with a 2,647 acre (4.14 square miles, 10.71 square kilometers) watershed. Brandy Creek is 19,300 feet (5882 m) and flows southwest before merging with Willow Creek.

Willow Creek is a second-order perennial stream with a 5,498 acre watershed (8.6 square miles, 22.25 square kilometers). Willow Creek is 29,500 feet (9000 m) in length and it flows into New Bullards Bar Reservoir one mile after its confluence with Brandy Creek (Wilson and Looff, 2017).[2]

There are two concrete DCDs in the Willow Creek Watershed, one on Horse Valley Creek and one on Willow Creek (Figure 3). The Horse Valley Creek DCD sits at an elevation of approximately 2,650 ft (807 m) above mean sea level and restrains a sediment deposit approximately ¾ of a mile (~1.2 km) long with an estimated volume of 147,561 yd^3 (112,819m^3; Etris, 2018). The Horse Valley Creek DCD is a concrete structure approximately 26 ft (8 m) high with a thickness of 10 ft (3 m) at the top of the dam, and spans 100 ft (31 m) across Horse Valley Creek.

The Willow Creek DCD sits at an elevation of approximately 2620 ft (798.58 m) above mean sea level and restrains a sediment deposit approximately ½ mile (~0.8 km) long with an estimated volume of 478,113 yd^3 (365,544 m^3; Etris, 2018). The Willow Creek debris control dam is a concrete structure approximately 80 ft (24.4 m) high, with a thickness of 10 ft (3m) at the top of the dam, and spans 100 ft (31 m) across Willow Creek.

[2] In regards to their suitability as fish habitat all three creeks in the Willow Creek Watershed are considered class 2 perennial streams (Wilson and Looff, 2017; Fairfull and Withridge, 2003).

The hills surrounding both dams are vegetated with pine and oak, while the sediment deposit trapped behind each of the DCDs is covered with *Rubus armeniacus* (Himalayan blackberry), *Equisetum laevigatum* (smooth horsetail), and white birch trees (*Betula papyrifera*). As both Willow Creek and Horse Valley Creek are perennial streams flowing over and through unconsolidated gravels, the sediment deposits behind each of the DCDs are saturated throughout the year (Figure 4).

Figure 4. A picture of one of the pits dug into the sediment deposit behind the Horse Valley Creek DCD. When the pit was dug, water began pouring into it. In this pit the groundwater level was only a few inches beneath the surface.

The Willow Creek Watershed was chosen as the site for this study because of the long history of hydraulic mining that occurred in the watershed. The Willow Creek

Watershed was hydraulically mined in both the unlicensed and licensed periods of hydraulic mining. Historical records (Fraser, 1927) indicate that some of the hydraulic mining operations that worked the Eocene river deposits in the Willow Creek Watershed include:

- The Brandy Creek
- Weeds Point Diggings
- Horse Valley
- Jaubert
- Galena Hill
- Depot Hill
- Nevada
- Railroad Hill

Today, a number of hydraulic mining sites may still be discharging hydraulic mining debris into Horse Valley Creek, Brandy Creek, and Willow Creek (Figure 5):

- ❑ Horse Valley Creek
  - Young's Hill Diggings
  - The North Cut of Weeds Point Diggings
  - Galena Hill Diggings
  - The eastern side of Horse Valley
- ❑ Willow Creek
  - Railroad Hill
  - Jaubert Diggings
  - The south cut of Weeds Point Diggings

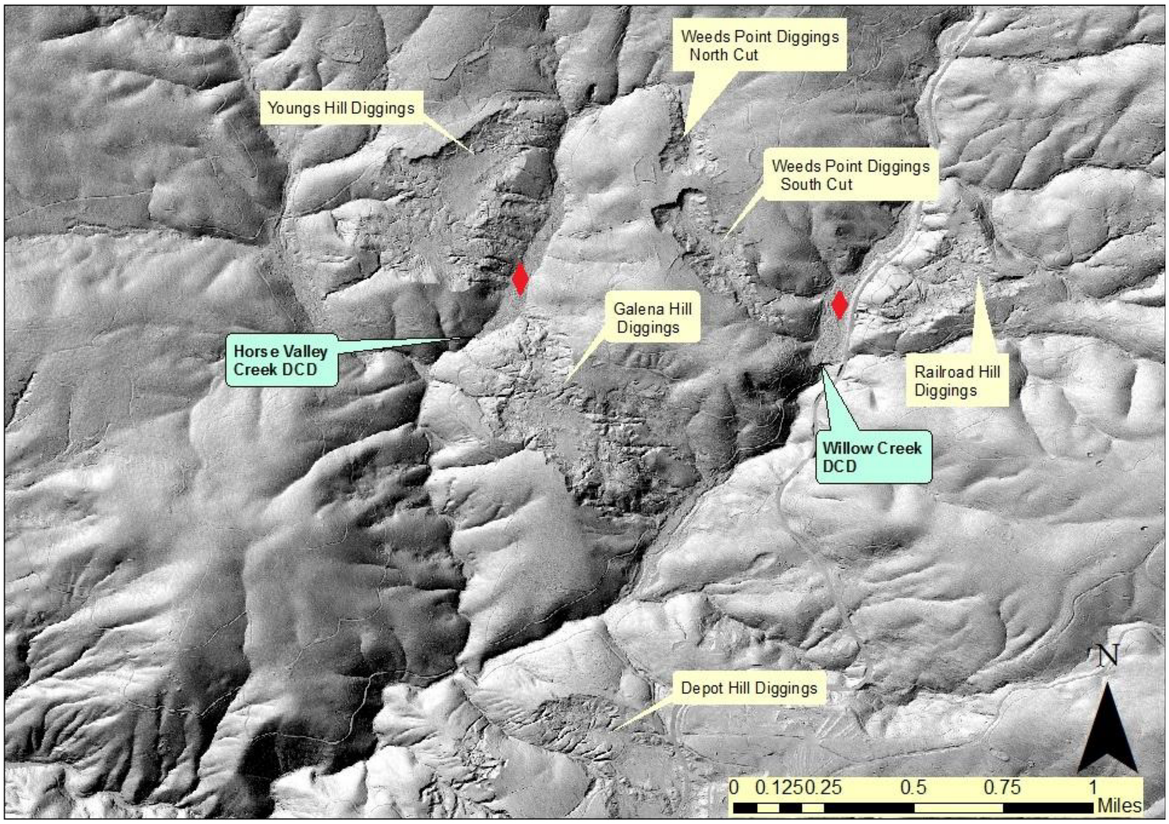


Figure 5. A LiDAR image showing the excavated areas on the landscape from hydraulic mining in the Willow Creek Watershed. This image shows the diggings at Young's Hill, Galena Hill, Weed's Point and Railroad Hill, as well as the sediment deposits trapped behind the DCDs (two red diamonds) in the watershed.

- Brandy Creek
  - Galena Hill Diggings
  - Young's Hill Diggings

Purpose

The purpose of this study was to determine if James' method for locating and quantifying HMS in the Bear River watershed using a sediment mixing ratio can be applied in the Willow Creek Watershed to answer four questions:

1. What effect did hydraulic mining have on the percentage of white quartz pebbles (in the 6-64 mm range) in the Willow Creek Watershed as compared with in-situ auriferous gravels.

2. Do the sediment mixing ratios of samples taken along the riparian corridors in the Willow Creek Watershed show longitudinal trends related to the movement of historical hydraulic mining sediment in the watershed?

3. How do the sediment mixing ratios of laterally connected sampling populations; mine tailings, lower terrace and gravel bar samples, compare with each other in the Willow Creek Watershed?

4. Is there a difference in the average grain size or the sediment mixing ratios of samples collected within the first foot (0-1 ft depth) as compared to samples collected within the second foot (1-2 ft depth) from the deposits behind the two DCDs in the Willow Creek Watershed?

These questions were answered through a combination of research into the historical records of mines within the Willow Creek Watershed and field-based sampling of sediment deposits within the Willow Creek Watershed.

CHAPTER II

METHODS

Historical Assessment

The history of hydraulic mining sediment production and deposition in the Willow Creek Watershed was investigated using California Debris Commission (CDC) records and research conducted in the historical archives of local Northern California libraries. The CDC records were provided by Dr. Allan James of the University of South Carolina. Additional research was conducted at historical archives preserved at libraries in Nevada and Yuba counties (the Searls Historical Library and the California Room in the Yuba County Library, respectively). With assistance from archivists, primary source documents on hydraulic mining in the Willow Creek Watershed were obtained including: articles from local newspapers, historical maps of mines throughout the counties, and litigation records between miners and farmers in the late 19th century. These archival resources provided historical information of mining activities in the Willow Creek Watershed and the distribution of hydraulic mining sediment.

Identification and Analysis of Hydraulic Mining Sediment

To research the location and movement of hydraulic mining sediments (HMS) in the Willow Creek Watershed, a method was needed for identifying and quantifying HMS. Previous work demonstrated that the presence of white quartz gravels in poorly sorted deposit in the Sierra Nevada Foothills Metamorphic Belt was indicative of historical hydraulic mine sediments (James, 1991). James' study conducted in the Bear

River watershed quantified the percentage of white quartz in a sediment deposit that can be directly attributed to historical hydraulic mining. He found the percent HMS in a sample could be estimated by comparing the amount of white quartz in the sample to other, non-quartz constituents. This was done by creating a sediment mixing ratio (%MS) for gravel deposits in the Bear River watershed.

The sediment mixing ratio is defined by the percent white quartz in a sample that is undiluted HMS and the % white quartz present if no hydraulic mining occurred in the watershed; these values are then used as constants in Equation 1:

$$\%MS = \frac{(\%Qs - \%Qo) * 100\%}{(\%Qt - \%Qo)} \tag{1}$$

Where:

%MS= The sediment mixing ratio of a sample. This is the percentage of the sample that is hydraulic mining sediment (HMS).

%*Qs* = the percent white quartz in a sample. Samples may be derived from HMS, non-mining sediment (other sources), or a combination of both.

%*Qt* = the percent of white quartz expected in a deposit of undiluted HMS, hereafter referred to as mine tailings.

%*Qo* = the percent white quartz in non-mining sources of alluvium above hydraulic mines or in areas with mass wasting of deposits undisturbed by anthropogenic forces.

As an example, in James' 1991 study, he determined that a sample containing 57% or more white quartz represented a deposit that was 100% hydraulic mining sediment. He accomplished this by sampling the white quartz percentage in undiluted hydraulic mining sediment (which he identified as mine tailings, %Qt) that were close to the mine pits from which they were originally mined. He also found that samples free of the influence of hydraulic mining would be composed of just 3% white quartz (%Qo). He selected these samples from undisturbed areas in the upper watershed above any mining activity. Applying these two values as his constants (%*Qt* and %*Qo*, respectively), Equation 1 was reduced to:

$$\begin{aligned}\%\mathrm{MS} &= \frac{(\%Q_s - 3\%)}{(57\% - 3\%)} \cdot 100\% \\ &= 1.9 \cdot (\%Q_s) - 5.6\%\end{aligned} \tag{2}$$

From this equation, James took one variable, the percent white quartz in a sediment sample (%*Qs*), and determined the percentage of that sample attributed to hydraulic mining sediment (HMS), and then quantified the relationship as the sediment mixing ratio (%*MS*). James (1991, p. 136) continued by saying, “The method may also be applicable to tailing identification and sediment mixing studies throughout the mining districts of the northern Sierra Nevada through application of [the method] and appropriate sampling.” Methods developed by James (1991) were adapted and applied to the Willow Creek Watershed for this research.

To extend methods developed by James to the Willow Creek Watershed, three broad classes of samples (two control groups and one experimental group) were collected. Of the two control groups, the first, termed mine tailings (%*Qt*), were samples taken from high terraces directly downstream from the outlet of a hydraulic mine. It is assumed the high terrace was deposited during the period of unlicensed hydraulic mining. These samples represented a white quartz percentage characteristic of undiluted HMS. The second control group, termed other alluvium (%*Qo,)* was collected from areas upstream of any documented historical hydraulic mining in the watershed. These samples represented the white quartz percent characteristic of sediment derived from the watershed if hydraulic mining had never occurred. The final group of samples were used to determine the percent white quartz in a sample (%*Qs)*. These samples were collected from sediment deposits around the watershed. Their white quartz percentages were analyzed using Equation 1 to determine what percentage of each sample was directly attributable to hydraulic mining.

A digital elevation model (DEM) of the Willow Creek watershed was created using LiDAR. The LiDAR was flown by the Tahoe National Forest Service (TNF) using an Airborne Laser Terrain Mapper (ALTM) flown in 2013/14. The data were resolved into a "Hillshade" relief with a 1 m^2 pixel resolution by the National Center for Airborne Laser Mapping (NCALM). The LiDAR data were used to locate potential sampling sites that were then confirmed by field reconnaissance.

For the mine tailings sample (%*Qt*), 12 samples were taken from high terraces on Willow Creek and Brandy Creek near the hydraulic mines from which the sediment originated. These high terraces were assumed to represent undiluted HMS deposited during the period of unlicensed hydraulic mining. Possible sampling sites were located on the DEM in the lab, then their presence and suitability for sampling was confirmed by direct observation in the field. Sample sites were chosen to be at least 10 ft (3.3 m) above the active stream channel, either from the exposed side of a terrace or from the highest point on a terrace. Sample sites were chosen to limit the possibility of dilution by sediments unrelated to hydraulic mining.

Seven (7) %Qo (other alluvium, non-mining) sediment samples were collected on Horse Valley Creek upstream from areas where historical hydraulic mining was documented to have occurred. Historical mine sites were located using the DEM. A DEM is a useful tool for identifying hydraulic mining features due to the distinctive signature that hydraulic mining left on the landscape (Figure 6). Samples were taken exclusively from Horse Valley Creek because Brandy Creek and Willow Creek showed evidence of historical hydraulic mining throughout their watersheds up to their headwaters. The samples from Horse Valley Creek were considered representative of the other alluvium end member, those sediment deposits free of the influence of hydraulic mining, throughout the Willow Creek Watershed because of the small size of the watershed and the relative homogeneity of the country rock in the watershed.

Field samples were taken from gravel bars as well as low terraces to capture spatial and temporal variation in the % white quartz in other alluvium. It is assumed that lower terrace samples predate the gravel bar samples, and that gravel bar samples are those which are actively being reworked by ongoing hydrological processes.

Sample Collection

Sample locations were chosen based on the topographic signature visible in the LiDAR. The topographic signature includes terracing, instream deposits and hydraulic mine pits or scarps. Sampling locations were refined in the field based on proximity to the sampling locations identified in the LiDAR, accessibility and the presence of exposed gravels. Thirteen samples were taken from deposits located upstream of the DCDs on Horse Valley Creek and Willow Creek. Low terrace samples and gravel bar samples were collected in active stream channels throughout the watershed. Low terrace samples were considered active channel samples, because they can be altered by ongoing hydrological events in the stream channels of Willow Creek. Enough sediment

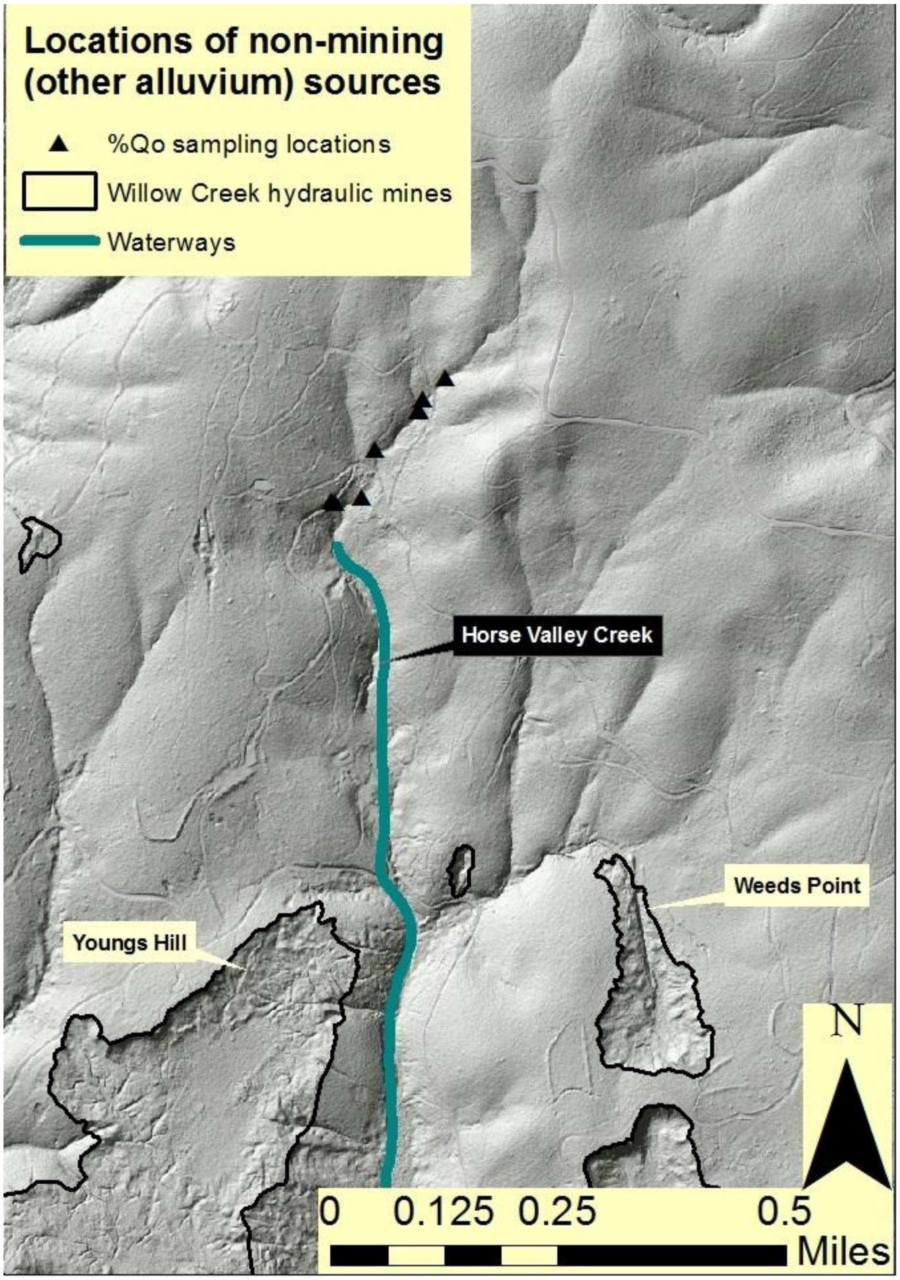


Figure 6. LiDAR imagery of the Horse Valley Creek area. Notice the gently sloping landscape in the northern part of the section, where no hydraulic mining occurred. Samples taken from this area are assumed to be free from the influence of historical hydraulic mining. Contrast this with the two hydraulic mines in the southern part of the section, Youngs Hill and Weeds Point Diggings, where mining did occur. This figure illustrates the distinctive landscape features that are the result of historical hydraulic mining and the use of LiDAR to identify sampling locations.

was collected to fill a 5 gallon bucket and where possible was washed in the field using a 4mm (2 phi) sieve and bagged for later processing (Figure 7)

Figure 7. The researcher washing fines from a gravel bar sample gathered from just above Horse Valley Creek DCD. Two buckets were employed, one had a sieve with an aperture size of 4 mm at the bottom. Sediment samples were washed using creek water, then washed again at California State University, Chico, through a sieve with a 4.75 mm aperture (to clean the gravels) and a 6 mm aperture, then analyzed to determine the sample's white quartz content.

<u>Other Alluvium Samples</u>

Other alluvium samples (%Qo), samples free of the hydraulic mining sediment, were collected in Horse Valley Creek (*n*=7, Figure 6). Seven samples were taken from gravel bars and low terraces located upstream of any evidence of historical hydraulic mining. Because Horse Valley Creek is ephemeral in this part of its reach, and it wasn't possible to wash samples in the field, the samples were bagged and carried out of the field for later processing in the lab.

Mine Tailings Samples

Mine tailing samples (%Qt) were taken from high terraces surrounding Willow Creek and Brandy Creek (*n*=12, Figure 8). It was assumed that these sediments were emplaced during the period of unlicensed hydraulic mining, before the Sawyer injunction of 1884, as evidenced by the height of the terraces above the active channel and the volume of the terrace deposits (James, 1991). Samples from terrace walls were gathered from 1-ft below the terrace bench to ensure samples were not diluted by surficial erosion of the landscape following completion of hydraulic mining. For those terraces where a near-vertical eroding cliff face was not present, the point of highest elevation on the terrace was located and a pit was dug to a depth sufficient to reach the gravel layer.

Low Terrace and Gravel Bar Samples

Twenty two low terrace and twelve gravel bar samples were collected throughout the Willow Creek Watershed (*n*=22 and *n*=12 respectively, Figure 9). The low terrace samples were collected from at least 1 ft (0.33 m) below the bench of the terrace. Gravel samples were gathered from the surface of gravel bars within the active channels.

Samples Collected from Deposits Behind DCDs

Samples were collected from the deposits behind the DCDs on Horse Valley Creek and Willow Creek. Ten samples (*n*=10) were collected from the sediment deposit trapped behind the Horse Valley Creek DCD and three samples (*n*=3) were taken from the sediment deposit trapped behind the Willow Creek DCD. The discrepancy sampled

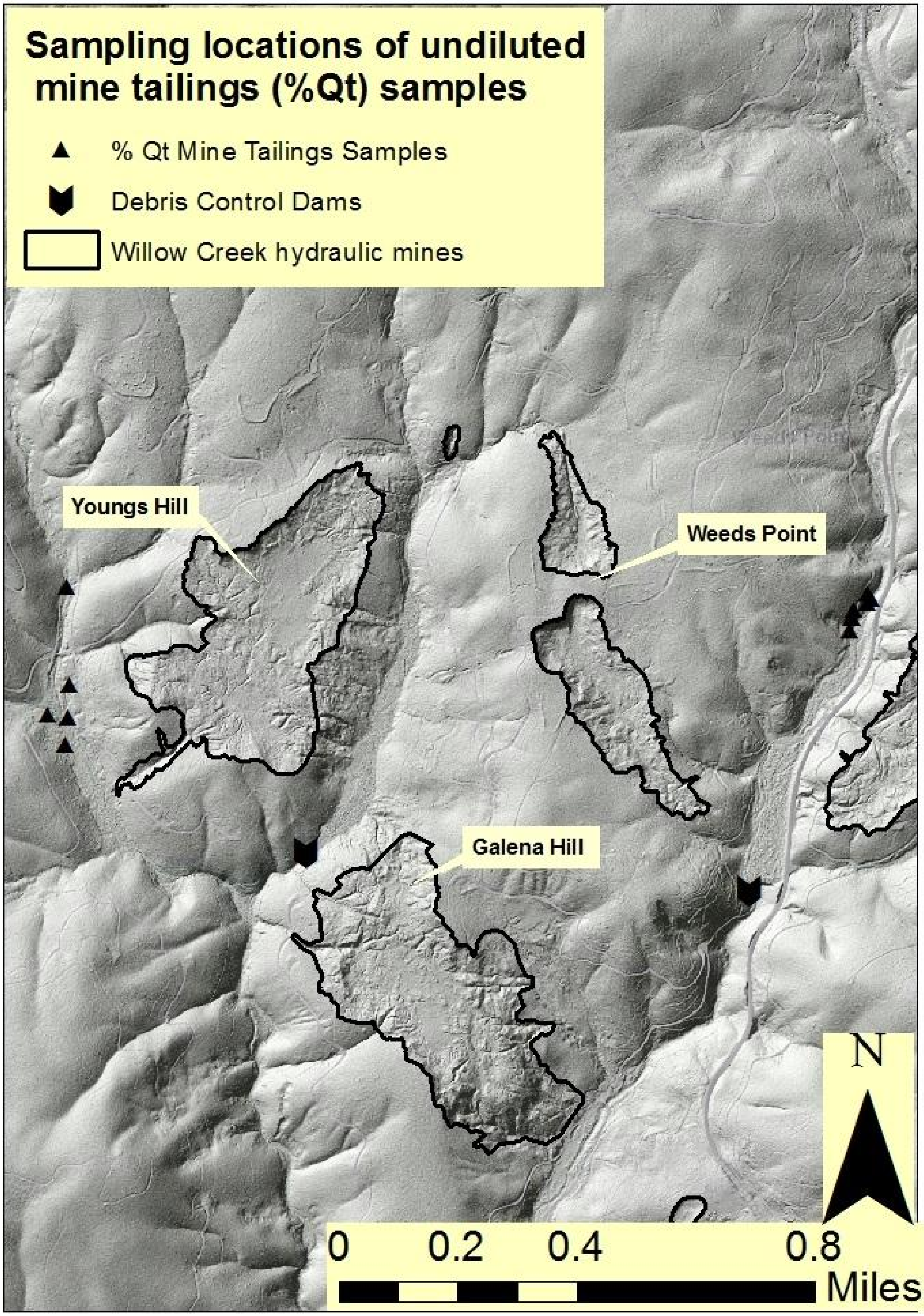


Figure 8. Location of mine tailing samples taken in the Willow Creek Watershed. Mine tailing samples were taken from high terraces (those terraces greater than 10 ft (3.3 m) above the active channel) and are assumed to be derived from undiluted HMS.

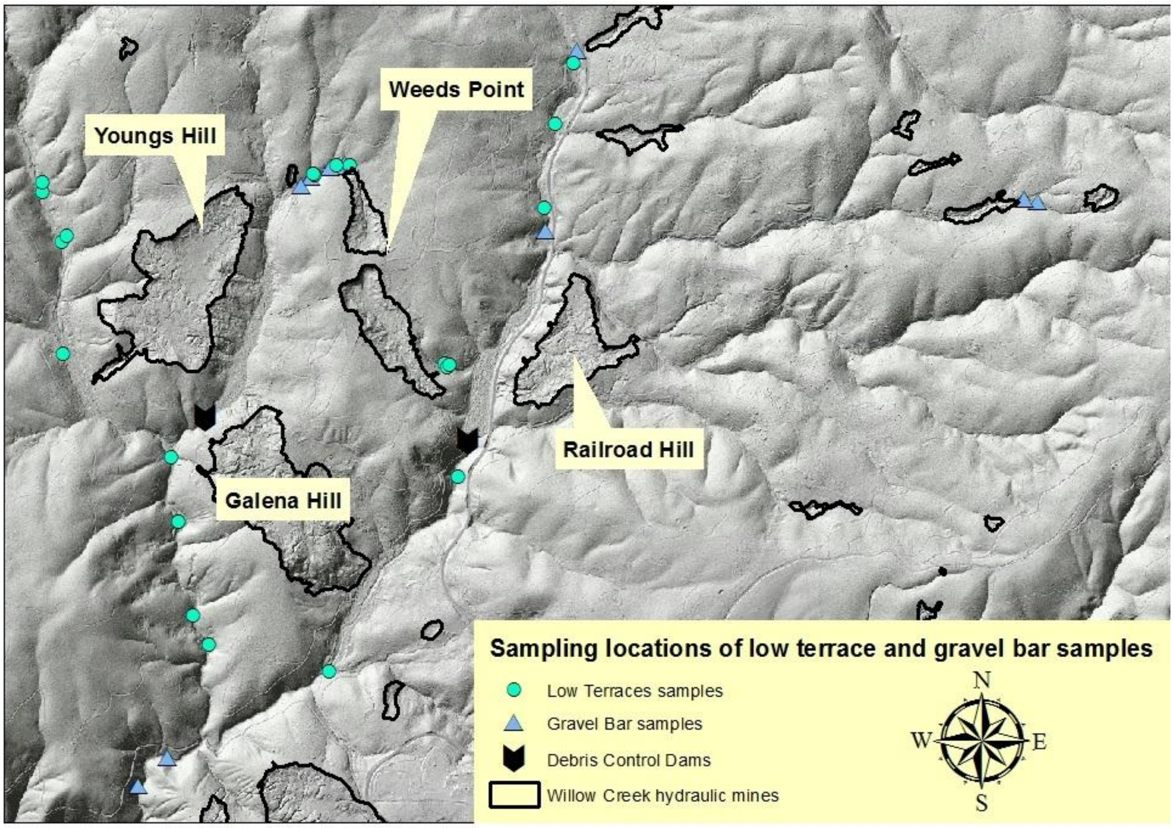


Figure 9. Locations of low terrace and gravel bar samples collected in the Willow Creek Watershed. These samples are considered active channel samples, which are samples that can be altered by ongoing hydrological events in the stream channels of Willow Creek.

in the number of samples collected from each DCD resulted from land tenure and site access issues. To gather a sample, a 1-meter square section was cleared on the sediment deposit. Enough sediment was gathered from the first 1-ft (measured vertically) of the square meter to fill a 5-gallon bucket (this sample was labeled 'deposit: 0-1ft'). The pit was then excavated to a depth of 1-ft and the next foot of the sediment deposit was and labeled "deposit: 1-2 ft." These samples were washed in the field and sieved through a 4 mm (phi #2) sieve. All samples were then placed in plastic bags and transported to the lab for analysis.

Sample Processing

All sediment samples were transported to the lab for analysis. Samples were washed and sieved through a 4.75 mm sieve (# 4 sieve, between 2 and 2.5 phi) in the lab to remove fines and aid visual separation of the pebbles. The reduced sample was then run through a 6 mm sieve to remove smaller pebbles, conforming to James' 1991 methods. The remaining pebbles were spread-out until they were evenly distributed over a 1 square meter alphanumeric grid that had previously been drawn on a table in the lab (Figure 10). The grid was divided into 100 sections, with each section measuring 100 cm^2 (10 cm x 10 cm). A random number generator (Random.org, 2018) was used to select

Figure 10. A photo of the 1 m^2 alpha-numeric grid used to select sections from which to count pebbles. Each square in the grid is 10x10 cm.

which sections to count. Grid selection continued until 100 pebbles had been tallied. If 100 pebbles had been counted, and there were still pebbles in a grid section to be counted, the remaining pebbles in that grid were added to the count (Figure 10).

Once a section was selected, all of the pebbles in that section were collected (including any pebbles touching the lines delineating the section) and segregated by visual inspection into the categories "white quartz" or "other." Visual inspection can be expected to differentiate the pebbles collected with a high degree of accuracy because minerals that appear similar to white quartz, such as white feldspathoids, are rare in this geologic province (James, 1991). Pebbles less than 75% white quartz (as visually determined by the researcher) were deemed "other." Additionally, the intermediate axis (b-axis), of each pebble was measured with a ruler and recorded.

Sediment Mixing Ratio

A two-tailed, Wilcoxon rank sum test of equivalency of means was used to compare the other alluvium and mine tailings populations. The null hypothesis was that the means of the two populations were not significantly different, and the assumption that the two populations were distinctly different could not be rejected. For statistical results the significance level (α) was set at p=0.1, and all statistical analysis was done using the statistical programming language R (R Core Team, 2018).

Once the average values for mine tailings (%*Qt)* and other alluvium (%*Qo)* were determined, these values were placed into Equation 1. The percent white quartz in each sample (%*Qs*) was used in Equation 1 to determine the sediment mixing ratio (%MS) and from this, the percentage of that sample, and therefore the sediment deposit from which it originated, could be directly attributed to historical hydraulic mining.

CHAPTER III

RESULTS

Sampling

Eighty-one sites were sampled to yield 90 samples (Figure 11). When the sediment deposits behind the Horse Valley Creek and Willow Creek DCDs were collected samples were divided into surface (0-1ft depth) and subsurface (1-2ft depth), resulting in two samples for each site.

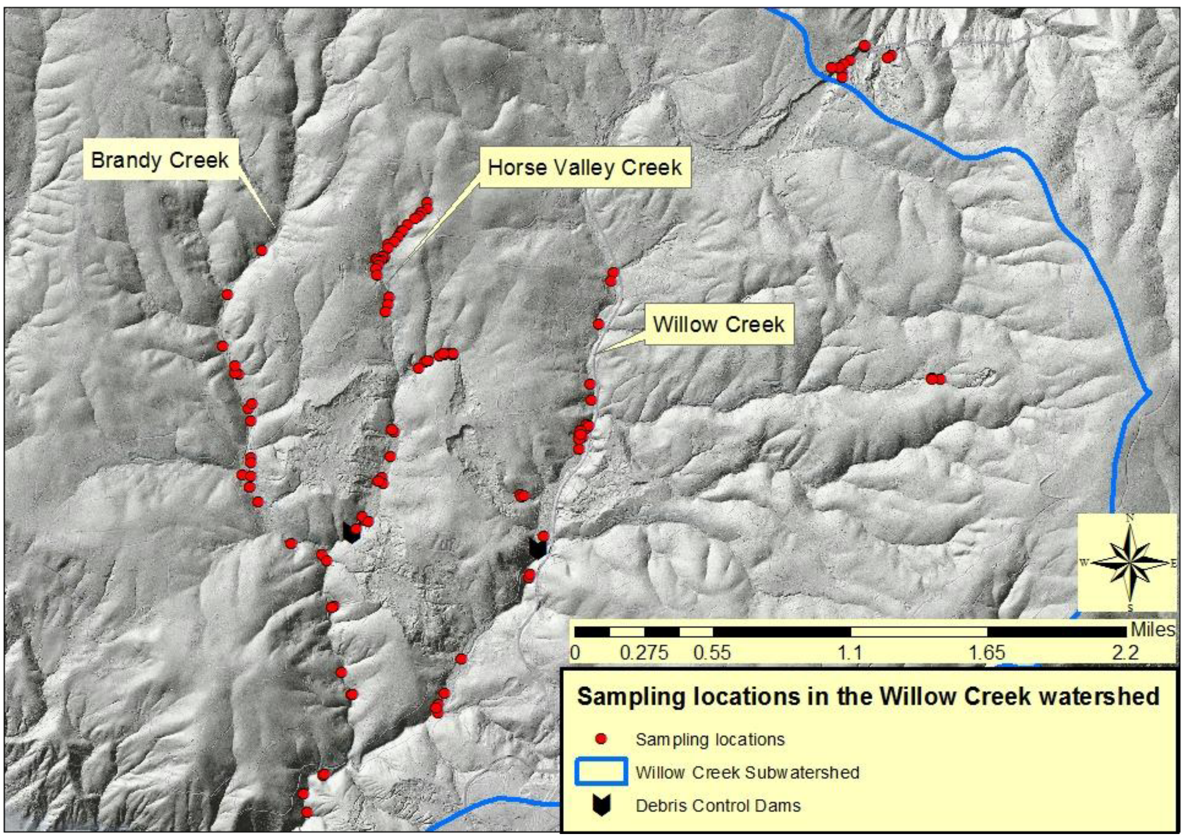


Figure 11. The location of all samples (n=90) taken within the Willow Creek watershed. The two debris control dams (DCDs) in the watershed are marked by black arrows.

Sediment Mixing Ratio

Before the sediment mixing ratio (%*MS*) for the Willow Creek Watershed could be ascertained, the two constants in the mixing ratio equation, "mine tailings" (%*Qt*) and "other alluvium" (%*Qo*), were established. Seven locations were sampled to determine the mean value of the "other alluvium" variable, and 12 locations were sampled to determine the mean value of the "mine tailings" variable. The average percentage for "other alluvium" samples was 2.9% white quartz (*n*=7, Figure 12), and the average percentage for the "mine tailings" samples was 50.3% white quartz (*n* = 12).

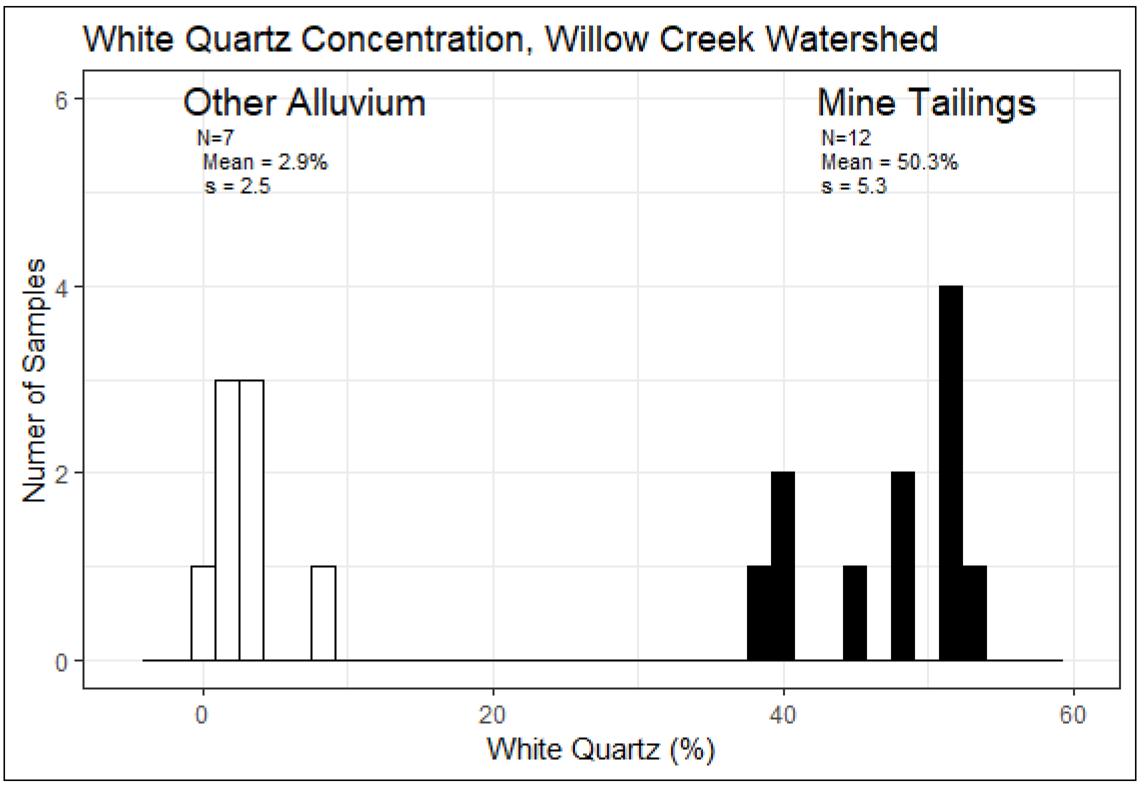


Figure 12. Comparison of the white quartz percentage seen in other alluvium (%Qo) samples (n=7) with the white quartz percentage seen in mine tailings (%Qt) samples (n=12). Other Alluvium samples were taken from areas in the Willow Creek Watershed upstream of where historical hydraulic mining has been documented to have occurred, and therefore free of hydraulic mining sediment; mine Tailings samples were taken from high terraces below areas of hydraulic mining in the Willow Creek Watershed.

These two groups of data were significantly different (n = 19, W = 0, p-value < 0.05, Wilcoxon rank-sum test, Figure 12). A similar graph from James' 1991 study in the Bear River watershed is included for comparative purposes (Figure 13). The mean white quartz percentages of the other alluvium and mine tailings samples, 2.9% and 50.3%, respectively, were used in the sediment mixing ratio equation (Equation 3).

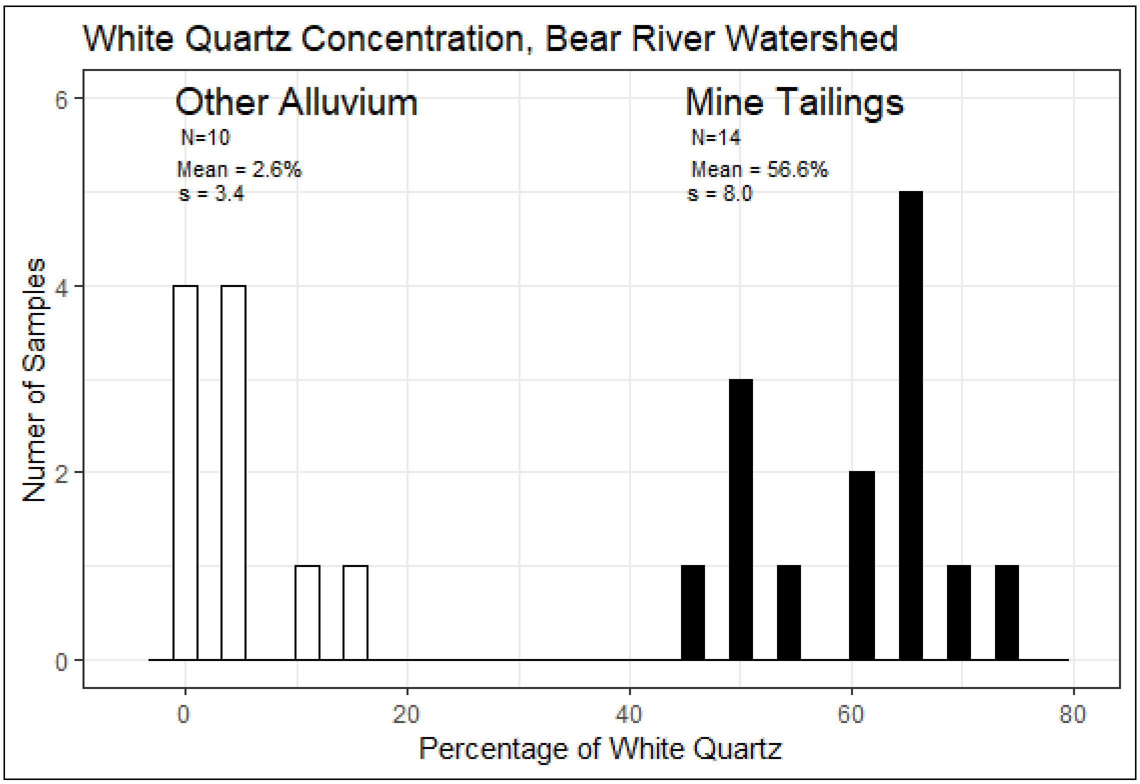


Figure 13. White quartz percentages from James' 1991 study examining the white quartz percentages of sediment deposits in the Bear River watershed. The difference between the two populations, other alluvium (%Qo) and mine tailings (%Qt), was used by James to create his sediment mixing ratio (%MS) relation. This graph was modified from the original, hand-drawn graph that appears in James, 1991.

The variation seen between the two sample groups suggests the samples come from significantly different populations and can be used as variables in the sediment mixing equation (Equation 3). Using the %Qo and %Qt found in this study, Equation 3 yields the following relation:

$$\%MS = (\%Qs - 2.9) * \frac{100}{50.3 - 2.9} \tag{3}$$

This relation further reduces to Equation 4:

$$\%MS = (\%Qs - 2.9) * 2.1 \tag{4}$$

The relationship established in Equation 4 was used to determine the sediment mixing ratio of sediment deposits throughout the Willow Creek Watershed.

Samples were divided into five sample groups based on their sampling location and field observations of the deposits' geomorphic signatures. These five groups and the number of samples in each group are: In-situ Auriferous Gravels, Lower Terrace, Gravel Bar, DCD, 0-1ft, and DCD 1-2ft.

1 **In-situ Auriferous Gravels**: samples taken from in-situ auriferous gravels exposed in the upper Willow Creek Watershed. These samples were exposed during the construction of SR 49 in 1934 ("California State Route 49," 2018) and represent auriferous gravels that were never exposed to the processes of hydraulic mining (n=13). These samples are not considered "Other Alluvium" because without excavation by anthropogenic forces (highway construction) these gravels would not be exposed and would therefore not be a part of the naturally occurring white quartz percentage. It is assumed that had these in-situ auriferous gravels been exposed during the period of active mining they would have been mined using the hydraulic method.

2 **Lower Terrace**: samples taken from low terraces in the Willow Creek Watershed deposited after the period of unlicensed hydraulic mining, when all of the "Mine tailings" samples were emplaced and later incised (n=22).

3 **Gravel Bar**: samples taken from gravel bars in the active channels within the Willow Creek Watershed. Together with the lower terrace samples, the gravel bar samples represent "active channel deposits," i.e., deposits that are actively being reworked in the watershed and could be influenced by contemporary hydrological conditions (n=12).

4 **DCD, 0-1ft**: samples taken from the upper 1 ft (0.33 m) of the sediment deposit behind the Willow Creek and Horse Valley Creek DCDs (n=9).

5 **DCD 1-2ft**: samples taken from depths of 1-2 ft on the sediment deposits behind the Willow Creek and Horse Valley Creek DCD's (n=11)

The sediment mixing ratios for each of these sample groups were calculated using Equation 4. Figure 14 provides a box-plot distribution of these five data sets plus the mine Tailings and other Alluvium. Data from the two DCD deposit samples are combined in a single Deposit category.

White Quartz Percentage of in-Situ Auriferous Gravel Samples Compared with Mine Tailings Samples

The white quartz percentages (quartz particles in the 6-64 mm range) of in-situ auriferous gravel deposits were compared with mine tailing's deposits in the Willow Creek Watershed as a way to measure the effect of hydraulic mining. Samples of the two populations were collected and analyzed (Figure 15) and found to be significantly different (n = 25, W = 43, p < 0.1, Wilcoxon rank-sum test). The mean concentration of

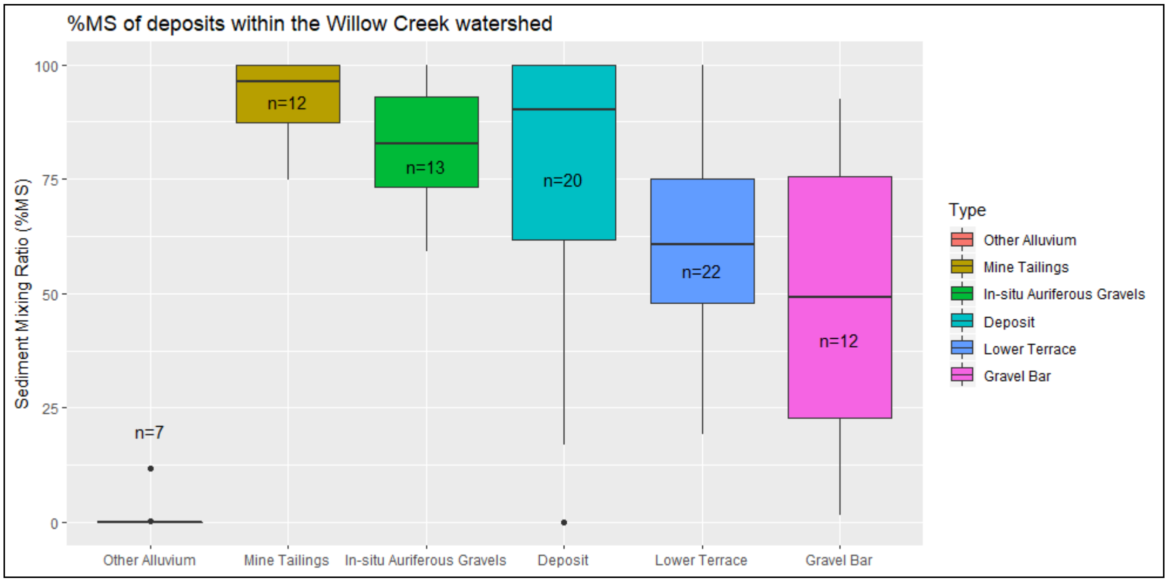


Figure 14. A box plot of the sediment mixing ratios (%MS) for six sample groups. The sediment mixing ratios of the four sediment deposits found in the Willow Creek Watershed (in-situ auriferous gravels, deposit, lower terrace and gravel bar deposits) are presented on the right side of the figure, while the two control variables, other alluvium (%Qo) and mine tailings (%Qt) deposits, are presented on the left. This graph illustrates the variability of the sediment mixing ratios among sediment deposits in the Willow Creek Watershed.

white quartz in the in-situ auriferous gravels was 43%, and the mean concentration of white quartz in the mine tailings was 50%. These data suggest hydraulic mining increased the white quartz percentages in mine tailing samples approximately 7% from the in-situ auriferous gravels.

Longitudinal Trends

The sediment mixing ratios of samples taken along Willow Creek, Brandy Creek, and the reach from the North Cut of Weeds Point Diggings to Horse Valley Creek were examined to determine if there are any apparent longitudinal trends related to the movement of historical hydraulic mining sediment. The three creeks offered the opportunity to examine reaches with different sediment storage histories, each the result of anthropogenic mining processes.

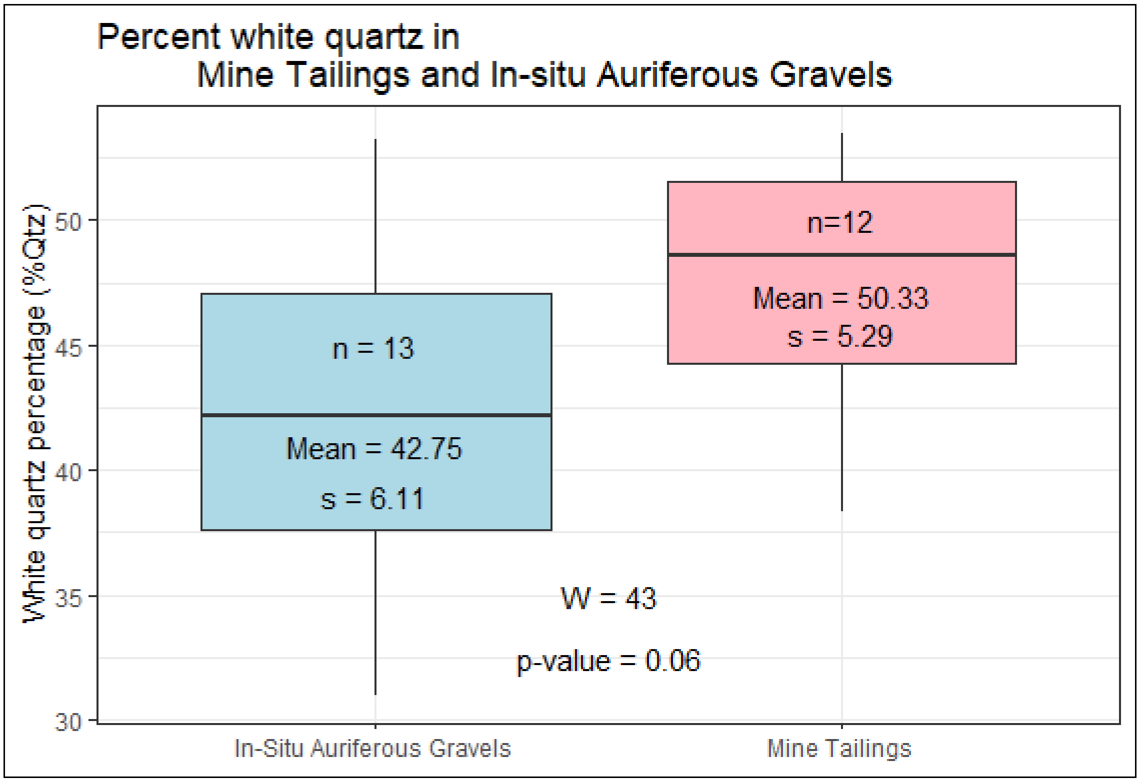


Figure 15. Comparison of the white quartz percentage of in-situ auriferous gravels from the Willow Creek Watershed with those found in mine tailings from high terraces in the Willow Creek Watershed.

Willow Creek. Nine samples were gathered along Willow Creek, from immediately downstream of Jaubert Diggings hydraulic mine to just upstream of New Bullards Bar Reservoir (Figure 16). There was a downstream trend in the sediment mixing ratios of samples taken from the active channel deposits (lower terrace and gravel bar deposits) in Willow Creek (%MS=84.84 to %MS=57.18). The samples can be divided into two populations, those upstream of the Willow Creek DCD and those downstream of the DCD (Figure 17). A two-tailed Wilcoxon test found the %MS of the two populations to be significantly different (Figure 18, n=9, W=18, p-value < 0.1). This demonstrates that the DCD on Willow Creek continues to hold back hydraulic mining

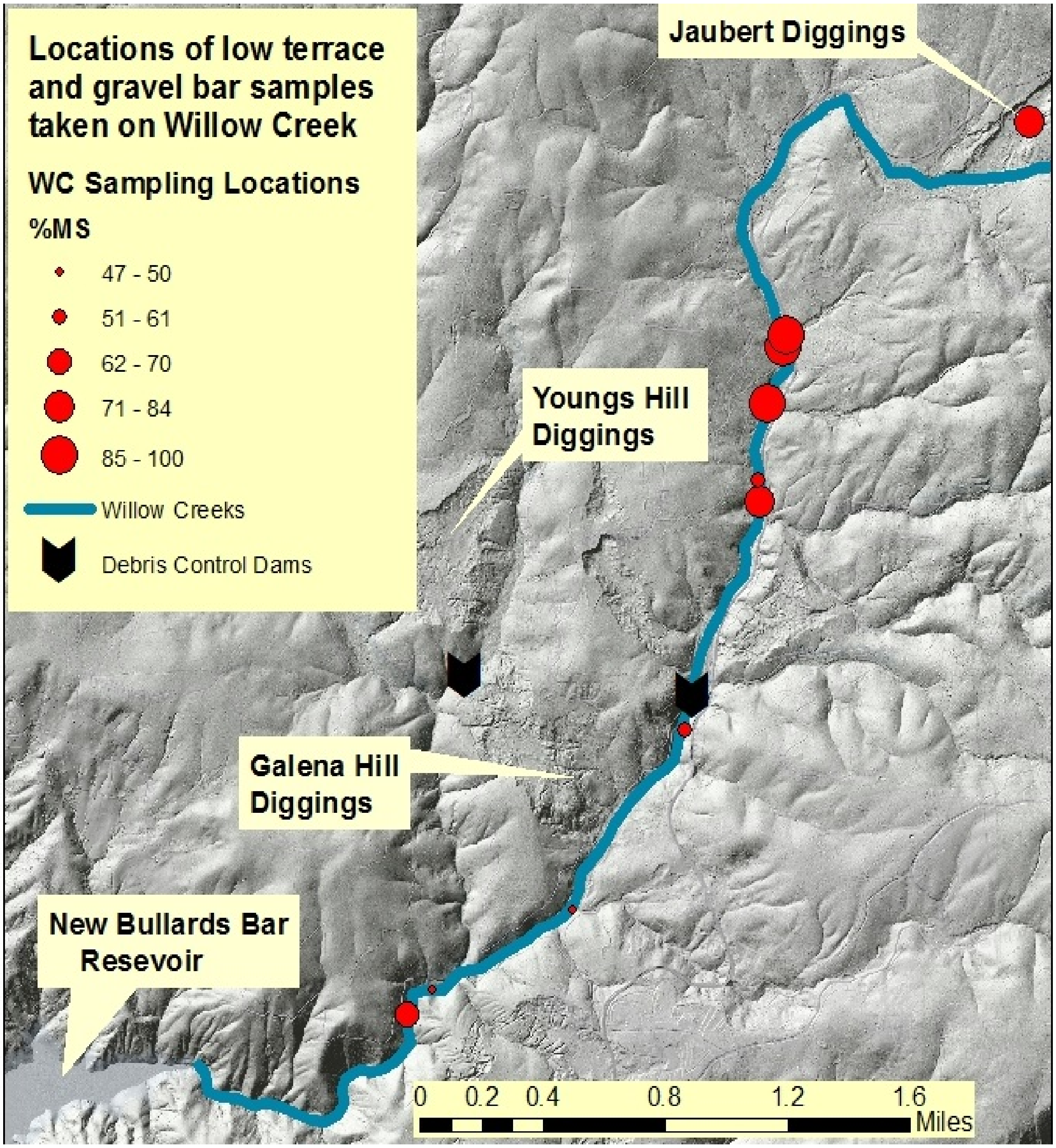


Figure 16. Sampling locations on Willow Creek. The size of the circles is proportional to the sediment mixing ratios of the samples (n=9). The sample taken at Jaubert Diggings is an average of the in-situ auriferous gravel samples taken from that location (μ=84.0). On Willow Creek, the sediment mixing ratios decreased from upstream to downstream across the debris control dam.

sediment (particles measuring 6 mm - 64 mm along the B-axis) preventing the sediment from moving downstream of the dam.

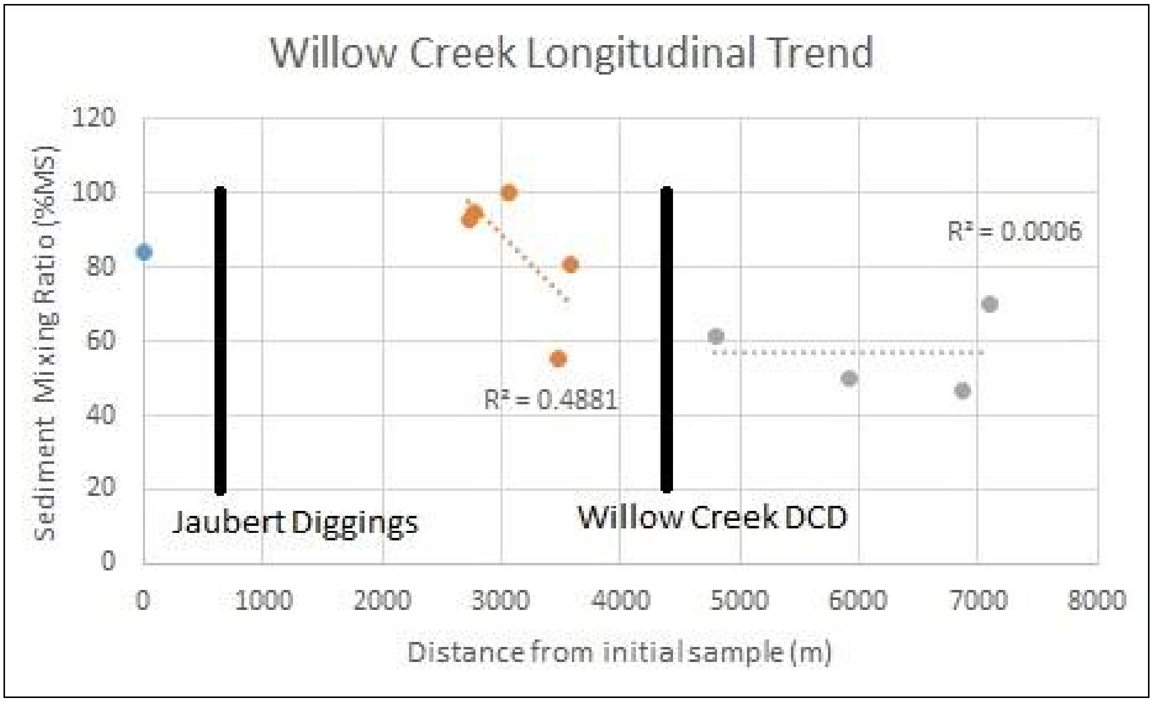


Figure 17. Change in sediment mixing ratios with distance downstream from Jaubert diggings for samples taken from Willow Creek. Jaubert Diggings, a sediment source, and the Willow Creek debris control dam (DCD), a sediment barrier. Both are indicated by the two black lines. Two distinct populations are apparent, those samples taken above the DCD and those taken below the DCD. Differences between the sediment mixing ratios of the two populations are significant (n=9, W=18, p=0.06), indicating the DCD is having the effect of restraining hydraulic sediment (particles measuring 6 mm - 64 mm along the B-axis) above the DCD and preventing them from migrating into the lower reaches of Willow Creek.

Brandy Creek. The sediment mixing ratios of samples collected along Brandy Creek (Figure 19) were plotted to assess the longitudinal trend from upstream to downstream (n=9). A Wilcoxon rank-sum test of samples taken upstream of Young's Hill road (n=4) and downstream of Young's Hill road (n=5) found the two populations to be significantly different (n=9, W=0, $p < 0.05$, Figure 20). The two populations are separated by Young's Hill road, but their difference is not attributed to the road. As seen in the Willow Creek data, the sediment mixing ratios appear to be from two distinct

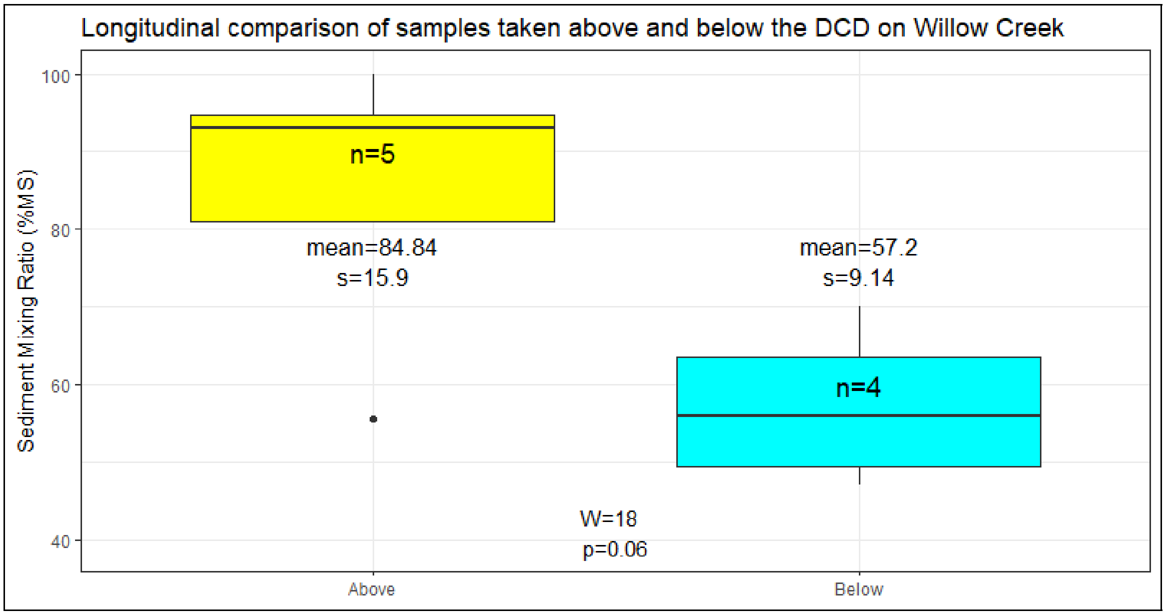


Figure 18. Comparison of the sediment mixing ratios (%MS) of samples taken above and below the debris control dam on Willow Creek. The two populations are significantly different (n=9, W=18, p=0.06, Wilcoxon rank-sum test). Samples are from the active channel (low terrace and gravel bar samples) and therefore subjected to modern hydrological events. This graph illustrates the dam is having an effect on the sediment mixing ratios of sediment deposits on Willow Creek (for sediment particles measuring 6 mm - 64 mm).

populations: the upstream population with lower mixing ratios (%MS), and the downstream populations with higher mixing ratios (Figure 21). Unlike Willow Creek, however, there is no extant DCD to explain the break in the two populations. Furthermore, unlike in Willow Creek, the sediment mixing ratios of samples taken in Brandy Creek decrease in an upstream direction.

<u>Horse Valley Creek</u>. The sediment mixing ratios of samples collected from Horse Valley Creek between the tunnel outlet of the North Cut of Weeds Point mine were used to create a longitudinal trend of the Horse Valley Creek drainage. Figure 22 is a LiDAR image of the mine outlet and shows the area over which the samples were collected. A scatter plot was created of these sediment mixing ratios down the reach, and

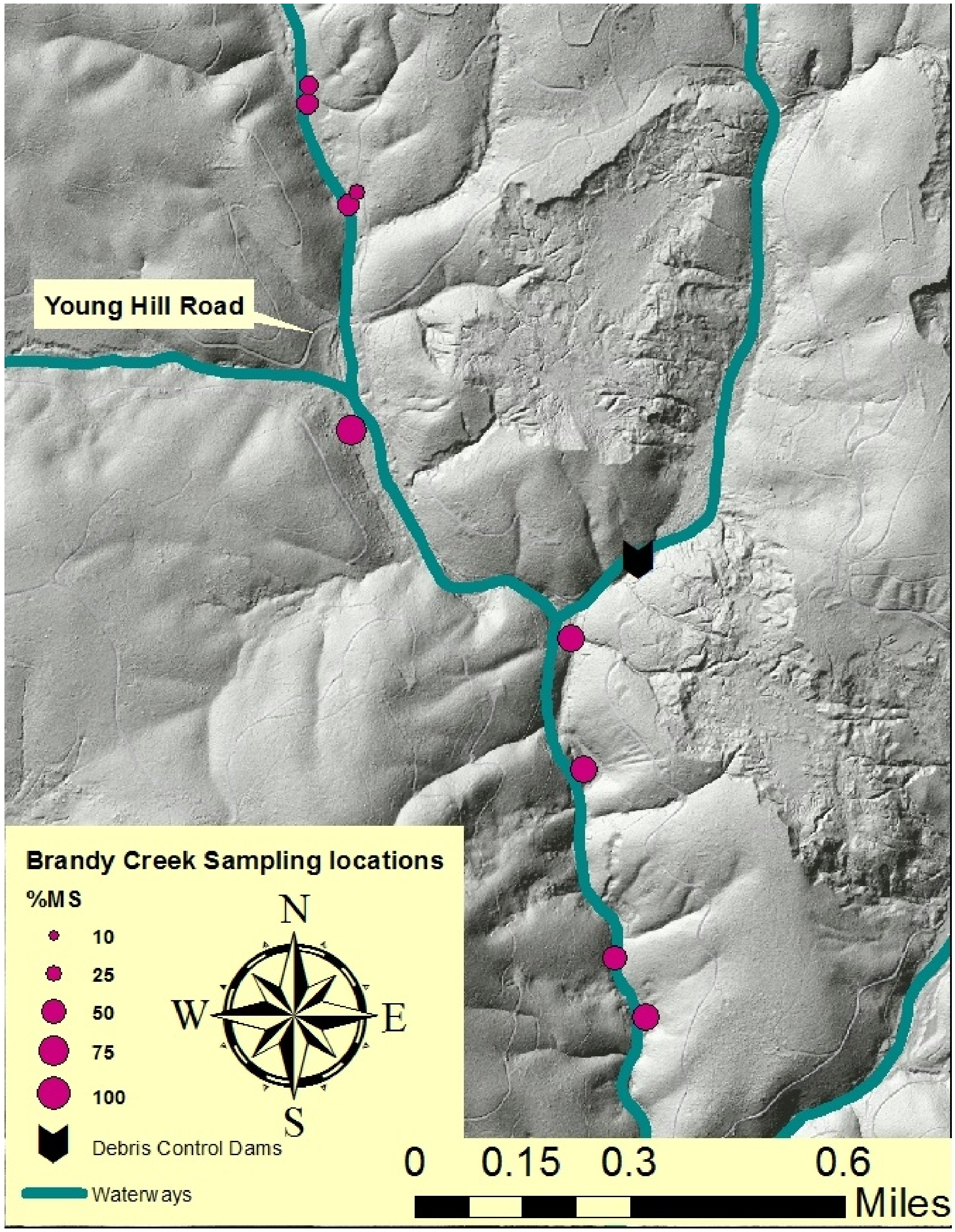


Figure 19. A LiDAR image of Brandy Creek showing the sites where active channel (gravel bar and low terrace) sediment samples were collected. The relative size of the circles indicates the approximate sediment mixing ratios (%MS) of the samples. Youngs Hill and Galena Hill Diggings, the two mines which released HMS into Brandy Creek are indicated on the map, as well as Young's Hill road.

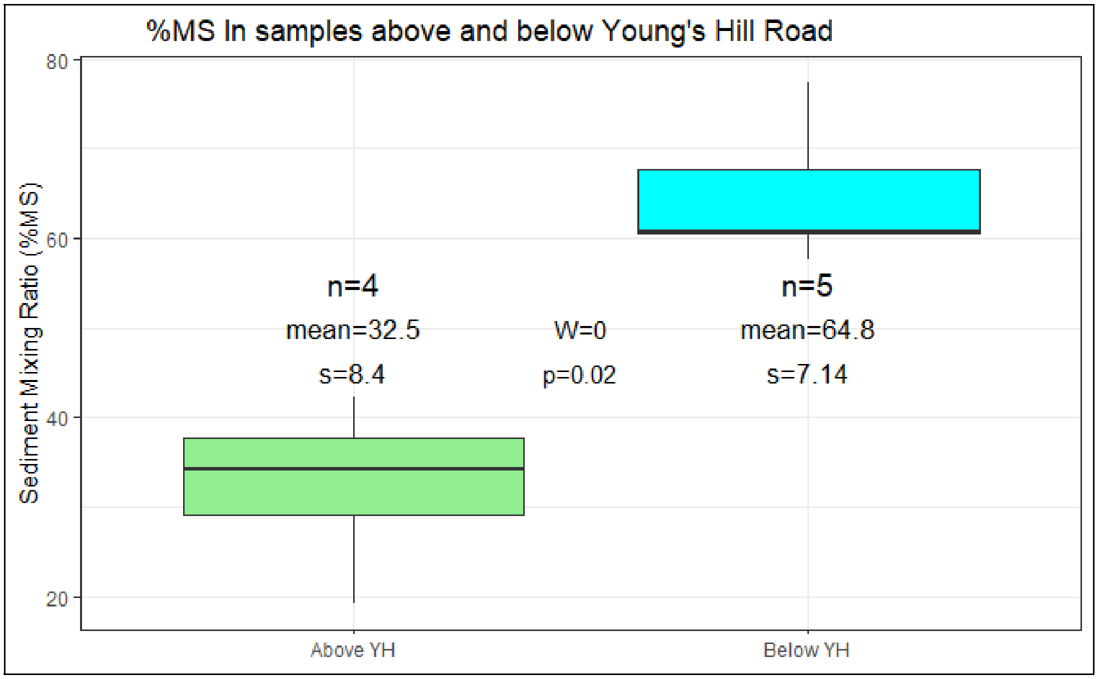


Figure 20. A comparison of the sediment mixing ratios (%MS) seen in samples taken above Young's Hill road (n=4) and below Young's Hill road (n=5). A Wilcoxon rank-sum test found the two populations to be significantly different.

a downward trend, from ~91 %MS to ~ 20 %MS, was observed from the upstream source to the downstream depositional zone (Figure 23).

Laterally Connected Populations

To compare the sediment mixing ratios of the three laterally connected populations (mine tailings, lower terrace and gravel bar samples) in the Willow Creek Watershed, samples of each population were collected (12, 22 and 12 samples respectively) and analyzed to determine their white quartz percentages. Figure 24 is an idealized cross section showing the relation between the mine tailings (high terrace) samples and the low terrace and gravel bar (active channel) samples. The conceptual model of lateral connectivity is based on two assumptions:

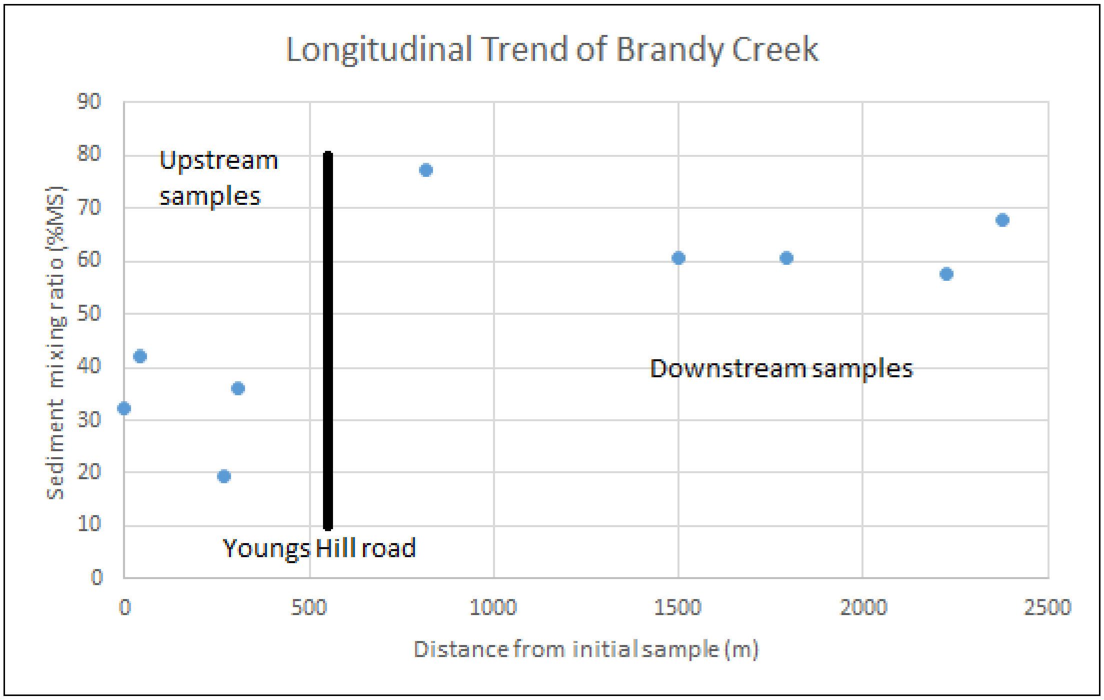


Figure 21. Change in sediment mixing ratios with distance downstream from sediment deposits in Brandy Creek. The furthest upstream sample taken from the in-channel deposits in Brandy Creek to the sample taken farthest downstream before the confluence with Willow Creek. Youngs Hill road is represented by the vertical black line. Unlike on Willow Creek, the sediment mixing ratio (%MS) of the active channel deposits trends towards higher percentages of hydraulic mining sediment downstream. There is no extant DCD on Brandy Creek, and there are several sediment sources that could explain the differences in the longitudinal trend between the two reaches (see Figure 35).

1. The high terraces, composed entirely of undiluted HMS (termed “mine tailings” in this study), were emplaced before the Sawyer injunction, during the period of unlicensed hydraulic mining. Since the quantity of HMS mobilized during the period of unlicensed hydraulic mining was much greater than that mobilized during the period of licensed hydraulic mining, the former period is when the high terraces were deposited, and the channel later incised through these deposits. The volume of the mine tailings deposits and distance above the active channel suggests this assumption is valid (Gilbert, 1917; Whitney, 1880).

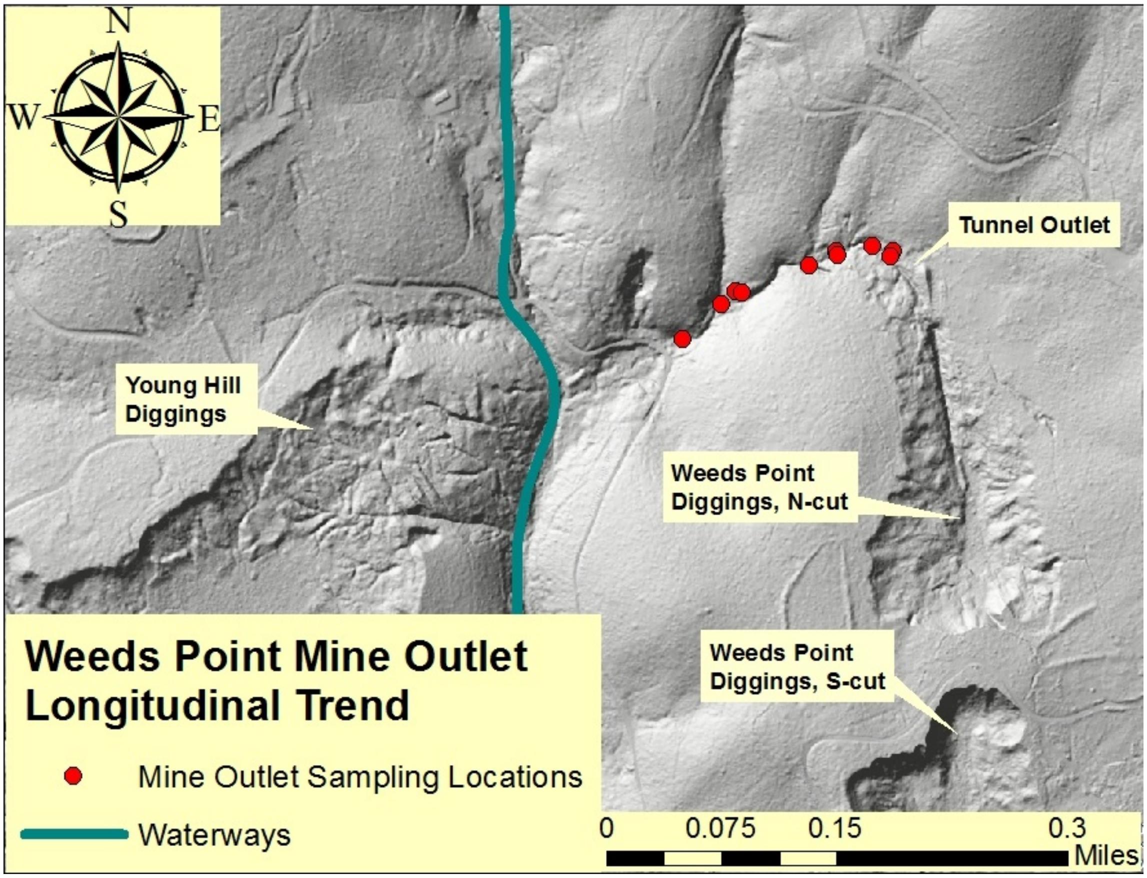


Figure 22. A LiDAR image showing the tunnel outlet of the North Cut of Weeds Point Diggings to the confluence with Horse Valley Creek (green line). This reach is ~300m long, and nine samples were collected along its length. Over this short distance, there is a noticeable downward trend in the sediment mixing ratios (%MS) of samples, from near 100%MS at the mine outlet to ~20%MS in samples taken near Horse Valley Creek.

2. Low terrace deposits were emplaced after the Sawyer injunction, during the period of licensed hydraulic mining. The location of the low terraces, within the incised channels that cut through the mine tailings deposits, suggests this assumption is valid.

The sediment mixing ratios (%MS) of the three populations decreased from the undiluted HMS of the mine tailings deposits (high terraces) to the gravels actively moving through the watershed (Figure 25). The sediment mixing ratio of the mine tailings (high terraces) was 100% (n=12). The average sediment mixing ratio of the lower

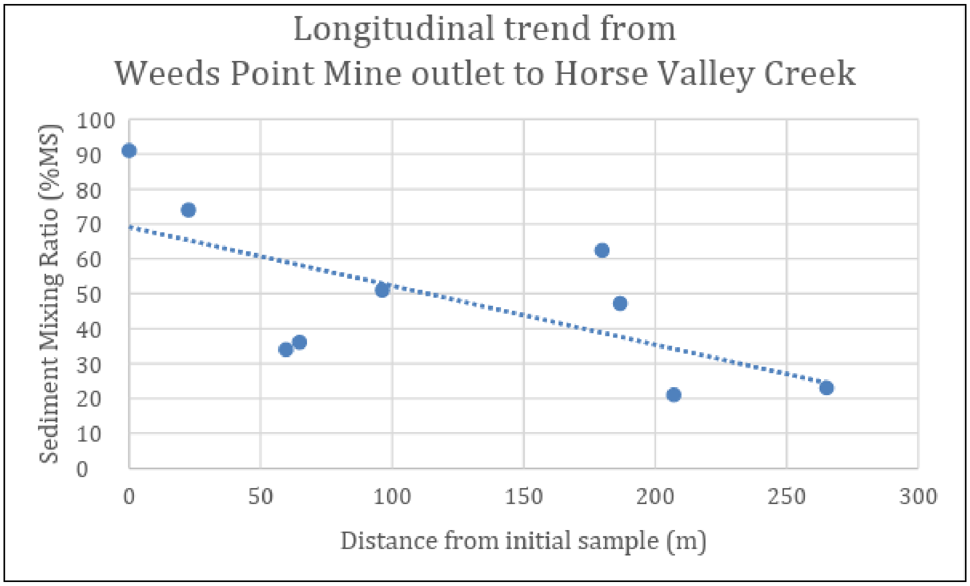


Figure 23. Sediment mixing ratios with distance downstream for gravel bar and low terrace samples along the channel from the outlet of the North Cut of the Weeds Point Diggings. Samples were taken immediately downstream of the mine outlet to the final sample collected ~260-ft downstream, just above the confluence with Horse Valley Creek.

terraces was 62% (*n*=22). The average sediment mixing ratio of gravel bars was 49% (*n*=12). The sediment mixing ratios of the active channel deposits were higher than those of the "other alluvium" samples (%MS = 2.9, *n*=7, Figure 26). Other alluvium samples were gathered upstream of documented hydraulic mines and were therefore considered free from the influence of hydraulic mining activity. These data indicate historical hydraulic mining is having an ongoing influence on the sediment profiles and sediment transport in the Willow Creek Watershed.

Deposit Behind the Horse Valley Creek DCD

The grain size (of sediments in the 6 mm-64 mm range) and sediment mixing ratios of samples taken from the first foot (0-1 ft, *n*=7) and the second foot (1-2ft, *n*=8) of the sediment deposit behind the Horse Valley Creek DCD were compared and

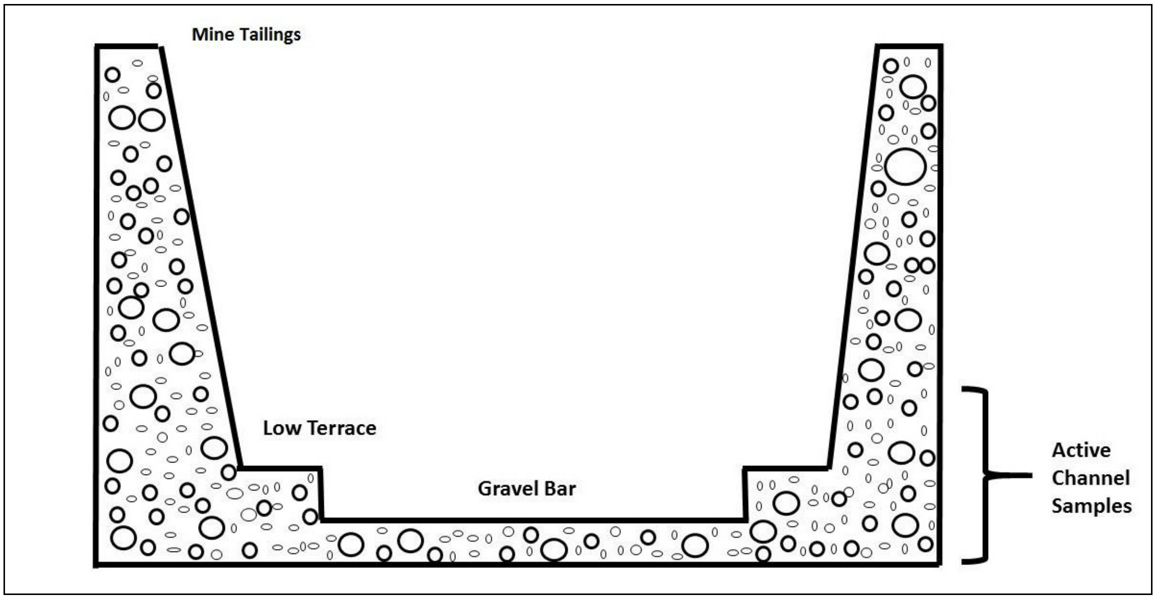


Figure 24. A conceptual model of a channel cross-section found in the Willow Creek Watershed. Hydraulic mine sediment (HMS) from the mine tailings deposits moved downslope under the influence of gravity. The lower terraces were emplaced later, after the period of unlicensed hydraulic mining, and were a mixture of hydraulic mining sediment from the high terraces and other alluvium from processes (fluvial and otherwise) unrelated to hydraulic mining. The gravel bar samples were similarly a mixture of mine tailings and other alluvial samples. The lower terrace and gravel bar samples were collectively active channel samples because they can be deposited and mixed by present-day hydrological events. In contrast, the mine tailings samples are not diluted by ongoing hydrologic processes.

analyzed (Figure 27). To compare the grain size of the samples, a Mann-Whitney U test was performed on the mean b-axis lengths of the pebbles in the 0-1 ft samples and the 1-2 ft samples of all samples from both depths (7 sampling pits in total). When the sample means of the two populations were found to be significantly different ($v=3$, p-value < 0.1, Figure 28). The mean of the b-axis lengths (D_{50}) in the 0-1 ft population and the 1-2 ft population were similar, 9.04 mm and 9.87mm respectively. It must be noted that, following the method described in James, 1991, all sediments outside the range of 6 mm-64 mm were discarded, and therefore were not part of the comparison.

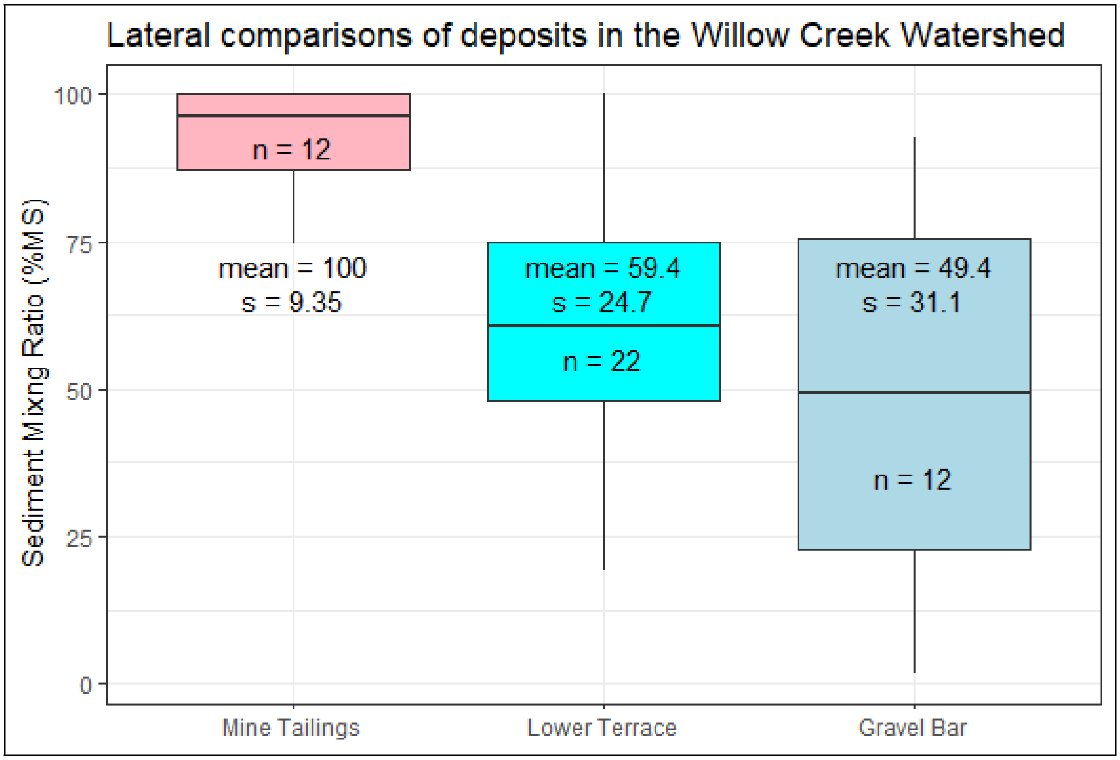


Figure 25. Comparison of the sediment mixing ratios (%MS) of the laterally connected populations, mine tailings (high terrace) samples (μ =100%), lower terrace samples (μ= 62%) and gravel bar samples (μ=49%).

When the sediment mixing ratios between the 0-1 ft and 1-2 ft samples were compared (Figure 29), no significant difference was detected between the two populations (n= 15, W=16, p > 0.1, Wilcoxon rank-sum test)). The reason for the different number of samples between the two groups is because the fines (sediment which measure below 6 mm along the b axis) were discarded in this study, resulting in nearly the entire sediment sample being washed away in some sampling locations. Samples where less than 30 pebbles were recovered from a 5-gallon bucket were not included in this study to limit undercoverage bias in samples.[1]

[1] **Undercoverage** occurs when some members of the population are inadequately represented in the sample." (Stat Trek, 2019)

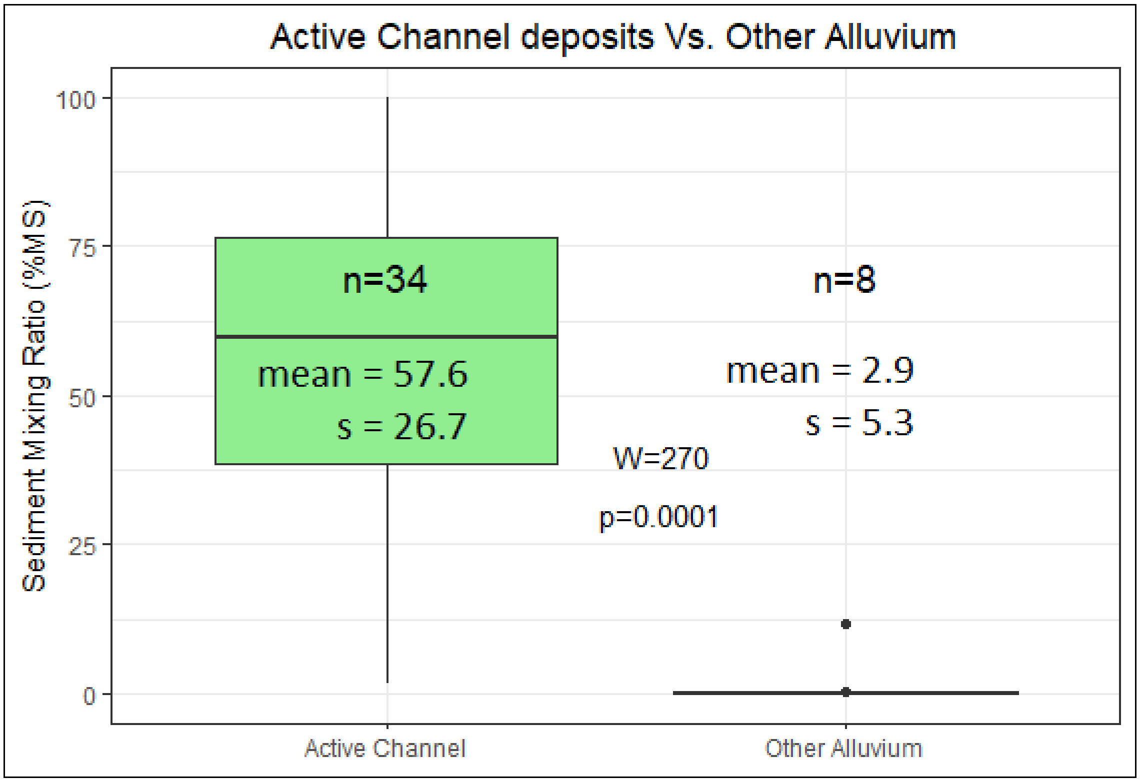


Figure 26. A comparison of the sediment mixing ratios (%MS) samples taken from stream channels (low terraces and gravel bars) and those taken from areas unaffected by hydraulic mining, termed other alluvium samples. These data show historical hydraulic mining is having an ongoing influence on the sediment profiles and sediment transport seen in the Willow Creek Watershed.

Historical Review

The CDC began issuing licenses to hydraulic mining companies in 1894 and continued until 1954, the year the last license was issued. During this period, CDC records indicate 1,284 licenses were issued, permitting 31,924,000 yd^3 (24,407,649 m^3) of sediment to be mined (California Debris Commission Archives, n.d.). This is a fraction of the 1.1 billion yd^3 (841,010,000 m^3) of sediment estimated to have been mined during the period of unlicensed mining (Gilbert, 1917), but represents a substantial volume of sediment, some of which remains in the Sierra Nevada foothills behind DCDs, in high terraces and active channel deposits (gravel bars and low terraces). According to

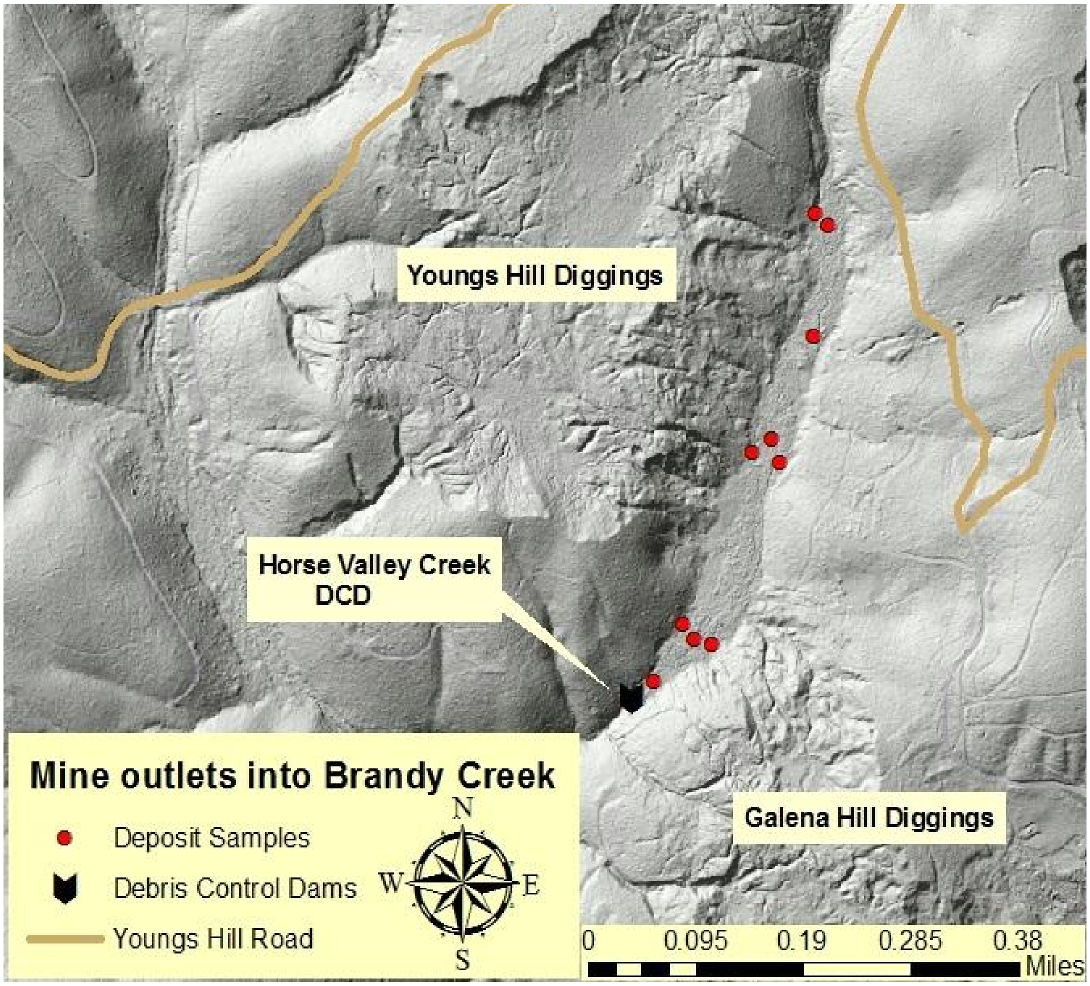


Figure 27. A LiDAR image showing the locations where sampling pits were dug on the deposit behind the DCD on Horse Valley Creek. Ten sampling pits were dug to yield 7 samples from the first foot (0-1 ft) and 8 samples from the second foot (1-2 ft). The discrepancy between sampling pits excavated and samples collected is due to the size range of sediment analyzed for this study. Any sediments which did not fall within the 6-64 mm range were discarded, and in some sampling locations this resulted in all of the sample being discarded.

the CDC, this figure reached 1,555,000,000 yd³ (1,188,882,000 m³) by 1909, 44% of which had been washed into the Yuba River (Hagwood, 1981).[2]

[2] Gilbert arrived at his estimate of 1.1 billion yd³ by doing surveys and surface reconstructions. The estimate of 31,924,000 yd³ was made by Dr. James through summation of volumes licensed to be mined in CDC records. The estimate of 1,555,000,000 yd³ for the total amount of debris washed was reported in a comprehensive history of the CDC in a report on their history for the U.S. Army Corps of Engineers (Hagwood, 1981, p. 21). No word on how they arrived at this estimate.

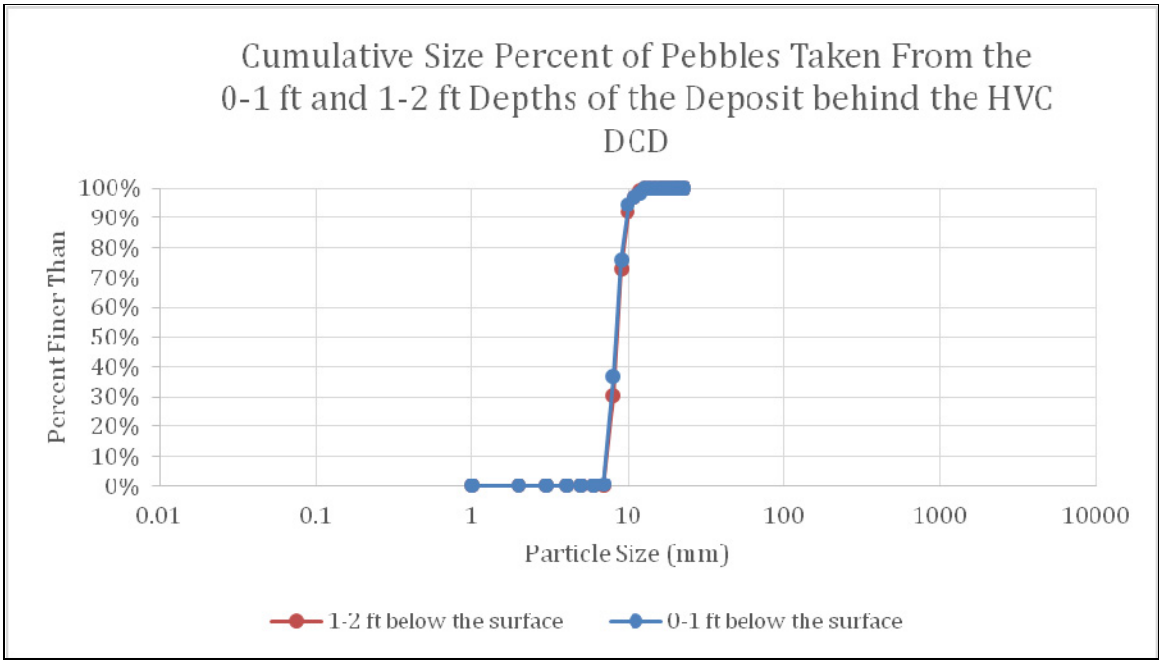


Figure 28. Cumulative grain size distributions for sediment samples taken from the first foot (0-1 ft) and the second foot (1-2 ft) depths of the sediment deposits behind the Horse Valley Creek debris control dam. The mean grain sizes of the two sample populations were not significantly different (v=3, p > 0.1). The mean grain size of the 0-1 ft population was 9.07 and the mean grain size of the 1-2 ft population was 10.03.

The Camptonville mining district is largely located within the Willow Creek Watershed. The Camptonville mining district was a productive mining district for 90 years, from the first discovery of gold in the creeks within the district in 1851, to the closing of the south cut of Weeds Point diggings in 1941 (California Debris Commission Archives, n.d.).[3] Whitney (1880) estimated that from 1860-1875, the Camptonville mining district produced $8,000,000 of gold (~$206,000,000 in today's currency). The mines of the Camptonville mining district were mentioned several times in the Sawyer deposition (Woodruff vs. North Bloomfield Gravel Mining Company, 1883). J.P.

[3] The last CDC license issued for mining in the Willow Creek watershed was #1282, issued September 3, 1952. The license was issued, but there is no indication in the records that any sediment was excavated, or that any mining occurred.

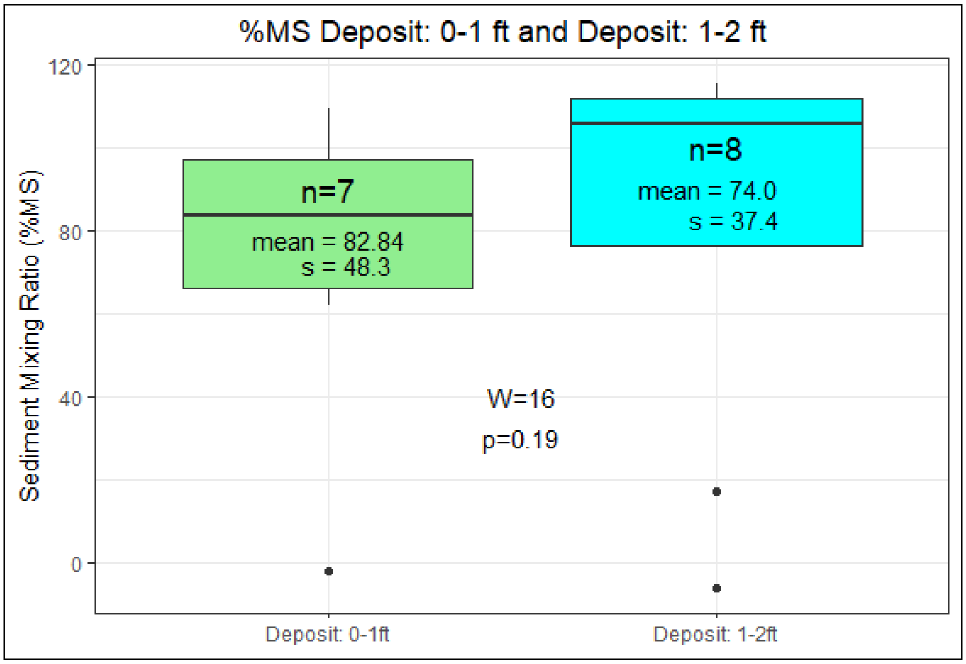


Figure 29. Comparison of the sediment mixing ratios (%MS) seen in the samples taken from the first foot (0-1 ft) and the second foot (1-2 ft) depths of the sediment deposits behind the Horse Valley Creek debris control dam. Population means were not significantly different (n=15, W=16, p=0.19, Wilcoxon rank-sum test).

Browne, a one-time miner and banker living in Camptonville (Woodruff vs. North Bloomfield Gravel Mining Company, 1883), was called as a witness for the defendant (North Bloomfield Mining Company) and testified that the majority of debris produced by mines in the Camptonville mining district was discharged into the North Yuba River through the tributaries of Willow Creek (Woodruff vs. North Bloomfield Gravel Mining Company, 1883).[4] Production was greatest from 1857-1863. Production lagged as easily accessible auriferous gravels were mined out, but it never truly ceased, even in the period between the Sawyer injunction and the Caminetti Act (Hagwood, 1981). Dr. R. Weaver wrote an exhaustive report of the Youngs Hill diggings hydraulic mine, the largest mine

[4] In 1883 (the year of this deposition), according to the defendant, the deposits at Railroad Hill had been played out and only Galena Hill and Young's Hill diggings were in current production.

in the Willow Creek Watershed, for the United States Forest Service (Wilson and Looff, 2017). The report included a thorough history of the hydraulic mines in the Willow Creek Watershed, the ownership of said mines and the ditches that supplied the water necessary for hydraulic mining.

The earliest record of a debris control structure in the Willow Creek Watershed was July 15, 1895, when Depot Hill applied for a license to store sediment behind a DCD of unknown construction.[5] The next day, on July 16, 1895, three other hydraulic mines in the Willow Creek Watershed, Galena Hill, Young's Hill and Horse Valley, applied for licenses to mine using the hydraulic method (Licenses #133, #131 and #130, respectively; California Debris Commission Archives, n.d.). CDC records indicate the Horse Valley mine planned to store their HMS behind a brush dam with a capacity to store 12,000 yd^3 (9174 m^3) of debris (licenses # 130, 1895; California Debris Commission Archives, n.d.). Young's Hill planned to store their hydraulic mine sediment behind a log-crib dam in a "dry gulch" assumed to be Brandy Creek (Wilson and Looff, 2017), and Galena Hill planned to store their hydraulic mine sediment in the mine pit. Gilbert (1917) mentions the productive mines of the Camptonville mining district in his study, reporting their production over several field seasons (Figure 30).

The next mention of Horse Valley in the CDC records comes in 1910, when the Horse Valley Mining Company had a license revoked (lic. #728, 1906; California Debris Commission Archives, n.d.). While there is no record of the date, this license was issued or what debris containment strategy the operators of the mine planned to utilize,

[5] This license was revoked May 10, 1909, because the operator failed to keep a pool of water behind the dam while operating. The minutes of this CDC meeting can be found in Appendix A (Hagwood, 1981).

TABLE 6.—*Volume of hydraulic excavation in part of the Yuba River basin as estimated by G. K. Gilbert in 1908 and by F. C. Turner in 1889–90.*

[Excavation expressed in thousands of cubic yards.]

District, mine, or locality and excavation therein.		Total excavation.	
1908	1889–90	1908	1889–90
Camptonville (7,100), Youngs Hill (7,500), Galena Hill (4,400), Weeds Point (3,000).	Willow Creek and Camptonville (5,800+1,500).	22,000	7,300
Indian Hill	Indian Hill	7,800	4,500
Moores Flat (21,000), Orleans Flat (3,400), Snow Point (3,900).	Moores Flat, Orleans Flat, and Snow Point	28,300	26,000
Woolsey Flat	Woolsey Flat	20,700	4,100
Badger Hill and English Co.	Badger Hill and Cherokee (10,000), English Co. (7,000).	22,600	17,000
North Bloomfield (main pit, 64,400; minor pits, 13,600).	North Bloomfield (29,000) Last Chance, Porter, etc. (3,000).	78,000	32,000
North Columbia (main pit, 89,500); Howleys, Ohio, Neversweat, etc. (2,560).	Columbia Hill (20,000+20,000)	92,060	40,000
Union Gravel	Union Gravel	9,100	10,000
Yuba (Grizzly)	Grizzly Hill	1,400	1,000
Paterson and vicinity	Paterson claims (5,000), Montezuma Hill (500)	7,800	5,500
North San Juan (25,350), Manzanita and American (47,900), Bed Rock (10,050), Buck Eye (12,650).	North San Juan and part American (20,000+500), Sweetland Creek, Birchville, Manzanita and part American (60,000).	95,950	80,500
Esperance (and Kinney)	Esperance	3,500	1,500
French Corral	French Corral	16,050	31,000
Omega	Omega	22,700	12,000
Alpha and vicinity	Alpha (5,000), Place, Merrill, etc.	9,000	7,000
Sailor Flat and Blue Tent	Sailor Flat and Blue Tent	46,200	15,000
Cement Hill (?)	Nevada City, Cement Hill	1,800	2,550
Rough and Ready, Randolph Hill and vicinity	Rough and Ready, Randolph Hill	910	3,000
Nevada City (Manzanita or Sugar Loaf, 6,000; Hirschman, etc., 6,400).	Nevada City, Sugar Loaf	12,400	10,000
Murchies, McCutcheon, Charonnat, etc	Murchies, Gold Flat, etc	2,100	500
Scotts Flat	Scotts Flat	18,600	12,000
Smartsville and Timbuctoo (24,460), Mooney Flat (3,800).	Smartsville, Timbuctoo, and Mooney Flat	28,260	44,800
Sicard Flat	Sicard Flat	3,030	1,700
Depot Hill	No record	3,900	....
Railroad Hill	.....do	2,700	....
Two miles west of Parks Bar Bridge	.....do	320	....
Dry Creek	.....do	40	....
Two miles west of Grass Valley	.....do	30	....
		557,250	368,950
Percentage		151	100

Figure 30. A table from Gilbert's 1917 report on HMS in the Sierra Nevada region. This table provides estimates of total excavated volumes of hydraulic mines from two periods, 1889-1890 and 1908, respectively. The hydraulic mines being worked in the Camptonville mining district are listed at the top of the table, and it is reported that 7,300 yd³ (5,581 m³) were mined from these mines by 1890. An additional 14,700 yd³ (11,239 m³) was mined by 1908. Two mines in the Camptonville mining district, Depot Hill (3,900 yd³ (2,982 m³) excavated by 1908) and Railroad Hill (2,700 yd³ (2,064 m³) excavated by 1908) were not included in this calculation because no records were found for these two mines in the 1889-1890 season. All values are reported in thousands of cubic yards.

CDC records indicate that licenses 700-753 were issued in 1906 (California Debris Commission Archives, n.d.). This license was revoked June 14, 1910, for unknown reasons. Possible reasons for license revocation include the debris containment strategy reached capacity, the debris control dam failed, or the mine operators were not following CDC guidelines (James, 2005). Records for this license indicate that 2,600 yd^3 (1988 m^3) of sediment were worked prior to the license being revoked. In a report to the United States Forest Service on the Young's Hill Diggings property, the Horse Valley Mining Company was said to have temporarily stopped working the Eocene gravels in the Horse Valley Creek area in order to build a new, more permanent debris containment structure (Wilson and Looff, 2017). Some of the extant terraces may be the result of this early licensing period, before the construction of concrete DCDs in the Willow Creek watershed.

The concrete arch dam that sits in Horse Valley Creek today was approved and licensed December 1, 1915 (Lic. # 905, 1915; California Debris Commission Archives, n.d.). This debris control dam was licensed as a 26-foot high concrete arch dam with a capacity to store 70,000 yd^3 (53,519 m^3) of sediment. This dam was built to retain hydraulic mining debris from the North Cut of Weed's Point Mine and the eastern margin of the Young's Hill property in Horse Valley Creek (Figure 7; "Rush Work On Dam," 1915; Wilson and Looff, 2017). Both operations worked under the name of Horse Valley Mining Company and used the same license, and both operations stored their hydraulic mining debris behind the Horse Valley Creek DCD. The license that allowed mining to continue on this property was revoked November 11, 1920, for unknown reasons (CDC licence #905; California Debris Commission Archives, n.d.). Approximately 3,400 yd^3 (2,600 m^3) of sediment were purportedly mined before the license was revoked. In a 1923 unsigned report to potential investors in the mine at Weed's Point, the author claimed the Horse Valley Creek DCD only had 23,000 yd^3 (17,585 m^3) of storage capacity remaining

8 years after the dam's initial construction ("Report on the Horse Valley Placer Mine," 1923). However, while this implies 47,000 yd³ (35,934 m³) of sediment had accumulated over 8 years, the volume of hydraulic mine sediment worked at this time was not reported in CDC records. It is not known at what time the DCDs reached capacity in the Willow Creek Watershed, either during active mining operations or by capturing sediment after mining had concluded, but today both DCDs restrain a sediment deposit over twice the volume which they were originally licensed for.

The Horse Valley Mining Company returned to hydraulic mining in 1931 and 1932 and stored an additional 19,200 yd³ (14,679 m³) of sediment behind the Horse Valley Creek DCD (lic. # 1,030, 1931; lic # 1,064, 1932; California Debris Commission Archives, n.d.). License #1,064, the final license issued by the CDC to retain hydraulic mining sediment behind the Horse Valley Creek DCD, was revoked January 6, 1937. Mining continued in the area at the Weed's Point mine (Lic. #s 1188, 1198 and 1250; California Debris Commission Archives, n.d.), but most of this period's mining seemed to be in the southern cut of the Weed's Point mine. Debris from the southern cut hydraulic mining operation was retained by the Willow Creek DCD and did not flow into Horse Valley Creek (California Debris Commission Archives, n.d.). Weed's Point was the last hydraulic mining operation in the Camptonville mining district. After this operation shut down in 1941 (after mobilizing 4900 yd³ (4480 m³) of sediment), no more licensed hydraulic mining occurred in Yuba County (California Debris Commission Archives, n.d.).[6]

[6] One named hydraulic mine in the Willow Creek watershed, Depot Hill, was issued a license in 1952, but CDC records do not indicate that the license was ever used or that any hydraulic mining took place.

CHAPTER IV

DISCUSSION

Historical Assessment

In the realm of geological sciences, studies of anthropogenic impacts upon landscapes often have a uniquely powerful tool, the eyewitness account. In geology, scientists must make inferences based on landforms, stratigraphic layers and the geochemistry of deposits. In contrast, studies done on humans' recent impacts upon their environment have artifacts, ruins, or even the accounts of the agents of change written at the time they were affecting that change. Examination of the historical record has been a common practice in studies of human impacts, and those done on the geomorphic changes wrought by hydraulic mining on the landscape of the Sierra Nevada gold belt are no exception. When Whitney (1880) wrote his report on the auriferous gravels of the Sierra Nevada, he did so by talking to the miners who worked those gravels. In Gilbert's (1917) report, he made use of stream gage records to determine the changes in channel bed morphology due to the movement of HMS. In more recent studies, James & Singer (2008) used historical records of floods and sedimentation on the Sacramento River to give perspective to the Lower Sacramento flood control system. This research found the historical record to be similarly helpful. The history of sediment retention behind DCDs in the Willow Creek Watershed was obtained from CDC records. The history of the Camptonville mining district was explored by obtaining first-hand written accounts of the mines and reports made at the time. This literature provided insight into the hydraulic mining practices that created the geomorphic features present in the Willow Creek Watershed. Other questions remain, namely:

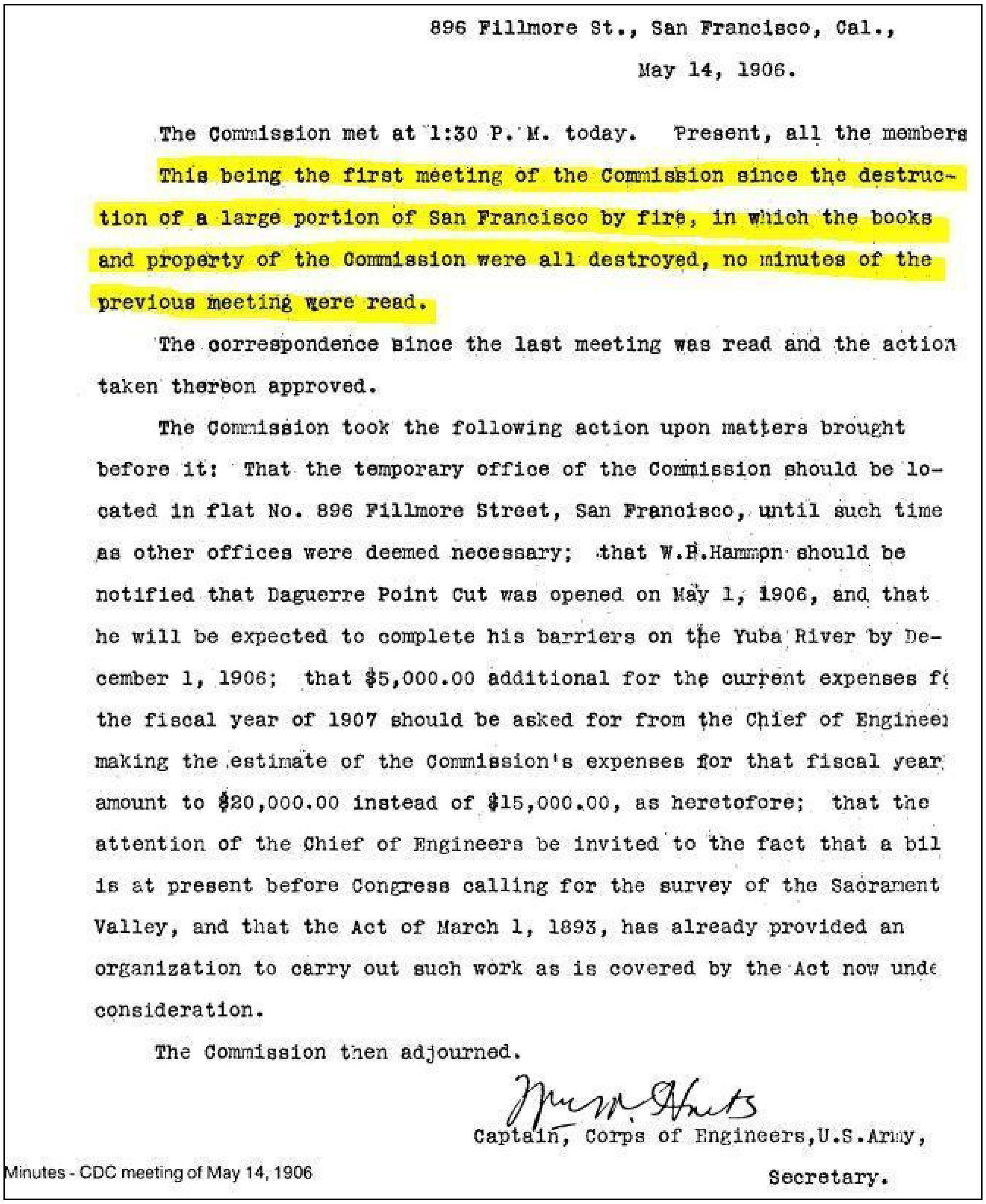
1. How much sediment was produced by mines in the Willow Creek Watershed and where is that sediment now?

2. How much of the sediment deposits in the Willow Creek Watershed are directly attributable to hydraulic mining and how much is from other, non-mining sources?

The latter question can be estimated using the sediment mixing ratio (%MS) developed in this research. The former presents unique challenges (refer to Etris (2018) for a detailed discussion). The historical record puts important constraints on this question, and the numbers in the literature should be considered estimates for several reasons. First, the historical record is incomplete. During the period of unlicensed hydraulic mining, the miners did not keep records of the volume of sediment they mobilized. When Whitney (1880) reported the volumes of gravels moved by mines, he used crude volume calculations coupled with records of water used in each mine (recorded in miner's inches).[1]

Second, the CDC licenses are also not a very reliable source to extrapolate the volumes of sediment mined. These records are incomplete, as many of the records were lost in the San Francisco fire (Figure 31; Hagwood, 1981). Because the CDC was mainly concerned with sediment storage, not production, any sediment not captured behind a debris control structure would not be accounted for in the CDC records. This means the

[1] A miner's inch is a unit of flow defined by the amount of water that would flow through a hole of 1 square inch under a given pressure. The quantitative definition of the miner's inch varies geographically. In California it is defined as 1/50 ft^3/s.



896 Fillmore St., San Francisco, Cal.,

May 14, 1906.

The Commission met at 1:30 P. M. today. Present, all the members

This being the first meeting of the Commission since the destruction of a large portion of San Francisco by fire, in which the books and property of the Commission were all destroyed, no minutes of the previous meeting were read.

The correspondence since the last meeting was read and the action taken thereon approved.

The Commission took the following action upon matters brought before it: That the temporary office of the Commission should be located in flat No. 896 Fillmore Street, San Francisco, until such time as other offices were deemed necessary; that W.H.Hammon should be notified that Daguerre Point Cut was opened on May 1, 1906, and that he will be expected to complete his barriers on the Yuba River by December 1, 1906; that $5,000.00 additional for the current expenses f(the fiscal year of 1907 should be asked for from the Chief of Enginee making the estimate of the Commission's expenses for that fiscal year amount to $20,000.00 instead of $15,000.00, as heretofore; that the attention of the Chief of Engineers be invited to the fact that a bil is at present before Congress calling for the survey of the Sacrament Valley, and that the Act of March 1, 1893, has already provided an organization to carry out such work as is covered by the Act now unde consideration.

The Commission then adjourned.

Captain, Corps of Engineers, U.S.Army,

Secretary.

Minutes - CDC meeting of May 14, 1906

Figure 31. The minutes of the California Debris Commission meeting from May, 14, 1906. This was the first meeting held after the San Francisco fire of 1906 in which the Commission discussed the destruction of all books and records held in their office. The highlighting was added by the author.

entire suspended sediment load produced by the mine during the period of licensed hydraulic mining would be unaccounted for. According to a study conducted by Curtis and Kelsey (1998) of sedimentation due to hydraulic mining in Steephollow Creek,

> due to in situ chemical weathering of the source sediments and subsequent abrasion related to the hydraulic process, approximately 40 % of the non-durable bedload sized particles were converted to suspendable sized material during transport and deposition. (p. 34)

The process of hydraulic mining has the effect of reducing large percentages of the bedload sized particles to suspended load, which would then be carried out of the watershed and not accounted for in CDC records.

A third reason sediment storage estimates should not be taken at face value is that miners had a financial incentive to under report the volume of material they expected to mine. In essence, they cheated. Hydraulic mining did not rebound to its former volumes following the Caminetti decision because the requirement to restrain HMS behind a dam or in a pit proved too onerous for the miners to turn a profit (James, 2005). If a dam reached capacity, then hydraulic mining had to cease. According to James (as related to the author in a conversation on December 18, 2016), this gave miners an incentive to try and extend the life of their mines by bypassing their debris containment method in some manner.

The question of the volumes of sediment mined from various hydraulic mines and stored in nearby sediment deposits was recently explored using geospatial data and field verification. Etris (2018) estimated the volumes of historical hydraulic mines by reconstructing the topographic contours of the hills around the mine pits. This reconstructed topography was added to the existing surface to estimate the volume of sediment removed from the mines (Etris, 2018). Estimates of the historical hydraulic mine volumes removed from the landscape using topographic reconstruction are:

- Jaubert Diggins: 3,534,115 m^3 (2,702,024 yd^3)
- Young's Hill Diggings: 4,940,973 m^3 (3,777,644 yd^3)

- Galena Hill Diggings: 2,970,242 m³ (4,940,973 yd³)

Hydraulic mining volumes of Young's Hill Diggings reported by Gilbert (1917), is 5,700,000 m³ (reported as 7,500,000 yds³ in the Gilbert report). These are ~760,000 m³ greater than the Ertis study found for Young's Hill Diggings. Gilbert arrived at his estimate by conducting extensive surveys of mine pits in 1908, following the end of hydraulic mining at the Young's Hill mine (Gilbert, 1917). The discrepancy between the two volume estimates is likely the mass wasting of the Young's Hill pit walls during the 109 years between the two studies (Etris, 2018). Comparison of these two methods increases confidence in the reliability of the topographic reconstruction method, which can provide new estimates for the volume of hydraulic mine sediments produced by mines that lack good historical estimates.

By comparing the numbers' reported by Gilbert for existing mines with those found using topographic reconstruction (Etris, 2018), it may be possible to extrapolate an average pit in-fill rate for the mines in the Sierra Nevada gold belt. With this relation it is possible to take the present mine volume found using a DEM and estimate the original volume of a mine pit. This estimate can then be constrained by creating a sediment mixing ratio for the watershed the mine occupies to determine what percent of the sediment deposits surrounding the mine are directly attributed to the mine, and what percentage is from mass wasting of the surrounding country rock.

The Sediment Mixing Ratio

Numerous authors have noted the white quartz content of the auriferous gravels that were hydraulicly mined in search of gold in the Sacramento and San Joaquin watersheds (Whitney, 1880; Gilbert, 1917; Petersen, et al., 1968; James, 1991). This white quartz content was similarly used to identify sediment deposits derived from legacy HMS (Yeend, 1974). James, in his 1991 study of HMS in the Bear River watershed, studied the amount of white quartz in sediment deposits. His research found a sediment deposit comprised of ~57% white quartz in the gravel size range (6 mm to 64mm) could be assumed to be comprised of 100% HMS. This research extended James' methodology to the Willow Creek Watershed. Extension of this method to the Willow Creek Watershed was warranted because the same geologic processes caused auriferous, white quartz veins to intrude into the country rock overlying the Sierra Nevada batholith during the late Jurassic and early Cretaceous (Dodge and Bateman, 1977; Bierlein et al., 2008). Likewise, similar geologic processes were eroding that country rock throughout the uplifting period in the Sierra Nevada region, resulting in similar alluvial deposits being emplaced in the Eocene paleo-channels throughout the Sierra Nevada metamorphic belt (Yeend, 1974). Finally, the same hydraulic mining methods were used to work these similar sedimentary deposits in both watersheds. These mining methods became progressively more standardized as early individual mine claims were consolidated into larger mining operations owned by interstate and international investors (Hagwood, 1981). Therefore, auriferous gravel deposits, worked by similar mining methods, would logically result in sediment deposits with a similar composition of mine sediment.

The white quartz percentage found in this study is comparable to that found in James' 1991 study, but it is not the same. The difference could be due to several factors. First, the paleo-river channels that run through each watershed and were worked by the miners are similar but not identical (Whitney, 1880; Lindgren, 1911). The sediment profiles for modern rivers, even those that run through similar geologic settings and are subject to similar geomorphic and hydrologic processes, are different (Anderson et al., 2005). Sediment profiles are even different on the various reaches of the same river (Goode and Wohl, 2010). It would follow that the sediment profiles, and therefore the white quartz percentages, of the sediment deposits on hydraulically mined reaches of distinct paleo-river channels would be somewhat different.

While the Eocene auriferous channels the miners worked were emplaced by similar geomorphic processes, the bedrock upon which these sediments were deposited and the rocks that subsequently buried the channels in each watershed were not the same. Both the North Yuba River watershed (of which the Willow Creek Watershed is part) and the Bear River watershed flow through the Sierra Nevada western metamorphic belt (Figures 32 and 33). Along their courses, the rivers flow through many different rock types, due to the agglomeration of numerous exotic oceanic terranes along the western margin of the North American continent (Harden, 2004). Likewise, the post-depositional history of the two watersheds is different. The 100% HMS discussed here and by James (1991), is not 100% white quartz. The process of hydraulic mining has the effect of increasing the composition, and therefore the percentage, of white quartz seen in HMS deposits. But substantial portions of these sediment deposits are derived from the surrounding country rock and incorporated into the HMS deposits (James, 1991). If the country rocks in one watershed, as compared to those in another watershed, were more susceptible to physical weathering and conversion to suspended load rather than bedload by the processes of hydraulic mining, it follows that there would be different white quartz percentages seen in HMS deposits of their respective sediment deposits.

The geologic map of the Chico quadrangle shows that the Bear River (Figure 32) flows through bedrock that includes relatively non-resistant Oligocene-Miocene rhyolite tuffs, Paleozoic metavolcanics and the Calaveras formation (chert, argillite and limestone). Willow Creek, by comparison, flows through comparatively resistant Yuba River granites and Paleozoic-Mesozoic metasedimentary, metadiorite and ultramafic rocks (Figure 33). Since the bedrock of the Bear River watershed is less resistant to erosion and the bedrock of the Willow Creek Watershed is more resistant to erosion, more bedrock in the Bear River watershed would be converted to suspended load, while more bedrock in the Willow Creek Watershed would be converted to bedload through the processes of hydraulic mining. This may account for the difference in the percent white quartz seen in HMS deposits in the Bear River watershed compared to the percent white quartz seen in the Willow Creek Watershed.

Finally, while every effort was made to follow the methods used in James' 1991 study, some error may arise due to sampling technique. James assessed a much larger watershed, 220,000 acres compared with 29,504 acres in the Willow Creek Watershed. The mine tailings deposits sampled by James were well-exposed cliffs downstream of hydraulic mines on either side of the Bear River (Figure 34). Where possible, similar deposits were sampled in this study, but at times, these well exposed terraces were not available. In these instances, terrace tops were sampled rather than the aggrading side of a terrace. Only the highest points on these terraces were sampled to limit contamination, but this discrepancy in sampling procedure may have resulted in some "other alluvium" becoming mixed with mine tailing samples, resulting in an lower number being represented as HMS.

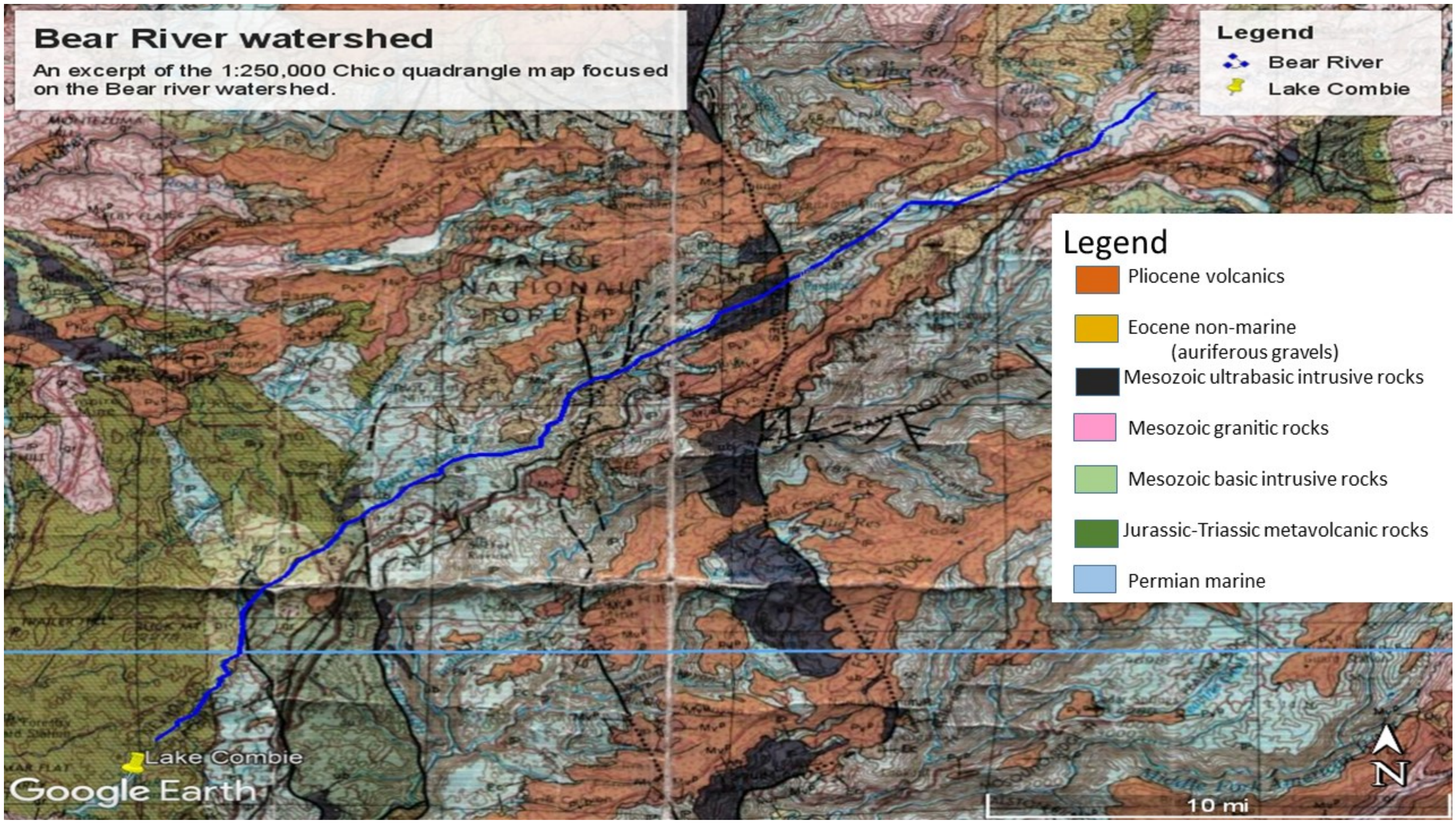


Figure 32. A close-up view of the geologic map of the Bear River area northeast of Rollins Reservoir. Lake Combie (yellow pin) and the Bear River (blue line) are highlighted for orientation purposes. Auriferous gravels (Tg) are seen in both the Bear and Willow Creek Watersheds, but the bedrock over which each river flows is different. The Bear River flows over comparatively less resistant Oligocene-Miocene rhyolite tuffs, Paleozoic metavolcanics and the Calaveras formation. This map is an excerpt of the original (Burnett & Jennings, 1962).

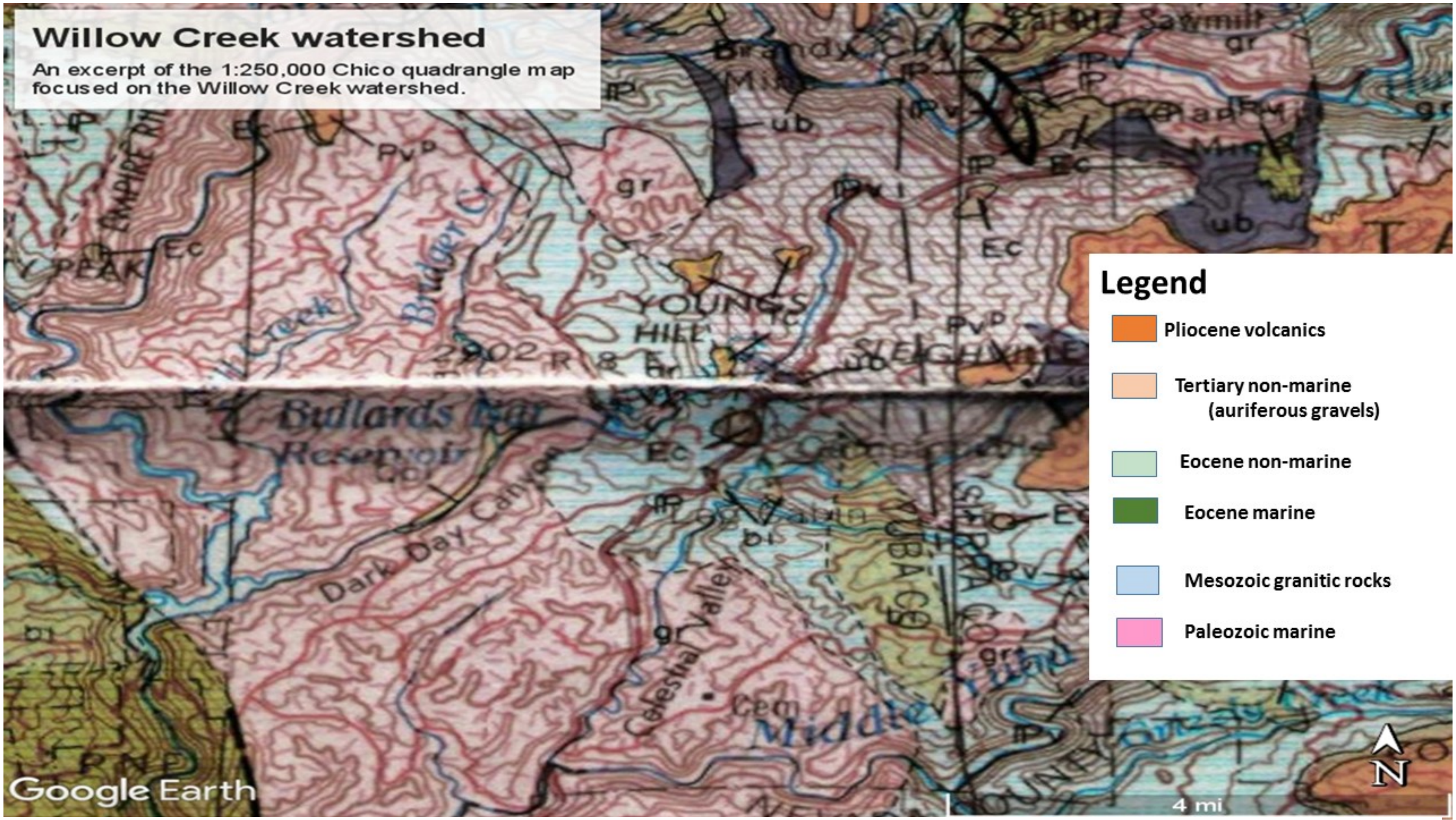


Figure 33. A close up of the geologic map of the Willow Creek area northeast of New Bullards Bar reservoir where this study was conducted. Auriferous gravels (Tg, yellow blobs surrounding the Youngs Hill label) are seen in both the Bear and Willow Creek Watersheds, but the bedrock over which each river flows is different. Willow Creek flows over relatively resistant units, such as the Yuba River granites and Paleozoic-Mesozoic metasedimentary rocks, meta-diorites and ultramafics. This map is an excerpt of the original (Burnett & Jennings, 1962).

Figure 34. A photo taken by Dr. Allan James in 2016 of the mine tailings deposits on the Bear River. Note the white quartz pebbles in the foreground and the well-exposed cliff faces comprised of mine tailings from the unlicensed hydraulic mining period (personal communication, James, 2016).

White Quartz Percentage of In-Situ Auriferous
Gravels As Compared with Mine Tailings

Historical hydraulic mining had the effect of concentrating the white quartz percentages of the mine tailings deposits produced by the hydraulic mining of in-situ auriferous gravels in the Willow Creek Watershed. This effect is consistent with that found by Peterson et al. (1968) and James (personal communication, 2017). When an area is hydraulically mined, pressurized water is directed at walls of sediment to mobilize the sediment for sluicing that liberates the gold within the sediment (Hagwood, 1981). In certain instances, this process is preceded by blasting the wall or cutting a drift (a horizontal or inclined passage) into the pit wall to encourage mass wasting of the pit wall (Hagwood, 1981). These powerful processes direct destructive forces against the sediments that comprise the pit wall.

The Moh's hardness scale describes the relative hardness of minerals from 1 (soft) to 10 (hard). On the Moh's hardness scale, quartz has a hardness of 7, making it relatively resistant to abrasion compared to other minerals. The metasedimentary and volcanic rocks that make up the other sediment clasts commonly found in Eocene paleo-channels of the Sierra Nevada are less resistant to erosional processes (physical and chemical) than quartz (Mol, 2014; Moses et al., 2014). These sediment clasts are more likely to break down under the process of hydraulic mining. The size of the sediments assessed in this study (gravels in the 6-64 mm range) would be considered bedload under most hydrologic conditions in the Willow Creek Watershed. Particles pulverized by hydraulic mining become suspended in the water column (suspended load) and leave the system. Hydraulic mining introduced large volumes of water into waterways, and much of the smaller sediment sizes were carried out of the mine sites in which they originated to be deposited later in downstream, lower energy environments. What remained were the more resistant white quartz pebbles addressed in this study. These two factors, the pulverization of less resistant clasts and the removal of fine-grained sediments via suspended load under artificial hydrologic conditions, have the effect of increasing the white quartz concentrations in mine tailing deposits.

Longitudinal Trends in the Willow Creek Watershed

Upstream-to-downstream longitudinal trends at three locations are presented in this study: Willow Creek, Brandy Creek and the outlet of the North Cut of Weeds Point mine to Horse Valley Creek.

Willow Creek. Willow Creek is the only waterway examined in this study whose longitudinal trend passes over a debris control dam (DCD). The upstream sampling site on Willow Creek is located near Jaubert Diggings, a source of hydraulic mining sediment. Five in-channel sediment samples were collected above the DCD on Willow Creek and four sediment samples were collected below the dam. The sediment mixing ratios of samples collected upstream of the DCD ranged from 100% to 56%. Sediment mixing ratios of samples collected downstream of the DCD ranged from 70% to 47% (Figure 18). This indicates the DCD is preventing HMS from Jaubert Diggings from moving downstream of the dam (for sediments measuring 6mm-64 mm along the b-axis). Mine tailings deposits upstream of the DCD on Willow Creek contain the highest percent of hydraulic mine sediment. These sediments were emplaced during the period of unlicensed hydraulic mining.

Jaubert Diggings, the source of mine tailings emplaced to create the high terraces, is upstream of the DCD on Willow Creek. The outlet of the southern cut of Weeds Point mine, for which the Willow Creek DCD was originally built, is also located upstream of the DCD. This means all likely sources of HMS in the Willow Creek Watershed are located upstream of the DCD. Dams have the effect of starving downstream reaches of sediment (gravels) that normally would continue to supply bedload to reaches downstream of a dam under natural (undamed) conditions (Schmidt and Wilcock, 2008). There is no immediate evidence of a mine tailings deposit that supplied undiluted hydraulic mine sediment to the channel downstream of the DCD on Willow Creek.

With the Willow Creek DCD arresting mine sediment from upstream sources, and no likely contribution of mine sediment from sources downstream of the dam, it is logical the sediment mixing ratios of mine deposits would decrease below the dam. The other possible source of hydraulic mine sediment on the reach of Willow Creek below the DCD is a mine outlet from Galena Hill. This outlet is not a likely source of hydraulic mine sediment for this reach because when the owners of Galena Hill diggings applied for the license to continue hydraulic mining, they chose to store their mobilized sediment within the mine pit (CDC license 133, 1895; California Debris Commission Archives, n.d.). The proposed method to arrest hydraulic mine sediment in the Galena Hill Diggins required inspection and approval by the CDC before hydraulic mining could begin (Hagwood, 1981). In order to use the mine pit as the storage of mine sediment, the CDC would have required these outlets to be sealed off before hydraulic mining would be allowed to commence. In a study conducted during the summer of 2017, Gail Bakker, a retired geologist with the United States Forest Service, assessed hydraulic mine pits throughout the Tahoe National Forest. Results from the Galena Hill Diggings assessment of hydrologic pathways from the mine pit found no evidence of significant flow or sediment movement from the mine pit into Willow Creek along this reach (Bakker, 2018). This study, however, shows that sediment mixing ratios in the gravels below the

DCD have not reached the levels of the “other alluvium” samples found in this watershed. Thus, the DCDs on Willow Creek, and likely the one on Horse Valley Creek, are having the ongoing effect of restraining HMS (in the 6 mm-64 mm grain size) upstream of the DCDs. This study shows that the Willow Creek and Horse Valley Creek DCDs continue to impact the composition and geomorphology of sediments in the Willow Creek Watershed.

Brandy Creek. The major sediment sources to the lower reach of Brandy Creek are the mine tailings deposits (high terraces) along either side of the creek downstream of Youngs Hill Road, and mine outlets from Youngs Hill and Galena Hill Diggings. The result is the unusually high sediment mixing ratios (%MS) seen in active channel samples in the reach of Brandy Creek downstream of Youngs Hill Road. There is no debris control dam on Brandy Creek, but the longitudinal sediment trend of the creek is still greatly influenced by historical hydraulic mining. Nine samples were collected on Brandy Creek, and when the sediment mixing ratios of the samples were examined, two distinct groups were observed. The four samples collected farthest upstream had a distinctly lower sediment mixing ratio than the five samples collected farther downstream (Figure 19). These results contradict the results from Willow Creek, however, there are several important differences between the two reaches. The DCD on Willow Creek separates the sediment source and the mine tailings deposits from the lower reaches. The LiDAR image of Brandy Creek, (Figure 20) shows there are no significant hydraulic mining features upstream of the first four sampling locations. The significant feature between the two groups is a series of mine outlets (both channels and tunnels) from Young’s Hill and Galena Hill into Brandy Creek (Figure 35). During the period of

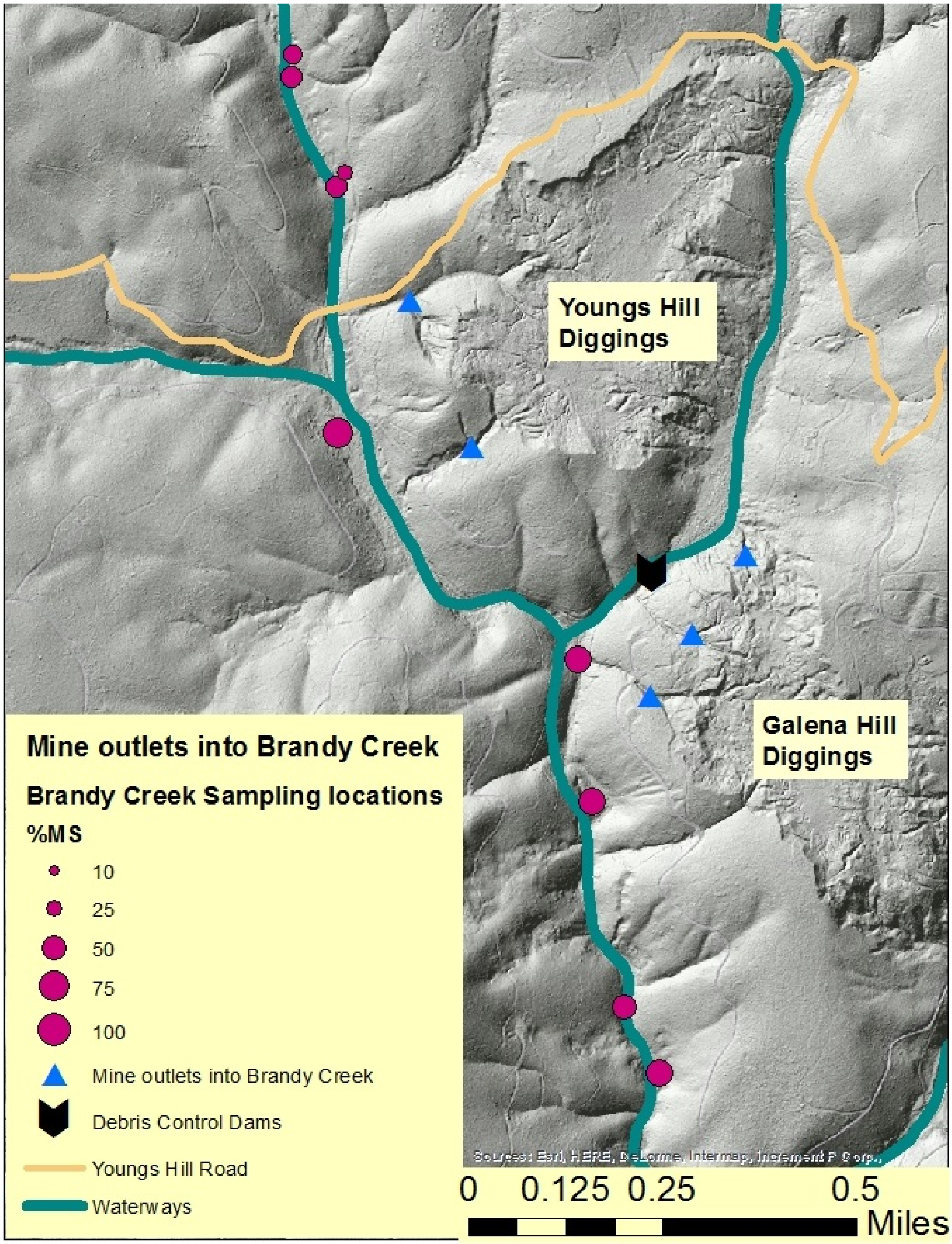


Figure 35. A LiDAR image of Brandy Creek, including sampling locations. The blue triangles denote channels through which sediment could leave Galena Hill Diggins and Youngs Hill Diggings. The values of the sediment mixing ratios of samples are denoted by the relative size of the magenta circles. Note how the sediment mixing ratios of gravel samples increases past Youngs Hill road, below the first tributary flowing from Youngs Hill Diggings.

unlicensed hydraulic mining, these two mine outlets were likely used to remove sediment from the hydraulic mine pit. The sediment was flushed into Brandy Creek to make room in the mine pit for further excavation of the mine wall. The mine outlets were likely used as secondary sluices for gold recovery. Mine sediment from these outlets created the high terraces comprised of undiluted HMS (termed "mine tailings" in this study) along either side of Brandy Creek. Mining continued in both Galena Hill and Young's Hill during the period of licensed hydraulic mining. Young's Hill planned to store the HMS by restraining it behind a brush dam in a "dry gulch" (CDC license #131; California Debris Commission Archives, n.d.). This "dry gulch" is believed to be Brandy Creek (Wilson and Looff, 2017). The dam, like many other brush dams, did not last, but the low terraces seen on Brandy Creek could be due to incision into terraces created before the failure of the brush dam during the period of licensed hydraulic mining. This interpretation is based on the fact that the amount of mine sediment permitted to be stored during the period of licensed hydraulic mining was reported to be 7500 cubic yards (CDC license #131), which is substantially less than the cumulative 7,500,000 cubic yards of mine sediment which Gilbert reported to have been mined by 1908 (Figure 11; Gilbert, 1917).

Young's Hill Road (Figure 35) is not a barrier to the movement of sediment downstream. Most of the high terraces (comprised of undiluted hydraulic mining sediment) are located downstream of the road, so the sediment mixing ratios of samples do not decrease downstream of the road. The road is not a hard impediment, as there is a culvert running beneath the road large enough for a person to walk through with little trouble (Figure 36). This means that during hydrological events of sufficient intensity, there is a path for bedload to travel downstream (the culvert is flush with the creek

Figure 36. The researcher standing in the downstream end of the culvert beneath Youngs Hill Road. The upstream thalweg is flush with the culvert, allowing sediment passage.

thalweg on the upstream side with a 1.5 ft (0.46 m) drop on the downstream side). Since there are few significant HMS sources upstream of the road, the sediment not being mobilized would have higher amounts of country rock, (other alluvium) and a lower percentage of white quartz.

A more complete understanding of the history of hydraulic mining in the licensed and unlicensed periods, the historic and current sources of HMS in the watershed, and the formation of natural and anthropogenic landform features is necessary to better understand the present-day locations of HMS deposits within the Willow Creek Watershed. Several mine outlets exist from Galena Hill Diggings into Brandy Creek

(Figure 35). These northern mine outlets into Brandy Creek, unlike those that drain into Willow Creek, exhibit evidence of significant flow and signs of sediment movement (Bakker, 2018). This indicates that HMS licensed to be stored in the Galena Hill mine pit may be moving into Brandy Creek through these outlets, resulting in the higher sediment mixing ratios of samples collected in the lower reach of the longitudinal sampling. These results show that HMS is not evenly distributed throughout the Willow Creek Watershed.

Horse Valley Creek. The decline in the sediment mixing ratio (%MS) of samples taken from the North Cut of Weeds Point Diggings to the confluence with Horse Valley Creek is attributed to the lack of HMS inputs and the lack of flow in the upstream section of the channel. At just under 300 m, this is the shortest reach considered in this study. The longitudinal trend of sediment mixing ratios of active channel deposits varies from 91% HMS near the mine tunnel outlet to 21% near the confluence with Horse Valley Creek (Figure 23).

The tunnel from the North Cut of Weeds Point mine has collapsed, which likely occurred sometime after the final CDC license issued for sediment retention behind the Horse Valley Creek DCD was revoked in 1937 (CDC licence #1064). This is the only reach in the watershed in which there are no surviving high terraces to supply hydraulic mine sediment (Figure 37). Taken together, these two facts indicate there are no inputs of HMS to this reach other than those eroding from active channel (low terrace and gravel bar) deposits. As the low terraces in the upper section of the reach erode, they deposit their HMS in the stream channel making them available for transport should sufficient flows occur.

Figure 37. A downstream view of the channel connecting the North Cut of Weeds Point mine to Horse Valley Creek. Channel banks are bedrock, and no high terraces are present, nor were any present as the channel widened-out downstream. The collapsed tunnel from the North Cut of Weeds Point Mine is immediately upstream. There are no high terraces to deliver HMS to this reach, and there is no flow in this reach until an artisanal spring emerges ~100 m downstream from this point.

The longitudinal trend of the North Cut of Weeds Point mine to Horse Valley Creek presents a unique opportunity in this watershed to show how the sediment mixing ratios (%*MS*) in a reach with limited flow and no additional HMS evolves over the course of a short stream channel. The outlet channel from the North Cut of Weeds Point Diggings to Horse Valley Creek is ~3 m wide, with steep walls (>45°) on either side of the channel (Figure 37). The stream channel is dry through the first 100 m of its course, and after this, a spring emerges and flows until joining Horse Valley Creek. Because the tunnel, designed to convey HMS to the channel, is blocked off the only flow, and therefore sediment input, for the upstream samples in this reach is that provided by mass wasting of the channel walls. There is insufficient flow to move the gravels in the active channel, and sufficient flow would not accumulate until further down the watershed where the perennial stream, coupled with the increased area behind the pour point, would allow active mixing of gravels to occur. The walls of the steep-sided valley continue to erode into the stream channel, further depressing sediment mixing ratios (%MS) of active channel deposits found in the downstream sections of the longitudinal trend.

Laterally Connected Populations

When G.K. Gilbert wrote his landmark 1917 report on hydraulic mining debris in the Sierra Nevada region, he postulated that HMS stored in piedmont deposits and mountain stream channels would act in a manner analogous to a water wave (Gilbert, 1917). He argued that with the source of the HMS no longer actively supplying sediment to Sierra Nevada rivers, the HMS would leave these river systems relatively quickly (on the order of decades), and the HMS supply in these rivers would become a relatively minor sediment input, compared with other anthropogenic sources (Gilbert, 1917). There are several flaws, however, with this argument. Mountain streams, which had been choked with HMS while active mining was occurring, quickly incised through the unconsolidated HMS and once again flowed over bedrock, creating high terraces composed of mine tailings that were removed from common stream channel processes (James, 2006). Gilbert’s assumption that HMS would move through Sierra Nevada river systems and be gone by the mid-20th century (James, 2006) ignored the storage in high terraces that were no longer connected to present-day flow regimes. Rather than acting as a normal distribution in a sediment curve, with sediment entering a system, reaching a maximum abundance, and leaving the system relatively quickly, the continued sediment supply of these out-of-channel, mine-tailings deposits in high terraces positively skews the sediment distribution curve to the right (Figure 38). This means the time that it would take a river system to reach a post-disturbance state of equilibrium would be several orders of magnitude higher, on the timescale of 10^4 years rather than 10^1 or 10^2 years (James, 1999).

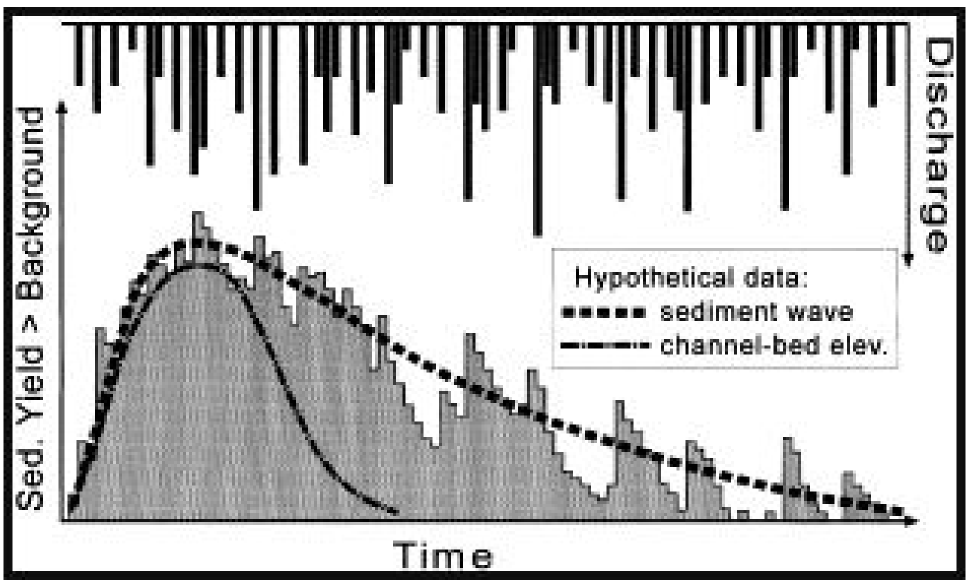


Figure 38. A hypothetical right skewed sediment wave. The channel-bed elevations show a symmetrical distribution over time, but the sediment load of the channel continues to be elevated long after the channel has returned to grade. This is due to erosion of out of channel storage into the channel. This model stands in contrast to Gilberts (1917) sediment wave model which predicts that both the channel grade and sediment yields of a channel would be normally distributed over time. Figure adapted from James (1999).

Mine tailings deposits in the Willow Creek Watershed exist as high terraces outside the active stream channel, further supporting this theory. These high terraces have a consistently high sediment mixing ratio because they are comprised of undiluted HMS emplaced during the period of active hydraulic mining. The gravel bar deposits from the active channel have a lower sediment mixing ratio than the mine tailings deposits, yet higher than would be expected by Gilbert's sediment wave model. If Gilbert's model were accurate, the sediment mixing ratio of the gravel bar deposits would be similar to those found in other, non-mining alluvium samples. Results from this study indicate the two populations are significantly different (n=19, W=94, $p < 0.05$), meaning that HMSs are having an on ongoing effect on the bedload sediments in the creeks of the Willow Creek Watershed.

The relationship between the mine tailings and gravel bar populations, and their respective relationships to the low terrace population, is more difficult to interpret using the sediment mixing ratios of these deposits. Low terrace deposits have a sediment mixing ratio between the gravel bar and mine tailings populations, therefore it would be reasonable to assume the three populations are related, and HMS enters the gravel bar deposits by erosion of the low terrace deposits, which are in turn the result of erosion of the mine tailings deposits. This link is suggested but cannot be made conclusively by data presented in this study for two reasons.

First, there is no temporal data associated with the low terraces. The only constraints on the age of the low terraces is they had to be deposited sometime between when the mine tailings deposits were emplaced and modern day. It is not known what hydrologic event resulted in the formation of the low terrace deposits, only that channel incision had to occur after this hydrologic (terrace forming) event. It is reasonable to assume that any event with sufficient flow to mobilize the mass of sediment in the terraces today would also serve to erode the mine tailings deposits (high terraces) to a greater degree than would occur under normal hydrologic conditions (Baker, 1977). This would mean that a sediment deposit with a larger percentage of white quartz would be deposited as hydrologic conditions returned to normal. This is reflected in the sediment mixing ratio of the low terraces; whose values lie between that of the gravel bar and mine tailings deposits. What is not known is whether the gravels in the channel are the result of:

1. the erosion of the low terraces directly into the channel,
2. erosion of the mine tailings deposits and subsequent mixing of the mine tailings sediments with other alluvium also mobilized during a single event, or
3. some mixture of the two.

Second, while Figure 25 is an idealized representation of the stream channel cross-sectional relationship between the three sample populations, it does not necessarily reflect field conditions in the Willow Creek Watershed. The spatial distribution of the mine tailings deposits (high terraces) in the Willow Creek Watershed is geographically limited. Often there are low terraces and gravel bar deposits with no corresponding high terrace, mine tailings deposit in the immediate vicinity. This may be because high terraces were never formed due to geomorphic constraints of the steep valley walls, or because the existing low terraces are formed by a combination of mass wasting of high terraces and present day erosional/depositional processes. What is known is that mass wasting of the mine tailings deposits by gravity alone directly into the low terraces would not be able to account for the present-day distribution of low terraces in the Willow Creek Watershed. To resolve the specific relation between the three populations, a study of the age and provenance of the sediment in the low terraces would need to be conducted (possibly using cosmogenic dating of low terrace sediments or conducting a sediment transport study using tracers). Such an analysis was outside the scope of this study.

Deposit Behind the Horse Valley Creek DCD

When this study was originally undertaken, it was postulated that there would be a size and composition difference between sediments located in the surface of the deposit (0-1 ft) and those located in the subsurface of the deposit (1-2 ft) behind the Horse Valley Creek debris control dam (DCD). The method employed fails to capture the full variability seen in the field. The problems with the methodology include the arbitrary nature of the proposed layers and the fact that all particles smaller than 6 mm were discarded.

When samples were gathered from the sediment deposits behind the Horse Valley Creek DCD, each sampling pit was segregated into two groups based on the depth at which the sample was gathered. As a field study of the sediment behind an existing debris control dam had never been done, no "best practices" existed for sampling such a deposit. The two sampling groups, 0-1 ft and 1-2 ft, were suggested as a way of capturing the variability in the size and composition of sediment clasts between the two sampling groups. When sediment samples were collected in the field, two distinct layers were observed, however, these layers had little relation to the depths chosen for sampling in this study. The two layers observed in the field were a fine-grained surface layer and a coarse-grained sub-surface, hydraulic mining layer. The surface layer was nearly devoid of gravels and comprised of fine-grained muds and silts (Figure 39). The coarse-grained hydraulic mining layer was comprised of gravels with consistently high sediment mixing ratios (Figure 30). The depth of these layers varied along the deposit. Some sampling pits

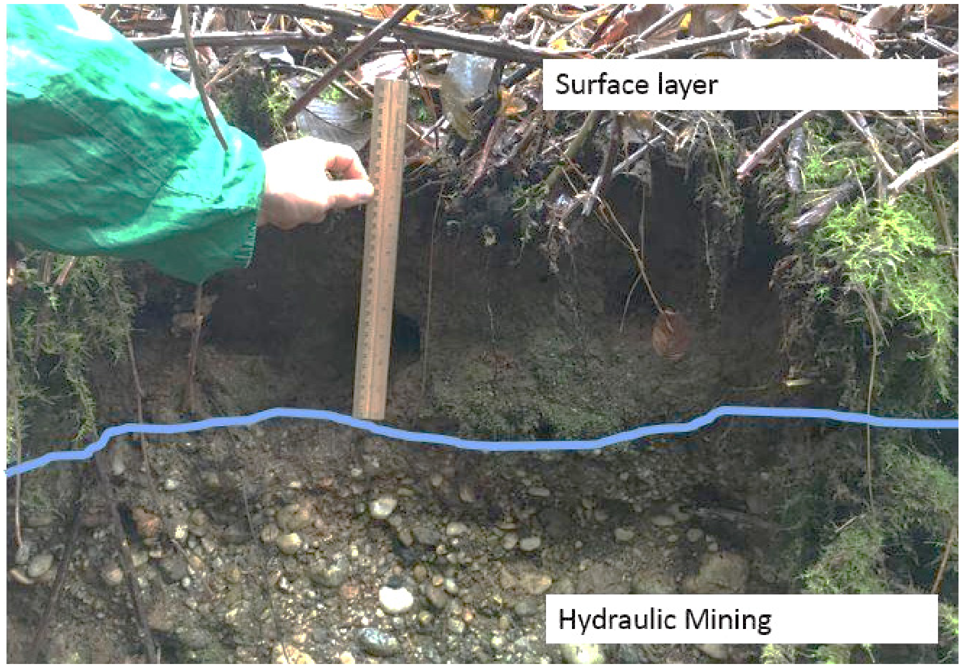


Figure 39. The exposed bank of Horse Valley Creek. This exposure exhibits two distinct layers seen in the deposit, the "surface" and "hydraulic mining" layers. The blue line is provided to demarcate the boundary between the two depositional features. In this image the surface layer is ~1 ft deep. This depth varies throughout the deposit.

did not encounter the fine-grained surface layer, only coarse-grained hydraulic mining gravels visible just beneath the vegetation covering the deposit.

Regarding the positive result of this analysis, this researcher suggests there may be a fining trend at the top of the hydraulic mining layer that is being captured by sampling the 0-1 ft population and comparing it to the 1-2 ft population. It is suggested that a more thorough grain size analysis be conducted by taking sediment cores from the deposit behind the DCD and measuring the average grain size of particles at regular intervals. Before such a study is conducted it should be noted that the deposit was often difficult to sample because of access complications including land tenure issues, digging by hand in saturated soils, and the presence of extensive blackberry vines and underbrush covering the deposit.

Additionally, quantifying the white quartz content in the deposit was flawed due to the size range of sediments analyzed. Following procedures outlined in James' 1991, gravel samples were washed to remove the fines and segregate the gravels in the 6-64 mm size range for analysis. This gives an incomplete picture of the sediment profile of a deposit and could lead one to assume the surface layer of a deposit was comprised of more HMS than was actually present. This produced the discrepancy between the numbers of samples collected from each of the two depth populations. Ten sampling pits were dug into the deposits behind the Horse Valley Creek DCD, but only 7 sediment samples were collected from the 0-1ft depth and 8 sediment samples from the 1-2 ft depth. Of the 10 sampling pits dug into the deposit behind the DCD, coarse-grained hydraulic mining sediment was not encountered in the first foot excavated from three of the sampling pits, and the entire 5-gallon sediment sample was <6mm in size resulting in the whole sample being washed away. In two instances, the hydraulic mining layer was not reached when the pit was dug to the 2 ft depth. It is recommended that alternative methods be used to analyze sediment deposits behind DCDs. A more complete characterization of the sediments could be accomplished by separating an entire sample by grain size using the wet sieving technique and a sieve tower. Smaller particle sizes (<0.063mm) could be collected and sized using laser particle size analysis techniques (Zhang et al., 2017). This would indicate the percentage of the deposit composed of fine-grained particles, which are more likely to have mercury adsorbed onto them, and more likely to act as a vessel for mercury to enter the trophic web in downstream ecosystems (Fleck et al., 2011).

CHAPTER V

CONCLUSION

In a 1991 study of the Bear River watershed, James used a mineralogical tracer, (rounded white quartz pebbles between 6-64 mm along the b-axis), to determine what percentage of a particular sediment deposit was the result of historical hydraulic mining. He concluded that a sediment deposit with ≥ 57% white quartz in this size range was comprised of 100% hydraulic mining sediment (HMS). With this knowledge, he developed a relation that allowed him to determine the percent HMS of sediment deposits throughout the Bear River watershed.

This analysis was applied to the Willow Creek Watershed in Yuba County, CA. Results indicate a deposit with ≥ 50% rounded white quartz pebbles in the 6-64 mm range is comprised of 100% HMS. Using this relationship, the sediment mixing ratio (%MS) of sediment deposits throughout the Willow Creek Watershed was determined. The sediment mixing ratio of these deposits was then used to make inferences regarding the storage and movement of HMS throughout the Willow Creek Watershed. The successful implementation of this methodology in the Willow Creek Watershed suggests that, given the right sampling regime, this methodology could be extended to other watersheds in the Sierra Nevada metamorphic belt affected by historical hydraulic mining.

The percent white quartz from in-situ auriferous gravels that the miners originally worked was compared to undiluted hydraulic mine sediments. Results indicate the process of hydraulic mining concentrates white quartz pebbles in undiluted HMS deposits downstream of the mines an average of 7% compared to in-situ auriferous gravels in the Willow Creek Watershed. The sediment mixing ratios of samples collected from upstream to downstream do not follow a single pattern but rather reflect the spacing of HMS sources and barriers to sediment movement (such as DCDs) along each reach. The sediment mixing ratio (%*MS*) of sediment deposits decreases laterally across the channel from the mine tailings deposits in the high terraces (n=12, %MS=100%) to the lower terraces (n=22, %MS=62.1%) to the gravel bar deposits (n=12, %MS=49.3%), reflecting the history of sediment storage in the Willow Creek Watershed.

When the sediment deposit behind the DCD on Horse Valley Creek was examined, the applied methodology resulted in no significant difference in the sediment mixing ratios between the 0-1 ft depth of the deposit and the subsequent 1-2 ft depth of the deposit. The average grain size of the 0-1 ft depth population is not measurably different from the 1-2 ft depth population, but this is likely due to the small sample size examined and the result fails to capture the full variability seen in the field. The result was attributed to an experimental design that resulted in all grain sizes <6 mm being discarded, and not a reflection of actual field conditions.

CHAPTER VI

FUTURE WORK

The presence of historical hydraulic mine sediment in a deposit in a given watershed can be estimated by the sediment mixing ratio of that deposit. This information is of great interest to geomorphologists studying a watershed's response to historical disturbances.

The history of hydraulic mining reveals the wider significance of this study and suggests future research. During the periods of both licensed and unlicensed hydraulic mining, mercury was used to amalgamate the gold particles contained within auriferous gravels. Like the sediments that remain in the watersheds from which they were originally derived, mercury also remains, some of which is trapped in these sediment deposits (Howle et al., 2016). The amount of HMS in a watershed is a significant predictor of the level of mercury contamination in that watershed (Alpers et al., 2016, Howle et al., 2016).

Mercury contamination of rivers draining the Sierra Nevada gold belt is a persistent concern to stakeholders, such as land owners, health workers, and members of the public (Schober et al., 2003). If a relationship can be demonstrated between the sediment mixing ratio of a deposit and the amount of mercury in that deposit, stakeholders would have a low cost, mineralogical proxy for potential mercury contamination. This may not be a perfect relationship, but it would inform stakeholders where potential mercury hotspots may be located so further analysis could be done on the deposits. It is recommended that future work in the Willow Creek Watershed focus on sampling the fine sediments (<0.063 mm) to further develop this relationship.[1]

Another possibility for future research is to constrain the timing of the low terrace deposition within Willow Creek Watershed. From the lateral relationship between the high terraces and low terraces, it can be inferred that the low terraces were deposited sometime after the end of unlicensed hydraulic mining, following incision of the high terraces which created the channel into which the low terraces could be deposited. What event precipitated their deposition, and when this event occurred however, is unknown. It would be of interest to learn when these deposits were emplaced, either during the period of licensed hydraulic mining or in a later hydrological event. This could possibly be accomplished using cosmogenic dating techniques or dendrochronology performed on trees growing on these deposits.

Results from this study suggest a crude method for characterizing the sediment deposits behind DCDs. As previously noted, the two layers ("surface" and "hydraulic mining") can be separated by their gravel content, the former almost devoid of gravels and the latter dominated by gravels. If one were to take an iron pole and sink it through the fine-grained surface layer, the depth to the coarse-grained hydraulic mining layer could be determined. Repeating this procedure over the deposit would make it possible to construct a map of the coarse-grained subsurface hydraulic mining layer. With this subsurface map, and using integration as described in a recent geospatial survey of hydraulic mining deposits in the Tahoe National Forest (James et al., 2019), it may be

[1] Mercury adsorbs onto fine particles (those with a grain size <0.063 mm). A positive correlation has been drawn between the contamination of the fine particles and the extent of hydraulic mining in a system (Slowey et al., 2005).

possible to estimate volumes of both the fine-grained surface and coarse-grained subsurface hydraulic mining layers restrained behind a DCD.

The stratigraphy of a deposit behind a debris control dam could be determined with cores that provide the entire vertical profile of the sediment deposit for mercury analysis. Though an initial analysis of the sediment constrained by the debris control dam was performed in this study, it is recommended that a more thorough evaluation be performed. With the appropriately sized drill rig, sediment cores could be obtained from a range of depths in the deposit behind the DCDs. This may not show the full extent of mercury in a sedimentary deposit behind a DCD, as was shown in the sediments behind Englebright Dam (Alpers et al., 2002) because occasionally mercury may occur in relatively large globules randomly dispersed within the sediments of these deposits.[2] However, core analysis of the fines could provide a baseline estimate of the amount of mercury in the deposit, as well as an understanding of its vertical distribution within the deposit.

[2] Englebright Dam was built in 1941 to allow for further hydraulic mining in the Upper Yuba River Watershed by storing HMS behind the dam in compliance with CDC requirements. Due to falling gold prices post-construction hydraulic mining didn't resume, and today the Englebright Dam is principally used for hydropower and recreation (James, 2005).

REFERENCES CITED

REFERENCES

Alpers, C.N., Hunerlach, M.P., May, J.T., et al., 2002, Environmental legacy of the California Gold Rush: 1. Mercury contamination and bioaccumulation associated with abandoned placer-gold mines: Paper No. 64-5 presented to the 2002 Denver Annual Meeting (October 27-30, 2002).

Alpers, C.N., Yee, J.L., Ackerman, J.T., Orlando, J.L., Slotton, D.G., and Marvin-DiPasquale, M. C., 2016, Prediction of fish and sediment mercury in streams using landscape variables and historical mining: Science of the Total Environment, v. 571, p. 364-379, doi:10.1016/j.scitotenv.2016.05.088.

Anderson, J.K., Wondzell, S.M., Gooseff, M.N., and Haggerty, R., 2005, Patterns in stream longitudinal profiles and implications for hyporheic exchange flow at the H. J. Andrews Experimental Forest, Oregon, USA: Hydrologic Processes, v. 19, p. 2931–2949, doi:10.1002/hyp.5791.

Andrews, J.T., and Eberl, D.D., 2012, Determination of sediment provenance by unmixing the mineralogy of source-area sediments: The “SedUnMix” program: Marine Geology, v. 291, p. 24-33, doi:10.1016/j.margeo.2011.10.007.

Ashley, R.P., Rytuba, J.J., Rogers, R., Kotlyar, B.B., and Lawler, D., 2002, Preliminary report on mercury geochemistry of placer gold dredge tailings, sediments, bedrock, and waters in the Clear Creek restoration area, Shasta County, California: U.S. Geological Survey Open-File Report 02-401, 47 p.: https://pubs.usgs.gov/of/2002/0401/ (March 2017).

Association of State Dam Safety Officials (ASDSO), 2017, Dam safety facts: www.damsafety.org (March 2017).

Babiarz, C.L., and Andren, A.W., 1995, Total concentrations of mercury in Wisconson (USA) lakes and rivers: Water, Air and Soil Pollution, v. 83, p. 173-183, doi: 10.1007/BF00482602.

Baker, V.R., 1977, Stream-channel response to floods, with examples from central Texas: Bulletin of the Geological Society of America, v. 88, no. 8, p. 1057-1071, doi:10.1130/0016-7606(1977)88.

Bakker, G., 2018, Headwaters mercury source reduction project; field conditions and recommended remedial actions, Galena Hill Mine. Draft report prepared for the Tahoe National Forest, (in press).

Bernhoft, R.A., 2012, Mercury toxicity and treatment: a review of the literature: Journal of Environmental and Public Health, v. 2012, 10 p., doi: 10.1155/2012/460508

Bierlein, F.P., Northover, H.J., Groves, D.I., Goldfarb, R.J., and Marsh, E.E., 2008, Controls on mineralization in the Sierra foothills gold province, central California, USA: A GIS-based reconnaissance prospectively analysis: Australian Journal of Earth Sciences, v. 55, no. 1, p. 61-78, doi: 10.1080/08120090701581398.

Burnett, J.L., and Jennings, C.W., 1962, Geologic map of California, Chico sheet – Olaf P. Jenkins edition: California Div. Mines and Geology, scale 1:250,000, 1 sheet

California Debris Commission (CDC) Archives, n.d., Miscellaneous records of C.D.C. Obtained through U.S. Army Corps of Engineers, Sacramento Division, Summer, 1989. Bryte warehouse Box #187. [Archives originally obtained in 1980, location may have changed]

California State Route 49, 2018, Wikipedia: https://en.wikipedia.org/w/index.php?title=California_State_Route_49&oldid=865141018 (November 2018).

Childs, J.R., Snyder, N.P., and Hampton, M.A., 2003, Bathymetric and geophysical surveys of Englebright Lake, Yuba-Nevada Counties, California: US Department of the Interior, US Geological Survey, Open-File Report 03-383, 20 pp., https://pubs.usgs.gov/of/2003/0383/ (March 2017).

Churchill, R., 1999, Insights into California mercury production and mercury availability for the gold mining industry from the historical record: Geological Society of America, Abstracts with Program, v. 31, no. 6, p. 45.

Cordy, P., Veiga, M.M., Salih, I., Al-Saadi, S., Console, S., Garcia, O., Mesa, L.A., et al., 2011, Mercury contamination from artisanal gold mining in Antioquia, Colombia: The world's highest per capita mercury pollution: Science of the Total Environment, v. 410, p. 154-160, doi: 10.1016/j.scitotenv.2011.09.006.

Curtis, J., and Kelsey H.M., 1998, Quantification of historical channel changes due to the influx of hydraulic mining debris, Steephollow Creek, Nevada County, California: Geological Society of America Abstracts, v. 30, no. 7, p. 293.

Dodge, F.C., and Bateman, P.C., 1977, The Sierra Nevada batholith, California, USA and spatially related mineral deposits: Geologic Society of Malaysia, Bulletin 9, p. 17-29.

Domagalski, J., 2001, Mercury and methylmercury in water and sediment of the Sacramento River basin, California: Applied Geochemistry, v. 16, no., 15, p. 1677–1691, doi: 10.1016/S0883-2927(01)00068-3.

Etris B., 2018, Using LiDAR, ArcGIS, and on-the-ground data collection to describe geomorphometric characteristics of hydraulic mining features in the Yuba River watershed [Masters thesis]: Chico, California State University, 228 p.

Fairfull, S., and Withridge, G, 2003, Why do fish need to cross the road? Fish passage requirements for waterway crossings: NSW Fisheries, Cronulla, 16 p.: https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0004/633505/Why-do-fish-need-to-cross-the-road_booklet.pdf (March 2017).

Fencl J.S., Mather M.E., Costigan K.H., and Daniels M.D., 2015, How big of an effect do small dams have? Using geomorphological footprints to quantify spatial impact of low-head dams and identify patterns of across-dam variation: PLoS ONE, v. 10, no. 11: e0141210, https://doi.org/10.1371/journal.pone.0141210 (March 2017).

Fleck, J.A., Alpers, C.N., Marvin-DiPasquale, M., Hothem, R.L., Wright, S.A., Ellett, K., Beaulieu, E., et al., 2011, The effects of sediment and mercury mobilization in the South Yuba River and Humbug Creek confluence Area, Nevada County, California: Concentrations, speciation, and environmental fate—Part 1: Field characterization: U.S. Geological Survey Open-File Report, 2010-1325A, 104 p., doi: 10.3133/ofr20101325A.

Forstner, U., 1982, Accumulative phases for heavy metals in limnic sediments: Hydrobiologia, v. 91, p. 269-284, doi: 10.1007/BF02391944.

Fraser, A.G., 1927, Report on the Horse Valley hydraulic placers: Private correspondence to C.E. Hayden, consulting mining engineer, San Francisco, California. [Archived at the Searls Historical Library, Nevada City, 95959]

Ghoshal, S., James, L.A., Singer, M.B., and Aalto, R., 2010, Channel and floodplain change analysis over a 100-year period: Lower Yuba River, California: Remote Sensing, v. 2, p. 1797-1825, doi:10.3390/rs2071797.

Gilbert, G.K., 1917, Hydraulic-mining debris in the Sierra Nevada: United States Geological Survey Professional Paper, v. 105, 188 p., doi:10.3133/pp105.

Goode, J.R., and Wohl E., 2010, Substrate controls on the longitudinal profile of bedrock channels: Implications for reach‐scale roughness: Journal of Geophysical Research, v. 115, F03018, doi:10.1029/2008JF001188.

Hagwood, J.J. Jr., 1981, The California Debris Commission: A history: U.S. Army Corps of Engineers, Sacramento District, Sacramento, 102 pp, doi: 10.2307/3104791.

Harden, D.R., 2004, California geology, Second edition: Upper Saddle River, New Jersey, Prentice Hall, p. 156-212.

Howle, J.F., Alpers, C.N., Bawden, G.W., and Bond, S., 2016, Quantifying the eroded volume of mercury-contaminated sediment using terrestrial laser scanning at Stocking Flat, Deer Creek, Nevada County, California, 2010–13: U.S. Geological Survey Scientific Investigations Report 2015–5179, doi: 10.3133/sir20155179.

Hunerlach, M.P., Rytuba, J.J., and Alpers, C.N., 1999, Mercury contamination from hydraulic placer-gold mining in the Dutch Flat mining district, California, *in* Morganwalp, D.W., and Buxton, H.T., eds., U.S. Geological Survey toxic substances hydrology program—Proceedings of the technical meeting, Charleston, South Carolina, March 8-12, 1999, U.S. Geological Survey Water-Resources Investigations Report 99-4018B, p. 179-189: http://ca.water.usgs.gov/mercury/dutch/wrir994018b.pdf (May 2013).

James, L.A, 1991, Quartz concentration as an index of sediment mixing: Hydraulic mine-tailings in the Sierra Nevada, California. Geomorphology, v. 4, p. 125-144, doi: 10.1016/0169-555X(91)90024-5.

James, L.A., 1999, Time and the persistence of alluvium: River engineering, fluvial geomorphology, and mining sediment in California: Geomorphology, v. 31, p. 265–290, doi:10.1016/S0169-555X(99)00084-7.

James, L.A., 2005, Sediment from hydraulic mining detained by Englebright and small Dams in the Yuba basin: Geomorphology, v. 71, p. 202-226, doi: 10.1016/j.geomorph.2004.02.016.

James, L.A., 2006, Bed waves at the basin scale: implications for river management and restoration. Earth surface processes and landforms: Journal of the British Geomorphological Research Group, v. 31, no. 13, p.1692-1706, doi:10.1002/esp.1432.

James, L.A., and Singer, M., 2008, Development of the lower Sacramento Valley flood-control system: Historical perspective: Natural Hazards Review, v. 9, doi:10.1061/(ASCE)1527-6988(2008)9:3(125).

James L.A., Monohan C., and Ertis B., 2019, Long-term hydraulic mining sediment budgets: Connectivity as a management tool: Science of the Total Environment, v. 651, p. 2024-2035, doi:10.1016/j.scitotenv.2018.09.358.

Jo, S., Woo, H. D., Kwon, H. J., Oh, S. Y., Park, J. D., Hong, Y. S., Pyo, H., et al., 2015, Estimation of the biological half-life of methylmercury using a population toxicokinetic model: International Journal of Environmental Research and Public Health, v. 12, no. 8, p. 9054-9067, doi:10.3390/ijerph120809054.

Krabbenhoft, D.P., and Rickert, D.A., 1995, Mercury contamination of aquatic ecosystems: U.S. Geological Survey Fact Sheet FS-216-95, 4 p.: https://pubs.usgs.gov/fs/1995/fs216-95/ (March 2019).

Lawson, N.M., and Mason, R.P., 1998, Accumulation of mercury in estuarine food chains: Biogeochemistry, v. 40, no. 2-3, p. 235-247, doi: 10.1023/A:100595921.

Lindgren, W., 1911, The Tertiary gravels of the Sierra Nevada: U.S. Geological Survey Professional Paper 73, doi: 10.3133/pp73: https://pubs.er.usgs.gov/publication/pp73 (May 2018).

Marsh, E.E., Goldfarb, R.J., Kunk, M.J., Groves, D.I., Bierlein, F.P., and Creaser, R.A., 2008, New constraints on the timing of gold formation in the Sierra Foothills province, central California. Ores and orogenesis: Circum-Pacific tectonics, geologic evolution, and ore deposits: Arizona Geological Society Digest, v. 22, p. 369-388.

Mergler, D., Anderson, H.A., Chan, L.H.M., Mahaffey, K.R., Murray, M., Sakamoto, M. and Stern, A.H., 2007, Methylmercury exposure and health effects in humans: a worldwide concern: AMBIO: A Journal of the Human Environment, v. 36, no. 1, p. 3-12, http://dx.doi.org/10.1579/0044-7447(2007)36%5b3:MEAHEI%5d2.0.CO;2 (May 2018).

Mol, L., 2014, Section 1.3.2.: Measuring rock hardness in the field, *in* Clarke, L.E., and Nield, J.M., eds., Geomorphological Techniques (online edition): London, British Society for Geomorphology, 8 p.: https://www.geomorphology.org.uk/geomorph_techniques (June 2018).

Moir, H.J., and Pasternack, G.B., 2010, Substrate requirements of spawning Chinook salmon (*Oncorhynchus tshawytscha*) are dependent on local channel hydraulics: River Research and Applications, v. 26, p. 456–468, doi: 10.1002/rra.1292.

Moray, E.D., Thodal, C.E., and Marvin-DiPasquale, M., 2017, Long-term trends of surface-water mercury and methylmercury concentrations downstream of historic mining within the Carson River watershed: Environmental Pollution, v. 229, p. 1006-1018, doi: 10.1016/j.envpol.2017.07.090.

Moses, C., Robinson, D., and Barlow, J., 2014, Methods for measuring rock surface weathering and erosion: A critical review: Earth-Science Review, v, 135, p. 141-161, doi:10.1016/j.earscirev.2014.04.006.

National Hydrography Dataset (NHD), 2002, National Geospatial Program Office, United States Geological Survey: https://usgsmrs.cr.usgs.gov/NHDHelp/WebHelp/NHD_Help/Introduction_to_the_NHD/Feature_Attribution/Stream_Order.htm (November 2017).

Nriagu, J.O., 1994, Mercury pollution from the past mining of gold and silver in the Americas: Science of the Total Environment, v. 149, p. 167-181, doi:10.1016/0048-9697(94)90177-5.

Pejchar, L., and Warner, K., 2001, A river might run through it again: Criteria for consideration of dam removal and interim lessons from California: Environmental Management, v. 28, no. 5, p. 561-575, doi: 10.1007/s002670010.

Peterson, D.W., Yeend, W.E., Oliver, H.W., and Mattick, R.E., 1968, Tertiary gold-bearing channel gravel in northern Nevada County, California: United States. Geological Survey Circular 566, 28 p.: https://pubs.usgs.gov/circ/1968/0566/report.pdf (August 2017).

Report on the Horse Valley Placer Mine, Camptonville, Yuba County, California, 1923, File at the Grover Heinrichs Mining Collection, Arizona Geological Survey, Tucson Arizona.

"Rush Work On Dam," September 24, 1915, The Marysville Appeal, p. 4.

Schmidt, J.C., Webb, R.H. Valdez, R.A. Marzolf, G.R., and Steve, L.E., 1998, Science and values in river restoration in the Grand Canyon: Bioscience, v. 48, p. 735-747, doi:10.2307/1313336.

Schmidt, J.C., and P.R. Wilcock, 2008, Metrics for assessing the downstream effects of dams: Water Resource Research, v. 44, W04404, 19 p.

Schober, S., Sinks, T., and Jones, R., 2003, Blood mercury levels in U.S. children and women of childbearing age, 1999-2000: Journal of the American Medical Association, v. 289, p 1667-1674, doi: 10.1001/jama.289.13.1667.

Simmons-Willis, T.A., Clarkson, T.W., and Ballatori, N., 2002, Transport of a neurotoxicant by molecular mimicry: The methylmercury–L-cysteine complex is a substrate for human L-type large neutral amino acid transporter (LAT) 1 and LAT2: Biochemical Journal, v. 367, no. 1, p. 239-246, doi: 10.1042/BJ20020841.

Singer, M.B., Harrison, L.R., Donovan, P.M., Blum, J.D., and Marvin-DiPasquale, M., 2016, Hydrologic indicators of hot spots and hot moments of mercury methylation potential along river corridors: Science of the Total Environment, v. 568, p. 697-711, doi:10.1016/j.scitotenv.2016.03.005.

Slotton, D.G., Ayers, S.M., Reuter, J.E., and Goldman C.R., 1997, Gold mining impacts on food chain mercury in northwestern Sierra Nevada streams: Larry Walker Associates, Sacramento River Watershed Mercury Control Planning Project—Report for the Sacramento Regional County Sanitation District, App. B, p. 1-74: https://escholarship.org/uc/item/58h617dr (August 2018).

Slowey, A.J., Rytuba, J.J., and Brown, G.E. Jr., 2005, Speciation of mercury and mode of transport from placer gold mine tailings: Environmental Science & Technology, v. 39, no. 6, p. 1547-1554, doi:10.1021/es049113z.

Stat Trek, 2019, Bias in survey sampling: https://stattrek.com/survey-research/survey-bias.aspx (April, 2019).

Strahler, A.N., 1954, Quantitative geomorphology of erosional landscapes. Nineteenth International Geologic Congress, v. 13, no. 15, p. 341-354.

Tucker, W.B., and Waring, C.A., 1917, Mines and mineral resources of the counties of the El Dorado, Placer, Sacramento and Yuba Counties, state mineralogist report biennial period 1915-1916: California State Mining Bureau, 171 p.: https://books.google.com/books?id=NvENAQAAIAAJ&printsec=frontcover&source=gbs_ViewAPI#v=onepage&q&f=false (August 2018).

U.S. Congress, 1917, The Congressional Record, containing the proceedings and debates of the second session of the Sixty-Fourth Congress of the United States of America, Volume 54: Washington, D.C., Government Printing Office.

Whitney, J.D., 1880, The auriferous gravels of the Sierra Nevada of California, Volume 1: Cambridge, MA, University Press, John Wilson and Son, 638 p.

Wilson, D. and Looff, T.O., 2017, Final preliminary assessment and site inspection report: Youngs Hill Diggings, Yuba River Ranger District, Tahoe National Forest, CA: Nevada City, CA: ECM Consultants, U.S. Department of Agriculture, Forest Service, Tahoe National Forest.

Woodruff vs. North Bloomfield Gravel Mining Company, 1883: California Ninth Circuit Court: https://law.resource.org/pub/us/case/reporter/F/0018/0018.f.0753.pdf.

Yeend W.E., 1974, Gold-bearing gravel of the ancestral Yuba River, Sierra Nevada, California: U.S. Geological Survey Professional Paper 772, 44 p.: https://pubs.usgs.gov/pp/0772/report.pdf (April 2018).

Zhang, Y., Hu, C., Wang, X., Wang, M., Jiang, Z., and Li, J., 2017, An improved method of laser particle size analysis and its applications in identification of lacustrine tempestite and beach bar: An example from the Dongying depression: Journal of Earth Science, v. 28, n. 6, p.1145-1152, doi: 10.1007/s12583-016-0930-1.

APPENDIX A

ADDITIONAL MINING DOCUMENTATION

The minutes from a meeting of the California Debris Commission that took place on May 10, 1909. The highlighted portion of the text explains that Depot Hill, a hydraulic mine in the Willow Creek Watershed, is having its license revoked for failing to maintain a pool at least 2 ft behind its DCD. Fourteen other dams' mines outside the Willow Creek Watershed are mentioned as having their licenses revoked because there is not future work to be done. The highlight was added by the author (Hagwood, 1981).

503 Market St., San Francisco, Cal.,

May 10, 1909.

The Commission met at 3:15 p.m. today. Present, all the members.

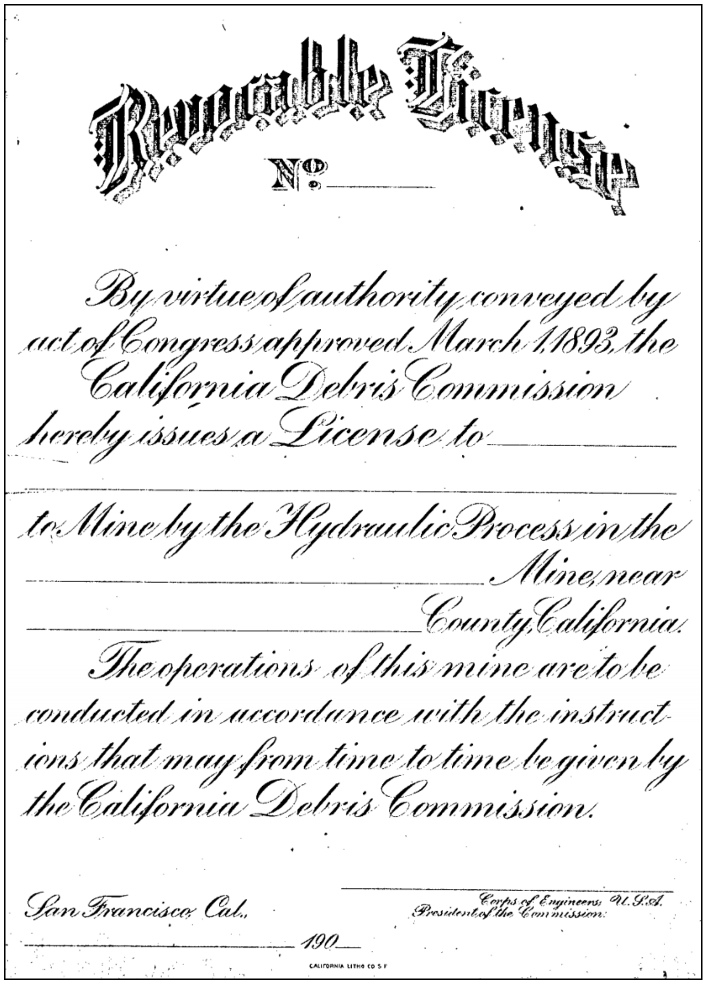
The minutes of the last meeting (April 27) were read and approved.

The correspondence requiring the action of the Commission was read and the following action taken: That the license of the Depot Hill Mine (127) be revoked on account of failure of operator to keep a pool while operating; that the licenses of the following mines be revoked on account of no future operations: Yellow Jacket (807), Gaylord (775), Republic (794), Spanish John (80), Gold Run (805), San Domingo (784), Denmark Placer (809), Southern Cross (786), St. George (708), Imperial (718), Salt Creek and Flat Gulch (800), (14) Moosehead (725), Home (780) and Brown Bear (801); that the licenses of the following mines be suspended on account of no further work this season: Lone Star (835) and Wallace Canyon (763); that the authority to construct dams granted the following mines be recalled, no work having been done, or work having been abandoned: Reece & West (843), El Dorado (836), Yuba (828), Corbiere and Bean (9), Clark Placer (839), Paragon (826), Lancha Plana (565), Trayner Placer (798), Lone Star (829), Concordia (830); that the licenses of the following mines be restored: Wah Kee (792) (pending inspection) and Philo Haven (528).

The Commission then adjourned.

Captain, Corps of Engineers, U.S.Army,
Secretary.

A blank CDC license, used by the CDC to permit an operator to mine by the hydraulic method (Hagwood, 1981).


Revocable License

No. ______

By virtue of authority conveyed by act of Congress approved March 1 1893 the California Debris Commission hereby issues a License to ______

______

to Mine by the Hydraulic Process in the ______ Mine near ______ County, California.

The operations of this mine are to be conducted in accordance with the instructions that may from time to time be given by the California Debris Commission.

San Francisco, Cal. ______ 190__

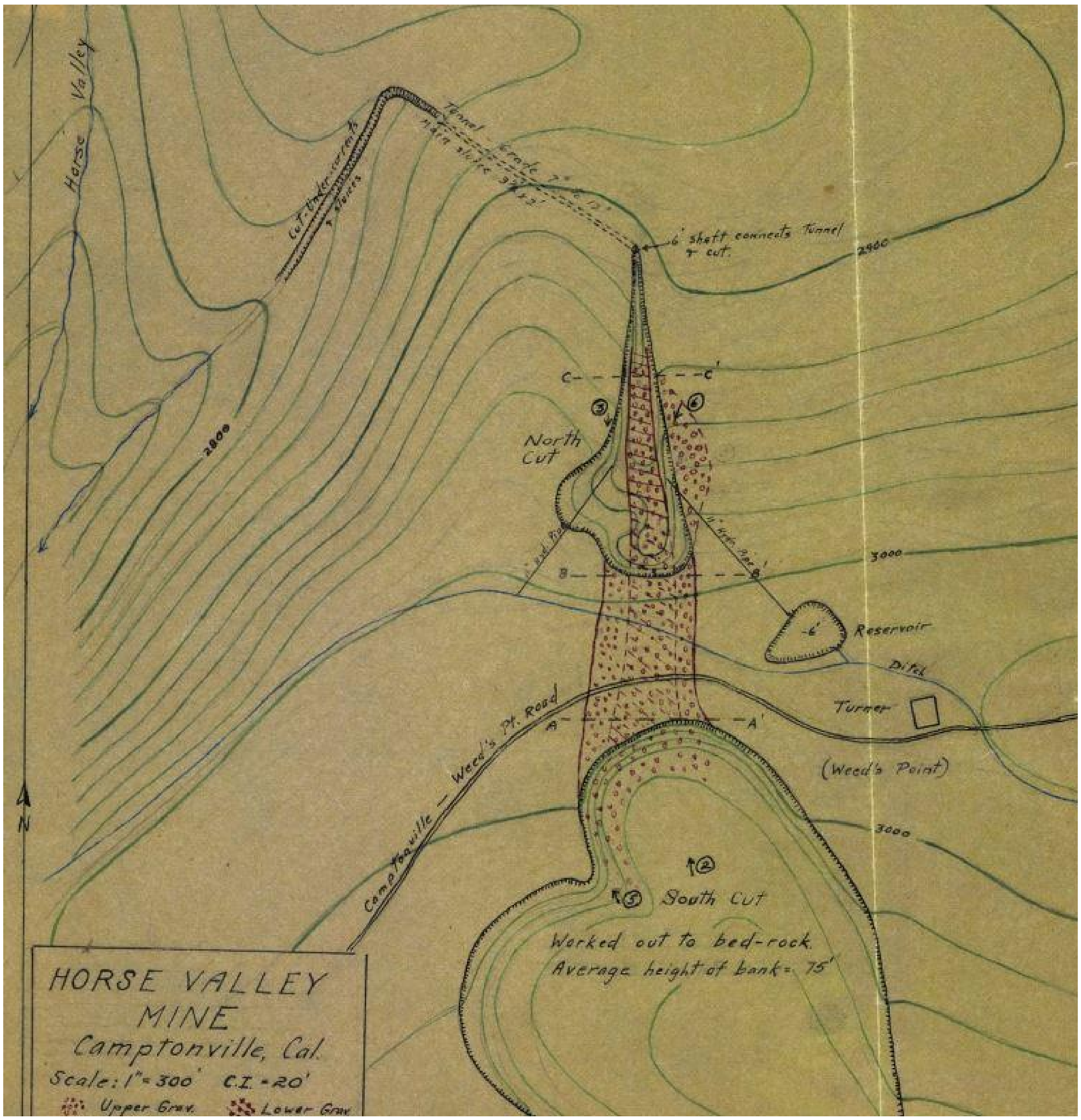
______
Corps of Engineers, U.S.A.
President of the Commission.

California Litho Co S F

The Fineness of gold coming from mines in the Camptonville Area, from Whitney, 1880.

Locality.	Fineness.	Value.
Camptonville	.930 – .935	$ 18.35
Galena Hill	.940	18.40 – 18.50
Young's Hill	.940	18.40
Weed's Point	.925	18 25
Railroad Hill	.925	18.25
Depot Hill	.910	18.00
Indian Hill	.925	18.25 – 18.35

A hand-drawn topographic map of the northern and southern cuts of Weeds Point mine in 1927. The locations of the ditch that fed water to the reservoir and the pipe that ran from the reservoir to the hydraulic monitor in the North cut are shown. The tunnel that conveyed HMS to Horse Valley Creek is shown at the top of the map. Two distinct layers of in-situ auriferous gravels are drawn on the map. The blue gravel, the richer deposit, is much thinner than the overlying white gravels, which has less gold. ("Report on the Horse Valley Placer Mine," 1923)



Pebble Count

Population type	Alpha-numeric designation	date collected	Latitude	longitude	Top or bottom (deposit only)	Sediment Mixing Ratio	D50
Deposit	HVC-DEP-001	2017-12-29	39.47712	-121.057	Top	100	8
Deposit	HVC-DEP-001	2017-12-29	39.47712	-121.057	Bottom	96.6	10
Deposit	HVC-DEP-002	2017-12-29	39.47726	-121.058	Top	0	8
Deposit	HVC-DEP-002	2017-12-29	39.47726	-121.058	Bottom	17.2	8
Deposit	HVC-DEP-003	2018-01-11	39.47576	-121.058	Top	NA	NA
Deposit	HVC-DEP-003	2018-01-11	39.47576	-121.058	Bottom	100	10
Deposit	HVC-DEP-004	2018-01-11	39.47451	-121.058	Top	100	8.5
Deposit	HVC-DEP-004	2018-01-11	39.47451	-121.058	Bottom	100	9
Deposit	HVC-DEP-005	2018-01-11	39.47421	-121.058	Top	100	8
Deposit	HVC-DEP-005	2018-01-11	39.47421	-121.058	Bottom	100	9
Deposit	HVC-DEP-006	2018-01-11	39.47435	-121.059	Top	100	8
Deposit	HVC-DEP-006	2018-01-11	39.47435	-121.059	Bottom	100	8
Deposit	HMS-DEP-007	2018-02-03	39.47208	-121.06	Top	100	7
Deposit	HMS-DEP-007	2018-02-03	39.47208	-121.06	Bottom	82.4	8
Deposit	HMS-DEP-008	2018-02-03	39.47226	-121.06	Top	NA	NA
Deposit	HMS-DEP-008	2018-02-03	39.47226	-121.06	Bottom	NA	NA
Deposit	HMS-DEP-009	2018-02-03	39.47201	-121.059	Top	97.1	8
Deposit	HMS-DEP-009	2018-02-03	39.47201	-121.059	Bottom	0	8
Deposit	HMS-DEP-010	2018-02-03	39.47158	-121.06	NA	NA	NA
Deposit	HMS-DEP-010	2018-02-03	39.47158	-121.06	NA	NA	NA
Deposit	WC-DEP-001	2018-03-30	39.47094	-121.046	Top	NA	NA
Deposit	WC-DEP-001	2018-03-30	39.47094	-121.046	Bottom	91.4	9
Deposit	WC-DEP-002	2018-03-30	39.47663	-121.043	Top	89	12
Deposit	WC-DEP-002	2018-03-30	39.47663	-121.043	Bottom	89.2	10
Deposit	WC-DEP-003	2018-03-30	39.47594	-121.044	Top	53.9	8
Deposit	WC-DEP-003	2018-03-30	39.47594	-121.044	Bottom	61.1	8
Gravel Bar	UD-001	2018-04-13	39.47948294	-121.0164549	NA	0	10.5
Gravel Bar	UD-002	2018-04-13	39.47948293	-121.0164549	NA	0	9
Gravel Bar	WC-TER-011	2018-06-21	39.45743493	-121.0632011	NA	47.1	Lost
Gravel Bar	WC-TER-012	2018-06-21	39.45631777	-121.0647529	NA	70.4	Lost
Gravel Bar	WC-TER-017	2018-08-07	39.47873743	-121.0425934	NA	80.8	8
Gravel Bar	WC-TER-021	2018-08-07	39.48606992	-121.0407142	NA	92.3	8.25
Gravel Bar	HMS-100-002	11/5/2017	39.481802	-121.053759	NA	100	9
Gravel Bar	HMS-100-003	11/5/2017	39.481429	-121.054377	NA	97.1	10
Gravel Bar	HMS-100-004	11/5/2017	39.48111	-121.0544	NA	47.1	9
Gravel Bar	HMS-100-006	11/5/2017	39.481224	-121.054661	NA	61.8	9
Gravel Bar	HMS-100-009	11/5/2017	39.481124	-121.055285	NA	26.5	9.5
Gravel Bar	HMS-100-010	11/5/2017	39.480648	-121.055190\	NA	29.4	12
In-Situ Auriferous Gravels	RC-001	2018-06-21	39.49814	-121.02	NA	99.3	9
In-Situ Auriferous Gravels	RC-002	2018-06-21	39.49829	-121.02	NA	71.9	Lost
In-Situ Auriferous Gravels	RC-003	2018-06-21	39.49888	-121.022	NA	71.9	Lost
In-Situ Auriferous Gravels	RC-004	2018-06-21	39.49888	-121.022	NA	80.4	8.5
In-Situ Auriferous Gravels	RC-005	2018-06-21	39.49739	-121.023	NA	80.4	Lost
In-Situ Auriferous Gravels	RC-006	2018-06-21	39.49709	-121.023	NA	57.2	Lost
In-Situ Auriferous Gravels	RC-007	2018-06-21	39.49803	-121.023	NA	65.6	Lost
In-Situ Auriferous Gravels	RC-008	2018-06-21	39.49788	-121.023	NA	82.5	8.5
In-Situ Auriferous Gravels	RC-009	2018-06-21	39.49765	-121.024	NA	99.4	9.5
In-Situ Auriferous Gravels	RC-010	2018-06-21	39.49765	-121.024	NA	71.9	9
In-Situ Auriferous Gravels	RC-011	2018-06-21	39.49764	-121.024	NA	90.9	9
Low Terrace	HVC-TER-001	2018-02-17	39.46205	-121.061	NA	94.11	8.5
Low Terrace	HVC-TER-002	2018-02-17	39.46328	-121.062	NA	82.35	10
Low Terrace	HVC-TER-003	2018-02-17	39.46711	-121.062	NA	76.5	9
Low Terrace	HVC-TER-004	2018-02-17	39.46978	-121.063	NA	79.4	9.5
Low Terrace	HVC-TER-005	2018-02-17	39.47411	-121.068	NA	100	10
Low Terrace	WC-TER-004	2018-03-30	39.46086	-121.055	NA	50.25	8
Low Terrace	WC-TER-006	2018-06-19	39.46871732	-121.0474695	NA	61.45	Lost
Low Terrace	WC-TER-007	2018-06-21	39.47868875	-121.0682053	NA	36.1	Lost

Population type	Alpha-numeric designation	date collected	Latitude	longitude	Top or bottom (deposit only)	Sediment Mixing Ratio	D50
Low Terrace	WC-TER-008	2018-06-21	39.47895217	-121.0679786	NA	19.23	Lost
Low Terrace	WC-TER-009	2018-06-21	39.48075724	-121.0692178	NA	42.25	
Low Terrace	WC-TER-019	2018-08-07	39.4831012	-121.0419378	NA	100	8
Low Terrace	WC-TER-020	2018-08-07	39.48556815	-121.0409106	NA	94.6	8
Low terrace	WD-100-001	2018-04-13	39.47334	-121.048	NA	80.71	9
Low terrace	WD-100-002	2018-04-13	39.47321	-121.048	NA	65.34	11
Low terrace	WD-100-003	2018-04-13	39.47329	-121.048	NA	58.78	8.25
Low Terrace	HMS-100-001	11/5/2017	39.481802	-121.053759	NA	100	9
Low Terrace	HMS-100-005	11/5/2017	39.481224	-121.054661	NA	36.1	9
Low Terrace	HMS-100-007	11/5/2017	39.481245	-121.055099	NA	62.4	9
Low Terrace	HMS-100-008	11/5/2017	39.481245	-121.055099	NA	47.22	8
Lower Terrace	WC-TER-010	2018-06-21	39.48115122	-121.0691794	NA	32.42	
NA	WC-TER-018	2018-08-07	39.4796716	-121.0426427	NA		9
Other Alluvium	HMS-0-001	2017-11-09	39.48911	-121.056	NA	0	9
Other Alluvium	HMS-0-002	2017-11-09	39.48878	-121.057	NA	-8.82353	12
Other Alluvium	HMS-0-003	2017-11-09	39.4886	-121.057	NA	0	12.25
Other Alluvium	HMS-0-004	2017-11-09	39.48798	-121.058	NA	-2.94118	8.75
Other Alluvium	HMS-0-005	2017-11-09	39.48723	-121.058	NA	17.64706	10
Other Alluvium	HMS-0-006	2017-11-09	39.48718	-121.058	NA	0	9
Other Alluvium	HMs-0-007	2017-11-09	39.48716	-121.058	NA	-5.88235	10
Upper Terrace	HVC-TER-006	2018-02-17	39.47485	-121.069	NA	100	12
Upper Terrace	WC-TER-001	2018-03-30	39.47678	-121.044	NA	74.7	9
Upper Terrace	WC-TER-002	2018-03-30	39.47678	-121.044	NA	100	9
Upper Terrace	WC-TER-003	2018-03-30	39.47736	-121.043	NA	96.3	11
Upper Terrace	WC-TER-005	2018-03-30	39.46113	-121.055	NA	78.3	9
Upper Terrace	WC-TER-013	2018-08-07	39.47722649	-121.0428706	NA	78.3	10
Upper Terrace	WC-TER-014	2018-08-07	39.47712874	-121.0430189	NA	95.5	9
Upper Terrace	WC-TER-015	2018-08-07	39.47647383	-121.0435709	NA	96.4	9
Upper Terrace	WC-TER-016	2018-08-07	39.47698596	-121.0434676	NA	90.3	8
Upper Terrace	WC-TER-022	2018-08-07	39.47478846	-121.0681845	NA	100	8
Upper Terrace	WC-TER-023	2018-08-07	39.47555995	-121.0681117	NA	100	9.25
Upper Terrace	WC-TER-024	2018-08-07	39.47794105	-121.0681266	NA	100	9