



Long-term hydraulic mining sediment budgets: Connectivity as a management tool

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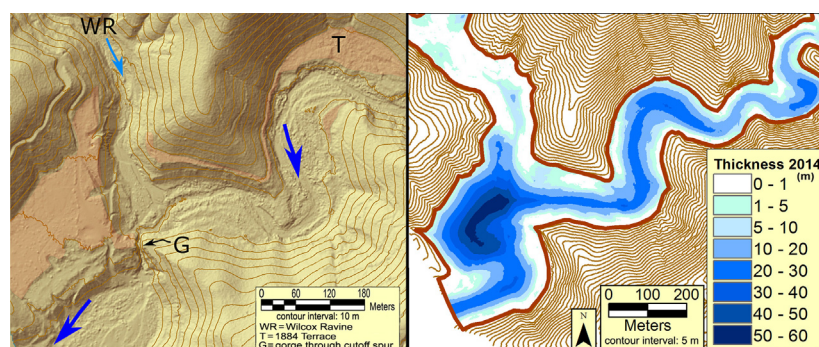
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HIGHLIGHTS

- Large volumes of Hg-laden hydraulic mining sediment (HMS) are mapped.
- Geomorphometry and high resolution topographic data can produce sediment budgets.
- $23.5 \times 10^6 \text{ m}^3$ HMS produced; more local storage than previous estimates or theory.
- HMS connectivity with channel system varied in space and time.
- Longitudinal, lateral, and vertical connectivity can be used to manage the HMS.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:

Received 28 June 2018

Received in revised form 25 September 2018

Accepted 28 September 2018

Available online 30 September 2018

Keywords:

Hydraulic mining sediment

Sediment budget

Geomorphometry

Connectivity

ABSTRACT

Approximately $1.1 \times 10^9 \text{ m}^3$ of sediment were produced by late nineteenth century hydraulic gold mining in the Sierra Nevada of northern California. Modern geospatial methods combined with 2014 airborne LiDAR $1 \times 1\text{-m}$ data are used to map and model a distributed sediment budget for upper Steephollow Creek, one of the most severely impacted catchments in the region. Digital elevation models (DEMs) were developed for three times using geomorphometry to construct sediment budgets. The 2014 surface is from the LiDAR bare-earth DEM, the pre-mining surface before 1853 was interpolated from contours extended along ridges and pre-mining valley bottoms, and the 1884 maximum aggradation surface was interpolated from contours extended across high terraces. Mine pit volumes indicate that $\sim 23.5 \times 10^6 \text{ m}^3$ of hydraulic mining sediment (HMS) was produced in the 54.6 km^2 study catchment. Volumes of HMS stored in the catchment were computed for 2014 ($3.75 \times 10^6 \text{ m}^3$) and for ca. 1884 at the time of maximum aggradation ($7.15 \times 10^6 \text{ m}^3$). The 2014 storage is 16% of the sediment produced in the catchment, indicating a sediment delivery ratio (SDR) of 84% of the HMS from the basin, which is higher than most agricultural basins and indicates a strong longitudinal sediment connectivity in this region. Storage in 1884 represents 30% of production indicating a SDR of 70% during the period of mining. Dynamics and strong scale dependencies of sediment connectivity are documented with regard to space and time. Over the past 130 years, $3.57 \times 10^6 \text{ m}^3$ —approximately half of the storage in upper Steephollow Creek—was eroded and carried out of the catchment.

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1. Introduction

Hydraulic gold mining produced more than a billion m^3 of hydraulic mining sediment (HMS) in the late 19th century over a period of

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31 years (1853–1884) in the northwestern Sierra Nevada of northern California. The HMS, which is often contaminated with mercury, filled canyons below the mines and extended to the San Francisco Bay >200 km downstream. An early regional sediment budget (Gilbert, 1917) estimated total HMS production and storage volumes across the mining districts and the Sacramento Valley below. Contemporary estimates of HMS storage in the mountains and downstream were based primarily on surficial exposures and were lumped at the large basin scale; e.g., the North, Middle, and South Yuba, and Bear River Basins. Few sediment budget measurements have been made of these deposits in the modern period and the original estimates by Gilbert and his predecessors of sediment production, storage, and removal from the mountains have not been updated or mapped at higher resolutions.

1.1. Hydraulic mining and early sediment budgets

Hydraulic gold mining was invented in northern California in 1853 and quickly spread through the northwestern Sierra foothills. Hydraulic mining uses water under pressure to move large volumes of sediment, so it requires a large supply of water and high local relief to ensure sufficient hydraulic head. Steep slopes below the mines, sluices and tunnels were required to remove waste materials. Water was delivered along ridges by extensive canal systems to the mines that were typically more than a hundred meters above the canyon bottoms. This system was highly effective at exhuming gravel from auriferous conglomerates, processing them through extensive sluice systems laden with Hg, and producing large volumes of hydraulic mining sediment (HMS). The sedimentation that ensued overwhelmed the sediment transport capacity of the rivers below and caused episodic channel aggradation, as well as environmental damage and economic losses that resulted in the process being largely enjoined after 1884. Although some licensed hydraulic mining occurred after 1884, relatively small volumes of sediment were produced, so—as Gilbert (1917) did—exhumed mine-pit volumes measured in this study are assumed to represent the primary period of mining, 1853–1884. The licensed period is important as the time in which a series of debris control dams were constructed for the explicit purpose of storing HMS. Storage of HMS behind these structures is often perceived as a major component of the HMS remaining in the mountains.

Early estimates of HMS production were made in the late 19th century based on the amount of water used by each mine (Benyaud et al., 1891). One of the first quantitative sediment budgets ever published was the large-scale budget made by G.K. Gilbert (1917) for HMS in the northern Sierra Nevada (James et al., 2017). Gilbert adjusted previous estimates of sediment production based on his plane-table map surveys of representative mine pits that indicated exhumed mine-pit volumes were 1.51 times earlier estimates. Gilbert applied this adjustment to all of the mines in the region and estimated that the total production of HMS was $\sim 1.1 \times 10^9 \text{ m}^3$, which was derived mostly from the Yuba ($523 \times 10^6 \text{ m}^3$) and Bear ($271 \times 10^6 \text{ m}^3$) basins. Gilbert's (1917) HMS budget indicates that only 12% of the $871 \times 10^6 \text{ m}^3$ of sediment produced in the Feather River basin (including the Yuba and Bear basins), remained in the mountains. The large proportion (88%) of HMS delivered downstream indicates a high sediment delivery ratio (SDR), which is implicitly related to high longitudinal connectivity (Bracken and Croke, 2007; Cavalli et al., 2013). The early computations by Gilbert (1917) have not been repeated and do not include details on production or storage in individual catchments. Gilbert's estimates of storage in the mountains were based on earlier 19th century field surveys of a reconnaissance nature that lacked subsurface information or analyses (Turner, 1891). The need to know where HMS is stored and the potential capabilities of newly acquired airborne LiDAR call for a modern re-assessment with spatially distributed local-scale sediment budgets.

1.2. Mercury contamination in hydraulic mining sediment (HMS)

In recent decades the HMS has been shown to be contaminated with mercury (Hg) that is not native to the Sierra Nevada but was imported

for use in gold processing (Bowie, 1905; Hunerlach et al., 1999; Alpers et al., 2016). Elemental Hg forms an amalgam with gold, which settled out in sluices and was collected and heated in retorts to volatilize the Hg and recover the gold. Based on contemporary mine records, $11.8 \times 10^6 \text{ kg}$ of Hg were applied in mines of the region from 1860 to 1880 and losses to the environment were from 10 to 30% (Bowie, 1905). Hydraulic mine operations were associated with the highest losses of Hg, which persists in hydraulic mining sediment (HMS) and can travel long distances and contaminate the aquatic environment (Rytuba, 2005). In addition, liquid elemental Hg has been observed in sediment within hydraulic sluice tunnels and in bed sediment of Sierra Nevada rivers in historically mined regions (Hunerlach et al., 1999, 2004). Despite the fact that unregulated hydraulic mining ceased in 1884 and many debris-control dams were built to hold back the hydraulic mine waste, inorganic Hg from hydraulic mine sites continues to be transported during storm events and deposited into aquatic ecosystems where it can methylate and become incorporated into the food web (Fleck et al., 2011). A positive relationship between Hg bioaccumulation in aquatic ecosystems and the intensity of hydraulic mining has been documented in the Sierra Nevada (Alpers et al., 2016; Hunerlach et al., 1999; May et al., 2000). High concentrations of Hg in HMS, combined with an improved understanding of methylation and biomagnification processes (Alpers et al., 2008; Fleck et al., 2011; Marvin-DiPasquale et al., 2011; Stewart et al., 2008), call for a detailed inventory of HMS that can direct a science-based policy for stabilizing or treating the HMS.

1.3. Geomorphometric sediment budgets and connectivity

Conservation of mass between sediment sources and sinks allows computations of erosion, deposition, and storage by balancing changes in sediment volume in various components of a geomorphic system. Thus, by what is known as the morphologic or inverse method, sediment budgets can be computed from geomorphic change detection (Gaeuman et al., 2003; Vericat et al., 2017). These methods are usually applied to relatively short time periods over which repeat surveys can be made and differenced (Brasington et al., 2000; Lane, 2000), but they can also be applied to historic change where detailed topographic data can be developed for older surfaces (James et al., 2009). For example, a DEM can be interpolated from historic contour lines and subtracted from a more recent DEM and the DEM of difference (DoD) can be used to compute volumes, locate areas of erosion and sedimentation, and construct historic sediment budgets (James et al., 2012). These historic budgets allow a quantitative assessment of sediment deposition, remobilization, and transport over time that can indicate the dynamics and spatial patterns of large-scale environmental change.

Geomorphic change is driven primarily by forces and fluxes to which the systems are closely linked. Knowledge of how tightly environmental systems are connected by processes or fluxes of energy, materials, or biota, therefore, is essential to understanding or predicting changes in those systems (Fryirs et al., 2007). Connectivity may be expressed in terms of sediment, hydrology, geochemistry, rivers, or landscapes (Wohl et al., 2017). Fluvial sediment connectivity, a focus of this study, varies with flow competence, grain size, and proximity (Hooke, 2003) and governs storage potential and residence times (Madej, 1989). Connectivity of water, energy, or material may be described as longitudinal, referring to up- or downstream fluxes or linkages, lateral, referring to cross-valley exchanges between channels, floodplains, and hillslopes, or vertical, referring to changes in the channel bed (Aalto et al., 2008; Kondolf et al., 2006). Erosion of sediment stored in terraces requires both lateral connectivity to allow competent flows to reach the sediment and longitudinal connectivity to carry the sediment out of the reach. Several studies in mountainous regions have shown the feasibility of using geomorphometric methods to model catchment-scale sediment connectivity. For example, Cavalli et al. (2013) adapted Borselli

et al.'s (2008) geomorphometric index for use with aerial LiDAR in Alpine catchments to develop an Index of Connectivity (IC) based on slope, drainage area, and other physiographic factors such as roughness. They used the IC to contrast two subcatchments with regard to connectivity with both main channels and catchment outlets.

Sediment *continuity*, a related concept, describes spatial or temporal interruptions between deposits (Hooke, 2003; Grant et al., 2017). Low longitudinal continuity may occur as isolated bars even if sediment easily passes through the gaps (Hooke, 2003). In the classic wave theory of hydraulic mining sediment described by Gilbert (1917), sediment in the mountains was tightly connected to the Sacramento Valley but spatially discontinuous through long stretches of steep, narrow canyons that had little sediment storage. In many of the mined basins of the northwestern Sierra, HMS was so deep that large areas of sediment were continuous. Near the upper limits of the mines, however, especially after subsequent erosion, valley bottom deposits of HMS can be discontinuous in space.

1.4. Objectives

This multidisciplinary study examines sedimentary, geomorphic, and topographic data with two primary objectives. A preliminary objective that was quickly affirmed, was to determine how well geomorphometry with LiDAR topographic data can identify mining features. Specifically, high-resolution airborne LiDAR data acquired in 2013 and 2014 were used to detect mine rims, tunnels, debris-control dams, canals, water and sediment storage reservoirs, terrace scarps, tailings fans, and other features associated with hydraulic mining and sediment deposits. Another set of objectives was to measure volumes of HMS production, storage, and reworking, to develop sediment budgets for two time periods. The HMS budgets are used to identify factors governing local storage and connectivity in response to a massive sedimentation event over a centennial time scale. Developing sediment budgets at the scale of large basins is beyond the scope of this study due to the limited extent of LiDAR coverage and limited resources. Instead, this study is focused on a proof-of-concept for geospatial methods applied to a 55-km² catchment. A hypothesis is tested that the proportion of HMS production that remains stored locally is >12% of the volume produced; i.e., the proportion of HMS storage estimated by Gilbert (1917). Assumptions that only a small proportion of the HMS remained in local storage have prevailed in the region despite the presence of massive terraces and fans of HMS, so this test has both practical and theoretical implications.

2. Study area

The Yuba and Bear basins, located in the western slopes of the northern Sierra Nevada in California, received most of the HMS. The ancestral Yuba River, an Eocene river system (Lindgren, 1911), was raised by tectonic uplift of the Sierra Nevada and now exists as a series of widespread auriferous channel gravels along ridges >100 m above the modern canyon bottoms. Subcatchments in the Yuba and Bear Basins, and especially Steephollow Creek in the Bear Basin, are the focus of this study. Volumes of seven hydraulic mines and two debris control dams in Willow Valley Creek of the North Yuba and two mines in Scotchman Creek of the South Yuba basin were measured. In addition, a sediment budget was computed for upper Steephollow Creek, a 54.6 km² catchment, based on a volumetric analysis of several hydraulic mines and storage in channels, terraces, a tailings fan, and behind a debris-control dam (Fig. 1). The Steephollow Creek analysis was limited to areas above Wilcox Ravine, where LiDAR topographic data are available, so a few mines and extensive deposits of HMW in lower Steephollow Creek were not included. Steephollow Creek flows in a long, linear catchment with high relief (maximum relief was 1067 m in 2014). This is a steep, well-dissected landscape with an average slope of 21.6° as measured from a 1 × 1 m LiDAR DEM, so colluvial storage is limited.

3. Materials and methods

Sediment budgets are based on topographic surfaces at three points in time: the pre-mining surface before 1853, the penultimate mining surface when channel aggradation was at a maximum ca. 1884, and a modern surface when the LiDAR data were flown in 2013 and 2014. These three surfaces were used to compute local changes in volumes (sediment budgets) in and below the mine pits during two periods: from pre-mining to ca. 1884 and from ca. 1884 to 2014.

3.1. LiDAR topographic data and identification of hydraulic mine features

This study utilized a high-resolution (1-m grid) bare-earth airborne LiDAR digital elevation model (DEM) developed for the U.S. Forest Service, Tahoe National Forest in 2013 and 2014. An Optech Gemini Airborne Laser Terrain Mapper (ALTM) equipped with an Optech 12-bit waveform digitizer mounted in a twin-engine Piper Navajo PA-31 was flown in 46 flights covering a total area of over 5000 km². The average pulse density of the resulting point cloud was 8.5 pulses/m². The resulting return data were processed to remove vegetation, buildings, etc. from point clouds to develop the 1-m bare-earth DEM that was obtained for this study. The LiDAR data do not cover western portions of the catchments—such as lower Steephollow Creek—where substantial amounts of hydraulic mining and HMS storage occurred. Hillshade visualizations derived from the 1-m bare-earth LiDAR DEM were used to identify and map geomorphic and mining features (Fig. 2). Geomorphic elements associated with hydraulic mines include mine rims, canals supplying water to the mines, and tunnels used to remove water and HMS from mines. Features below the mines associated with HMS include debris control dams, fluvial terraces, and tailings fans. Most of these features are not detectable on aerial photography and had not been mapped previously. The canals are particularly useful for identifying small unmapped hydraulic mine pits.

3.2. Volumes of HMS produced and stored

Volumes of HMS produced by mines and exhumed from mine pits were computed by DEMs of difference (DoD); i.e., by subtracting the modern LiDAR DEM (DEM₂₀₁₄) from a DEM representing the pre-mining surface DEM_{PM}:

$$\text{DoD}_{\text{MINE}} = \text{DEM}_{\text{PM}} - \text{DEM}_{2014} \quad (1)$$

where DoD_{MINE} is the DEM of difference representing the depths and volumes within the mine pit, DEM₂₀₁₄ is the LiDAR bare-earth surface, and DEM_{PM} is the pre-mining surface. DEM_{PM} was developed by manually extending 5-m contours across the mine pit and interpolating the contours in a GIS (Fig. 3). Several methods for interpolating pre-mining surfaces were tested within the ArcGIS (ESRI®) toolkit, but the Topo-to-Raster method was used exclusively for interpolations in Steephollow Creek. To generate the pre-mining and 1884 maximum valley fill surfaces, it was critical to include breaklines or contours to constrain the general topography of reconstructions. Some portions of mines were exhumed on ridgetops, some on sides of ridges, and others in depressions, depending on the relationships between the auriferous paleogravels and the topography of the site. Simple interpolations of pre-mining topography from the modern pit rims tended to build approximately planar surfaces that underestimate volumes removed by mines on ridgetops and overestimate volumes of mines in hollows (Fig. 4). Planar interpolations can introduce large errors, so interpolations were constrained by simulating pre-mine elevations with contours and interpolating elevation surfaces from the contours with the topo-to-raster tool.

All the DoD grids produced in this study were tested for negative numbers that tend to occur along boundaries. Boundary issues were fixed by adjusting the contours and re-interpolating, and all negative

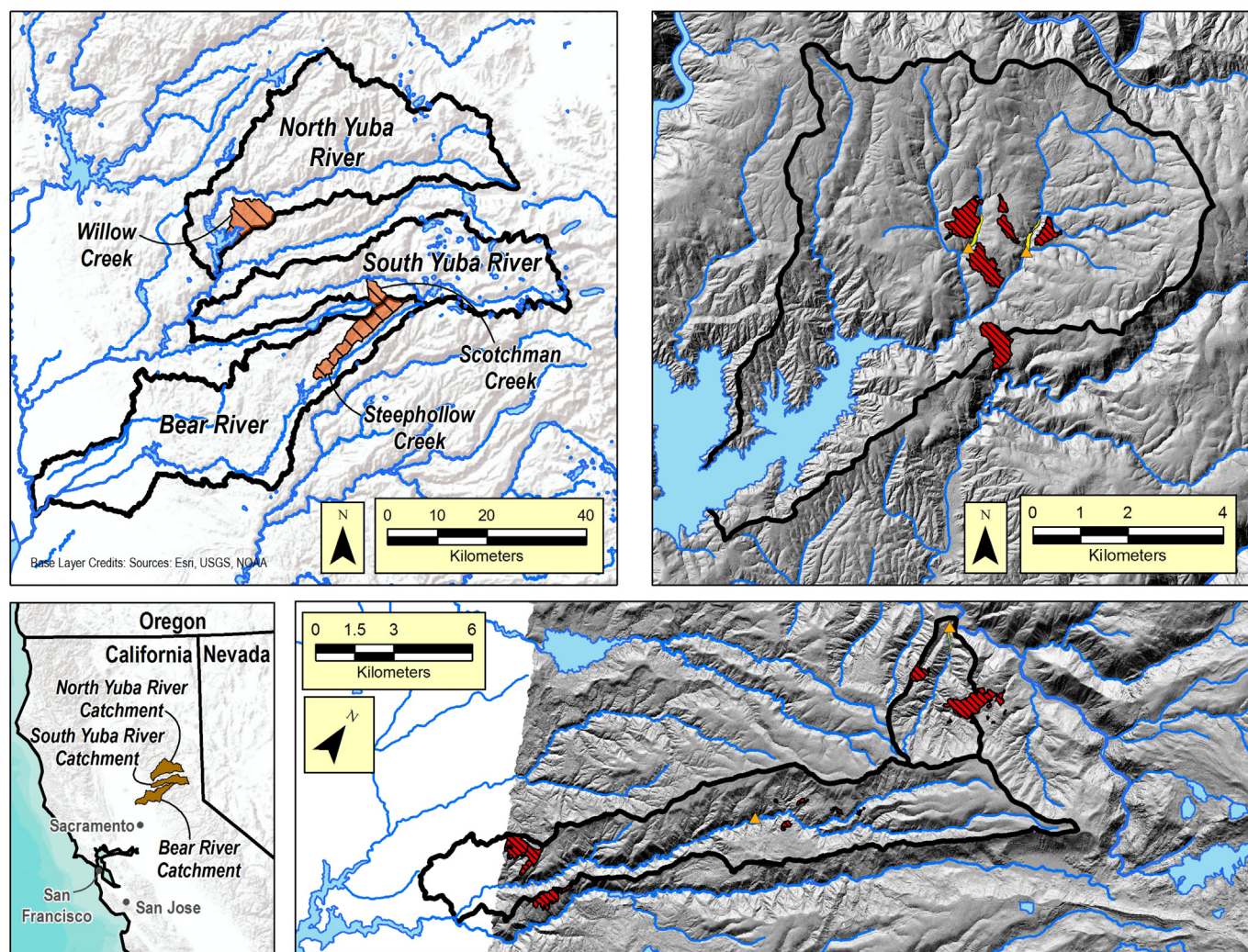


Fig. 1. Location maps. (Bottom Left) Bear River and North and South Yuba Basins in the northwestern Sierra Nevada of northern California. (Top Left) Willow, Scotchman, and Steephollow Catchments within the North Yuba and Bear River basins. (Top Right) Willow Creek Catchment with Youngs Hill Mine and Horse Valley Creek and Willow Creek debris control dams. (Bottom Right) Scotchman Creek (flows north) and Steephollow Creek (flows southwest) Catchments with hydraulic mines and HMS deposits.

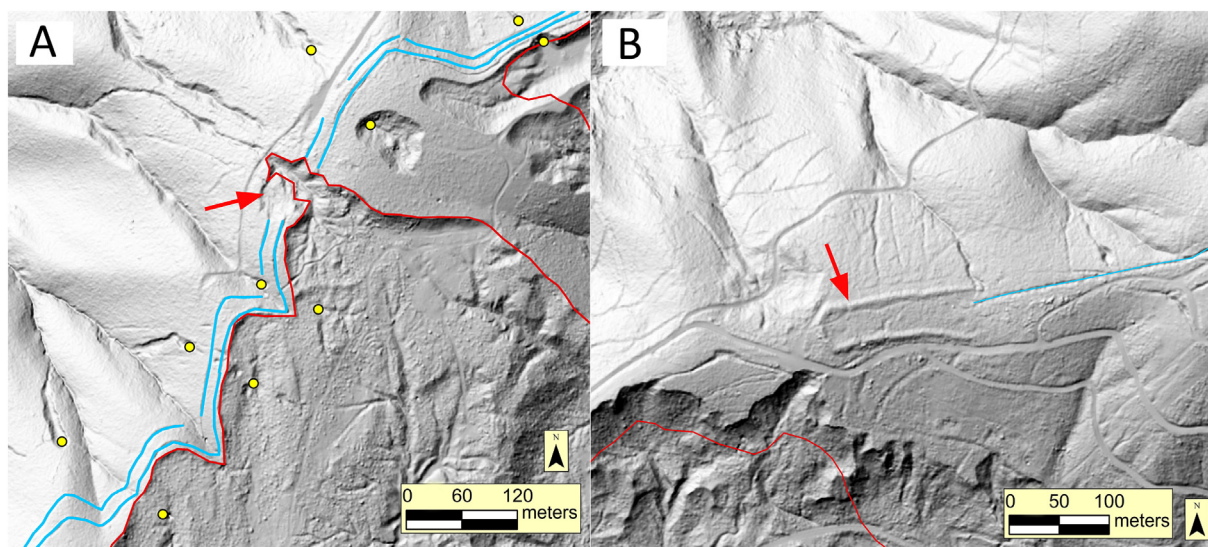


Fig. 2. Hydraulic mine features in the Steephollow Creek Catchment on 1-m LiDAR hillshaded imagery. (A) Canals flowing northeast to southwest along the rim of the Christmas Hill Mine. Point pairs are adits to tunnels under the canals. Canals collapsed (arrow) at one point, which disrupted mining. (B) Ridgetop reservoir (arrow) at end of the lower canal in Panel A. The reservoir is about 1 ha in area and supplied water at ~100 m of head to Little York Mine at bottom of image.

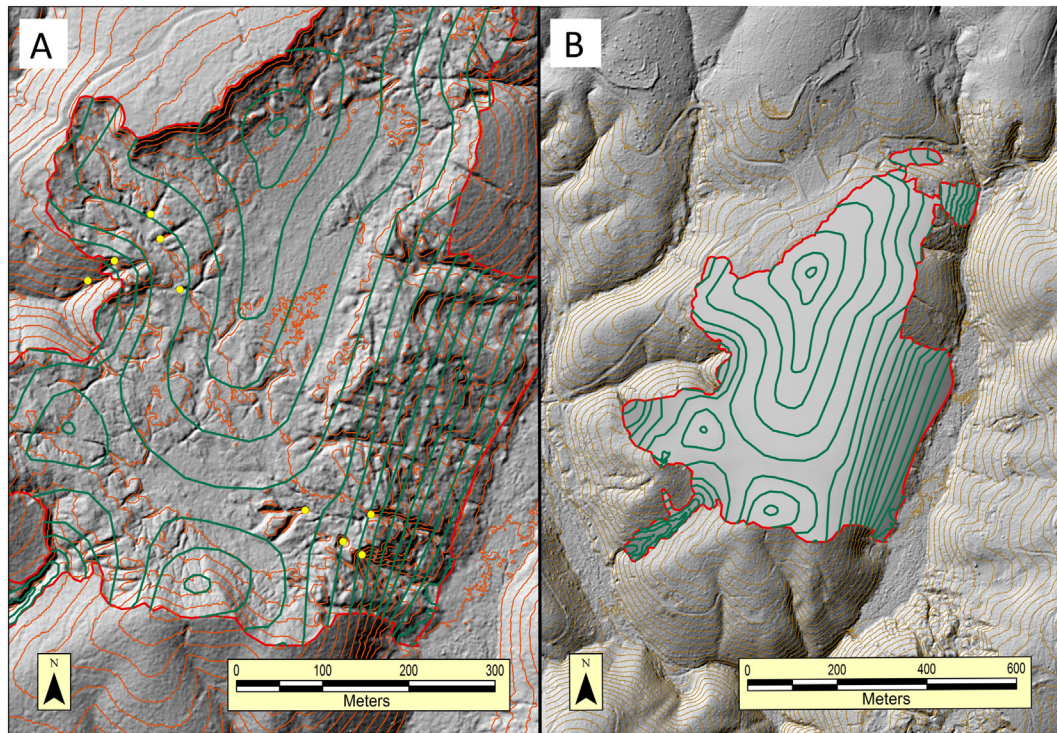


Fig. 3. Youngs Hill hydraulic mine. (A) LiDAR shaded relief (DEM_{2014}) and 5 m contours (light lines) with 5-m contours added manually for the pre-mining surface (dark lines). Yellow points are tunnel adits. (B) Same features as A but with interpolated surface in shaded relief (DEM_{PM}).

values were set to zero before computing volumes. The DoD_{MINE} thickness values were multiplied by the area of each grid cell and summed to compute volumes removed from the mine. In this case, cell areas were 1 m^2 , so each depth is equivalent to the volume of the cell and summing cell depths gave the volumetric sums.

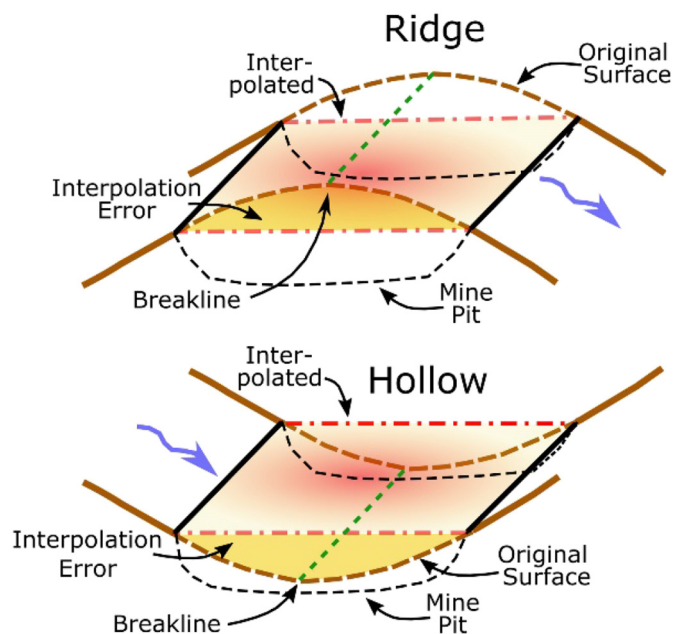


Fig. 4. Schematic of ridge-top mines (top) and valley bottom mines (bottom). Interpolations that are simply bounded by rims of mine pits will tend to be relatively planar, so volumes from ridges are underestimated and volumes from hollows are overestimated. Contours or other forms of breaklines are needed to train the results and minimize this error.

Mine volumes at five of the mines (Railroad, Youngs Hill, Weed's Point, Galena Hill, and Camptonville) in the Willow Creek Catchment of North Yuba were compared to volumes computed by Gilbert (1917) to validate volumes computed by the geomorphometric methods used in this study. Gilbert (1917) measured mine pit volumes with plane-table mapping and manual contouring between 1907 and 1908. Gilbert's volumes were estimated without the aid of modern mapping technology or remote sensing data, so they should not be assumed to be more accurate than those provided here. The topography of the mines since Gilbert's study may have changed due to licensed hydraulic mining and erosion. Licensed mining produced a relatively small volume in proportion to the period prior to 1884 (James, 2005) and much of that late HMS, along with erosion of mine side-slopes, was stored within the mine pits and caused no net change in volume.

Sediment budgets were generated for the areas of Steephollow Creek within the range of available LiDAR data from the Wilcox Ravine fan upstream; i.e., for the Steephollow Catchment above Steephollow Crossing (hereafter the catchment). The budget includes all the mines and deposits within the catchment except the west You Bet Mine, which is beyond the LiDAR data boundary and delivered most of its sediment south of the catchment below Wilcox Ravine, although some tunnels linked it to Wilcox Ravine. Production of HMS in the catchment was largely from the southeast and central You Bet Mines, but did not include the north mine which flows away from Steephollow Creek. Most of the HMS produced by the Christmas Hill Mine flowed south away from Steephollow Creek, but tunnels delivered an estimated 20% of the Christmas Hill HMS to Steephollow Creek.

The modern volume of HMS stored in valleys was determined by modeling a DEM for the pre-mining valley bottom surface (DEM_{PM}) and subtracting it from the LiDAR DEM of the 2014 valley bottoms (DEM_{2014}):

$$DoD_{2014} = DEM_{2014} - DEM_{PM} \quad (2)$$

where DoD_{2014} is the DEM of difference representing thicknesses of HMS in the modern channels, terraces, and fans. The DEM_{PM} was modeled by manually extending 5-m contours down valley sides to near the channel bed. Hillslope profile shapes can have a considerable effect on the depth of valleys and volumes of valley fill. Fortunately, side slopes and the long profile are straight throughout upper Steephollow canyon away from HMS deposits, which constrained the spacing of contours under the HMS to relatively constant distances. To test the apparent linearity of slopes, 20 valley side slopes from 10 valley cross sections in Steephollow Canyon above and away from the mines were sampled at a 1-m horizontal interval using profiles from the LiDAR DEM over elevation ranges from all but the lowest 5 m above the valley floor up to 50 to 80 m. These slopes are so straight that regressions of elevation on distance produced coefficients of determination (R^2) ranging between 0.994 and 0.9999 for the 20 sections (Fig. 5). Channel bottoms in the valley cross sections are flatter than side slopes, but these shapes were limited to the bottom 2 to 4 m above the channel bottom—a single 5-m contour—over a channel width ranging from only 11 to 19 m. Given these constraints on valley cross-section shapes, contours were extended manually beneath the HMS in Steephollow Canyon using a constant spacing of 5-m contours down to the next-to-last contour. The resulting pre-mining valley bottom contours were interpolated to produce the pre-mining DEM_{PM} . Subtraction of the DEM_{PM} from the modern surface gave the thicknesses and volumes of HMS stored in the valleys in 2014 when the LiDAR data were acquired (Eq. (2)).

Storage of HMS at the penultimate time of maximum aggradation was computed for the catchment by mapping contours for high terrace and fan profiles from the 1-m LiDAR data and interpolating the surface. Terraces often show clearly on hill-shaded renditions of the data, but they were enhanced using a roughness grid (standard deviations of a 5×5 grid of degree slope) to facilitate identification of breaks in slopes (Fig. 6). After terraces and fans were outlined, 1-m contours were manually mapped as constrained by elevations of contours on the modern LiDAR data. These contours were interpolated to produce the maximum penultimate surface elevations (DEM_{MAX}). The total amount of sediment stored in the catchment at the time of the maximum aggradation was computed as the penultimate aggraded surface minus the pre-mining surface:

$$DoD_{MAX} = DEM_{MAX} - DEM_{PM} \quad (3)$$

Volumes of HMS that were eroded from the time of maximum aggradation to the time of LiDAR data acquisition (1884 to 2014) were computed by subtracting the volume present in 2014 from the volume in 1884. Alternatively, thicknesses and volumes of erosion up to 2014

(DoD_E) can be computed by subtracting modern surface elevations from the penultimate aggraded 1884 surface:

$$DoD_E = DEM_{MAX} - DEM_{2014} \quad (4)$$

Debris control dams were constructed to trap HMS during a period of licensed hydraulic mining after 1893. Volumes of HMS stored behind dams in 2014 were computed for three dams; two in the Willow Creek Catchment (Willow Creek and Horse Valley Creek dams) and another in the Steephollow Catchment (Swamp Angel Dam). Reservoir volumes for the Willow Creek and Horse Valley Creek dams were computed by constructing trapezoidal valley-bottom cross sections at 50-m intervals. For the Swamp Angel reservoir, the same contour method used to extend linear side slopes beneath the pre-mining valley bottom surface (DEM_{PM}), was used to construct the pre-mining surface behind the dam, which was subtracted from the modern surface to compute volumes of HMS (Eq. (2)). Storage behind Swamp Angel dam is included in the Steephollow sediment budget.

3.3. Error evaluation of spatial analysis

Errors in spatial analyses such as geomorphic change detection can be considerable and represent uncertainties that could potentially undermine the validity of estimations (Mowrer and Congalton, 2000). In some applications, filtering of small values of DoDs may be warranted to avoid the inclusion of spurious differences between DEMs generated by errors (Wheaton et al., 2009). A general concept that is helpful in this regard is that the relative importance of errors decreases as the signal-to-noise ratio gets larger (Griffith et al., 1999; James et al., 2012). For example, when topographic change is large relative to uncertainties associated with the elevation data, the likelihood is small that change measurements are primarily due to errors. This is generally the case with topographic changes in the Steephollow mine pits and valley bottoms where uncertainties associated with the reconstructed pre-mining surfaces are small relative to the large geomorphic changes. Given the large signal-to-noise ratios, the raw DEMs were differenced and no filtering of changes was performed. The largest uncertainties in these budgets are associated with the topography of the pre-mining canyon bottoms, but construction of an error budget for these uncertainties would be largely speculative.

4. Theory

Based on Gilbert's (1917) sediment budget for hydraulic mines of the Sierra Nevada, only 12% of the HMS produced in the Yuba and

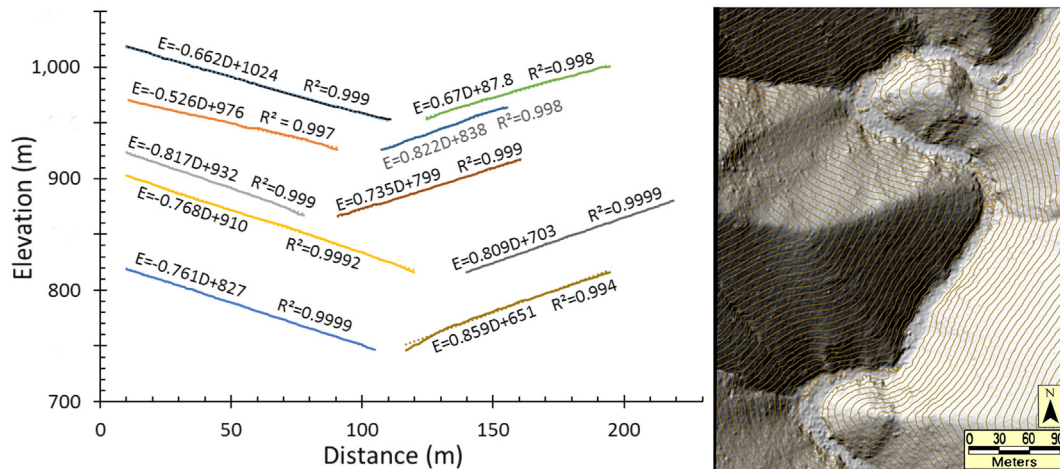


Fig. 5. Linearity of valley side slopes in Steephollow Creek down to the bottom-most 5-m contour. Linearity facilitated accurate reconstruction of pre-mining valley bottom contours beneath the HMS.

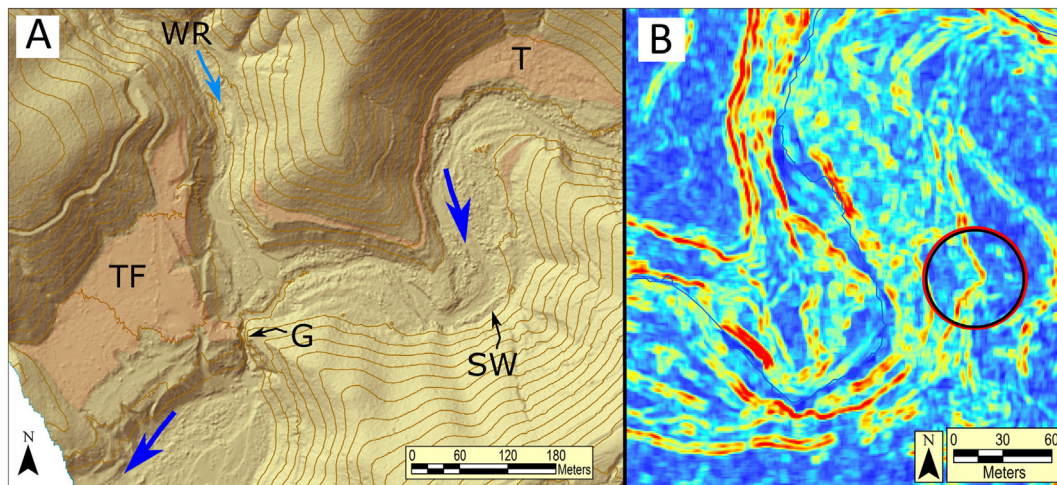


Fig. 6. Mapping terraces and fans near Steephollow Crossing by identifying surfaces on LiDAR 1-m imagery. (A) Shaded LiDAR topography with 10-m contours showing a tailings fan (TF), terrace (T), gorge (G), and slack-water deposits (SW) behind the tailings dam below Wilcox Ravine (WR). (B) Roughness grid enhances terrace treads to facilitate identification.

Bear Basins remained stored in the mountains near the mines at the time of his analysis (ca. 1908). Most (88%) of the HMS was believed to have been delivered downstream to the Sacramento Valley and beyond. This high delivery ratio represents a strong longitudinal sediment connectivity and is in contrast with many studies of non-mountainous agricultural regions in North America that have demonstrated sediment delivery ratios <10% (Roehl, 1962; Meade, 1982; Phillips, 1991; Beach, 1994). In fact, low delivery ratios have been identified as a geomorphic paradox (Trimble, 1977; Walling, 1983). They not only imply low longitudinal sediment connectivity between sediment sources and downstream catchments but also indicate an inherent non-equilibrium in fluvial systems in which hillslopes are down-wearing while valley bottoms are filling. High sediment connectivity between hillslopes and channels in Alpine headwater catchments has been demonstrated but does not necessarily ensure the down-valley transport of sediment to larger catchments (Cavalli et al., 2013). The large proportion of HMS delivered in Gilbert's estimate, coupled with the importance of these processes to fundamental geomorphic theories of SDRs and longitudinal connectivity, calls for a validation of Gilbert's (1917) budget with modern measurement methods. This study recomputes HMS production in seven mine pits formerly measured by Gilbert and examines the feasibility of making accurate measurements of HMS production and storage to compute budgets and delivery ratios in one test catchment. Ultimately, budgets should be constructed for catchments effected by mining throughout the region and recalculations of sediment production, storage, and transport should be conducted for a comprehensive test of delivery ratios and connectivity in the Sierra Nevada.

5. Results

5.1. Validation of sediment production measurements

Validations of volumetric results are limited to mine pits where HMS production reference data are available. As a preliminary test of mine pit interpolation methods, volumes of seven hydraulic mine pits that had been surveyed by Gilbert (1917) were recomputed by interpolating reconstructed and LiDAR-derived contours. Mine-pit volumes computed for this study are comparable with Gilbert's (1917) volumes with differences ranging from $-793,000$ to $4,001,000 \text{ m}^3$ (-23% to $+23\%$) and an average difference of -2.2% (Fig. 7). This suggests that—on average—the volumes computed by this study are comparable to Gilbert's volumes measured ca. 1908. The largest difference was at the Omega Mine where this study measured a volume much greater than Gilbert's measurement. At least 2 million m^3 of sediment were mined under licensing arrangements after Gilbert's survey (James, 2005) and this

may explain approximately half of the discrepancy. The general agreement between volumes indicate that the LiDAR-contour method of measuring mine-pit volumes is valid for extension to volumetric estimates of mine pits that have not previously been measured. Although no independent data exist to test valley fill measurements, the region is ideally suited for the use of high-resolution LiDAR topographic data and geomorphometry to map and compute volumes of mines and HMS deposits accurately.

5.2. Sediment budget for Steephollow canyon

Volumes of HMS produced and stored in Steephollow Creek were measured for the area covered by LiDAR data; i.e., from the Wilcox Ravine confluence area upstream. The southeast and central You Bet Mines produced approximately $21.3 \times 10^6 \text{ m}^3$ or 90.6% of the HMS produced in the catchment (Table 1). The You Bet Mines are the largest in the Steephollow study area with the maximum thickness of HMS removed reaching as much as 63 m (Fig. 8). Most of the $5.1 \times 10^6 \text{ m}^3$ of HMS produced by the Christmas Hill Mine was delivered to the main channel of the Bear River to the east. Some HMS was delivered to Steephollow Creek through tunnels, however, and this was estimated to be 20% of the HMS produced by the mine. Thus, approximately $1.0 \times 10^6 \text{ m}^3$ of the HMS produced by the Christmas Hill mine is estimated to have been delivered to Steephollow Creek. Five smaller mines upstream in Steephollow Creek produced at total of $1.2 \times 10^6 \text{ m}^3$ or 5.1% of the HMS produced in the catchment (Table 1). Collectively, the mines in Steephollow Creek above Wilcox Ravine delivered approximately $23.5 \times 10^6 \text{ m}^3$, which represents 8.7% of Gilbert's (1917) estimated $271 \times 10^6 \text{ m}^3$ of HMS produced in the Bear River Basin. This volume does not include mines in the lower Steephollow basin below Steephollow Crossing.

Volumes of HMS stored in valley bottoms of the catchment in 2014—as computed by Eq. (2)—were a total $3.75 \times 10^6 \text{ m}^3$ which is 15.9% of the sediment produced in the catchment (Table 2). Most (61%) of the HMS storage is contained in the main tailings fan below Wilcox Ravine and most of the remaining HMS storage occurs in the main channel within 1.5 km upstream of the Wilcox Ravine confluence (Fig. 9A & B). The three other storage areas (Swamp Angel Dam, the upper main channel, and Wilcox Ravine) hold approximately $0.15 \times 10^6 \text{ m}^3$ of HMS each or ~4% of the catchment storage at each site. The volume of HMS stored in valley bottoms of the catchment at the time of maximum aggradation (ca. 1884)—as computed by Eq. (3)—totaled $7.15 \times 10^6 \text{ m}^3$, which was almost twice the volume stored in 2014 (Table 2). This volume represents 30.4% of the sediment produced in the catchment. The maximum thicknesses of HMS in 1884 was >60 m under the Wilcox Ravine fan,

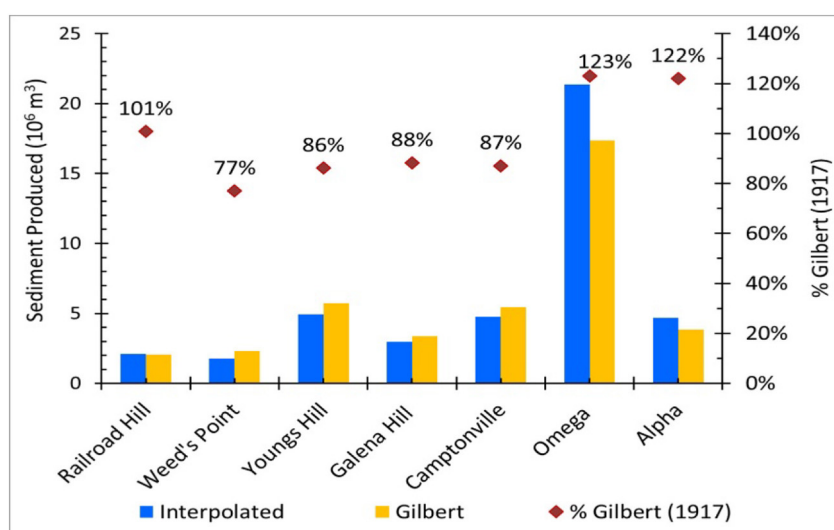


Fig. 7. Comparisons of hydraulic mine pit volumes. Volumes measured by Gilbert (1917) using field surveys are similar to volumes from this study using geospatial analysis to interpolate 5-m contours with LiDAR data.

which is in accordance with a contemporary estimate of 60 m (Whitney, 1880; James, 2004). The spatial pattern in 1884 was dominated by storage in the main fan and middle channel areas, but a higher proportion was stored in Wilcox Ravine and the upper channel than in 2014 (Fig. 9C & D). Erosion of $3.57 \times 10^6 \text{ m}^3$ of HMS between 1884 and 2014 was half of the initial deposit. Erosion was particularly high in the upper channel and the steep Wilcox Ravine, where most of the HMS was removed, leaving only small remnant terraces and armored bed material.

Valley-spur cutoffs, where aggraded channels are superposed onto bedrock at the inside bends of valley meanders, have been recognized as a mechanism that can create narrow gorges (James, 2004). The cutoff spur at Wilcox Ravine tailings fan is well known and was anticipated by F.C. Turner (1891), a contemporary sedimentation engineer. These gorges disrupt longitudinal connectivity and encourage long-term storage of HMS. The DoD processing of sediment thicknesses by this study records such features as areas of negative HMS thickness where the channel cut into bedrock. Although the negative values are removed from volumetric computations, they can indicate channel realignments and HMS repositories. In the Steephollow catchment, a previously unknown cutoff spur was discovered by this process (Fig. 10). During the incision phase of the post-mining period, the channel crossed over and incised into the buried ridge on the inside of a bend. Incision into bedrock locked the channel in this position and a large reservoir of

HMS stored in the former channel around the outside of the meander bend is now decoupled from the new channel. These cutoff spurs restrict vertical and lateral erosion of the channel and lower connectivity.

Volumes of HMS currently stored behind debris control dams are a relatively small proportion of the sediment produced and stored in the respective basins. The volumes held behind Willow Creek and Horse Valley Creek debris control dams were 0.37 and $0.11 \times 10^6 \text{ m}^3$, respectively. This volume represents only a small proportion of the overall HMS produced upstream. For example, Youngs Hill, one of three hydraulic mines above the Horse Valley Creek debris control dam, produced $\sim 4.94 \times 10^6 \text{ m}^3$, so the sediment held behind the dam represents only 2.3% of the sediment generated by this mine alone. Storage of $0.16 \times 10^6 \text{ m}^3$ of HMS behind the Swamp Angel Dam in the Steephollow catchment (Fig. 11) represents only 0.68% of HMS produced in the catchment and only 4.4% of the HMS stored in the catchment in 2014.

6. Discussion

This study benefits from a relatively well-controlled environmental experiment. An extreme volume of $1.1 \times 10^9 \text{ m}^3$ of HMS was produced in the region within 31 years (1853–1884) with a rapid acceleration of production after 1853 and an abrupt cessation in 1884. The episode represents an average denudation of 43.0 cm over the upper Steephollow catchment or 1.39 cm/yr for 31 years. Although licensed mining proceeded from 1893 to ca. 1950, only a small proportion (~2%) of the total HMS volume was produced after 1884. This relatively well-defined mega-pulse of HMS provides an excellent opportunity to study the dynamics of sediment transport behavior at a centennial time scale. The sediment budget for Steephollow Catchment reveals long-term sediment connectivity processes and potential strategies for manipulating connectivity to control sediment behavior.

6.1. Longitudinal connectivity and sediment delivery ratios

The transport, storage, and remobilization of episodically produced sediment in this region involves local connectivity between hillslopes and the adjoining valleys as well as regional connectivity between the mountains and relatively flat valleys 30 to 50 km below. At the local scale, 30% of the HMS produced was stored in the catchment in 1884, which was reduced by channel erosion to 16% stored by 2014. Both of these volumes support the hypothesis that local storage of HMS is larger than the average regional storage of 12% estimated by Gilbert (1917) for

Table 1
Mine pit volumes $\text{DoD}_{\text{mine}} = \text{DEM}_{\text{PM}} - \text{DEM}_{2014}$ (Eq. (1)).

Mine	Volume produced $\text{m}^3 \times 10^6$	Volume to Steephollow (%)	Volume to Steephollow $\text{m}^3 \times 10^6$	Steephollow production (%)
Xmas Hill	5.10	20	1.02	4.33%
Xmas Hill North	0.35	100	0.35	1.47%
Xmas NSW	0.17	0	0.00	0.00%
Remington Hill	0.31	100	0.31	1.31%
N. Steephollow	0.11	100	0.11	0.46%
Melburn Hill	0.43	100	0.43	1.85%
Subtotal	6.47		2.22	9.42%
You Bet Mines				
Southeast	6.13	100	6.13	26.05%
Central	15.18	100	15.18	64.53%
North	12.39	0	0	0
Subtotal	33.70		21.31	90.58%
Grand total	40.17		23.53	100.0%

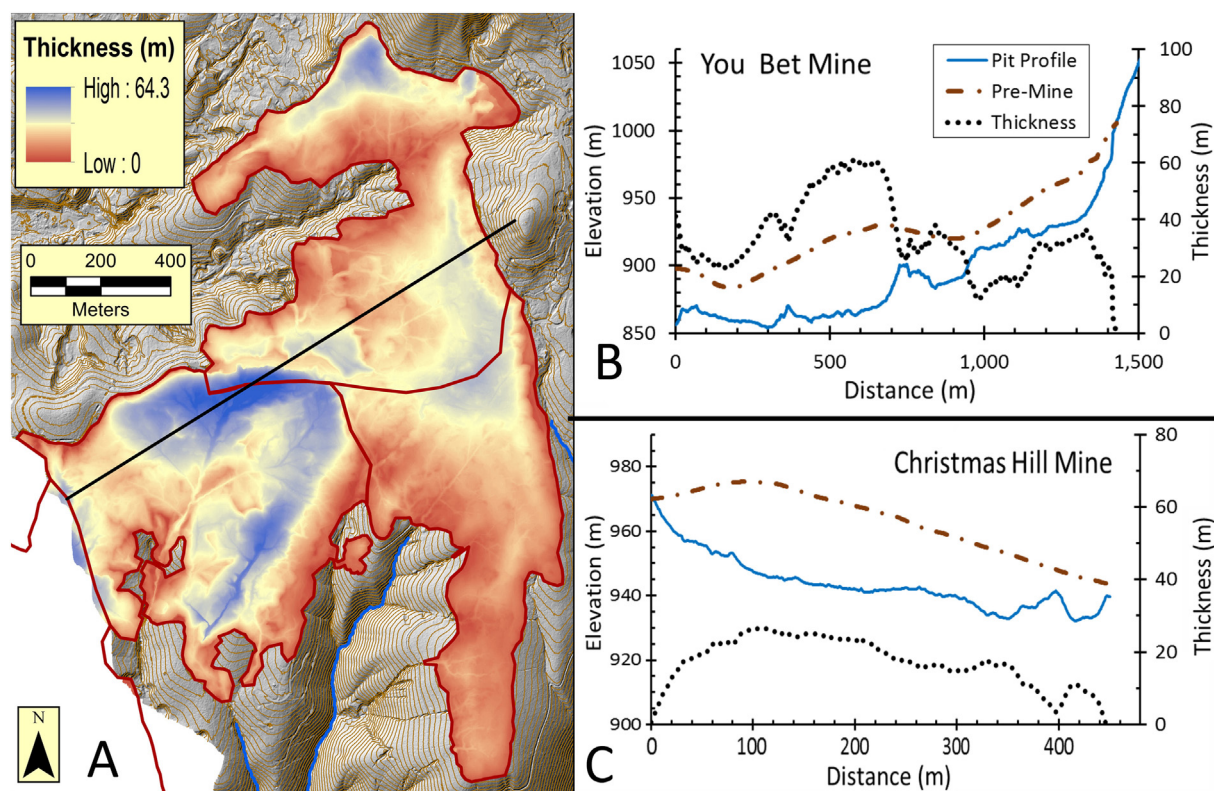


Fig. 8. Hydraulic mines. (A) Thickness of HMS removed from You Bet Mines with 5-m contours of the 2014 surface outside the mines. Straight line is section shown in B. (B) Vertical section across You Bet Mines. (C) Vertical section across Christmas Hill Mine.

the mountains of the Feather River basin, which includes both the Yuba and Bear basins. The stored proportion would be much larger if the entire Steepollow catchment was included. A large volume of HMS is

Table 2
Sediment storage.

	Volume $\text{m}^3 \times 10^6$	Proportion 1884 Local storage (%)	Proportion 2014 Local storage (%)	Proportion Production (%)	SDR (%)
HMS stored 2014	$\text{DoD}_{2014} = \text{DEM}_{2014} - \text{DEM}_{\text{PM}}$ (Eq. (2))				
Swamp	0.164	NA	4.38	0.07	
Angel Dam					
Upper	0.134	1.87	3.58	0.57	
Middle	1.014	14.18	27.07	4.31	
Main Fan	2.282	31.91	60.92	9.70	
Wilcox	0.152	2.13	4.06	0.65	
Ravine					
Total	3.746	50.1	100.0	15.92	84.08
HMS storage ca. 1884	$\text{DoD}_{\text{MAX}} = \text{DEM}_{\text{MAX}} - \text{DEM}_{\text{PM}}$ (Eq. (3))				
Upper	0.459	6.42		1.95	
Middle	1.776	24.84		7.55	
Main Fan	3.746	52.38		15.92	
Wilcox Ravine	1.170	16.35		4.97	
Total stored in 1884:	7.151	100.0		30.39	69.61
HMS eroded since 1884	$\text{DoD}_E = \text{DEM}_{\text{MAX}} - \text{DEM}_{2014}$ (Eq. (4))				
Upper	0.325				
Middle	0.762				
Main Fan	1.464				
Wilcox Ravine	1.018				
Total Eroded by 2014	3.569				

stored along Steepollow Creek in the 2.5 km below the study area to the confluence with the Bear River. This area includes high terraces of HMS and a major tailings fan in Birdseye Canyon that are beyond the extent of available LiDAR data and were not included in the sediment budgets.

At the regional scale, longitudinal sediment connectivity can be expressed in terms of sediment delivery ratios (SDR). The HMS that left the catchment and was not stored locally gives SDRs of 69.6% and 84.1% in 1884 and 2014, respectively. The hypothesis that SDRs were less than the regional 88% estimated by Gilbert is supported by this analysis, which documents more sediment storage in the mountainous Steepollow Catchment than would be predicted from previous regional estimates. Nevertheless, these SDR values are high relative to many North American studies (Novotny and Chester, 1989), due to strong connectivity between the Sierra mountains and the Sacramento valley. Vast deposits of HMS in the Sacramento Valley 50 km downstream of the mines and transport of HMS through San Francisco Bay have shown this high longitudinal connectivity since Gilbert's (1917) work. In the main tributaries of the Yuba and American Rivers, the ridgetop mines fed HMS into deep narrow canyons where flows with high stream powers quickly carried the sediment to the Sacramento Valley (James, 2006). In smaller tributaries, such as Steepollow Creek however, the sediment transport capacity of channels could be overwhelmed, resulting in a moderate component of the HMS being stored locally. The high SDRs in 1884 and 2014 are in keeping with broader studies that include data from mountainous regions (Einsele and Hinderer, 1997; de Vente et al., 2007; Diodato and Grauso, 2009). In mountainous areas, SDRs and connectivity are related to slope (Cavalli et al., 2013), topographic relief, and related morphological features such as narrow valley bottoms. Topographic controls in the Steepollow catchment involved superpositioning of the aggraded channel onto a bedrock ridge that resulted in a bedrock gorge that isolated much of the Wilcox Ravine tailings fan from the channel (James, 2004). Consequently, connectivity between

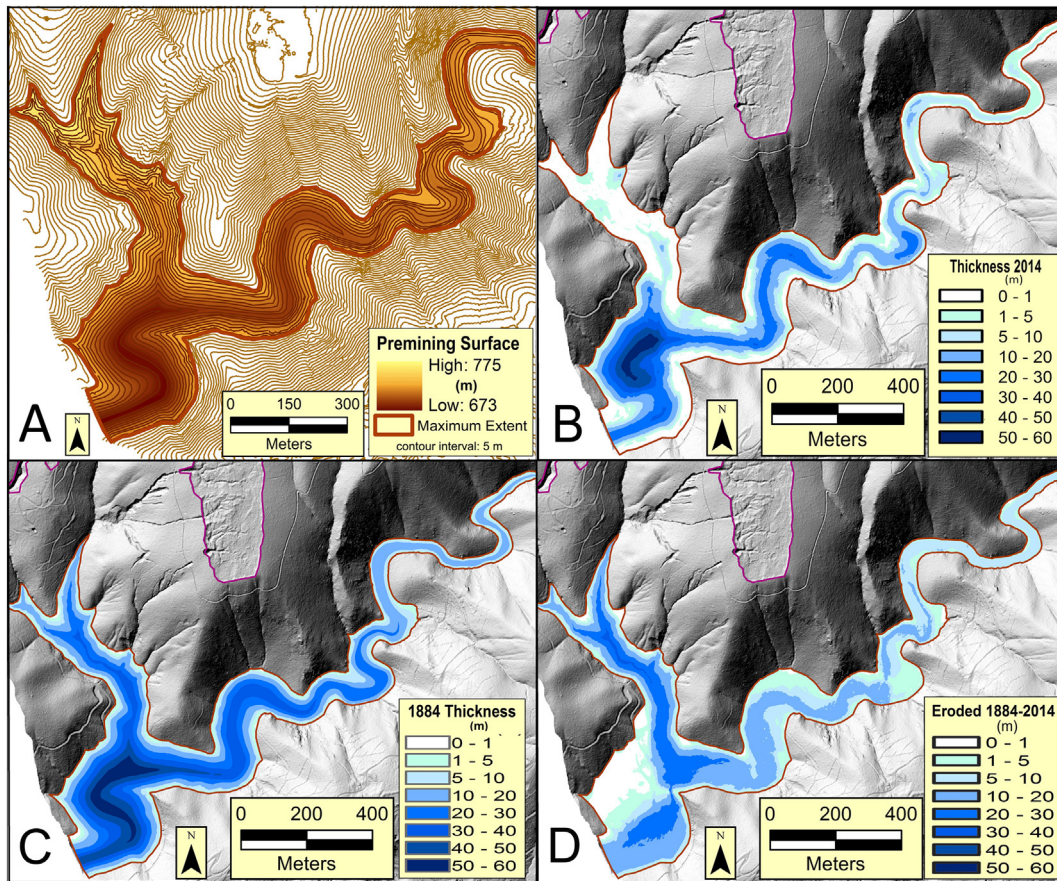


Fig. 9. Geospatial processing of Steephollow Creek near Wilcox Ravine. (A) 5-m contours for the pre-mining surface were reconstructed and used to compute the DEM_{PM}. The 5-m contours on upper slopes outside of the terrace contacts (bold line) are from the modern LiDAR DEM₂₀₁₄. (B) Thicknesses of HMS in 2014 were computed by subtracting DEM_{PM} from the modern LiDAR DEM₂₀₁₄. (C) The 1-m contours of the penultimate maximum aggraded HMS surface, ca. 1884, were interpolated to construct DEM_{MAX}. The surface of the Wilcox Ravine tailings fan sloped up Steephollow Creek above Wilcox Ravine in 1884. (D) Thicknesses of HMS eroded between 1884 and 2014 were obtained by subtracting DEM₂₀₁₄ from DEM_{MAX}.

the channel and the largest HMS deposits is limited and erosion of the HMS now proceeds primarily by gully and mass wasting of terrace and fan scarps and slow channel-bed incision governed by a knickpoint at the gorge. The increase in SDR for the catchment from 70% in 1884 to 84% in

2014 documents the dynamic nature of longitudinal connectivity between the mines and downstream areas. Connectivity slowed through time with the removal and armoring of available sediment, but long-term erosion resulted in an increase in the SDR through time.

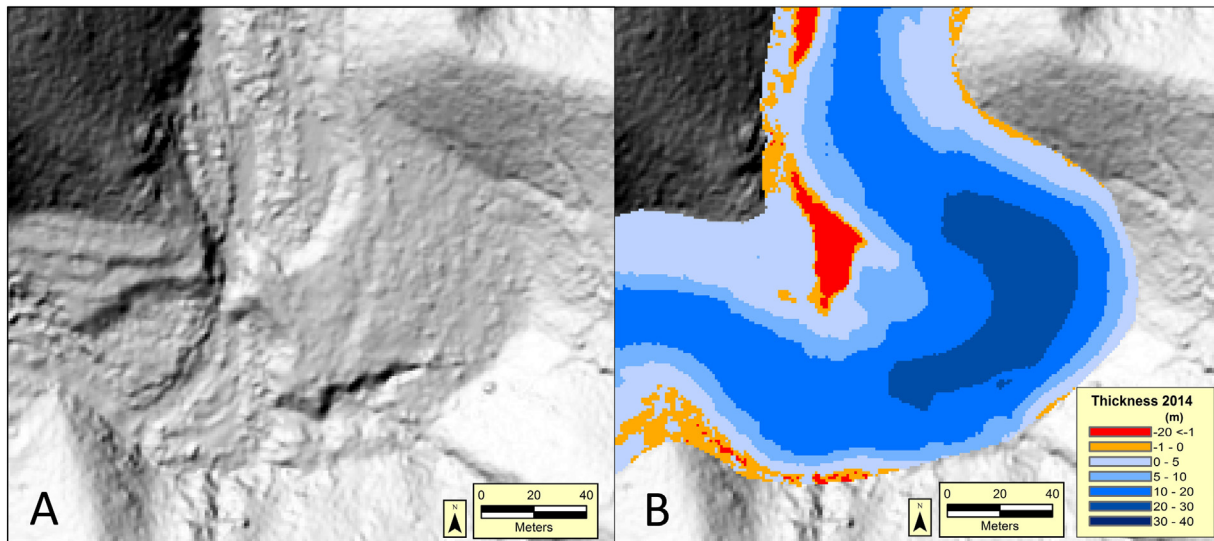


Fig. 10. Previously unrecognized cutoff spur in Steephollow Creek ~1.1 km upstream from the well-known Steephollow Crossing gorge. (A) LiDAR shaded relief map showing a high terrace of HMS filling the outer bend and a shallow gorge cutting north-south at the west valley margin. (B) HMS thickness map of the site with negative values (highlighted) at the gorge and deep channel fill in the bend.

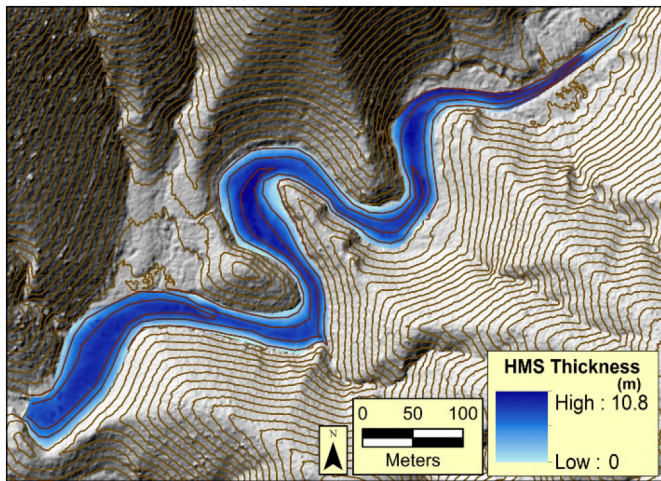


Fig. 11. Thickness of HMS deposits stored behind Swamp Angel debris-control dam. Total volume stored is $0.16 \times 10^6 \text{ m}^3$ or 4.4% of HMS stored in the catchment in 2014.

6.2. Connectivity as a management strategy in the Yuba and Bear River basins

A coordinated and explicit policy is needed to identify and stabilize stored HMS. Identification of sources of Hg-contaminated sediment from mine pits, terraces, debris control dams, and tunnels is a critical component to the management of Hg exposure to humans and wildlife in the Sierra Nevada and downstream. The State Water Resources Control Board and nine Regional Water Quality Control Boards are developing a Hg-control program for sources to reservoirs, specifically mines. Extending the methods used in this study from catchment to broader scales encompassing the entire Yuba and Bear River basins will help to prioritize remedial activities. This study reveals the magnitude of HMS storage in terrace, fan, and channel-fill deposits. Although debris control dams represent well-known locations of HMS storage with Hg contamination, they contain a relatively small proportion of the HMS compared to other less well-documented HMS storage sites. The integrity of the dams and removal of Hg-contaminated sediment from these sites should be considered as a management strategy, but the primary source of HMS is storage in terraces, tailings fans, and channel beds. Given the large magnitude of HMS storage, strategies relying entirely upon removal or treatment of the HMS will be extremely expensive. Stabilization of deposits should be a key component of a management strategy and can be considered from the perspective of managing longitudinal, lateral, and vertical connectivity. Approximately half of the initial HMS deposit in the Stepphollow Catchment eroded in the 130 years from 1884 to 2014. Initial erosion rates were likely rapid and decreased through time as early accounts describe rapid incision (Turner, 1891).

Sediment connectivity can be manipulated to minimize future releases of HMS. To a large extent, lateral and vertical connectivity by fluvial processes decreases through time as channels incise into bedrock or become armored. This process of passive stabilization tends to isolate large volumes of sediment in terrace and fan deposits above active flows or beneath armored beds. As channel incision and armoring isolate the sediment, moderate-magnitude floods become less effective at entraining sediment. However, lateral connectivity of fan and terrace scarps continues slowly by mass wasting and fluvial processes acting directly on these surfaces. Ongoing gullying of the Wilcox fan and erosion of other deposits maintain long-term lateral connectivity and sediment production. The potential toxicity of HMS is such that slow erosion and release should be curtailed. Lateral connectivity can be reduced by stabilizing terrace and fan scarps to minimize erosion and sediment production by lateral channel migration, rilling, gullying, or mass wasting. Longitudinal connectivity between mines and channels can be

disrupted by sealing tunnels to reduce sediment discharges, stabilizing eroding mine pit scarps, and rerouting drainage around contaminated mine pits. Not all tunnels are known, but many can be detected on the LiDAR data (Fig. 2). Longitudinal and vertical connectivity in channels can be reduced by preventing further downvalley sediment transport or incision of main channels. Normally, river-channel management should encourage natural processes such as channel lateral migration and vertical adjustments. The need to stabilize HMS deposits, however, calls for a degree of engineering aimed at preventing bed incision and sediment transport. Existing choke points at bedrock gorges can be exploited with armor or dams to arrest erosion and transport, but the first step in mitigation efforts is the development of spatially distributed sediment budgets at the catchment scale to identify and map HMS volumes and connectivity.

7. Conclusion

Geospatial methods of mapping past and modern morphological features can produce spatially distributed sediment budgets. Although data on known volumes to validate these measurements are limited, high-resolution airborne LiDAR data combined with geomorphometric methods appear to produce accurate sediment budgets for HMS at the local to catchment scale. Local budgets do not exist at present and the methods outlined in this study could be applied widely across the northwestern Sierra Nevada where numerous mine pits and HMS deposits have not been mapped or measured. Topographic surfaces were constructed with $1 \times 1\text{-m}$ DEMs at three times. The modern surface (2014) is mapped by 1-m airborne LiDAR. Pre-mining topography at mine pits and buried valley bottoms were modeled by extending hill-side contours, and topographic surfaces at the time of maximum aggradation (ca. 1884) were derived by extending contours from historical terrace treads. DEMs constructed for the three times were used to map and compute volumes of HMS in 1884 and 2014 and to develop distributed sediment budgets that reveal catchment-scale processes over the past 160 years including locations of sediment production, storage, and subsequent erosion. Much of the HMS sediment was initially stored locally and continues to be reworked. The Swamp Angel debris control dam is full of sediment but only holds 4.4% of the HMS in the catchment. Most of the sediment within the study area is stored in fans and terraces in or near the Wilcox Ravine tailings fan. Reworking between 1884 and 2014 occurred preferentially in steep tributaries but the fan deposit, which is largely protected from main channels by bedrock structures, continues to slowly erode by mass wasting and gullying.

The fixed period of HMS production, which was terminated in 1884, enables evaluation of long-term sedimentation dynamics. The substantial decrease in storage by erosion of $3.5 \times 10^6 \text{ m}^3$ of HMS from Stepphollow Creek after 1884 represents an increase in the delivery of the HMS downstream over this period. This increase in SDR demonstrates the importance of time to measures of sediment connectivity following large episodic events. If sediment delivery is computed over a short period following an event, the proportion delivered may be much less than if measured over longer periods of time. These dynamics are complicated by changes in rates of sediment remobilization that likely decrease through time. Tailings fans and terraces are relicts of former historical aggradation processes and can become decoupled from on-going fluvial processes by channel incision into bedrock or armoring. Thus, sediment connectivity not only governs the initial sensitivity of systems to anthropogenic changes, but also can rapidly evolve following anthropogenic changes.

Given the large volumes of HMS documented by this study and the likely contamination of the deposits by Hg, stabilization of the HMS deposits in situ is needed. Sediment connectivity can be manipulated as a sediment management tool and remediation strategy. Lateral connectivity of HMS terraces and fans can be disrupted by isolating or armoring terrace scarps and fans to prevent erosion, whereas longitudinal and vertical connectivity can be disrupted to arrest down-valley transport

by sealing tunnels, remediating mine pits, removing sediment from deposits, or stabilizing eroding gorges, terraces, or fans. Incision into gorges through cutoff spurs decreased longitudinal sediment connectivity and this can be manipulated by armoring or damming gorges to discourage down-valley transport from the mining districts.

Acknowledgements

The U.S. Forest Service, Tahoe National Forest, provided LiDAR bare-earth topographic data to make this research possible. The Sierra Fund, dedicated to understanding the impacts of the California Gold Rush and restoring ecosystem resiliency, provided staff time and field assistance to this project. Chen-Ling Hung provided helpful GIS advice. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi: <https://doi.org/10.1016/j.scitotenv.2018.09.358>. These data include the Google map of the most important areas described in this article.

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