Corrections

SUSTAINABILITY SCIENCE


The authors note that Table 1 appeared incorrectly. The corrected table appears below. Additionally, the authors note that on page 20886, left column, first paragraph, lines 2–4, “In 2000, about 50% of the N surplus (138 Tg) was lost through denitrisation (67 Tg) (Table 1)” should instead appear as “In 2000, about 50% of the N surplus (138 Tg) was lost through denitrisation (67 Tg including N₂O and NO emissions) (Table 1).” Both the online article and the print article have been corrected.

Table 1. Global input terms (fertilizer, manure excluding NH₃ emission from animal houses and storage systems, biological N₂ fixation, and atmospheric N deposition), soil budget (total, arable land, and grassland) and the various loss terms for N [NH₃ volatilization, denitrification (excluding N₂O and NO), and N₂O and NO emission], nitrate leaching and runoff, and P runoff for 1900, 1950, 2000, and 2050 for the baseline and five variants.

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*IAASTD projection serves as the base; EX, 10% of the production in mixed systems is moved to pastoral systems; FE, 10% lower excretion rates in mixed and industrial systems; ST, 20% reduced emissions from animal houses and ST systems; IM, recycling of animal manure that is used as fuel or building material or is unused manure in the baseline and with better integration of animal manure in mixed systems in countries where manure contributes less than 25% total N or P inputs in crop production; DI, as in IAASTD projection but with 10% of ruminant meat production replaced by poultry meat.

†Excluding manure that is not recycled in the agricultural system, such as manure stored in lagoons or manure used as fuel.

‡Excluding NH₃ emission from animal houses and storage systems, which is presented separately.

§N₂O emissions include direct emissions and indirect emissions from leached N and atmospheric N deposition.

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ENVIRONMENTAL SCIENCES


The authors note that on page 18440, left column, second full paragraph, line 8 “Hg mass (~200 kg)” should instead appear as “Hg mass (~200 t).”

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Enduring legacy of a toxic fan via episodic redistribution of California gold mining debris

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The interrelationships between hydrologically driven evolution of legacy landscapes downstream of major mining districts and the contamination of lowland ecosystems are poorly understood over centennial time scales. Here, we demonstrate within piedmont valleys of California’s Sierra Nevada, through new and historical data supported by modeling, that anthropogenic fans produced by 19th century gold mining comprise an episodically persistent source of sediment-adsorbed Hg to lowlands. Within the enormous, iconic Yuba Fan, we highlight (i) an apparent shift in the relative processes of fan evolution from gradual vertical channel entrenchment to punctuated lateral erosion of fan terraces, thus enabling entrainment of large volumes of Hg-laden sediment during individual floods, and (ii) systematic intrafan redistribution and downstream progradation of fan sediment into the Central Valley, triggered by terrace erosion during increasingly long, 10-y flood events. Each major flood apparently erodes stored sediment and delivers to sensitive lowlands the equivalent of ~10–30% of the entire postmining Sierran Hg mass so far conveyed to the San Francisco Bay-Delta (SFBD). This process of protracted but episodic erosion of legacy sediment and associated Hg is likely to persist for >10 y. It creates, within an immense swath of river corridor up to 10-fold higher than geographical "hot spots" of atmospheric Hg deposition. These immense mining sediment slugs choked Sierra rivers, which aggraded tens of meters in confined piedmont valleys, and formed anthropogenic fans grading to the margins of the Central Valley, including the ~252 × 10⁶ m³ Yuba Fan (10) (Fig. 1 A and B). Since that time, sediment-bound Hg has contaminated fish and waterfowl of the San Francisco Bay-Delta (SFBD) (13, 14). However, the dominant modern geographical sources of Hg, as well as the processes, patterns, and time scale of its delivery to this downstream ecosystem, are debated (15–17), partly due to the lack of a generic understanding of postmining fan evolution. It is unclear whether there are modern sources of Hg to this system and by what set of physical and biogeochemical processes Hg may penetrate these sensitive ecosystems. The legacy impacts of historical mining are therefore not fully comprehended, in part, because of incomplete knowledge of the magnitude and frequency of processes contributing to fan evolution and sediment exhaustion.

Following cessation of hydraulic mining, Sierra valley aggradation was succeeded by vertical channel incision into piedmont fans, producing historical terraces along channels (10). James (18) demonstrated that ~90% of the original sediment deposit delivered to the Bear River valley (Fig. L1) remained in terrace storage >100 y after mining and hypothesized that modern floods are capable of transporting it downstream. Apart from Gilbert’s classic work on bed-level change (10), generalizable theory for flood-based evolution of anthropogenic fans is absent, especially over the critical management time scale of decades to centuries in this and other fluvial systems (5, 6). This precludes predictions of mining sediment exhaustion time scales and the downstream risks of heavy metal contamination to food webs.

To fill this research gap, we analyzed high-resolution historical topographical and bathymetric data collected in 1906 and 1999, and interpreted them here within the context of: historical US Geological Survey (USGS) streamflow (Q) measurements and

Hg poses contamination risks to food webs globally (1, 2), particularly where sediment-bound Hg is delivered to topographically low, depositional environments with high methylation potential. Sediment is the vehicle for ~97% of transition metal mass loading to oceans (3), and the geomorphic configuration of stored contaminated sediment on land has important implications for its subsequent remineralization (4) and delivery to the base of food webs. Sediment displaced by industrial mines is typically contaminated by toxic metals such as Hg (5–7), which threaten lowland ecosystems downstream of mining sites around the world (e.g., refs. 6–9). This contaminated sediment often infills confined river valleys (10) as massive anthropogenic fans, similar to natural alluvial fans, which undergo subsequent incision once the supply of mining sediment is stopped. Such fans are likely to increase in ubiquity and scale across the globe as demand increases for mined metals and rare earth elements.

Nineteenth century hydraulic gold mining in California’s Sierra Nevada foothills (1853–1884) contemporaneously delivered ~1.1 km³ of Hg-contaminated sediment (10, 11) to downstream valleys at concentrations >10-fold higher than geographical “hot spots” of atmospheric Hg deposition (12). These immense mining sediment slugs choked Sierra rivers, which aggraded tens of meters in confined piedmont valleys, and formed anthropogenic fans grading to the margins of the Central Valley, including the ~252 × 10⁶ m³ Yuba Fan (10) (Fig. 1 A and B). Since that time, sediment-bound Hg has contaminated fish and waterfowl of the San Francisco Bay-Delta (SFBD) (13, 14). However, the dominant modern geographical sources of Hg, as well as the processes, patterns, and time scale of its delivery to this downstream ecosystem, are debated (15–17), partly due to the lack of a generic understanding of postmining fan evolution. It is unclear whether there are modern sources of Hg to this system and by what set of physical and biogeochemical processes Hg may penetrate these sensitive ecosystems. The legacy impacts of historical mining are therefore not fully comprehended, in part, because of incomplete knowledge of the magnitude and frequency of processes contributing to fan evolution and sediment exhaustion.

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**Significance**

This paper is of fundamental interest to the millions of residents living at the downstream end of this and other global river basins beset by industrial metals mining. Sediment-bound Hg has contaminated food webs of the San Francisco Bay-Delta, but the dominant geographical sources of Hg to downstream ecosystems in this and similar river basins are debated. Likewise, the processes by which Hg is delivered to lowlands and the patterns of its floodplain deposition are poorly understood. This research addresses a gap in generic theory of postmining fan evolution that enables anticipation, prediction, and management of contamination risk to food webs.


The authors declare no conflict of interest.

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fluctuation frequency; National Aeronautics and Space Administration flood imagery; and our newly developed geochemical dataset that includes total Hg concentration (HgT), Zr/Ni, and $^{137}$Cs, supported by physically based mathematical modeling of terrace erosion and flux of mining sediment during large floods (SI Methods).

**Results and Discussion**

Terrestrial/bathymetric topographical data, collected in 1906 and 1999, reveal that the Yuba River longitudinal profile has incised systematically over the entire fan in the past century, manifesting as substantial valley-floor lowering (i.e., erosion of the channel and adjacent floodplains) and terrace erosion in the upper fan and as vertical channel incision with modest (<1 m) floodplain aggradation in the lower fan (Fig. 1C). The riverbed level of the middle fan ("Yuba Gold Fields") has been affected by the presence of Daguerre Point and Barrier Dams, built to trap mining sediment. Barrier Dam was destroyed by a large flood in 1907 (10), resulting in a marked adjustment of the thalweg long profile (Fig. 1C). The reservoir behind Daguerre Point Dam (built in 1910) remains completely full of Hg-laden sediment (19), so it suppresses vertical incision within the Yuba Gold Fields and has negligible sediment trap efficiency during floods. Nevertheless, the overall centennial pattern of change appears to be systematic incision and redistribution of sediment from the

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**Fig. 1.** Yuba Fan. (A) HgT sediment sampling locations (red circles). The longitudinal transect along which mining sediment travels from the Sierra to the SFBD is shown in yellow. Sample sites A–F are described in the main text. Base: Shuttle Radar Topography Mission (SRTM) 1 arc-second. Yuba Fan delineation and hypothesized patterns of sediment redistribution and export (B) and longitudinal elevation profiles of the Yuba River channel bed, 1906 and 1999 (C). (Insets) Plots show cross-sectional change at sites A and B. *Fan incision rates for the early (10) and late 20th century are based on trends in water surface elevation. Supporting methodological description and data on slowing incision are provided in SI Methods and Table S1. ASL, above sea level.
narrow upper Yuba Fan to the relatively wide lower Yuba Fan (note floodplain deposition in the lower fan, Fig. 1C) and net fan export (Fig. 1B). Streamflow measurements at USGS gauges (SI Methods), corroborated by repeat cross-section surveys (20) and our own field observations of bed grain size, indicate that the average incision rate has slowed considerably in recent decades (Fig. 1C and Table S1), as coarse-grained premining riverbeds were reexcavated in the upper fan and a single-thread channel was reestablished in the lower fan (21). We hypothesize that once vertical incision retards, fan evacuation proceeds predominantly as lateral erosion of historical terraces by competent high flows (22).

Longitudinal patterns of sediment redistribution by floods are expressed in chemostratigraphy and measured by 176 values of HgT in the <63-μm fraction of sediment at 105 locations along the Yuba, Feather, and Bear Rivers (Fig. 1A, SI Methods, and Dataset S1). HgT values in the Sierra are naturally low [nonmining sediment contains HgT ≤ 0.08 μg/g (15), and Hg ore was mined and roasted in the Coast Ranges to produce elemental Hg that was transported to the Sierra for use in gold mining (11)]. Therefore, HgT in Sierra alluvium is a discriminating tracer of mining activity (15). Our HgT data range over two orders of magnitude, and thus easily distinguish stratigraphic units containing historical sediment from gold mines [regional characterization of pre- v. postmining sediment is provided by Bouse et al. (15)], constrained by documented channel change (21).

Some important generalizations emerge:

i) Contact between pre- and postmining sediment layers consists of at least an order-of-magnitude increase in HgT in the anthropogenic sediment (Fig. 2B–D). Furthermore, upper stratigraphic sections from relatively recent floods typically contain lower values of HgT (0.18 μg/g or greater than threefold average background values) compared with underlying historical layers (Fig. 2B and Dataset S1), which apparently reflects Hg dilution through the mixing of mining and nonmining sediment, as observed in other fluvial systems (5, 6).

ii) Deposits that were recently reworked by channel incision/migration have lower HgT than those that were not (compare Fig. 2B and E vs. C and D), because incision/migration dilutes HgT by incorporating premining sediment from upstream sources. Consequently, modern channel bed/bar sediment is generally lower in HgT than fine fractions of floodplain sediment deposited during fan emplacement.

iii) Large stores of undiluted mining sediment in historical terraces of the upper fan contain high HgT (>1 μg/g) and are susceptible to flood-based erosion (Fig. 2A).

iv) Great masses of sediment from various parts of Yuba Fan travel into the Central Valley during floods, as observed in bank sections along the Feather River and in large splay deposits in lowland floodplains (Fig. 2E and F, respectively), which corroborates historical suspended sediment records (23) and remote sensing imagery (24). For example, our measurements showed that the 1986 flood (25) delivered to a lowland floodway a discrete sediment deposit of 2.5 × 10^6 m³ with HgT = 0.18 μg/g, equivalent to the uppermost deposits shown in Fig. 2B and E.

Recent deposit ages identified in the chemostratigraphy are supported by our own radionuclide measurements that characterize whether upper sediment layers were stable before or after bomb testing in the 1960s, which delivered meteoric fallout of 137Cs and therefore provides a marker horizon that can be used to date fluvial sediment deposits (26). For example, the uppermost surface (Fig. 2A) contains 137Cs = 13.7 mBq/g, indicating its longer term persistence. Lower inset terrace surfaces (Fig. 2A) and upper sediment layers (Fig. 2B and F) contain 0 mBq/g.

Fig. 2. Characteristic sampling sites and geochemical data arranged in downstream order. Red circles indicate approximate HgT sampling locations within the chemostratigraphy. White circles indicate approximate 137Cs sample locations from surface sediments. (A, C, and D) Intact mining sediment from the original mining period. (B, E, and F) Upper layers of reworked mining sediment mixed with background (nonmining) sediment. F is adapted from Singer et al. (25). E and F represent lowland sites downstream of the Yuba Fan along the Feather River (Fig. 1A).
indicating surfaces that have been recently eroded or that have been completely mixed (Fig. 2 B and F) in the past several decades.

The magnitude of major flood peaks has apparently not changed in recent decades, but these floods are longer in duration on rising and falling limbs (Fig. 3A), leading to higher potential for erosion of banks and terraces (27). Bankfull or terrace-saturating Yuba floods capable of mobilizing sediment from terraces and banks occurred approximately once per decade in the recent past (1986, 1997, and 2006; Fig. 3B). To assess the impact of such floods on the erosion of toxic terrace material in the upper fan and the subsequent partitioning of the eroded materials into bed load or suspended sediment load, we coupled a physically based model of terrace erosion with iterative calculations of bed material sediment flux and bed grain size evolution. Although numerous approximations were made (SI Methods), our modeling suggests that all recent major flood events induced terrace erosion and produced a subsequent pulse of fine-grained sediment downstream (Fig. 4A), whereas smaller flows (Q < 2,000 m³/s) did not. Because regional climate change currently manifests as a shift toward more intense rainstorms, driven by “atmospheric rivers” that produce larger and longer floods in the Sierra Nevada (28, 29), these lateral erosion events should become more frequent.

Such flood-based erosion of banks/terraces is corroborated by remotely sensed imagery, which reveals the disproportionate impact of floods in redistributing sediment within the Yuba Fan and exporting fine sediment from it. A 1997 flood image (Fig. 4B) shows a relatively high suspended sediment concentration (SSC) emerging from the Yuba River compared with the Feather River (which does not contain an upstream anthropogenic fan). High event-based SSC efflux from the Yuba Fan, consistent with historical sediment records (23), is further corroborated by hydrodynamic modeling of suspended sediment flux during recent major flood events. The model hindcasted fine sediment (<150 μm) export into the lower Feather River during each of the three recent major floods, producing per flood sediment flux an order of magnitude higher than the total sediment accumulation within the reservoir upstream of the Englebright Dam from 1941 to 2004 (30) (Fig. 4C). These factors suggest that most of the remaining mining sediment resides downstream of foothill dams and comprises an important source of modern sediment loads into the Central Valley.

![Fig. 3. Flood frequency and stage-discharge relationships for the upper and lower Yuba River Fan. (A) Frequency of historical hydrograph characteristics [peak discharge (Q), rising limb duration, and falling limb duration] shows differences before (1903–1940) and after (1968–2010) construction of upstream dams. (B) Stage-discharge curves for 1968–2010 highlight thresholds for terrace saturation (Upper fan) and bankfull discharge (Lower fan).](image)

![Fig. 4. Modeling results of flood event-based terrace erosion and sediment and Hg efflux from the Yuba Fan. (A) Terrace erosion modeling results show fine-sediment flux (Qs) produced solely by terrace failure during the three largest recent floods above a streamflow (Q) threshold (SI Methods). (B) National Aeronautics and Space Administration 1997 flood image. Bright colors indicate high reflectance by suspended sediment. (C) Modeled SSC for the 1997 flood peak captures the turbid signal in the actual flood image. Red circles indicate Feather/Yuba confluence on both historical and model images, with associated model uncertainties are propagated based on the SD of Q-Qs regression at the model boundary.](image)
Our analyses highlight the importance of anthropogenic fans in the apparent lateral-expansion stage of morphodynamic evolution as primary stores, sources, and downstream exporters of mining sediment and associated contaminants. Assuming that 90% of the Yuba Fan remains in storage [equivalent to estimates for the Bear River (18)], ~0.1% of mining sediment (both fine and coarse) is evacuated per decade by a single large flood event such as those outlined here, implying a source of contaminated sediments to lowlands that will last for $>10^3$ y (SI Methods). This is consistent with a right-skewed model of sediment exhaustion (31) punctuated by increasingly heavy-tailed flood frequency (28, 29), which could slightly shorten mining sediment exhaustion times.

Based on modeled fluxes for flood events and assuming (SI Methods) conservatively low HgT, equivalent to concentrations in recent lowland flood deposits (Fig. 2F), the recent major floods exported large masses of Hg from the Yuba Fan into the Central Valley (Fig. 4 B and C). Such per flood event-based contaminant flux, predominantly derived from historical terraces relative to channel/bar sediments (Fig. 5A), represents a substantial fraction of the cumulative Hg mass (~200 kg) that is estimated to have reached the SFBD since mining began (15). Therefore, most Hg exported from anthropogenic fans is apparently still stored in lowland floodplains and floodways upstream of the SFBD. It manifests as an ~70-km long swath of Hg contamination from the Yuba Fan into the Central Valley (Fig. 5A).

This interpretation is corroborated by an independent geochemical proxy for mine-derived sediments, Zr/Ni (15). Hydraulic mining sediments in the Sierra largely derive from highly weathered Eocene sediments from which gold was extracted, and thus have high Zr/Ni ratios due to the selective removal of Ni and relative immobility of Zr (15). We analyzed our samples for these elements and found a clear down-valley trend in Zr/Ni (Fig. 5B). The HgT data show much higher variability, primarily as a consequence of sampling at various topographical positions (Fig. 2), but roughly follow a similar trend. Each elemental signature of hydraulic mining is apparently diluted downstream through the Yuba Fan, the scatter in HgT notwithstanding, and is relatively concentrated in floodplain deposits near the fan margin (Fig. 5). These data support the redistribution of mining sediment from the upper to lower Yuba Fan and its punctuated export from the entire fan into the Central Valley (Fig. 1B). They are also consistent with Hg isotope ratios in shallow SFBD sediments, which suggest a persistent upstream (Sierran) Hg source (16, 32).

Lowland floodplains are potential hotspots for Hg methylation of mining debris. Fine-grained Hg from hydraulic mining is associated with sulfide minerals (19), which are prone to oxidation (to mercury sulfate) during transport. Once delivered to lowlands, these sediments are redeposited, producing contaminated floodplain surfaces that undergo frequent wetting/drying cycles. These cycles may stimulate resident sulfate-reducing bacteria to methylate the newly arrived Hg near the sediment–water interface at very high rates (33, 34), posing risks to food webs in this and other ecosystems beset by mining-induced displacement of contaminated sediment.

The enduring legacy of mining on a grand landscape scale entails persistent lateral erosion of anthropogenic fans that continues well after the slowing of initial vertical incision and return of the channel to its original bed level. This process stage of fan evolution apparently sustains the evacuation of legacy sediment, triggered by increasingly potent floods that effectively deliver toxic sediment slugs downstream into sensitive lowlands, thus augmenting a major potential source of food web contamination in tidal wetlands of the SFBD.

These links between upland legacy mining sediment and lowland contamination, which are germane to issues of river management such as licensing for mining or dams in this and other basins around the world, are enabled by the topographical position of stored sediment and the frequency/magnitude of flood events capable of transporting contaminated sediment over tens of kilometers. Our findings suggest dangerous synergies between the morphodynamic stage of fan evolution, regional shifts in climate, and contamination risks to lowland ecosystems and human populations.

**Methods**

This paper presents the culmination of a multipronged approach, including assessment of historical topographical datasets, investigation of historical streamflow measurements at USGS gauging stations to determine rates of incision, flood frequency analysis, interpretation of HgT chromatography, Zr/Ni geochemistry as an independent proxy for mining sediment, and use of $^{137}$Cs to establish age control for younger deposits. These approaches were combined with terrace erosion modeling based on slope stability tied to hyporheic infiltration, partitioning of failed material into suspended sediment load, and numerical modeling suspended flux through the fan (SI Methods).

Topographical longitudinal and cross-section profiles were extracted from historical maps and recent LiDAR tied to photogrammetry and sonar data (35). Stratified sediment samples for HgT ($n = 176$) were extracted from channel bars and bank exposures at field-identified sedimentary units ($n = 105$) typically in vertical sections. Samples were sieved through $<63$-μm stainless-steel sieves to compare a common sediment population across all sites. The resulting material was digested at a USGS Hg laboratory in Menlo Park, California. Digested samples were harvested and analyzed on a Tekran

![Fig. 5.](image)

**Fig. 5.** Downstream patterns of geochemistry within and beyond the Yuba Fan. Measured HgT (A) and Zr/Ni (B) in sediments (Dataset S1). Power relationships fit to all HgT (including all stratigraphic positions from each historical terrace) and Zr/Ni data within the Yuba Fan are given in Fig. S1. Colors in A refer to geographical domains listed at the top of the figure. Shaded oval indicate elevated geochemical concentrations downstream of the margins of anthropogenic fans.


Supporting Information

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SI Methods

Topographical Data Analysis. To characterize historical changes in topography, longitudinal (thalweg) and cross-section profiles were extracted and compared from 1906 California Debris Commission maps (1) and 1999 LiDAR tied to photogrammetry and sonar data by the US Army Corps of Engineers (2, 3). The mean horizontal root-mean-square error associated with georegistration of the four 1906 map sheets was 5.47 m; this is relatively high for georegistration of historic paper maps, which required mosaicking of panels with limited cultural features existing in 1906 (4). Supporting data on changes in topography (Table S1) came from an external source (5).

Streamflow Analysis. Streamflow measurements and historical daily discharges at US Geological Survey (USGS) gauging stations along the Yuba River below the Englebright Dam (site 11418000) and near Marysville (site 11421000) were obtained from http://waterdata.usgs.gov/nwis. Historical daily streamflow data at site 11418000 (pre- and postdam) were analyzed for frequency in annual peak discharge, time to peak (rising limb), and drawdown time (falling limb) based on empirical plotting positions (6), and the data were compared using the Kolmogorov–Smirnoff (K-S) statistic in MATLAB (MathWorks). These aspects of hydrograph shape provide insight into changes in the duration of flood events capable of infiltrating banks and terraces. Graphical differences in the values for rare floods are evident, even when the overall distributions are not significantly different (e.g., drawdown time). Statistics include annual flood peak (K-S = 0.378; P = 0.007), time to peak (K-S = 0.151; P = 0.028), and drawdown time (K-S = 0.097; P = 0.344). Although there is a significant difference between pre- and postdam annual flood peaks (mostly decreased in the postdam period), there do not appear to be differences for the largest floods. In contrast, there are no significant differences in rising or falling limb duration, even though there appear to be marked increases in both for the largest floods. Changes in bed elevation in Fig. 1 for the early 20th century were obtained from Gilbert (7).

Recent changes in bed elevation (incision) were computed using streamflow measurements during relatively low streamflow (Q) from USGS gauging stations to obtain internally consistent values of riverbed elevation (BE):

\[ BE = h - \left( \frac{A}{w} \right), \]

where \( h \) is measured flow stage, \( A \) is flow area, and \( w \) is flow width, assuming a rectangular cross-section (8). These individual values of \( BE_i \), where subscript \( i \) indicates an individual value of \( BE \), were then differentiated to obtain cumulative change in bed elevation (BEC) from the time series, which was annualized to obtain the values presented in Fig. 1:

\[ BEC = \sum_{i} BE_i - BE_{i-1}. \]

Sediment and Geochemical Analyses. Sediment samples were extracted from bank exposures at field-identified sedimentary units along vertical sections spanning the area from the Englebright Dam to the lowland Central Valley, including deposits along the Yuba, Feather, and Bear Rivers (Fig. 1). We obtained 176 samples from 105 locations, including several samples at banks/terraces within stratigraphy and individual samples on channel bars (Fig. S4 and Table S1). Samples in stratigraphy were noted in terms of their superposition (which layers were above other layers) and in terms of their geomorphic units. All sediment samples were sieved through <63-μm stainless-steel sieves to compare total Hg concentration (HgT) in a common sediment population across all sites. Furthermore, it has been shown that particles in this fine-grained fraction tend to adsorb most of the Hg (9, 10). The resulting material was digested in Teflon bombs with aqua regia and BrCl (11) in a class 1000 clean room at the USGS in Menlo Park, California. Digested samples were harvested and analyzed on a Tekran Series 2600 Automated Mercury Analysis System, a cold vapor atomic fluorescence spectroscopy detector. We used dual-stage gold preconcentration and SnCl\(_2\) reduction according to standard procedures (US Environmental Protection Agency method 1631). International Atomic Energy Agency (IAEA) 405 (estuarine sediment) was used as certified reference material. Detection limits are <0.02 ng/L. For analysis of the \(^{137}\)Cs and \(^{210}\)Pb fallout radionuclides, samples were dried, ground, and packed into counting containers to match a calibrated geometry. Activities were determined in the Exeter Radiometry Laboratory with High-Purity Germanium (HPGe) spectrometers (Ortec LOAX and GMX) featuring ancient lead shielding, digital electronics, and efficiency corrections to account for density variations. Zr and Ni were measured via Inductively Coupled Plasma Mass Spectrometry (ICP-MS) at Activation (ACT) Laboratories Ltd. and the Centre for Earth Resources at the University of St. Andrews. HgT data presented in Fig. 5 include all analyzed samples, comprising individual samples for bar or channel sediments (squares) and each of those extracted from multiple stratigraphic layers within historical terraces (circles). Thus, for many locations (i.e., distances downstream from the fan apex), multiple values of HgT are presented, producing scatter in the downstream trend. We did not integrate or aggregate HgT values. All HgT values are listed in Dataset SI, where sample codes indicate the position within stratigraphy. The letters (A, B, C, etc.) at the end of the sample code indicate the position within stratigraphy (alphabetically sorted from top to bottom layer).

Erosion Modeling. Physically based terrace erosion modeling was conducted at an indicative river valley cross-section bounded by large terraces (>17 m high) near the fan apex (Fig. 2A), using an adaptation of the infinite slope stability model for riverbanks (12). This model tracks the relationship between river flow stage and flow through porous media in the bank/terrace to compute a factor of safety (FoS) at quarter hourly time steps. The terrace/bank is divided into a series of vertical columns, and we assume the water surface elevation in the bank column abutting the channel is equal to that of the river. Water draining from and seeping into the bank is then calculated via 1D implementation of the Richards equation (for flow through a porous medium under unsaturated conditions) through the bank columns using the Dupuit–Forchheimer assumption (flow moves horizontally between columns, assuming no infiltration recharge from above or loss below); \[ \frac{\partial h}{\partial t} = \frac{K}{\varepsilon} (\nabla \cdot \frac{h}{\varepsilon}), \] where \( h \) is water surface elevation, \( t \) is time (time step is 15 min), \( K \) is permeability, \( \varepsilon \) is porosity, and \( x \) is distance into the terrace. The calculations of FoS include weight of the failure material block taking into account the degree of saturation (from the Richards equation); hydraulic uplift force (positive pore-water pressure in the saturated zone) (13); confining pressure; suction force (negative pore-water pressures from matric suction in the unsaturated zone) (13); and effective cohesion, based on a homogeneous characteriza-
tion of bank materials. The FoS is determined as the ratio between the physical resisting forces \( F_r \) and the forces driving bank erosion \( F_d \):

\[
\text{FoS} = \frac{F_r}{F_d}. \tag{S1}
\]

The resultant driving force is

\[
F_d = F_w \sin \beta - F_{cp} \sin \delta, \tag{S2}
\]

where \( F_w \) is the weight of a unit width of the failure block (newtons per meter), \( \beta \) is the angle of failure plane (degrees), \( F_{cp} \) is the hydrostatic confining pressure (newtons per meter), and \( \delta \) is the angle between the resultant of the hydrostatic confining pressure and the normal vector of the failure plane (degrees). This angle is computed based on water surface elevation from the Dupuit–Forchheimer equation. The resultant resisting force is

\[
F_r = c' L + F_{wuc} + (F_w \cos \beta + F_{cp} \cos \delta - F_{fl}) \tan \phi',
\]

where \( c' \) is the effective cohesion averaged across each individual riverbank soil layer (kilopascals); \( L \) is the length of failure plane (meters), which is calculated trigonometrically based on the bank height; \( F_{wuc} \) is the suction force due to negative pore-water pressure (newtons per meter), and \( \phi' \) is the angle of internal friction (degrees). \( F_{wuc} \), \( F_{fcp} \), and \( F_w \) are computed using water surface elevation output from the Dupuit–Forchheimer equation above, and \( F_{cp} \) is computed based on flow stage in the channel. More details on the model structure can be found in the article by Amiri-Tokaldany et al. (14). Parameter values for the model are listed below.

There is no substantial vegetation present in this environment, and no tension cracks were visible during an on-site survey, so such effects are excluded. Once the model identified terrestrial failure, we quantified the volume of the failed material (based on the column width of terrace at which the calculated FoS value is lowest), and the grain size distribution (GSD) of the riverbed material was updated based on percentage cover of the channel bed by failed material at the field-measured angle of repose at the bank toe. In other words, we compute the volume of failure and then drape it on the terrace toe at the angle of repose, determine what percentage of the channel bed it covers, and update the GSD for the whole cross-section based on this percentage contribution (4% for one-column fail, 12% for two-column fail, and 24% for three-column fail).

Relevant modeling parameters used include bank height = 16.7 m, terrace angle = 75°, and terrace toe angle = 33°, all based on field survey via laser range finder, and internal angle of friction = 38°, porosity = 38%, and permeability = 0.001 m/s, all based on values reported by Selby (15) for our measured terrace GSD (presented below). Effective cohesion was set to 100 kPa based on the value for clay (15), even though the terrace is composed of sand and gravel. This was because we noted chemical cementation of the terrace material in the field that afforded it more stability than would be typical for such materials. Column widths were set to 20 cm to accommodate the largest grain diameter measured in the field, and we computed slope stability for each column width separately. The measured GSDs in the terrace were as follows (fractions in each size class, followed by sieve diameters in parentheses): 0.01 (0.063 mm), 0.01 (0.125 mm), 0.04 (0.25 mm), 0.15 (0.5 mm), 0.09 (1 mm), 0.07 (2 mm), 0.08 (4 mm), 0.12 (8 mm), 0.18 (16 mm), 0.19 (32 mm), and 0.06 (64 mm). Flow data used to drive the hydrological model for each major flood event were extracted from USGS gauging records (SI Methods, Washload Flux Modeling).

Because the study was concerned with fine-sediment flux from terraces, we assumed no topographical changes to the cross-section. Grain sizes were measured in the field in detail at this site. The measured GSDs in the bed (based on bar sampling) were as follows (fractions followed by sieve diameters in parentheses): 0.06 (2 mm), 0.14 (4 mm), 0.12 (8 mm), 0.15 (16 mm), 0.31 (32 mm), and 0.22 (64 mm). Bed material sediment flux was computed iteratively for the cross-section, based on updated grain sizes and daily flow stage in the channel by the Singer–Dunne equation (16):

\[
qs = \alpha \rho_s U \left( c' - c_w \right) \sqrt{\left( \rho - 1 \right) \rho_s \rho_w},
\]

where \( qs \) is the unit bed material transport rate (kilograms per second) per meter of width of size class \( n \), \( \alpha \) is a dimensionless grain size-dependent parameter computed based on the GSD, \( \rho_s \) is the density of sediment (assumed to be 2,650 kg·m⁻³), \( U \) is the streamwise velocity (meters per second) computed via an empirical fit of the Darcy–Weisbach formula based on bed grain size (17), \( c* \) is the dimensionless shear stress for \( d_{so} \), \( t* \) is the dimensionless critical shear stress for \( d_{so} \) (assumed to be 0.045), \( t_n \) is the dimensionless shear stress computed for a particle in size class \( n \), \( \rho \) is the density of water (assumed to be 1,000 kg·m⁻³ for water at 10 °C), \( g \) is the gravitational acceleration (9.81 m·s⁻²), \( d_n \) is the characteristic grain size (meters) of the size class for which the computation is being made, \( f_{is} \) is the fraction of bed material in that grain size class, \( f_\ell \) is the channel flow depth (meters), and \( S \) is the water surface slope. This equation is fractional (computes flux for each size class) and is sensitive to bed material GSDs (18). Flux calculations were based on cross-section hydraulics, assuming steady uniform flow. Instantaneous fluxes were summed for each flood event to obtain hind-cast estimates of fine sediment flux transported through the cross-section. This modeling strategy represents the partitioning of eroded terrace sediment into bedload and suspended load that occurs upon bank/terrace failure. The analysis, done for a single cross-section in the Upper Fan (Fig. 24), where there is field and photographic evidence of past terrace failure, is indicative of the links between bank/terrace erosion and downstream sediment flux, and thus provides constraints on the flux of fine sediments during large floods.

Washload Flux Modeling. Fine sediment load in California’s Central Valley has been shown to be important in affecting conveyance capacity in floodways (19, 20), as well as for the net downstream transport of Hg (21, 22). Flood event inundation depths and suspended sediment concentrations in the Yuba River channel and its floodplains were modeled using TELEMAC 2-D (Laboratoire National d’Hydraulique, Paris, France) (23) and Sisyphe (a coproperty of the Centre d’Etudes Maritimes et Fluviales, Université de Technologie de Compiègne, Électricité de France, and the Société Grenobloise d’Études et d’Application Hydrauliques), a finite element hydrodynamic and washload transport modeling approach (24). Suspended sediment input was conservatively approximated as a point source within the Yuba Fan based on a rating curve developed between concentration and discharge from historical data from Yuba River near Marysville (USGS site 11421000). This curve represents a low estimate of sediment supply during large floods because it contains data collected in events smaller than those modeled here. We expect the curve would increase nonlinearly in large events due to the lateral erosion of banks/terraces. Because rating curves are fits between discharge and sediment concentration, we used the error on the slope of this curve to compute uncertainty in sediment loads for each modeled flood event presented in Fig. 4. The error in concentration was propagated by multiplying it by discharge to obtain values of uncertainty in sediment flux at the model boundary. These were summed over the entire hydrograph for each flood event to compute a total flood-event flux uncertainty. Although there is undoubtedly additional uncertainty in washload flux estimates.

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Based on hydrodynamics and interaction with sediment, this is not represented within the uncertainty values in Fig. 4.

These conservative estimates of sediment supply to the Yuba River at this location were routed through the Yuba and Feather Rivers to obtain total fluxes for the events of 1986 (10 d), 1997 (18 d), and 2006 (7 d). Details of the model are described by Kilham (24). Topography was defined using a seamless dataset of sonar channel bathymetry and high-resolution floodplain topography, resulting in a final mesh with an average channel element size of 10 m. Leveed sections defining the model side boundaries were characterized as impassable, and the upstream and downstream boundaries were kept open to allow for fluxes of sediment and water. Inundation depths were determined by solving the depth-averaged St. Venant equations with a resistance parameter characterizing the predominant land cover observed in each floodplain element based on classification of satellite imagery (24). Details of the governing equations can be found elsewhere (www.opentelemac.org/) (23). Sediment transport was accomplished by solving the depth-integrated advection–diffusion equation for a passive scalar (e.g., the particle concentrations). This assumes that the sediment velocity is equal to the mean fluid velocity modified for the effect of vertical settling. Deposition was modeled as a function of the size and weight of the particle, the suspended sediment concentration gradient, and an upward buoyant force dependent on the velocity and acceleration of both the particle and the flow. This approach is based on a definition of deposition by which sediment falls and, most importantly, sticks to the bed (25, 26). Erosion at these floodplain velocities was considered negligible, and it was set to zero. Previous studies on floodplain flow have shown that the shear velocities on lowland river floodplains are generally insufficient to cause erosion or resuspension of recently deposited sediment, except at the beginning of inundation (27). Model parameter values for TELEMAC/Sisyphe included median grain size = 0.03 mm; roughness coefficient (Manning’s n) for the channel = 0.055; settling velocity = 0.0078 m/s, based on the Krone formula; sediment density = 2,650 kg/m³; minimum water level = 0.1 m; water viscosity = 0.0000013 m²/s; porosity = 37.5%; longitudinal dispersion = 0.6; and transverse dispersion = 6.0.

The modeled concentrations were compared with sediment concentration values observed from space during floods for this area (17–19) (remote sensing methods). Our evidence from spectrally classified Landsat images shows that significant (>100 mg/L) concentrations persisted in the Yuba River 30 d after the peak of the 1986 event (28). As such, our approach provides a conservative estimate of event-based flux.

**Per Flood Flux Estimates.** We summed the total modeled mass flux (SI Methods, Washload Flux Modeling) and assumed a sediment bulk density of 1,200 kg/m³ (based on several field measurements of mining deposits) and average HgT of 0.18 μg/g. The latter is the mean of HgT values from 10 selected samples (set in boldface in SI Dataset 1) from the Lower Feather River and Lower Yuba Fan, representing recent (past several decades) deposition (Fig. 2) determined by 137Cs dating, field observation, and/or analysis of historical imagery. This conservative estimate is equivalent to the Hg concentration of the most recent flood deposits (uppermost stratigraphic layers, Fig. 2). These Hg flux estimates are presented in Fig. 4, and the uncertainties provided are based on the error in assigning the slope of the sediment rating curve (SI Methods, Washload Flux Modeling), rather than on variability in initial HgT or any parameter sensitivity in TELEMAC. We multiplied the flux uncertainty by the characteristic HgT to obtain the event-based uncertainty in Hg concentration for each flood. Then, the flux as a percentage of the total stored mass was calculated based on the original estimated mass of the Yuba Fan ca. 1880 (~252 × 10⁶ m³). We assume that suspended load comprises 85% of the total sediment load, with bedload flux making up the remaining 15%. Assuming 90% remaining in the fan deposit (29) and one large flood per decade, this yields a per flood total load flux of ~0.09% of the original deposit, thus requiring >10 y to evacuate sediment from hydraulic mining. These estimates are conservatively low for several reasons: (i) mining sediment is diluted with nonmining sediment by the time it reaches the fan outlet (Fig. 2); (ii) following progressive lateral erosion, lateral mining deposits will require progressively larger floods to access these sediments; and (iii) the mix of grain sizes within the Yuba Fan suggests that a significant proportion of the mining sediment will lag behind the washload exported described herein. Indeed, bedload flux rates are probably quite low at the fan outlet due to low water surface slope during flood.

**Multipronged Approach.** This paper presents the culmination of a multipronged, process-based approach that included assessment of historical topographical datasets, investigation of streamflow measurements at historical gauging stations to determine rates of bed elevation change, analysis of flood frequency, interpretation of chemostatigraphy using historical channel change data (from maps) along with HgT, inference from remotely sensed imagery, Zr/Ni geochemistry as an independent proxy for mining sediment, and 137Cs to establish age control for younger deposits. These approaches were combined with the modeling of terrace erosion by slope stability by taking into account the water table elevation in the terrace, partitioning of failed material into bedload vs. suspended sediment loads, and modeling of flow and suspended flux through the fan. These steps allow us to investigate dilution of a particular population of sediment in the downstream direction (30).

2. James LA, Hodgson ME, Ghoshal S, Latiolais MM (2012) Geomorphic change detection from spectrally classified Landsat images shows that significant (>100 mg/L) concentrations persisted in the Yuba River 30 d after the peak of the 1986 event (28). As such, our approach provides a conservative estimate of event-based flux.
4. James LA, Hodgson ME, Ghoshal S, Latiolais MM (2012) Geomorphic change detection from spectrally classified Landsat images shows that significant (>100 mg/L) concentrations persisted in the Yuba River 30 d after the peak of the 1986 event (28). As such, our approach provides a conservative estimate of event-based flux.
6. James LA, Hodgson ME, Ghoshal S, Latiolais MM (2012) Geomorphic change detection from spectrally classified Landsat images shows that significant (>100 mg/L) concentrations persisted in the Yuba River 30 d after the peak of the 1986 event (28). As such, our approach provides a conservative estimate of event-based flux.
24. Kilham NE (2009) Floodplain sedimentation on the Feather River, California: Combined use of remote sensing and numerical modeling to analyze contemporary deposition patterns in a historically mined basin. PhD dissertation (University of California, Santa Barbara, CA).

Fig. S1. Downstream relationships in HgT above background values and Zr/Ni through the Yuba Fan.

Table S1. Rates of degradation (feet per year) in the Lower Yuba Fan

<table>
<thead>
<tr>
<th>Years</th>
<th>XS2</th>
<th>XS3</th>
<th>XS9</th>
<th>XS11</th>
<th>XS13</th>
</tr>
</thead>
<tbody>
<tr>
<td>1899–1906</td>
<td>0.29</td>
<td>0.14</td>
<td>0.21</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>1906–1912</td>
<td>2.50</td>
<td>1.70</td>
<td>0.83</td>
<td>0.83</td>
<td>0.75</td>
</tr>
<tr>
<td>1912–1928</td>
<td>0.13</td>
<td>0.50</td>
<td>0.44</td>
<td>0.41</td>
<td></td>
</tr>
<tr>
<td>1928–1979</td>
<td>0.14</td>
<td>0.08</td>
<td>0.10</td>
<td>0.18</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Historical rates of channel degradation in the thalweg at various cross-sections within the lower Yuba Fan are reproduced from the work of Adler (5). That dissertation may be accessed to see the location of each cross-section.

Dataset S1. HgT and Zr/Ni values, distances downstream, and spatial/geomorphic classifications

Dataset S1

Boldfaced sample codes indicate samples from recent deposits averaged to obtain a characteristic value of HgT used to model Hg fluxes (see above), which are presented in Fig. 4.