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Sediment from hydraulic mining detained by Englebright and small dams in the Yuba basin

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Abstract

Recent initiatives to find ways to reintroduce anadromous fish to the Central Valley of California have identified the Yuba River as one of the best potential watersheds for expanding spawning habitat of spring-run chinook salmon and steelhead trout. Salmon spawning in the Yuba River would require substantial modifications or removal of Englebright Dam, a large dam (86 million m^3 capacity) built by the U.S. Army Corps of Engineers in 1941. An extensive on-going feasibility study by local, state, and federal organizations, therefore, is examining aspects of various dam-treatment scenarios that range from no action to complete dam removal.

This paper examines the extraordinary history of the watershed and resulting conditions pertinent to the feasibility of altering Englebright Dam. It seeks to accomplish four goals. First, historical geomorphic changes in the watershed are outlined that influence the physical context of the feasibility study. The Yuba watershed is centered in the hydraulic gold-mining region made famous by G.K. Gilbert (Gilbert, G.K., 1917. Hydraulic-mining débris in the Sierra Nevada. U.S. Geol. Survey Prof. Paper 105 154 pp.), and Englebright Dam was built as a *débris dam* to control the sediment from hydraulic mining. Second, recent findings of high concentrations of mercury in sediment and fish tissues in the watershed are briefly reviewed. Much mercury was applied during the 20th century. Third, historic data on 20th century hydraulic mining are presented that document numerous small dams built in the Yuba basin to detain mining sediment. Finally, field measurements of the texture and lithology of modern bed materials in the Yuba River basin are presented that demonstrate reworked sediment from mining is an important component of the modern sediment load and fine spawning gravels.

The complex anthropogenic geomorphic changes in the Yuba basin present a challenge with regards to responsible treatment of Englebright Dam. If toxic sediment is being reworked in the upper watershed, Englebright Reservoir may play an important role in protecting fish populations below in the Sacramento Valley. Where large volumes of mining sediment are stored behind small detention structures in the upper basin, they should be mapped and assayed for mercury. Stabilization or restoration options for these deposits should consider the potential role that they could play in supplying fine spawning gravel to the main channel.

Keywords: Hydraulic gold mining sediment; Dam removal; Aquatic restoration, Sierra Nevada, California

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1. Introduction

This paper examines recent geomorphic changes in the Yuba watershed that pertain to an extensive on-going study of the feasibility of altering or removing Englebright Reservoir. Basic goals of the paper are to briefly describe the Upper Yuba River Study Program and what is known about the potential for mercury toxicity of mine tailings, and to describe in detail the sedimentation history and modern sediment conditions in the basin. Emphasis of the paper is on the latter two topics. The sedimentation history is divided into a brief description of sedimentation from 19th century mining (covered in detail elsewhere) and of sediment from 20th century mining and detention dams in the basin. Previously unpublished data provide 20th century sediment production volumes from hydraulic gold mining and detention-dam storage capacities. Descriptions of modern channel-bed sediment are introduced based on previously unpublished field sampling.

The Yuba River in northern California has been recognized as a potential watershed for reintroducing anadromous fish to the Central Valley. Presently, however, Englebright Dam halts fish migrations at the lower foothills of the Sierra Nevada, so natural spawning would require treatment of Englebright Dam. Four possible dam-treatment options are presently under study: do nothing, build a record-high fish-bypass system, lower the dam, or completely remove the dam. Englebright Dam is a concrete arch dam 79 m high and 348 m long (Fig. 1). With a capacity of 86 million m^3 (70,000 ac-ft), Englebright Reservoir is large relative to most dam-removal projects (Graf et al., 2002). The dam was completed in 1941 for the explicit purpose of detaining sediment from hydraulic gold mining. Hydraulic mining produced prolific amounts of sediment in the watershed (Gilbert, 1917) and the dam was built to facilitate more hydraulic mining.

The history and geomorphic consequences of hydraulic gold mining in the Yuba watershed are relevant to the feasibility of dam removal and are a central topic of this paper. Earlier studies of geomorphic effects of massive production of mining sediment during the 19th century are reviewed. Misconceptions about the lack of persistent remobilization of this mining sediment stored in the upper basin are revisited with evidence of on-going sediment mobility. Contributions of fine gravel from this sediment may have great bearing on long-term sediment loads and toxicity downstream as well as the sustainability of salmonid spawning habitat. In addition to effects of 19th century mining and to Englebright Dam, the effects of 20th century licensed hydraulic mining are described. This period of mining has received little prior attention in the historical or scientific literature, but was accompanied by the

Fig. 1. Englebright Dam and Reservoir. Photograph by author, 2002.

construction of numerous detention structures in the Yuba basin to store mine tailings locally. These structures and associated sediment deposits should be located, tested for mercury, considered for treatment or removal, and factored into the feasibility study.

This paper does not make a recommendation for or against a particular treatment of Englebright Dam. Extensive studies are underway including analysis of cores from Englebright Reservoir to assess the sedimentology and geochemistry of reservoir sediment (Childs et al., 2003), and modeling of water and sediment transport in the watershed. A feasibility assessment would be premature until these studies are complete. Nor does this paper present results of pending and on-going scientific studies in the watershed. The relevant points made in this paper, however, have been provided to the appropriate work groups of those studies (e.g., UYRSP Tech. Review Panel, 2001).

1.1. Study area

The Yuba basin is on the western flank of the northern Sierra Nevada, California (Fig. 2). It flows out of glaciated granodiorites of the high Sierra through deep, steep-walled canyons of the Sierra foothills out to the flat Central Valley. The study area includes the Middle and South Yuba Rivers plus the lower North Yuba below Bullards Bar Dam (BBD). Most of the North Yuba River above its confluence with the Middle Yuba is excluded because New BBD

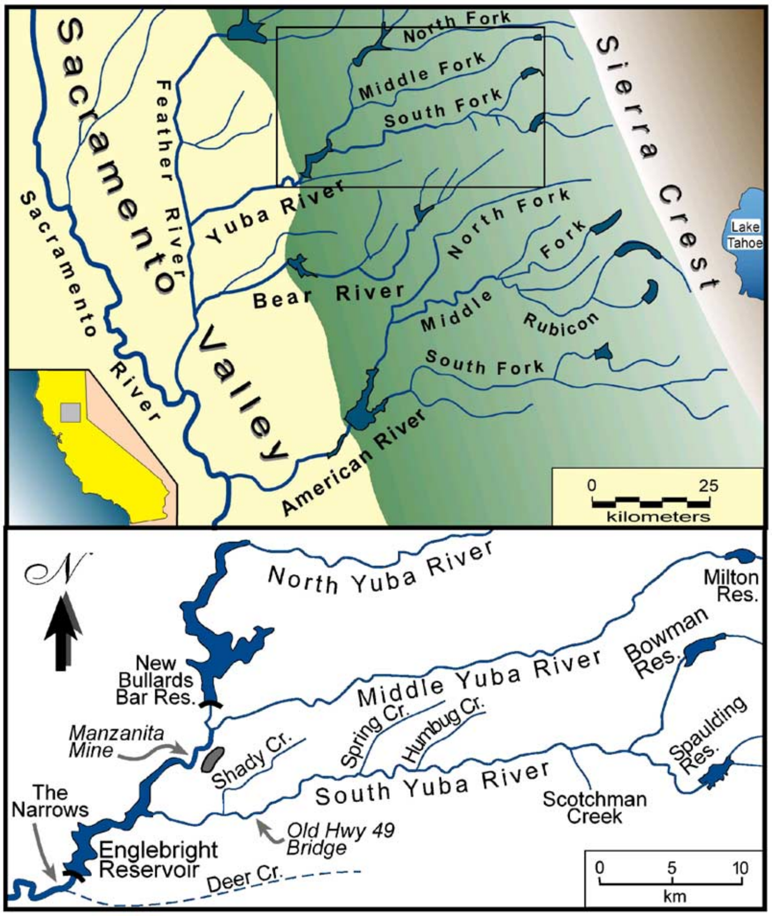

Fig. 2. Study area showing Middle and South Yuba flowing into Englebright and North Yuba into Bullards Bar.

(reservoir capacity 1.2 billion m^3) has controlled water and sediment since it was built in 1970. For the sake of simplicity, the Middle Yuba referred to in this report includes the lower North Yuba below New BBD. This is most relevant to the Manzanita Mine, a large hydraulic mine that discharged sediment to the North Yuba below its confluence with the Middle Yuba.

Geomorphically the Yuba watershed can be divided into two different drainage systems: relatively low-gradient upland tributaries with a capacity for long-term sediment storage, versus steep lower tributaries and main channels where stream powers are high, bed material is coarse, and little storage capacity exists. The upland tributary system can be further partitioned into two components: upland sediment production and in-stream sediment processes. Under natural conditions hill-slope erosion processes probably dominated sediment production, but in tributaries draining hydraulic mines vast deposits of mining sediment in the valley bottoms now dominate sediment production. Main Yuba canyons are about 300 m below the relatively flat ridge crests where the mines are located. This facilitated hydraulic mining because tailings were quickly disposed of by dumping them into the canyons below. Large floods with high stream powers remove all but the coarsest boulders from the steep, narrow canyons (Fig. 3). This removal explains the lack of long-term storage of mine tailings in the main channels while much sediment remains in the upper tributaries (Gilbert, 1917).

2. Upper Yuba River Study Program

An extensive study of the feasibility of changing Englebright Dam, known as the Upper Yuba River Study Program (UYRSP), was initiated in 1998, received funding of $6.7 million in December 2000, and continues at the time of this writing. The UYRSP is coordinated by CalFed, a cooperative effort of more than 20 State and Federal agencies working with local communities to improve the quality and reliability of water supplies in California, and to revive the San Francisco Bay–Delta ecosystem. Many projects occur within the extensive CalFed program, of which the UYRSP is but one. The ecosystem restoration objectives of CalFed—to restore ecological processes, habitats, and species diversity to the Bay–Delta ecosystem—are the primary motivation behind the UYRSP, although these objectives must be balanced with existing constraints including water supplies, flood control, recreation, and water quality.

The UYRSP is designed to encourage public participation based on a workgroup consisting of

Fig. 3. Coarse colluvial boulders in South Yuba at Highway 49 bridge. Fine sand and gravel can be sampled in interstices of boulders in pools, bars, and floodplains even at sites like this.

stakeholders in the area divided into three teams: River, Lake, and Agency teams. The first business of the Workgroup (*Phase I*) was to establish technical committees and to identify six focus areas for addressing the feasibility of introducing anadromous salmon: habitat, sediment, water quality, water supply-hydropower, flood-risk management, and economics. The project is now in *Phase II* in which the scopes of the six focus areas have been defined, data are being collected, and analysis will be conducted. Evaluations and recommendations of the various dam-treatment scenarios will take place in *Phase III* of the project planned for completion in 2007.

2.1. Goal to reintroduce chinook salmon and steelhead trout

Prior to mining in the 19th century and damming in the 20th century, the range of two species of anadromous salmon, spring-run chinook salmon (*Oncorhynchus tshawytscha*) and steelhead trout (*Oncorhynchus mykiss*), extended well beyond the present range and into the Sierra Nevada. Much of the former chinook salmon spawning habitat is no longer available because of dams in the lower foothills on all major rivers of the Central Valley. The current range of chinook salmon is largely limited to low-gradient rivers of the Central Valley that are not generally conducive to spawning. Steelhead trout ranges are potentially higher in elevation than chinook salmon but are also restricted by dams. An exception to the lack of foothill spawning habitat is found in Butte Creek where the recent removal of several dams opened up 30 km of the lower river to salmon spawning (Gleick, 2000).

Conservative estimates of the historical, pre-mining upper limits to California chinook salmon have been presented by Yoshiyama et al. (1996) where they could be established by direct evidence; especially by contemporary historical accounts. The pre-mining range of chinook salmon in the Middle and South Yuba Rivers is not known because of rapid disruptions of these rivers by intense mining operations prior to historical fish observations. The CalFed UYRSP was established to ascertain if introduction of chinook salmon and steelhead trout to the Yuba basin is biologically, environmentally, and socio-economically feasible.

3. Potential mercury toxicity of mine wastes

One of the most toxic elements commonly found in riparian environments is mercury. In the United States as of 1998, 2506 fish and wildlife consumption advisories were issued for all substances. Of these, more than 75% (1931) were for mercury (Alpers and Hunerlach, 2000). All segments of the San Francisco Bay are listed as impaired because of mercury contamination, so the State is required to establish total maximum daily loads (TMDL) for mercury that can be received by the Bay. Inorganic mercury was used extensively to extract gold, and much of it may remain in sluice boxes and mining-sediment deposits in the Yuba watershed. Local bioassays indicate high levels of mercury in fish tissues in the mining regions, especially in the South Yuba and Bear Rivers. Mercury concentrations in most game fish sampled from Englebright Reservoir were above 0.3 ppm, the screening threshold set by the Environmental Protection Agency (EPA), and in several cases approached 1.0 ppm, the Food and Drug Administration's (FDA) action level for mercury in commercial fish. A relationship has been shown between the amount of mercury in the tissues of aquatic organisms and the volume of hydraulic mining sediment produced in various watersheds (Fig. 4). Mercury levels in the Yuba and Bear River basins are clearly in need of close scrutiny.

Mercury continued to be used in 20th century hydraulic mining operations and thus may be found in

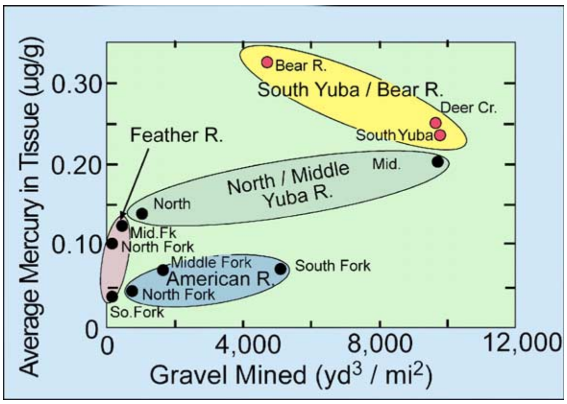

Fig. 4. Summary of mercury bioassays showing high tissue concentrations levels in South Yuba and Bear Rivers (Alpers and Hunerlach, 2000; Hunerlach et al., 1999).

relatively recent deposits as well as older, more extensive deposits of mine tailings. Mercury does not naturally occur in the Sierra Nevada in appreciable amounts but was imported from mines in the Coast Ranges. Historical production of mercury reflects the decline of hydraulic mining after the 1884 Sawyer court injunction but substantial production continued after that time (Fig. 5). Much mercury may have been used by licensed hydraulic mines in the Yuba after 1893. U.S. Geological Survey scientists recently found extremely high concentrations of mercury in tunnels draining the Polar Star and Southern Cross mines near Dutch Flat in the Bear River basin (Hunerlach et al., 1999). The Polar Star Mine was issued licenses to hydraulically mine 463,000 m^3 in 1894, 1,500,000 m^3 in 1898, and an unknown volume from 1906 to June, 1908 (Licenses #16, 193 and 737). An attempt by the author in the 1990s to repeat a photograph of the Polar Star mine taken ca. 1908 (Lindgren, 1911) proved impossible because the angle from the edge of the pit had changed; a large, high ledge on the southwest rim of the Polar Star pit had been removed after the Lindgren photograph was taken. This ledge had been over the upper Polar Star tunnel so the sediment must have been removed through the tunnel. Thus, the mercury found in the Polar Star tunnel is a product of 20th century mining. The Southern Cross mine was also issued a license to mine from 1908 to 1909 (Lic. #786). In 2000, the EPA spent approximately $1.5 million to remove mercury-contaminated sediment from abandoned sluices in tunnels draining the Polar Star and Southern Cross mines (CERCLIS, 2000).

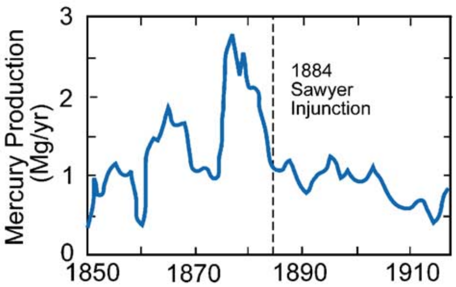

Fig. 5. Mercury production in Coast Range mines. Rapid rise and fall ~1875–1883 reflects use by hydraulic mining. Rise in mid-1890s may represent use by licensed hydraulic mines. Adapted from Alpers and Hunerlach (2000) and Hunerlach et al. (1999); based on data from Bradley (1918); assuming 34.5 kg (76 lb) per flask.

Substantial concentrations of inorganic mercury in Yuba River sediments are clearly cause for concern (May et al., 2000; Alpers and Hunerlach, 2000). Yet, work has just begun on the biological hazards of mercury in the Yuba watershed and advisories have only recently been issued (Alpers et al., 2002). The primary threat of mercury contamination arises from the potential conversion of inorganic mercury to methyl mercury, a highly toxic, organic form of mercury that accumulates in aquatic organisms and biomagnifies through aquatic food webs. Methyl mercury is hazardous to human health, and can adversely affect fish populations in quite low concentrations, particularly in early life stages (Wiener and Spry, 1996; Fjeld et al., 1998; Latif et al., 2001). The presence of mercury in a methylating environment could defeat attempts to restore salmon fisheries. The abundance of methyl mercury in the system, therefore, should be assessed along with environments conducive to mercury methylation or demethylation (UYRSP Tech Panel Report, 2001). The critical question to be addressed is the *net production* of methyl mercury (methylation minus demethylation) rather than the abundance of inorganic or total mercury (Bodaly et al., 1993; Wiener and Shields, 2000). Unfortunately, wetland environments may promote methylation and these are systems that CalFed seeks to enhance and protect in the lower Sacramento and Bay–Delta system downstream. The likelihood and consequences of introducing mercury to the lower Yuba, Feather, and Sacramento Rivers is an important component of the Englebright feasibility study.

4. Recent geomorphic and sedimentation history

Sedimentation and other geomorphic consequences of hydraulic gold mining in the Yuba basin were documented by Gilbert (1917). This section briefly reviews the early history and geomorphic results of hydraulic mining in the Yuba basin. It then examines an often overlooked period of 20th century mining and the dams and deposits associated with those activities. This is followed by descriptions of 20th century dams and mining-sediment production that were associated with hydraulic gold-mining activities in the watershed including a case study of Scotchman Creek.

4.1. Nineteenth century hydraulic mining sediment in the Yuba basin

Sediment production by hydraulic mining in California was unprecedented in the annals of mining and human impacts on the environment (Gilbert, 1917). Vast hydraulic mine pits were exhumed (Fig. 6) and sediment was released to rivers with no regard to the downstream consequences. The Yuba basin received more sediment from hydraulic mining than any other basin in the Sierra Nevada (Gilbert, 1917) and specific sediment production (volume per unit area) was second only to production in the Bear River (James, 1999). Within the Yuba basin, the South Yuba received more mining sediment than any of the other branches, and the smaller Middle Yuba basin had the highest specific production, particularly if the lower North Yuba below the Middle Yuba confluence is included (Table 1). This production represents 22 cm of denudation averaged across the entire South and Middle Yuba basins, or ~7 mm per year. Sedimentation was so devastating to flooding, agriculture, and navigation in the Sacramento Valley that an injunction was issued by Judge Lorenzo Sawyer in 1884 which may represent the first instance in United States history of an environmental enjoinder on such a lucrative industry. The history of this sedimentation episode has been well documented from both physical (Gilbert, 1917; James, 1989, 1999) and political/institutional perspectives (Kelley, 1959, 1989). Much of the sediment from this period passed down through the system (Gilbert, 1917). Yet, large volumes of sediment from 19th century hydraulic gold mining remain stored in upper tributaries of the Yuba watershed such as Scotchman Creek, Spring Creek, and Shady Creek (Fig. 7). Topographic surveys of these deposits are needed to map and inventory sediment storage.

4.2. Twentieth century hydraulic mining sediment in the Yuba basin

Most studies have ignored the persistent hydraulic gold mining that occurred after Judge Sawyer's 1884 injunction. Sadly, after a decade of judicial struggle by farmers to document the environmental destruction and halt hydraulic mining, only 9 years later Congress quietly passed legislation that allowed hydraulic mining to start back up. The Caminetti Act of 1893 legalized hydraulic mining based on a permitting system under the assumption that sediment produced by mining would be prevented from reaching navigable streams. Licenses were contingent upon provisions for the local storage of mine tailings, usually by the construction of a sediment-detention dam made of brush, logs, rock, or concrete. The permitting program was administered by the *California Debris Commission* (CDC), created by the

Fig. 6. Manzanita Mine near Sweetland ca. 1909; drains to lower North Yuba near Englebright Reservoir. Gilbert's 1909 survey found total volume mined was 37 million m^3. A California Debris Commission license for 806,000 m^3 (~2% of total volume) was issued in 1894. From Gilbert (1917; Plate 10).

Table 1
Sediment produced by hydraulic mining

	Drainage area		Volume produced (m^3 10^6)	Production/drainage area		Denudation		
	Total (km^2)	Mining (km^2)[a]		Total (mm)	Mining (mm)[a]	Total (mm/year)	Mining (mm/year)[a]	% 19th century production[d]
19th c. Mining (1853–1884): (31 years)								
Mid. Yuba	510	402	109[b]	214	272	6.90	8.76	
Mid+LNY[c]	560	432	179[b]	320	415	10.32	13.4	
So. Yuba	994	475	165[b]	166	348	5.36	11.2	
Total	1554	907	344[b]	222	380	7.15	12.2	
CDC 1893–1950 (conservative minimum estimate): (57 years)								
Mid. Yuba	510	402	0.81	1.6	2.0	0.028	0.035	1.16
Mid+LNY[c]	560	432	1.45	2.6	3.4	0.045	0.059	0.81
So. Yuba	994	475	3.40	3.4	7.2	0.060	0.126	2.06
Total	1554	907	4.81	3.1	5.3	0.054	0.093	1.40
So. Yuba[e]	994	475	1.70	1.7	3.6	0.030	0.063	1.03
Total[e]	1554	907	3.10	2.0	3.4	0.035	0.060	0.90

[a] Drainage area of mining districts: South Yuba below and including Scotchman Creek; Middle Yuba below Milton Reservoir.
[b] Volumes produced from Benyaurd et al. (1891) times 1.51 (Gilbert, 1917).
[c] Middle Yuba and Lower North Yuba below New Bullards Bar Dam.
[d] Licensed mining volume as % 19th century volume.
[e] Without mines licensed to dispose of tailings in Englebright Reservoir.

Caminetti Act within the War Department (now U.S. Army Corps of Engineers) (Hagwood, 1981). The CDC inspected detention structures and issued licenses for specific volumes of gravel releases based on the ability to detain sediment. Although this period of hydraulic mining began in 1893, it will be

Fig. 7. View up Shady Creek, South Yuba tributary, 1992. Large amounts of mining sediment stored in low-gradient upland tributaries, identified by sand and fine-gravel texture and white quartz. Evidence of reworking includes steep terrace scarps (long arrow) and historical features emerging from bed (old flume with square nails; short arrow at left).

referred to as *20th century mining* or *licensed mining* to distinguish it from the far more intense unregulated hydraulic mining prior to 1884 that will be referred to as *19th century mining*.

The 57-year period of 20th century mining (1893 to 1950) in the Yuba watershed lasted almost twice as long as the 31-year period (1853 to 1884) of unregulated mining. Most 20th century hydraulic mines operated briefly and produced little sediment, but some operated over extended periods, with repeated license renewals, and produced large volumes of sediment. Although the geomorphic effects of 20th century mining were subtle relative to earlier sedimentation, large sediment volumes were produced and stored near the mines, and mercury was apparently used profusely. The fate of this sediment is largely unknown, although a few known deposits are documented later in this paper. Gilbert (1917) noted evidence of recent mining in hydraulic pits of the Yuba basin in 1908, but felt that contemporary sediment production was insubstantial and inadequate to explain his initial estimates of sediment production in the Bear River that he thought were too high:

"During the surveys in 1908 it was easy to see that certain parts of the growth had sprung up, were of early date, and that other parts, still bare of vegetation, were relatively recent; but it was not practicable either to infer dates with approximate accuracy or to estimate separately the more recent work. It is believed, however, that the work subsequent to 1890 can account for only a small part of the discrepancy between the two estimates..." (Gilbert, 1917: 39)

Most CDC mining licenses involved the construction of detention structures that are described later. In a few cases, however, sediment was stored on the floor of an abandoned hydraulic mine pit. A notable example of pit storage is the Manzanita Mine (Fig. 6) that drains to the lower North Yuba below the Middle Yuba confluence a short distance above Englebright Reservoir. A license was granted in 1894 to store 806,000 m^3 of sediment in the floor of the former mine. The mine produced 637,000 m^3 by 1897 when the license was revoked. By 1898, an additional 142,000 m^3 was stored behind brush and earth dams and 42,000 m^3 was added to pit storage (CDC, nd). Based on a 1909 topographic survey of this mine pit, Gilbert (1917) concluded that a total of 37 million m^3 of sediment had been removed, so the licensed volume represents only about 2% of the total mined volume.

A summary of CDC records of 20th century mines and detention structures in the Yuba watershed is presented later in this paper. A summation of sediment-production volumes from CDC license data for the entire Sierra Nevada came to only 2.4% of the total sediment production from hydraulic mining (James, 1999). This represents a conservative minimum estimate because of missing records and incomplete accounting of sediment produced. Much more sediment may have been produced than the volumes reported by the CDC. While licensed mining sediment production was probably small relative to the peak rate of 19th century sediment production, the deposits influenced valley-bottom morphology and may continue to produce sediment. Furthermore, recent realizations about mercury associated with hydraulic mine tailings in the Sierra Nevada has increased the importance of locating these deposits due to their potential Hg toxicity.

4.3. History and nature of debris dams in the Yuba watershed

Three major periods of dam building can be identified that were associated with hydraulic gold mining. The earliest historic dams on main channels in the mining districts were by tailings fans associated with episodic sedimentation from 19th century hydraulic mining. A second period of dam construction ensued after 1893 with a proliferation of small sediment-detention dams built to qualify for 20th century hydraulic-mining licenses. Finally, the construction of Englebright Reservoir marks the modern period in which a large dam arrests the down-valley transport of mine tailings.

4.3.1. Tailings fans

In the early period of unregulated hydraulic mining, sediment from mining created large fans that dammed rivers and created lakes that acted as large sediment-storage repositories. These tailings fans have been documented in the Bear River including detailed contemporary accounts near Dutch Flat (James, 1988: pp. 48–50, 2004; James and Davis, 1994). A few tailings fans trapped large volumes of sediment behind valley spurs that later cut narrow bedrock notches. These valley-spur cutoffs were created when a tailings fan forced the main channel up against the far valley wall where it ultimately incised into the spur (James, 2004). Now the cutoff spur acts as a knickpoint controlling long-profile readjustments and retarding the release of mining sediment stored upstream. Two valley-spur cutoffs have been identified in the Bear River basin: at Steephollow Crossing and above Red Dog Ford. Although spur cutoffs have not been mapped in the Yuba basin, the landform previously was not recognized and they may have gone unnoticed. Spur cutoffs would not have formed on the South or Middle Yuba main channels because of high stream powers that eroded fan toes and prevented damming. Tailings fans in tributaries could hold large sediment repositories in the Yuba basin and should be mapped as sites of potential long-term sediment supplies.

4.3.2. Debris-control dams

Early in the period of licensed mining, basic procedures for detaining sediment with small impoundments were developed. During the first decade of licensed mining, the engineering of small detention structures was rudimentary, so many of these ephemeral structures washed out within a few years. The CDC (1904) soon developed guidelines with standard design structures for two types of detention structures: brush dams and log-crib dams. The standard CDC design for brush dams advocated use of live brush at least 3 m long with large limbs bent back and long, trimmed poles 10 to 30 cm in diameter. A brush layer was applied with butts pointing downstream, poles were laid over and wired perpendicular to the brush, and a layer of gravel or small stones was applied (Fig. 8). This sequence was repeated with multiple layers of brush, poles, and gravel offset upward so the face of the dam sloped steeply downstream. A pool of water at least 0.6 m deep was to be maintained while mining proceeded. In spite of this standardization of design, these structures were ephemeral and most were breached by large floods. Nevertheless, vestiges of these structures may anchor historical terraces along valley walls in the upper basin and a map inventory is needed. A summary of CDC records of detention structures in the Yuba watershed and mining sediment production associated with them is given later.

The standard CDC (1904) design for log-crib dams specified two walls of logs connected by cross-logs notched and bolted together (Fig. 9). The bottom and sides were supposed to be founded on bed rock and the cribs filled with stone and chinked with brush, twigs, and leaves, so the dam would maintain a pool at least 0.6 m deep during mining. Few crib dams have been located in the mining districts. Most were quickly breached (Gilbert, 1917), although crib-dam remnants may store tailings throughout the region

Fig. 8. Brush dam below Murchie Mine in South Yuba basin showing butts of brush pointing downstream and poles crossing. Photographed in 1908 by Gilbert (1917; Plate 26A).

Fig. 9. Log-crib dam on Spring Creek below North Columbia mine. November 1905. From Gilbert (1917; Plate 27A). Gilbert revisited this dam in October 1908, noting that it failed in 1907.

(e.g., Scotchman Creek described later). A contemporary description of brush and log-crib dams and their ephemeral nature is provided by G.K. Gilbert:

"In the early years of the commission's control its requirements were satisfied by dams of brush or of wooden cribs loaded with stone or gravel, and it is only in recent years that concrete dams have been prescribed. In a few projects separate spillways were provided for the streams on which brush and crib dams were built, but usually the streams were allowed to cross the crests of the dams, and in all such places the storage was not permanent. After the wood of brush and cribs has decayed, and often sooner, the dams are breached and the stored débris is exposed to wash." (Gilbert, 1917: 67)

Much sediment passed through the detention structures as was shown by channel changes below dams responding in phase with the production of mining sediment in the Bear River (James, 1999). Trap efficiencies of the small dams were low, so CDC estimates of 20th century sediment production may be systematically low to the extent that tailings were transported downstream without being accounted for. The proportion of delivered sediment detained by a reservoir (trap efficiency) is a function of reservoir capacity, magnitudes of inflow, volumes and textures of sediment, density currents, reservoir-operating policy, bathymetry, and the shape, type and location of outlets (Brown and Thorp, 1947; Brune, 1953). Trap efficiencies of moderately large reservoirs are typically between 50% and 98% (Colby, 1963: 35; Brown and Thorp, 1947) but may be considerably less for small pools such as the sediment-detention dams. Based on estimated yields of sediment and surveys of reservoir bathymetry, trap efficiencies for six small, low reservoirs in the lower Schuylkill River ranged from 2.1% to 31.4% with an average of 11.9% (Yorke et al., 1985). These reservoirs had mean widths between 109 and 175 m and capacities between 540,000 m^3 and 3,900,000 m^3, and were much larger than the typical brush dams and log-crib dams of the Sierra Nevada. Sediment yield is calculated from surveys of reservoir sedimentation as the ratio of stored volumes of sediment to trap efficiency (Vanoni, 1975), so a 20% trap efficiency would indicate sediment yields five times the volume of sediment stored in the detention structure. This does not adjust for reductions in trap efficiencies as reservoirs fill (Verstraeten and Poesen, 2000). These observations suggest that only a small percentage of the sediment produced by licensed 20th century mining was detained by crib dams even if leakage through dams and failures are discounted. Since sediment-production estimates given in CDC records were usually based on reservoir filling, actual sediment production was probably much greater than reported in CDC reports. For current planning purposes, however, the important issue is how many of these structures remain in small mining tributaries, how much sediment remains behind them, and whether or not these deposits contain mercury, acid, or other hazardous materials.

4.3.3. Englebright Dam

Englebright Dam was built in 1941 by the U.S. Army Corps of Engineers for the explicit purpose of storing hydraulic gold-mining sediment. The reservoir is narrow and 14 km long with a surface area of 330 ha. It stands in the lower foothills at an elevation of 160 m amsl and is accessible above the lower reaches only by boat. Englebright Dam supports local recreation and two minor hydropower plants, but provides negligible water storage or flood control. The dam was justified under the assumption that its cost would be recouped by hydraulic mines paying for sediment storage, but mining ceased shortly after dam construction. From 1941 to 1950, nine licenses to mine ~1.7 million m^3 of hydraulic mining sediment (2% of total reservoir capacity) were issued to mines in the South Yuba based on storage in Englebright Reservoir (Table 2). No record exists of CDC licenses in the Middle Yuba based on storage in Englebright Reservoir. In addition to the licensed volumes, reworking of sediment from earlier tailings must have delivered large volumes of sediment to the reservoir over the past 60 years. Sedimentation in the reservoir ranges from 6 to 31 m in depth and accounts for an approximately 25% loss of storage capacity (Childs et al., 2003).

4.4. CDC records of dams and sediment production

From 1893 through 1950, the CDC licensed hydraulic gold mining in the Yuba watershed and kept records of the size, nature, and location of detention structures for licensed mines. They also estimated volumes of sediment production from hydraulic mining based on inspections of fill behind dams. Existing records are sometimes conflicting and often incomplete, but they allow approximations to be made of locations and relative magnitudes of mining during this period. Although CDC records prior to 1906 were largely destroyed by the San Francisco fire, partial records of the early period are available in reports to Congress (Kidder, 1894, 1896, 1899). Later archival CDC records from 1905 to 1935 are better but also incomplete. Summaries have

Table 2
Conservative minimum volumes of 20th century sediment-detention structure storage capacities and mined volumes in the South and Middle Yuba basins

	South Yuba			Middle Yuba			Both Basins		
	N	Storage capacity, m^3	Volume mined, m^3	*N*	Capacity, m^3	Volume mined, m^3	*N*	Capacity, m^3	Volume mined, m^3
Licenses applied for	46			24			70		
Licenses refused	3			1			4		
No evidence license granted[a]	2			2			4		
Licenses granted for[b]:									
Brush dams	8	1,034,798	576,350	9	475,739	85,806	17	1,510,537	662,156
Log-crib dams	11	346,590	297,241	8	16,407	98,201	19	362,997	395,442
Concrete dams[c]	4	573,825	265,490	1	38,255	10,329	5	612,080	275,819
Earth or gravel dams	4	353,476	15,685	3	570,994	252,866	7	924,470	268,550
Pit storage	5	160,671	393,261	7	929,979	1,002,434	12	1,090,650	1,395,695
Subtotal:	32	2,469,360	1,548,027	28	2,031,374	1,449,635	60	4,500,734	2,997,662
Storage in Englebright (> 1940)	9	NA	1,667,233	0	NA	0	9	NA	1,667,233
Total with Englebright:	41		3,215,260	28		1,449,635	69		4,664,895

Source: CDC archives (n.d.); Kidder, 1894, 1896, 1899.
[a] Probably no mining at these sites. Does not include licenses known to have been refused.
[b] Includes only mines with evidence that license was granted, so the structure was built and inspected.
[c] Four licenses granted to Omega Mine for concrete dams at same site in Scotchman Creek. Fifth license for Sierra Hydraulic mine in Middle Yuba. Sixth application based on concrete dam in S. Yuba at Relief Hill refused.

been presented elsewhere of CDC records for licensed mining in the Bear and North Fork American Rivers (James, 1999). This section summarizes CDC records of 20th century mining in the South and Middle Yuba Rivers and presents a case study of licensed deliveries of mining-sediment and detention structures in Scotchman Creek.

4.4.1. Sediment production and storage capacities

Tallies of CDC license data for this study provide conservative minimum estimates of the number of hydraulic gold-mining licenses issued, the types of structures associated with the licenses, volumes of storage capacity, and sediment production associated with the structures. These results include only records for mines that were clearly located in the basin and for which the values were specified in one or more CDC documents based on licenses that were granted. The structures described were presumably built and inspected, as this was required for issuance of licenses. These values should be regarded as minimums for several reasons. First, many records throughout the period do not report dam capacities or sediment-production volumes. Storage capacities were given on only 42% of license reports and production volumes on only 39% of the reports. While many unreported values may have been associated with small or failed mine operations, the reported volumes are less than actual amounts because of lack of data for so many mines. Second, many records of licenses for the Yuba watershed are not included in this tally because they do not specify a location within the South or Middle Yuba. While they could be located in the North Yuba, lower Yuba, or Deer Creek basins, several may have been in the South or Middle Yuba basins. Twenty-six mines at unspecified locations in Yuba basin received licenses and an additional 13 unknown Yuba mines applied for licenses with an unknown outcome (no date of issue reported). Most of these licenses are from before 1906 when records are sparse. A third reason for underestimated sediment-production values stems from low trap efficiencies as described earlier. With these limitations in mind, examination of the CDC data provides a number of interesting patterns.

At least 69 licenses for hydraulic gold mining were issued from 1893 to 1948 in the South and Middle Yuba basins: 41 in the South Yuba and 28 in the Middle Yuba (Table 2). Licenses were based on a variety of sediment detention strategies, including storage in local mine pits (12), brush dams (17), log-crib dams (19), earth- or gravel-fill dams (7), concrete dams (5), and storage in Englebright Reservoir (9). The numbers indicate the number of licenses rather than the number of structures. Occasionally multiple licenses were issued for the same structure by raising a dam. For example, the concrete dam on Scotchman Creek was raised by additional concrete and by adding brush dams and other works on top as described in the next section.

The total reported storage capacity of small structures in the upper watershed was 4.5 million m^3: 2.4 million m^3 in the South Yuba and 2.0 million m^3 in the Middle Yuba. The relative importance of different types of detention structures can be estimated from the CDC records (Table 2). In a few cases, two types of detention were reported for a license, so the volume was equally apportioned to each type. For the Omega Mine on Scotchman Creek, the large capacity for an 1893 license was arbitrarily assigned 25% to a brush dam and 75% to a concrete dam. Brush dams provided the largest type of detention capacity, with pit and earth dams comprising the next largest capacities (Fig. 10A). Storage within existing hydraulic mine pits usually involved plugging tunnels or shifting sediment to a previously worked area and can be associated with wetlands that create a mercury-methylating environment. The relative importance of these methods varies substantially between the South and Middle Yuba. Pit storage was by far the dominant method in the Middle Yuba but was of little importance in the South Yuba. Most pit storage (68% of Middle Yuba and 58% of total pit storage) was in the Manzanita Mine near Sweetland (Fig. 6) where at least 637,000 m^3 of sediment was produced based on a license issued in 1894 to mine 806,000 m^3 (revoked in 1897). The license was obtained by damming tunnels that had drained the mine during 19th century operations. Without the capacity of the Manzanita Mine, pit storage was far less important. That single Manzanita Mine license represents 40% of the total known capacity of storage and 44% of the 20th century sediment produced in the Middle Yuba. The remaining sediment storage capacity and production was largely accounted for by earth-fill and brush dams (Fig. 10). In the South Yuba, a greater reliance

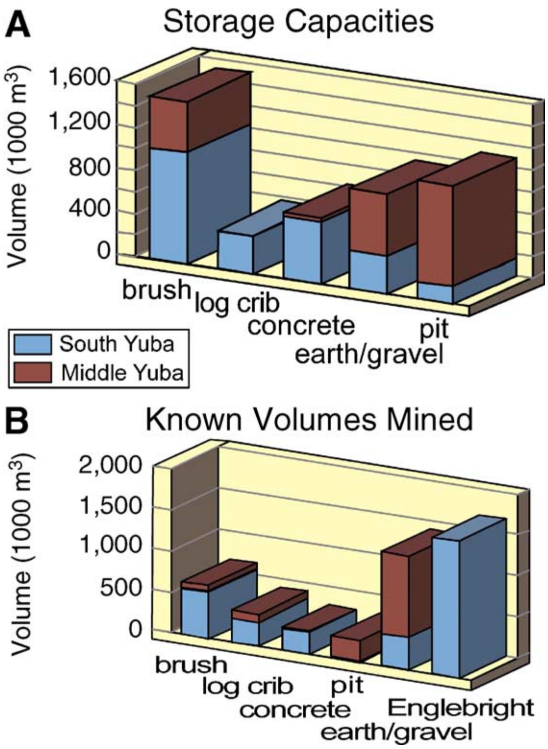

Fig. 10. Conservative minimum estimates of volumes associated with licensed hydraulic mining, 1893–1950. (A) Total dam storage capacities: South Yuba, 2.2 million m^3; Middle Yuba, 2.0 million m^3. (B) Total reported hydraulic mining sediment production: South Yuba, 3.4 million m^3 (1.7 without Englebright); Middle Yuba, 1.5 million m^3. Data from CDC archives.

was put on brush dams, the concrete dam on Scotchman Creek, log-crib dams, and earth-fill dams.

Total reported sediment produced by licensed hydraulic mining was 4.8 million m^3 including deliveries to Englebright Reservoir, with 3.2 million m^3 in the South Yuba (1.5 million m^3 without Englebright) and 1.4 million m^3 in the Middle Yuba (Table 2). Sediment produced for storage in Englebright Reservoir after 1941 was the single most-important source of sediment reported, and accounted for almost half of the reported hydraulic mining sediment produced in the South Yuba and a third of the sediment in the entire watershed (Fig. 10B). The sediment volumes for Englebright are probably complete and relatively accurate because they are based on water use, while the other volumes are probably severely underestimated. Nevertheless, a proliferation of hydraulic mining occurred in the 1940s associated with dam closure and this sediment was delivered directly to the reservoir. Recent coring of Englebright Reservoir revealed storage of ~22 million m^3 or approximately 25% of the initial reservoir capacity (Childs et al., 2003). The 1.67 million m^3 of mining sediment produced by licensed mining after 1940 for Englebright Reservoir (Table 2) represents 7.6% of the sediment now in the reservoir. This production was entirely in the South Yuba and mostly from Scotchman Creek (Table 3). Sediment production associated with other detention structures is generally less than storage capacities which may represent failure of structures before mining was complete, license revocations, or lack of reporting of mined volumes. In some cases, mined volumes are greater than reported storage capacities which probably represents unreported storage values. These estimates of licensed sediment production range between 1% and 2% of the total hydraulic mining sediment produced since 1853 (Table 1), but should be considered a conservative minimum estimate.

When these conservative values of licensed sediment production volumes are divided by drainage areas of the basins, the net denudation varies between 0.28 and 0.60 cm (Table 1). Three to six millimeters of denudation by 20th century mining is almost two orders of magnitude smaller than the exceptional 22 cm of total denudation in the Yuba basin caused by 19th century unregulated hydraulic mining. When averaged over the 57-year period of mining, denudation from 20th century, hydraulic mining ranges from 0.03 to 0.06 mm $year^{-1}$. These rates are substantial from the perspective of long-term erosion rates in large watersheds. They are an order of magnitude less than maximum regional denudation rates (~0.3 mm $year^{-1}$) and are comparable to long-term rates (0.03 to 0.06 mm $year^{-1}$) at tectonically stable Sierra Nevada granitic sites based on cosmogenic radionuclides (Riebe et al., 2001). If sediment production is averaged over the smaller areas of the mining districts, average denudation by mining is substantially higher (Table 1). At the extreme, total denudation of the entire South Yuba downstream of and including Scotchman Creek was more than a third of a meter, mostly because of unregulated 19th century mining. The conservative minimum estimates of denudation by licensed mining in the South and Middle Yuba mining districts are 7.2 and 3.4 mm, respectively;

Table 3
Dams and sediment on lower Scotchman Creek

Date	License #	Dam	Volume mined
ca. 1890	none	Log dam, 12.2 m high and 14 m long at crest; filled (Turner, 1891: 3049)	
1893	3	brush and gravel dam; rock spillway.	765,000 m^3 capacity
1904–1909	660	concrete dam; license revoked 1909.	16,100 m^3 mined
1914–1919	898	concrete dam with 12.8 m basket dam; raised 1919 +2.4 m; failed 1919.	344,000 m^3 mined
1922–1925	956	Deposited in local mine pit	2700 m^3 mined
1925–1929	978	1927: photo shows failed dam	8400 m^3 mined
1929	1007	dam raised 2.1 m; license revoked 1929	200,000 m^3 mined
1933–1941	1112	log-crib and concrete dam; license revoked 1941 (filled).	93,000 m^3 mined
1938–1939	1194	log-crib dam; license revoked 1939.	138,000 m^3 mined
1941–1943	1244	Englebright Reservoir	955,000 m^3 mined
??	1264	Englebright Reservoir	???
??	1270	Englebright Reservoir	???
1948–1950	1271	Englebright Reservoir	200,000 m^3 mined

Source: CDC records.

representing a substantial erosional event for such large areas.

4.4.2. Case study: 20th century dams and mining on Scotchman Creek

A long sequence of licensed mining took place in the Omega Mine which drains to Scotchman Creek (Table 3). This history, from CDC archives (n.d.), illustrates the complex nature of repeated dam construction, licensing, dam filling and failure, and sediment production. The sequence began with one of the first CDC licenses issued; a license in 1893 to produce 765,000 m^3 of sediment. Another license issued in 1904 for sediment discharges to a concrete dam was revoked in 1909 after 16,000 m^3 had been mined. Reasons for license revocation were not given but usually represent the filling or failure of a dam. In 1914 another license was issued to discharge sediment into a concrete dam with a 12-m-high "basket dam" addition. This dam failed in 1919 after the reservoir was filled with 344,000 m^3 of sediment but the dam was raised 2.4 m shortly afterwards. A CDC photograph shows lower Scotchman Creek in 1927 with a failed earth-fill dam (Fig. 11), but no mention is made of the failure in CDC records. In 1929, the dam was raised 2.1 m, 200,000 m^3 of sediment was mined, and

Fig. 11. Lower Scotchman Creek dam site, 1927. View downstream toward failed earth-fill dam; presumably same site as concrete dam. CDC archives.

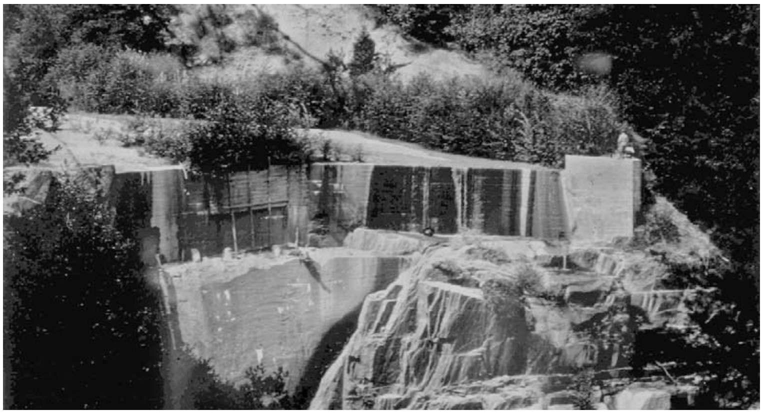

Fig. 12. Concrete gravity dam on lower Scotchman Creek showing lower section and an upper addition. Was full of sediment when photo taken, December 25, 1941. Dam intact and filled with sediment when visited occasionally since 1989. CDC archives, U.S. Army Corps of Engineers.

the license was revoked. In 1933, another license was issued for a concrete dam, and by 1941 93,000 m^3 of sediment had been mined, the dam had filled (Fig. 12), and the license was revoked.

A log-crib dam on Scotchman Creek was built in 1938 on top of tailings upstream of the concrete dam. The license was revoked in 1939 after 138,000 m^3 had been mined, presumably because the reservoir had filled. The log dam was breached by a large 1986 flood (Fig. 13) and deposits above the dam were regrading in 1989. The concrete dam downstream has remained filled with sediment, so the sediment released from the log-crib dam is being delivered downstream to Englebright Reservoir. A topographic cross-section of Scotchman Creek was surveyed in 1989 with rod, tape, and level 15 m above the concrete dam. The maximum top width of the mining sediment deposit was 58.5 m across a low mining-sediment terrace from valley wall to valley wall, and the channel bed in 1989 was only 1.5 m below this terrace.

Fig. 13. Log-crib dam on middle Scotchman Creek built in 1938. License revoked in 1939 (reservoir probably filled). Dam breached by 1986 flood and stored sediment was eroding in 1989 when photographed by author.

5. Modern river conditions

The contribution of reworked mine tailings is important to understanding future sediment loads in the basin, so the ability to identify and assess the mobility of this sediment is of great relevance. Fortunately, the texture and lithology of mining sediment are distinctive and readily allow identification of tailings and the degree to which they have been mixed (James, 1991). Field observations of channels in the Yuba basin indicate the presence of large volumes of historical sediment in terraces and channel bed materials in certain tributaries. A few of these deposits were sampled in the summer of 1989 using grid-sample counts of pebbles and bulk-sample sieving of channel materials. This section briefly describes the nature of channel-bed and low-bar samples and the patterns of mining sediment that they indicate.

5.1. Bed material textures

The Tertiary bench gravels that were mined for gold are dominated by fine gravel and sand. Mine tailings tend to be much finer-grained than the channel lag and colluvial materials common in channels lacking mining sediment. Thus, sediment from hydraulic mining tends to be relatively mobile and suitable for spawning habitat. Grid-samples (Wolman, 1954) of low-flow bed materials were collected at several sites within the South Yuba basin. Particle intermediate-axis dimensions were recorded to the nearest millimeter, and mean grain sizes were calculated by the method of moments (Table 4). Normally, fluvial bed sediment fines downstream as gradients decrease. This general pattern can be seen in the main channel (circles on Fig. 14) with two exceptions. The anomalously fine sample from the upper basin at a drainage area of 134 km^2 reflects the lack of coarse colluvium in wide valleys of the glaciated upper basin. Conversely, the anomalously coarse sample in the lower South Yuba at a drainage area of 800 km^2 is from an exceptionally narrow, steep stretch of canyon at Highway 49 where colluvial boulders dominate the channel (Fig. 15). The other four main-channel samples in the lower South Yuba, collected between Edwards Crossing and the Englebright delta, are relatively fine textured with mean grain sizes between 13 and 15 cm (Table 4).

Relatively fine sediment from mining dominates some of the tributaries in the Yuba watershed. Normally, tributaries have coarser bed materials than main channels and the textures will plot as an extension of the negatively sloped line on plots like Fig. 14. The combination of low-gradients and large amounts of fine-grained mining-sediment, however, results in the three tributary samples being substantially finer than bed sediment in the main channel. Shady Creek is clearly dominated by mining sediment and has fine, well-sorted bed material (Fig. 7). Humbug Creek conveyed tremendous volumes of mine tailings when it acted as the drain for the

Table 4
1989 bed load textures and white quartz (wtQtz) summary: grid-samples

Site	Drainage Area (km^2)	Total *N*	Mean mm	Mean Phi	%wtQtz total	%wtQtz ≤50 mm	*N* ≤50 mm
South Yuba channel							
at Cisco	134	61	222	−7.79	0.0	0.0	5
at Langs Xg	310	50	512	−9.00	2.0	0.0	1
above Scotchman Cr	532	100	228	−7.84	4.0	0.0	6
at Edwards Xg	710	100	132	−7.04	21.0	33.3	18
at Purdon Xg	745	101	149	−7.22	19.8	70.6	17
at Hwy. 49	801	60	524	−9.03	8.3	75.0	4
Bridgeport	993	50	128	−7.00	18.0	80.0	5
Bridgeport channel	993	50	150	−7.23	12.0	66.7	3
Tributaries							
Humbug Cr	16	53	77	−6.26	22.6	50.0	14
Shady Cr #10	32	100	43	−5.42	54.0	51.3	80
Shady Cr #8	38	100	27	−4.78	62.0	57.9	76

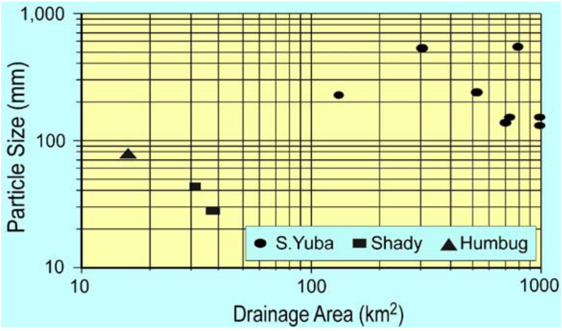

Fig. 14. Bed material textures are relatively fine in tributaries dominated by mine tailings but coarse in the South Yuba main channel that is dominated by channel lag. Grid-sample data, 1989.

Malakov Diggings. During the 1870s, a tunnel was bored beneath Humbug Creek and tailings bypassed the creek at an early date. The amount of mining sediment in the bed of Humbug Creek today is mitigated by thick vegetation stabilizing most deposits outside of the channel. Fine bed textures suggest, however, that reworked mining sediment still contributes a substantial amount of the modern bed load. This interpretation is supported by the presence of moderately high white quartz concentrations described in the next section. In short, bed material textures suggest that main channels are dominated by gravel, cobbles, colluvium, and channel lag materials but some tributaries are dominated by finer sediment from mining. Examination of the lithology of the bed materials corroborates this interpretation and indicates further that a population of relatively fine-grained mining sediment is passing through the reaches of the main channel.

5.2. Lithology of bed material

The percentage of white quartz pebbles in samples of bed material from these rivers can be a reliable indicator of the proportion of tailings from hydraulic mines that worked the auriferous Tertiary channels (James, 1991). This simple relationship with quartz facilitates field recognition of sediment from mining by its distinct white color, and allows quantitative assessments to be made of the dilution and mixing of sediment in the downstream direction. Sediment sampling was designed, therefore, to measure percentages of quartz to ascertain the relative importance of mine tailings in the stored material in and along channels at various locations within the watershed. Terrace and channel-bed materials were sampled, although only the results of bed material samples are reported here. Application of this method requires caution not to include sites that have gained quartz from roads and construction sites. Mining sediment quarried from river deposits is commonly used for aggregate, and may be introduced to watersheds where no mining occurred. Generally, such introductions are relatively minor and localized compared to sediment produced by hydraulic mining. Where possible, samples were collected above bridges to avoid contamination from roads.

Quartz pebbles were identified and recorded in the grid-samples of bed material described above during sampling. Although percent-frequency of quartz was calculated for each total sample, the more relevant statistic is the percent-frequency of quartz in pebbles no larger than 50 mm (Table 4). Sediment from mining tends to be finer than fluvial sediment from other sources, and by isolating the finer fractions of channel samples, the importance of mine tailings to the highly mobile portion of bed material can be determined.

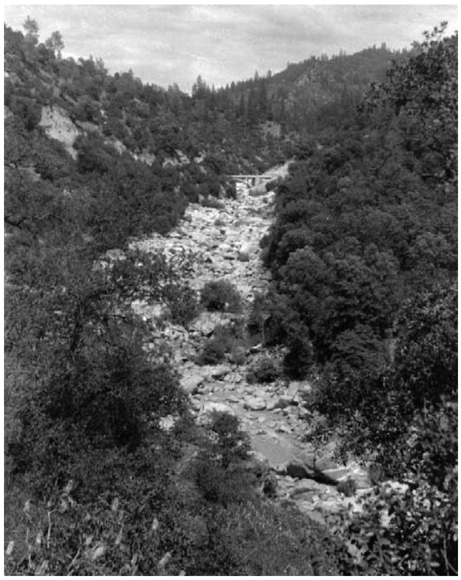

Fig. 15. View upstream on South Yuba toward Highway 49 bridge, showing dominance of coarse lag boulders in main channels. Photograph by W.D. Johnson, Jr., 1934. U.S.G.S. Field Records Library.

Above Scotchman Creek, grid-samples of main-channel bed material have few pebbles and lack white quartz pebbles. The number of pebbles and quartz concentrations increase rapidly downstream to high values that indicate a dominance of mine tailings in this fraction (Fig. 16A). This trend suggests the increasing presence of sediment from mining in the active bed load of the main South Yuba channel once it enters the mining districts. High concentrations of quartz and, therefore, sediment from mining are also present in bed materials of Shady and Humbug Creeks.

Although the size of the grid-samples range from 50 to 100 clasts, they often have too few clasts in the small pebble range to allow an unequivocal evaluation of the relationships described above (Table 4). In anticipation of this limitation, a second set of samples was collected in 1989 using an alternative method to expand the geographic range and size of quartz pebble samples. Bulk surface samples of pebbly bed material were collected from the low-flow channel bed and low bars with a folding shovel approximately to the depth of the coarsest grain size (usually < 10 cm). Each sample was air dried in the field and sieved through brass 20-cm-diameter sieves. White vein-quartz pebbles were separated in the 32–64, 16–32, and 4–8 mm fractions, and both quartz and non-quartz fractions were weighed in the field to the nearest 0.1 g using a portable digital balance. Summary data are presented here for percent white quartz (by weight) of the 16–32 mm fraction (Table 5).

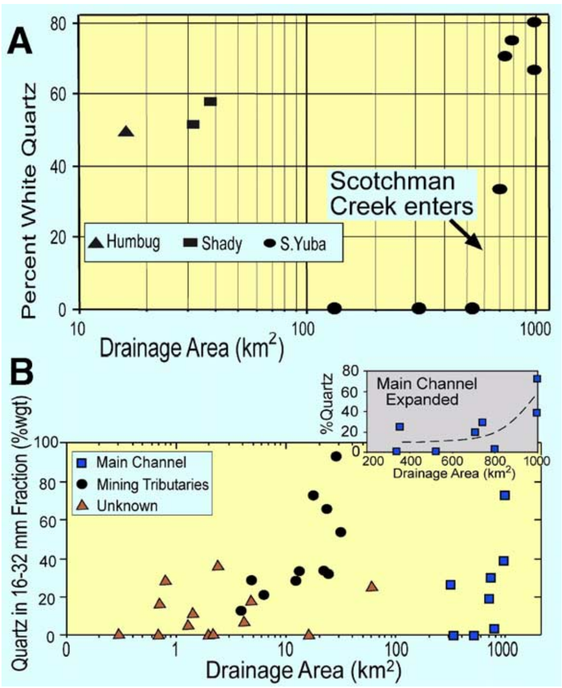

Fig. 16. Distinct lithology of sediment from hydraulic mining facilitates identification of mining. High white quartz concentrations in bed material indicate which tributaries carry mining sediment. (A) Quartz percentages of pebbles ≤50 mm from grid-samples of channel-bed material. High percentages in Shady and Humbug Creeks and lower South Yuba River indicate high contributions from reworked mining sediment. Low quartz contents above Scotchman Creek indicate little mining sediment in bed load. Sediment from mining is delivered to main South Yuba channel by Scotchman Creek. (B) Percent white quartz in the 16–32 mm fraction of sieved bulk samples. Main channel shows same pattern of increase below Scotchman Creek. Tributaries known to drain mines tend to have high quartz. Based on 1989 field data.

As expected, the percent quartz in bulk samples of bed materials of the South Yuba has a distinct spatial pattern and appears to be strongly related to the presence of sediment from hydraulic gold-mining. In agreement with the grid-samples, quartz pebbles are scarce above the mining districts but increase below Scotchman Creek (Fig. 16B). Two main-channel bulk samples above Scotchman Creek had no quartz and so little fine sediment was available at the third site that it should be disregarded. Increased quartz downstream in the main channel is interpreted as the presence of reworked sediment from mining in the fine fraction of the modern bed material. Bulk pebble samples also corroborate the presence of reworked mine tailings in the beds of tributaries draining hydraulic mines. For example, Shady and Scotchman Creeks are presumably dominated by hydraulic mining sediment because of the fine textures of bed materials and massive terraces of actively eroding mining sediment. Samples from tributaries draining known mines (round points in Fig. 16B) tend to contain high percentages of quartz, particularly the four samples from Shady Creek that all have more than 50% quartz. In contrast, the mining history of many tributaries is unknown. Several tributaries with no known hydraulic mines in the headwaters (triangles on Fig. 16B) have little or no quartz. For example, bed material sampled in Kentucky Creek near its mouth has no quartz and probably represents a lack of sediment from hydraulic

Table 5
Bed material composition in sieved pebbles (intermediate axes 16 to 32 mm)

Location	Other comments	32 mm>pebbles>16 mm wgt (g)	% Quartz by weight			Drainage area (km^2)
			Main	Mining	Unknown	
South Yuba						
Englebright	delta	216	72.2			994.0
Bridgeport	d/s bridge	641	38.5			993.0
Hwy. 49	d/s 49	445	3.0			801.0
Purdon Crossing	u/s bridge	565	29.5			745.0
Edwards Crossing	u/s bridge	400	19.1			710.0
at Scotchman Cr	u/s confluence	194	0.0			519.0
u/s Holbrook Flat	low bar; right bank	917	0.0			340.0
Jolly Boy Mine	low bar above mine	33	26.5			320.0
Tributaries						
Kentucky Cr	u/s bridge	233			0.0	16.0
French Corral	d/s bridge	527		21.1		6.5
French Corral	at 2nd bridge	738		28.2		5.0
Lower Shady	Reader Ranch	357		52.9		32.0
Shady Cr	below old Hwy. 49	212		92.6		29.0
Shady Cr	at Wildman10	760		65.5		23.4
Shady Cr	at Whittlesey	548		72.6		18.0
Kennebec Cr	u/s N. Bloomfield Rd.	341			29.2	0.8
Humbug Cr	d/s Pan Ravine	707		31.2		24.6
Pan Ravine	~20 m u/s Humbug	523			36.9	2.4
Humbug Cr	Site2	489		32.6		22.2
Humbug Trib	Relief Hill Rd.	329		12.6		4.0
Missouri Cn	30 m u/Relief Hill Rd.	495			0.0	2.1
McKilligan Cr	u/Relief H. Rd.	555			0.0	0.7
Thimblebry Cr	15 m u/Relief Hill Rd.	106			0.0	0.3
Logan Cr	450 m u/s Relief Hill Rd.	431			0.0	2.0
Poorman Cr	40 m u/s Relief Hill Rd.	421			26.1	60.7
Washington Cr	d/Br&Trb	511			18.5	4.9
Wash Cr Trib	nr Washington	949			17.0	0.7
Washington Cr	u/s bridge	390			7.4	4.2
Scotchman Cr	in pothole d/s dam	524		32.7		13.6
Scotchman Cr	u/s logdam	784		27.8		12.5
Missouri Cn	Scotchman trib	222			5.6	1.3
Rgt bank Trib	nr Holbrook Flat	624			11.6	1.4

Sample sites: Main=main channel. Mining=tributaries with at least one hydraulic mine. Unknown=tributaries that may or may not have received tailings.

mining in the active bed load. Many tributaries, including some that drain known mines, have intermediate concentrations of quartz between 10% and 40% that suggest continued contributions of sediment from mining but with a substantial amount of sediment dilution from other sources.

The textural and lithologic data support an interpretation that at least two populations of bed material are present in many locations in the watershed. Quartz-rich sediment from mining is relatively fine and mobile while lag gravels, colluvium, and the background sediment load from non-mining areas tend to be coarser and low in quartz. Stream powers are quite high in the main channels of the South and Middle Yuba Rivers and these channels have coarse lag deposits (Fig. 3). Yet even in these locations, fine sediment stored in pools, potholes, and interstices of boulder lags represents bed load that is being transported during high flows. These materials are rich in quartz and indicate that reworking of mine tailings continues to produce a high percentage of the sediment load in the basin.

6. Discussion

The high percent quartz in the 16–32 mm fraction of bed materials in the watershed indicates substantial volumes of sediment from mining are moving through the channel system. In Shady Creek, quartz concentrations in modern bed materials are so high that little other sediment could be present and reworking of sediment from mining must be the dominant sediment source. In other tributaries, such as Kentucky Creek, no hydraulic mining occurred or, if it occurred, the deposits may now be relatively stable. In the main South Yuba channel, textures and compositions of the bed sediment vary downstream with local hydraulic conditions. Yet, even in main channels within the mining districts, most sites have substantial proportions of sediment from mining in the fine-grained fraction, indicating that reworked mine tailings are now in transit. At least two sedimentary populations are present in these main-trunk samples: coarse lag and colluvial boulders that presumably move very little during typical annual floods, and fine-grained sediment from mining that is passing through the sections.

An enduring geomorphic concept that emerged from study of these deposits is G.K. Gilbert's (1917) symmetrical sediment-wave model. In this model, channel-bed elevation changes were specifically linked to sediment loads by likening the passage of sediment to the passage of a water wave. This model has been critiqued elsewhere and a revised skewed-wave concept has been proposed on the basis of observations in the Bear and American watersheds (James, 1989, 1997, 1999). Yet, the symmetrical wave has not previously been evaluated in the Yuba River where it was largely derived. Here, too, the concept that bed elevations provide a reliable measure of sediment loads is found to be in need of revision for the same reasons. First, in many South Yuba tributaries the storage and remobilization of sediment from mining continues in contrast to predictions of the symmetrical sediment-wave model. Second, the symmetrical wave model was based on the elevations of low flows on the channel bed at sites where channel-bed scour would be encouraged; either narrow gorges (Fig. 17) or leveed channel reaches. Finally, the elevation of the channel bed is a poor surrogate for sediment loads even in unbiased locations when sedimentation has occurred beyond the inner channel. The longitudinal profiles of severely aggraded channels tend to regrade long before sediment loads return to pre-aggradation levels. After channels incise, they

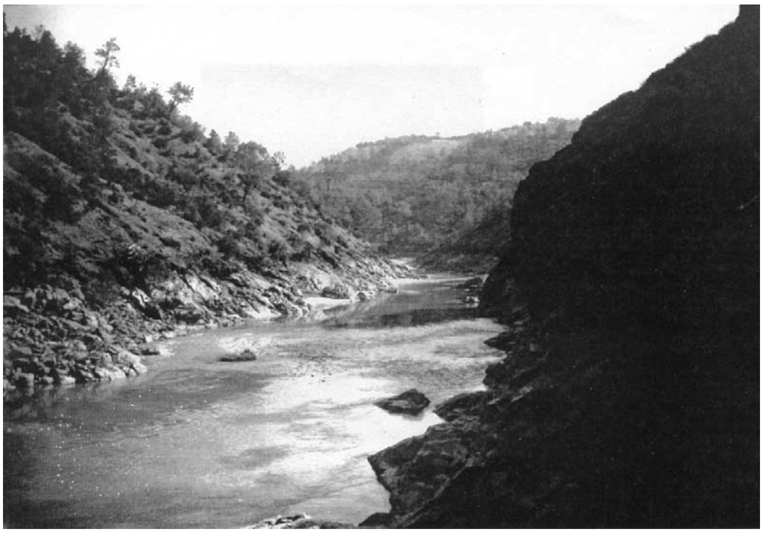

Fig. 17. View upstream on Yuba River through Englebright reservoir site "from a point 1 mile above the mouth of Deer Creek." Shows lack of sediment storage sites. Shoals in channel bed indicate on-going transport of sediment through the reach presumably dominated by contemporary or reworked sediment from mining. This site has been under water for 60 years. Photograph from U.S.G.S. Field Records Library. G.K. Gilbert collection; Photograph #3244.

continue to widen and rework sediment stored in floodplain and terrace deposits, thus maintaining elevated sediment loads. Yuba River channel beds rapidly returned to pre-mining elevations, but sediment loads have not returned to pre-mining levels. The mobility of sediment from mining is clearly indicated by the texture and lithology of bed materials throughout the mining districts. This and the obvious field evidence of sustained reworking of mine tailings in Scotchman, Spring, and Shady Creeks should not be overlooked.

Uncritical acceptance of the symmetrical-wave model would have several implications to the Englebright study. Implicit assumptions that most sediment from mining remaining in the watershed above Englebright Reservoir has been removed by erosion or permanently stored, would lead to the erroneous conclusion that the only sediment from hydraulic mining of relevance is now stored within Englebright Reservoir. Fortunately, the UYRSP has initiated a suspended-sediment monitoring program by the U.S. Geological Survey at Jones Bar that will allow first approximations to be made of fine-sediment loadings in the basin. Unfortunately, no funding exists for sampling bed load that is likely to be a major component of the total sediment load. The reservoir sediment-coring program will be crucial for determining sediment loads to Englebright Reservoir and for calibrating the sediment model being developed for the UYRSP. Given limited temporal and spatial resolutions of core data, however, uncertainty will likely require some subjective interpretations of the stratigraphic record for the last few decades. Thus, an understanding of the long-term dynamics of watershed processes over the past 62 years will be important and should consider the complex history of 19th and 20th century hydraulic mining and tailings stored in the upper tributaries.

7. Conclusions

CalFed is undertaking an elaborate, sophisticated study of the feasibility of altering or removing Englebright Dam. The potential rewards are extremely high: restoration of the salmon fishery in the Central Valley. The potential dangers are also extremely high: unleashing large volumes of possibly toxic sediment or reestablishing a salmon fishery only to find that spawning gravels are not sustainable. In addition to storage of vast volumes of sediment produced by 19th century mining, numerous small dams were built and filled with sediment after 1893. Unfortunately, neither the locations of the 20th century detention structures nor the volumes and chemistry of hydraulic gold-mining sediment they store have been mapped or inventoried. Where or how much sediment from mining remains in these tributaries is not known, and an inventory of the dams and deposits is greatly needed. Lamentably, little historic research exists on 20th century hydrologic changes in the Yuba basin. Gilbert's (1917) field observations in the Yuba watershed from 1905 to 1909 provide crucial contemporary documentation of the period but follow-up studies are needed.

The hydraulic-mining sedimentation history of the basin is complex and on-going. A pervasive modern belief in the region is that hydraulic gold mining ended in 1884 with Judge Sawyer's injunction and that the sediment from that period is now either gone or permanently stored. These assumptions are false. Field evidence shows that large volumes of tailings remain in upland tributaries, and CDC (nd) documents show that mining, dam construction, and local sediment storage was active in the Yuba watershed from 1893 to 1950. While 20th century hydraulic mining produced only a small percent of the historical sediment in the Yuba basin, construction of dams was required for the on-site retention of sediment, and the use of mercury was widespread. In some cases (e.g., Scotchman Creek), dams built during this period contain large reservoirs of mine tailings that are known to be actively eroding. Some of the dams plugged tunnels to allow storage of tailings in abandoned hydraulic mines where wetlands may now be sites of mercury methylation. For example, between 1894 and 1898 at least 679,000 m^3 of tailings were stored on the floor of the Manzanita Mine that now holds a large pond–wetland complex.

The on-going production of sediment from mine tailings is relevant to Englebright planning options through current and projected sediment loads, maintenance of salmonid spawning gravels in the upper river, and potential mercury toxicity. Field samples of bed material indicate that sediment from mining continues to move through the basin. Long-term storage of fine-grained sediment in main channels of the South and Middle Yuba has been negligible for almost a century (Gilbert, 1917), so it has been common to underestimate long-term storage and remobilization of mine tailings in remote tributaries of the watershed. Storage is substantial in some tributaries, however, and reworking of these deposits appears to be an important source of sediment. Furthermore, these sediment deliveries may be the primary source of fine gravel essential to spawning in main channels, and as these supplies are reduced through time habitats may decline. In other words, distinguishing between background sediment characteristics and contributions from mine tailings is essential to addressing questions of habitat sustainability. More research is needed on the importance of reworked tailings to spawning gravels in main channels.

Given the rapid historical changes to sediment deliveries and the apparent importance of reworked tailings to current spawning habitats, the feasibility of changes to Englebright Dam rests not only on the impacts of releasing sediment stored in the reservoir and current sediment loadings in the watershed. Feasibility of establishing a sustainable salmon fishery may also rest on the long-term dynamics of sediment production from tailings stored in the upper watershed. These dynamics include the potential long-term decline of fine spawning-gravel supplies as tailings are depleted as well as potential impacts of episodic releases from these sources if small orphan detention dams fail. The impacts of an episodic release of tailings may come as a brief but damaging flux of fine sediment or the permanent loss of a perennial source of fine gravel that could be important to entire reaches of the main channel. Where sediment-detention structures or tailings remain in the upper watershed, the potential for dam failure or sediment depletion and the impacts should be assessed. Dam remediation or stream restoration plans should be considered to remove, repair, or maintain small, poorly maintained, orphan dams filled with tailings (e.g., the breached log-crib dam and concrete dam on Scotchman Creek). These plans should consider not only the disposal or stabilization of sediment, but also the maintenance of gradual sediment releases to sustain spawning habitat. Such decisions need to be developed and coordinated with geochemical and biological studies that integrate findings of sediment toxicity and decisions about developing salmonid fisheries that may depend on sediment releases from these sites.

Managing this sediment system would be considerably easier if sediment from hydraulic mining could be conceptualized by a simple symmetrical sediment wave; that is, if reworking of tailings stored in the upper basin could be ignored and present sediment production rates could be assumed static. Unfortunately, neither the processes nor the history of sediment production in this watershed are simple, and management options must account for complex dynamics of a changing system.

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