SUSTAINED REWORKING OF HYDRAULIC MINING SEDIMENT IN CALIFORNIA: G. K. GILBERT'S SEDIMENT WAVE MODEL RECONSIDERED

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Abstract. Hydraulic gold mining in the Sierra Nevada, California (U.S.A.) generated large volumes of sediment in the 19th century. Probing indicates that vast mining sediment volumes remaining in the lower Bear Basin are twice previous estimates. Topographic surveys document several meters of mining sediment erosion in the basin following a 1986 flood. The continued storage and mobility of sediment in the basin indicate increased sediment loads over pre-mining levels and call for reevaluation of Gilbert's symmetrical sediment wave model. In basins where channel storage is substantial, a sediment wave should be right-skewed in respect to time due to protracted sediment releases from easily eroded, unconsolidated deposits.

Citation: James, L. A. 1993. Sustained reworking of hydraulic mining sediment in California: G. K. Gilbert's sediment wave model reconsidered. *Zeitschrift für Geomorphologie*, N. F.; Suppl.-Bd. 88: 49-66.

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Introduction

The long-term storage of sediment is of interest to engineers and geomorphologists because it has great bearing upon both sediment budgets and channel morphology. In addition, it is becoming increasingly clear that sediment storage represents a potential reservoir of toxic wastes that can be reintroduced to the environment during periods of channel erosion (GLYMPH and STOREY 1967, PHILLIPS 1986). The importance of sediment storage to sediment budgets is immediately apparent when the sediment mass balance equation is examined in its most elemental form:

$$I = O + \delta S \qquad \text{(eq. 1)}$$

where I is sediment input, O is sediment output, and δS is change in storage (DIETRICH & DUNNE 1978, SWANSON & OTHERS 1982). Many denudation studies assume that δS=0, although analyses of sediment delivery ratios have long indicated that this is not a rigorous approach (MANER 1958, ROEHL 1962, GLYMPH 1975, TRIMBLE 1975, 1977, DENDY & BOLTON 1976). In fact, the storage of sediment in channel systems is a critical component of the sediment budget over various time scales and accounts for sediment delivery ratios both less than and greater than unity (ANDERSON 1975, MEADE 1982, 1988, BERGSTROM 1982; WALLING 1983, 1988, KNOX 1989). Sediment storage is particularly important in studies of modern sediment yields due to accelerated rates of production by human activity (DOUGLAS 1967) and the high proportion of this sediment that is stored on floodplains. On Holocene time scales, large volumes of fluvial sediment storage resulted from land use changes in Europe (MACKLIN & LEWIN 1986) and in post-Columbian North America (KNOX 1972, 1977, TRIMBLE 1974, COSTA 1975). On very short time scales, storage has been related to channel morphology and sediment budgets in urbanizing channels (WOLMAN 1967), to seasonal sediment budgets on the Amazon River (MEADE & OTHERS 1985), and to exponential decreases in sediment loads in channels of experimental watersheds (SCHUMM, MOSLEY, & WEAVER, 1987:94). These realizations call for a reevaluation of a classic model of the transport of episodically introduced fluvial sediment.

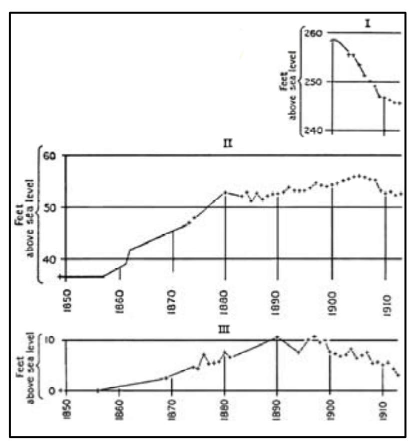
Gilbert's Sediment Wave Model

The renowned geomorphologist, G. K. Gilbert, published a brilliant and comprehensive analysis of the nature, extent, and behavior of historical sediment in the Sierra Nevada in which he advanced a conceptual model of sediment transport as similar to a water wave:

> *'The downstream movement of the great body of debris is thus analogous to the downstream movement of a great body of storm water... The debris wave differs from the water wave in ...that part of its overflow volume is permanently lodged outside the river channel.'* (GILBERT 1917:30)

This model was derived primarily from time series plots of channel low flow bed elevations (Fig. 1). Gilbert (1917:36,46) understood the importance of sediment storage to the attenuation of sediment waves and considered most of the valley and canyon deposits of the mountains to be temporary, even coarse material (p.28). The permanent deposits he described were largely in low gradient portions of the lower Sacramento River, in bays near San Francisco, and near the mines (Gilbert 1917:27,46). Gilbert predicted the rapid depletion of most mining sediment stored in the mountains other than that which could be regarded as permanently stored:

> *"After the lapse of, say, 50 years the annual tribute to the streams from both [piedmont and upland valley] deposits will have become so small that what then remains may be regarded as permanent."* (GILBERT 1917:67)



[Figure 1. Gilbert's (1917) sediment waves.]

From the prediction of rapid depletion of stored mining sediment arose the logical corollary that sediment loads would rapidly return to levels somewhat independent of mining sediment. Gilbert anticipated substantial sediment contributions from non-mining sources, however, and predicted future background sediment loads would be about four times greater than pre-mining levels due to these other anthropogenic sources:

> *"The additions to the débris output made by industries other than mining consist largely of soil waste, which is dominantly of fine grain... much of the finer material from mining went immediately to the bays and inundated lands, and that which rested by the way and is still in transit is dominantly coarse. As the stores of mining débris are gradually depleted the supply of coarse débris to the Sierra rivers will diminish, but there will be less change in the supply of fine débris."* (GILBERT 1917:64)

> *"[Loads of valley rivers], destined to diminish for some decades, will then have become practically constant but will be much larger than it was before the settlement of the country. Having formerly amounted, perhaps, to 2,000,000 yards annually, it will have a future average of not less than 8,000,000 yards. Assuming that a period of 50 years will close, for the rivers, the history of the hydraulic mining débris of the last century, we may now estimate for that period the rivers' entire work of transportation."* (GILBERT 1917:67)

It is clear from Gilbert's writings that, aside from this addition of post-mining sediment, he anticipated a depletion of the mining sediment within about 50 years. These predictions imply that sediment waves are symmetrical in respect to time insofar as the rate of return of sediment loads to pre-event levels is not greatly dissimilar to the rate of increase in loads from the onset of the event to peak levels. Thus, Gilbert's model will be referred to henceforth as the *symmetrical wave model*.

Gilbert may never have intended this symmetrical model to be rigorously employed as a general geomorphic law. As a pioneer in channel hydraulics, he understood the web of variables controlling channel incision (PYNE 1975, CHORLEY & BECKINSALE 1980). In fact, he advocated the construction of levees to promote channel incision (GILBERT 1917:26,31). The continued appearance of the model (LEOPOLD, WOLMAN, & MILLER 1964; GRAVES & ELIAB 1977) and the implications it has on sediment residence times call for a reexamination of the model's empirical basis. Derivation of the symmetrical sediment wave model assumes that bed elevation is proportional to sediment load. Basic hydraulic principles, many of them advanced by GILBERT (1914), however, indicate the involvement of other variables in relationships between bed elevation and sediment load (LEOPOLD & MADDOCK 1953). Bed elevations can change not only as channel depth and slope respond to sediment loads, but also in response to changes in channel width, roughness, plan-form, stream power, sediment caliber, etc. Channels of the Sierra Nevada foothills were hydraulically altered in ways that encouraged channel incision. Levee construction around Marysville and Sacramento (gage locations that established the empirical basis of Gilbert's model) encouraged channel incision by decreasing width, roughness, and sinuosity, and increasing depth. Thus, channel incision at these sites was encouraged independently of sediment loads and does not bear unbiased evidence of a return to sediment loads to pre-mining levels (JAMES 1989).

The symmetrical wave model also has implications toward delivery ratios of the hydraulic mining sediment. Sediment delivery ratios (D) are calculated as:

$$D = Y \cdot P^{-1} \qquad \text{(eq.2)}$$

where Y is sediment yield at the basin mouth and P is sediment production in the basin (SCHUMM 1977:71). GILBERT (1917:36) produced a diagram of sediment production and deposition in the bays adjoining San Francisco Bay in which magnitudes are not specified, but which allow sediment delivery ratios to be estimated from areas under the curves (Fig. 2). The original plot of sediment deposition terminated at 1914, when Gilbert's diagram suggests about 58% of the sediment produced by hydraulic mining had been deposited in the bays. He estimated that less than two-thirds of the sediment produced was stored in major deposits:

> *"The estimates of the deposits in bays, of the deposits in the channels of valley rivers, and of the largest piedmont deposits have a basis of measurement, but these estimates together account for less than two-thirds of the entire amount of waste".* (GILBERT 1917:46)

The depositional plot is extended beyond 1914 as a symmetrical curve (Fig.2), based on (1) Gilbert's predictions that sediment not eroded within 50 years could be regarded as permanently stored, and (2) modern plots of channel bed elevations which show the return to pre-mining levels by 1950 (JONES 1967, GRAVES & ELIAB 1977). Under this assumption of a symmetrical sediment distribution through time, Gilbert's hypothetical plot suggests that (1) about 77% of the mining sediment produced would have reached the bays by 1950 and that the rest would be stored, and (2) about 23% of the hydraulic mining sediment produced in the Sierra Nevada during the 19th century would now be permanently stored upstream of the bays.

Objectives

This study of hydraulic mining sediment in the Bear River, a tributary basin to Gilbert's type locale, examines sediment storage and mobility more than 100 years after the introduction of more than 200 10^6 m^3 of hydraulic mining sediment.

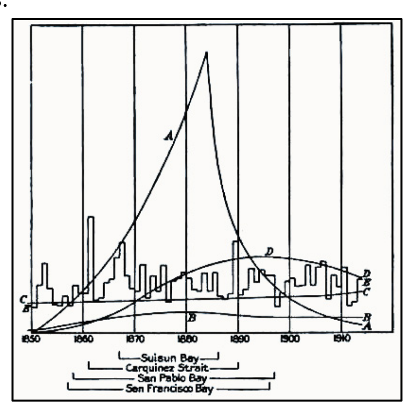


Figure 2. Gilbert's (1917) estimates of mining sediment production (A), soil erosion (B), fine-grained mining sediment not deposited on inundated lands (C), sediment delivered to bays (D), and relative precipitation (E).

The paper has three objectives. It documents the volume of sediment remaining in the lower Bear River California, it documents sustained sediment reworking and channel adjustments in the upper basin, and, based on these observations, it proposes a revision of G.K. GILBERT's (1917) symmetrical wave model. Sustained sediment storage and mobility is documented by several methods including subsurface coring, topographic surveys, repeat photography, and analysis of flood frequencies and bed material textures. These independent lines of evidence indicate not only that frequently occurring events are competent to move the mining sediment bed material, but also that vigorous reworking of the mining sediment is occurring. These results augment preliminary findings of an earlier report that very large volumes of sediment remain in the basin and continue to be mobilized (JAMES 1989). This paper concentrates on patterns of storage through time, although spatial patterns of storage are equally important (GRAF 1982, 1983).

Study Basin Characteristics

The Bear River drains a basin of about 1300 km^2 in the northern Sierra Nevada of California at around 39ºN latitude, 120ºW longitude (Fig. 3). The river flows out of steep canyons from the Sierran foothills into low alluvial plains of the Sacramento Valley, where it joins the Feather River, then the Sacramento River, and ultimately flows into the San Francisco Bay. The Yuba River, studied extensively by Gilbert, is a larger basin adjoining the Bear basin to the north. The longitudinal profile of the Bear River has a double concatenary curve, so sediment is stored in two low-gradient zones: (1) just below the mining districts and (2) in the lower basin. Little mining sediment was ever stored in the steep upper or middle reaches of the basin.

Pre-Mining Channels and the Sediment Influx

Evidence of pre-mining conditions and the timing of sedimentation is found in testimony given during litigation over mining in the Bear River (KEYES *VS*. LITTLE YORK *ET AL*. 1878) and by government surveys by the State Engineer (HALL 1880) and the U.S. Army (MENDELL 1882, TURNER 1891). Pre-mining mountain channels were steep and dominated by bedrock and colluvium, and high energy flows were competent to move as much fine, unconsolidated sediment as was normally produced in the basin (GILBERT 1917:15). Prior to deposition of the mining sediment, fine gravel was found only in 'small bars, rarely more than a few feet wide, and not over two feet [0.6 m] deep' (WISTAR 1914, cited by LLOYD 1985).

Hydraulic mining, which uses water under pressure, was invented in the South Yuba and Bear River basins beginning in 1853 (MAY 1970, ROHE 1985). The technology evolved from ground sluicing, the practice of using flowing water under atmospheric pressure, that dates to classical antiquity (MAY 1970). By 1860, several hydraulic mines were operating in the basin, and large deposits were already present in tributaries draining the mines. Sediment deliveries greatly exceeded the capacity of channels to carry their load, and channels aggraded with relatively fine-grained material. There were no major floods between 1848 and 1861, but an extremely large 1862 flood flushed 10 years of mining sediment out of the tributaries:

"Placer mining had been prosecuted by thousands of miners for 13 years, and the gulches and water courses of the foothills had been receiving deposits of gravel and sand all these years, and particularly in the first five or six years succeeding the discovery of gold. In all these years there had been no great flood. The prolonged and excessive high-water of 1862 brought down such masses of material that they could not escape observation. This flood was succeeded by others at intervals of six or seven years..."
(MENDELL 1881:2489)

Rates of main channel sedimentation accelerated in the 1870's, and by 1874 Bear River channels at some mountain sites had filled to nearly 24 m in the center, burying all but the tallest trees (Photo 1) (WHEATLAND FREE PRESS, Nov.21, 1874). Altimeter readings at two sites in the Bear River mining districts, made in 1870 and again in 1879, document 30 and 42 m of aggradation in 9 years, or 3.3 and 4.7 m yr^{-1}, respectively (WHITNEY 1880). These depths are minimums that must be added to depths of sediment already deposited by 1870, estimated to have been between 15 and 23 m (WHITNEY 1880:159).

Hydraulic mining was essentially enjoined in 1884 and had virtually ceased in the Sierra Nevada by 1890. Although licensed mining resumed on a small scale from 1893 to 1935, the total volume of sediment produced during this period was less than 2% of the volume produced earlier (JAMES 1988). Decreased sediment production after 1884 was accompanied by rapid channel incision in the mining districts along the Bear River and its two main tributaries, Steephollow and Greenhorn creeks, but channels tended to aggrade near confluences of these two creeks with Bear River (TURNER 1891). Channel elevation changes between 1880 and 1890 are summarized by an 1890 longitudinal profile superimposed on earlier profiles (Fig. 4). *Tailing fans* formed graded dams on main channels where tributaries, heavily laden with sediment from the mines, entered main valleys. Tailings fans, shown at Dutch Flat Canyon and at the Polar Star Dumps as bulges on the 1878 profile, had incised by 1890 and are locations of maximum vertical channel incision.

There is little record of conditions in the Bear basin since the turn of the century. Gilbert's field work around 1908 was concentrated in the Yuba basin where he concluded that sediment yields were primarily from upland creeks (GILBERT 1917):

"As a whole the dumps have yielded and are still yielding a large annual tribute to the streams... Drifting forward from the dumps... a large amount of débris gathered in the valleys of the upland creeks. This material is being fed to the rivers gradually and is perhaps at present the chief source of the rivers' supply of débris. The excavation of such deposits leaves a terraced valley, and as the stream works down toward its original channel, patches of terrace are here and there stranded on the slope in such positions as to be exempt from further attack..." (GILBERT 1917:27)

Gilbert's observations in the Yuba basin of depleted deposits in main channels and of tributary deposits soon to be isolated, and his documentation of rapid main channel incision in the Sacramento Valley led him to conclude that mining sediment that was not rapidly transported out of the mountains would be "permanently" stored. This paper will now examine the extent of deposits remaining in the Bear River basin and evidence that these deposits are being reworked.

Deposits in the Lower Bear River

Depths and volumes of the mining sediment deposit remaining in the lower Bear basin were determined by subsurface probing and soil maps using procedures elaborated elsewhere (JAMES 1989). The deposit was hand cored with a 2 cm diameter probe along 3 transects, and the surface topography was surveyed along these sections with rod and level. The resulting vertical sections (Fig. 5) reveal depths of aggradation ranging up to 5.1 m. The sections also reveal the nature of a well-documented channel avulsion from the county line to the present channel location between large levees.

Mean depths of mining sediment deposits were calculated as the ratio of cross-section area to top width. The surface area of mining sediment remaining in the lower basin was determined to be 50.1 km^2 from soils maps. The product of surface areas and mean depths of sections indicates that 106 million m^3 of historical sediment remains in the lower basin, more than double previous estimates (MENDELL 1880, GILBERT 1917, *cf.* JAMES 1989). Thus, the lower Bear River deposits support Gilbert's hypothetical model (Fig.2) insofar as there has been extensive long-term sediment storage upstream of the bays. Conversely, the prediction that mining sediment would be eroded or permanently stored by this time, is not born out by the lower Bear River data. Much of the lower Bear sediment is protected from erosion by levees, but substantial lateral channel migration has been observed in at least two channel reaches. Channel scour along a cross-section near the old Fort Camp Far West is documented by a pair of topographic surveys made in 1985 and in 1989 (Fig. 6). A 35 m wide terrace of mining sediment was eroded from this site exposing the underlying pre-mining surface, as is evidenced by exposure of roots of exhumed old tree stumps in the channel bed. Persistent reworking of mining sediment deposits by channel lateral migration in the lower Bear represents a substantial augmentation of local sediment production rates over pre-mining levels.

Upper Basin Deposits

Immense deposits of mining sediment remain in the upper basin in terraces and where tributaries draining the mines join main channels (Photo 2). A considerable body of field evidence of recent erosion and deposition in the upper basin, detailed by JAMES (1989), includes progradation of deltas in reservoirs, lack of mining sediment dilution with other sediment, terrace scarp retreat, competence of flows to entrain mining sediment bed material, and channel scour and fill. Terrace scarp retreat is indicated by active gullies, caving of trees, and by repeat photography (Photo 3). Mining sediment continues to be delivered to main channels by hillslope processes acting on stored sediment along channels.

Moderate magnitude flows are competent to easily entrain mining sediment bed material as was shown by flood frequency analysis and calculation of critical discharges (JAMES 1989). In short, talweg depths of critical flows (D_{max}) were calculated from coarse bed material textures (D_{mm}) using an empirical formula based on dimensionless slope (S) and particle size (KNOX 1987):

$$D_{max} = 0.0001\ D_{mm}^{1.21}\ S^{-0.57} \qquad \text{(eq.3).}$$

This formula is a hybrid of the BAKER-RITTER (1975) formula, but it incorporates slope as an independent variable. The coarsest 90% on cumulative frequency distributions of intermediate axis dimensions (D_{90}) was used for particle size and valley bottom topographic slope for energy slopes. Critical discharges (Q_c) were calculated using the Manning equation:

$$Q_c = A\ n^{-1}\ R^{0.67}\ S^{0.5} \qquad \text{(eq.4)}$$

where A is channel cross-section area and R is hydraulic radius, both determined by plotting D_{max} on channel cross-sections derived from topographic surveys. Manning roughness values (n) were determined from particle size distributions with an equation by LIMERINOS (1969). Critical discharges, calculated at 4 sites dominated by mining sediment and at 3 sites with mixed populations, are plotted against drainage area on figure 7.

A three-parameter lognormal frequency analysis of annual maximum floods at five gages in the basin estimated magnitudes of 2-, 5-, and 10-year floods. Curves drawn through these estimates (Fig.7) indicate that 2-year floods should be competent to move the coarsest 10% of bed material at all 4 sites dominated by mining sediment. The competence of frequently occurring events to move the mining sediment represents a substantial increase in sediment yields over pre-mining conditions when channels were dominated by bedrock and coarse lag materials.

The surface topography of deposits was surveyed in 1985 at several sites to document the geometry of deposits. Plots of these surveys graphically depict the area of sediment exhumed from cross-sections and suggest the large magnitude of sediment remaining in the subsurface and along valley walls (Fig.8). Terrace heights range up to 30 m above the channel bed in places, but depths of fill remain unknown. Channel cross-section surveys were repeated in 1989 to document areas of eroded mining sediment. Preliminary analysis of two channel cross-sections reveals considerable erosion at both sites (Fig.8). Erosion greatly exceeded deposition which reached a maximum of only 11 m^2 at Red Dog Ford where 46 m^2 was eroded (Table 1). There was no measurable deposition at the Buckeye Ford section which experienced a loss of about 83 m^2 of mining sediment from across the entire channel bed. These two sections are representative of the erosion along Greenhorn Creek, and multiplication of these net erosion areas by channel lengths documents a tremendous volume of eroded sediment.

The observed erosion is probably attributable to a large flood in 1986. Three-parameter lognormal probability analyses of annual maximum flood series data indicate that the 1986 flood was a relatively rare event in the lower basin, but not in the mountains. The recurrence interval of the 1986 flood at Wheatland (drainage area 756 km^2) was about 97 years, but the flow at the Rollins gage (272 km^2) had a recurrence interval of about 37 years (n=22). Further upstream on the Bear River (32 km^2) the 1986 flood was not an infrequent event, but had a return period of 5 years and ranked 4th on the annual maximum series (n=20). In spite of the frequent return period of floods the magnitude of the 1986 flood in the upper basin, much alluvium was clearly reworked. Channel erosion and incision in response to this moderate magnitude event represents the down-valley movement of a volume of sediment probably much greater than the dimensions of erosion documented by the cross-sections in Fig. 8.

Skewed Sediment Waves

These observations of sustained sediment storage and transport suggest that the timing of sediment transport in the Bear River has not conformed to Gilbert's symmetrical wave model. The considerable literature outlined in the introduction documents the importance of channel storage and argues that much sediment along channel margins is not stored permanently. The episodic introduction of large sediment volumes into a high energy, bedrock-dominated channel system augments sediment supplies until the stored sediment is depleted.

Sedimentation events have been likened to storm hydrographs in which *sedigraph peaks* derived from pulses of sediment are superimposed onto a *base sediment yield* contributed by relatively constant sediment production sources (SCHUMM, MOSLEY, & WEAVER 1987:74). Sediment hydrographs, or *sedigraphs*, are highly variable in shape and configuration due to the same large number of factors controlling storm hydrographs, as well as additional complications introduced by lag times between peak water discharge and peak sediment load (MARCUS 1989), greater measurement error (WARD 1984), and the importance of long-term storage (topic of this paper).

Several workers have implicitly or explicitly viewed depletion of sediment storage as an asymptotic process (KNOX 1972, SCHUMM, MOSLEY, & WEAVER 1987:94, JAMES 1989). GRAF (1977) has pointed out the existence of a theoretical framework for this phenomenon in the form of the *rate law*, whereby available energy and sediment return to pre-event levels at an ever-decreasing rate, much like isotopic half-lives. If this hypothetical relationship is correct, then decreases in sediment loads through time can be modeled as negative exponentials. Regardless of the particular mathematical function that proves appropriate for a given sediment pulse, it is likely that sediment waves in channels where sediment storage is substantial will be right-skewed in respect to time.

Sediment wave skewness also affects sediment delivery ratios which are used to calculate sediment yields and basin erosion, or to route sediment (BOYCE 1975). Sediment delivery estimation methods are based on the relationship between sediment delivery ratios and drainage area in a basin (PIEST, KRAMER, & HEINEMANN 1975, RENFRO 1975). Equation 1 indicates, however, that non-constant changes in storage through time will lead to shifts in the ratio of sediment output to input which is proportional to the sediment delivery ratio. Clearly, more research is needed to document the relationship between (1) the nature of sediment storage and production, and (2) the degree of skewness in the resulting sediment pulse.

Initial field work in the South Yuba Basin, where Gilbert conducted much of his field work, indicates much less storage in that basin than in the Bear Basin. Sediment storage and remobilization are substantial in some tributaries, but unlike the Bear River, main channels of the South Yuba are completely stripped of mining sediment and apparently never stored large quantities. Thus, the volume and longevity of mining sediment channel storage vary greatly between adjacent basins of the Sierra foothills. Differences in basin properties that explain these variations also determine sediment delivery ratios at a given time and sedigraph characteristics including skewness. Factors that determine sediment storage potential over a centennial time period are the subject of on-going research in the Sierra Nevada, California.

Conclusion

A large volume of mining sediment remains in the Bear River. About 106 million m^3 remain in the lower Bear basin, more than double previous estimates. These deposits cover 50 km^2 at mean depths from 2 to 3 m. In the upper basin a large, unknown mining sediment volume remains and is being reworked by moderate magnitude floods. Erosion, deposition, and high sediment mobility are shown by terrace scarp erosion, competency of frequent flows to entrain mining sediment bed material, and erosion at cross-sections documented by repeated surveys bracketing a four-year period during which a moderately large flood occurred.

Pre-mining channels of the upper basin were dominated by bedrock, so the high rates of sediment production documented here indicate that sediment loads have not returned to pre-mining levels. Gilbert's symmetrical wave model is inappropriate for the Bear River due to this sustained reworking of mining sediment stored in and along the channels. A skewed wave model recognizes the importance of channel storage to long-term sediment loads and implies that effects of episodic or cyclic sedimentation events in fluvial systems can be persistent.

Acknowledgements

I thank Laurence B. James for encouragement, field assistance, and logistic support. Dan Sarlitto and Bob Wilson assisted with field work. The University of South Carolina Cartography lab helped with graphics and photographic reproductions. This research was made possible, in part, through National Science Foundation grant #SES-8822436.

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References Cited

ANDERSON, H. W. (1975): Relative contributions of sediment from source areas and transport processes. - [In] Present and Prospective Technology for Predicting Sediment Yields and Sources: 66-73. Wash., D.C.: Agric. Res. Serv. Pub. ARS-S-40-61-65.

BAKER, V. R. & RITTER, D. F. (1975): Competence of rivers to transport coarse bedload material. - *Geol. Soc. Am. Bull.* **86**:975-978.

BERGSTROM, F. W. (1982): Episodic behavior in badlands: Its effects on channel morphology and sediment yields. -[In] SWANSON & OTHERS (Eds.): Sediment Budgets and Routing in Forested Drainage Basins: 59-66. U.S.D.A. Forest Serv., Pacific NW Forest & Range Exp. Sta. Gen. Tech. Rpt PNW-141.

BOYCE, R. C. (1975): Sediment routing with sediment-delivery ratios. - [In] Present and Prospective Technology for Predicting Sediment Yields and Sources: 61-65. Wash., D.C.: Agric. Res. Serv. Pub. ARS-S-40-61-65.

CHORLEY, R. J. & BECKINSALE, R. P. (1980): G. K. Gilbert's geomorphology. - [In] Yochelson, E. L. (ed.): The Scientific Ideas of G. K. Gilbert: 129-142. U.S. Geol. Surv. Spec. Paper **183**.

COSTA, J. E. (1975): Effects of agriculture on erosion and sedimentation in the Piedmont Province, Maryland. - *Geol. Soc. Am. Bull.* **86**:1281-1286.

DIETRICH, W. E. & DUNNE, T. (1978): Sediment budget for a small catchment in mountainous terrain. *Z. Geomorphol. Suppl.* **29**:191-206.

DENDY, F. E. & BOLTON, G. C. (1976): Sediment yield - runoff - drainage area relationships in the United States. - *J. Soil & Water Conserv.* **31**:264-266.

DOUGLAS, I. (1967): Man, vegetation and the sediment yields of rivers. - *Nature* **215**:925-928.

GILBERT, G.K. (1914): Transport of debris by running water. - *U.S. Geol. Sur. Prof. Paper* ***86***.

__ (1917): Hydraulic-Mining debris in the Sierra Nevada. - *U.S. Geol. Sur. Prof. Paper* ***105***.

GLYMPH, L. M. (1975): Evolving emphases in sediment-yield predictions. - [In] Present and Prospective Technology for Predicting Sediment Yields and Sources: 1-4. Wash., D.C.: Agric. Res. Serv. Pub. ARS-S-40-61-65.

GLYMPH, L. M. & STOREY, H. C. (1967): Sediment - its consequences and control. - *Am. Ass. Adv. Sci., Proc., Pub. 85*.

GRAF, W. L. (1977): The rate law in fluvial geomorphology. - *Am. J. Science* **277**:178-191.

__ (1982): Spatial variation of fluvial processes in semi-arid lands. - [In] THORN, C. E. (Ed.): Space and Time in Geomorphology: 193-217.

__ (1983): Variability of sediment removal in a semiarid watershed. *Water Res. Research* **19**:643-652.

GRAVES, W. and ELIAB, P. (1977): Sediment Study: Alternative Delta water facilities; Peripheral Canal Plan. *Calif. Dept. Water Resources, Central Div.*

HALL, W. H. (1880): Report of the State Engineer to the Legislature of California, Part II. Sacto., CA: Calif. Printing Office.

HEUER, W. H. (1891): Mining Debris California. House Doc. 267, 51st Congr., 2d Sess.

JAMES, L. A. (1988): Historical transport and storage of hydraulic mining sediment in the Bear River, Calif. Unpubl. *Ph.D. Diss., Univ. Wisc., Madison*.

__ (1989): Sustained storage and transport of hydraulic gold mining sediment in the Bear River, Calif. - *Annals Ass. Am. Geogr.* **79**: 570-592.

JONES, G. (1967): Alteration of the regimen of Sacramento River and tributary streams attributable to engineering activities during the past 116 years, Unpubl. paper. Am. Soc. Civil Engrs., Calif. State Archives.

KEYES VS. LITTLE YORK ET AL. (1878): Keyes *vs.* Little York Gold Washing Co. *et al*. *Calif. District Court, 10th Dist., Sutter Co.*

KNOX, J. C. (1972): Valley alluviation in Southwestern Wisconsin. - *Annals, Ass. Am. Geogr.* **62**:401-10.

__ (1977): Human impacts on Wisconsin stream channels. - *Annals, Ass. Am. Geog.* **67**:323-42.

__ (1987): Climatic influences on upper Mississippi Valley floods. - [In] BAKER, V. R., KOCHEL, R. C., & PATTON, P. C. (eds.): Flood Geomorphology.

__ (1989): Long- and short-term episodic storage and removal of sediment in watersheds of southwestern Wisconsin and northwestern Illinois. - [In] Sediment and the Environment: 157-164. Proc. Baltimore Symp., May 1989. Internat. Soc. Hydrol. Sci. Pub. **184**.

LEOPOLD, L. B. & MADDOCK, T., Jr. (1953): The hydraulic geometry of stream channels and some physiographic implications. - *U.S. Geol. Sur. Prof. Paper* ***252***.

LEOPOLD, L. B.; WOLMAN, M. G.; & MILLER, J. (1964): - [In] Fluvial Geomorphology. San Francisco: W. H. Freeman & Co.

LIMERINOS, J. T. (1969): Relation of Manning coefficient to measured bed roughness in stable natural channels. - *U.S. Geol. Sur. Prof. Paper* ***650-D***.

LLOYD, J. C. (1985): A forty-niner's account: Excerpts from the autobiography of Isaac Jones Wistar. *Calif. Geol.* **38**:273-281.

MACKLIN, M. G. and LEWIN, J. (1986): Terraced fills of Pleistocene and Holocene age in the Rheidol Valley, Wales. - *J. Quat. Sci.* **1**:21-34.

MANER, S. B. (1958): Factors affecting sediment delivery rates in the Red Hills physiographic area. - *Trans. Am. Geophys. Union* **39**:667-75.

MARCUS, W. A. (1989): Lag-time routing of suspended sediment concentrations during unsteady flow. - *Geol. Soc. Am. Bull.* **101**:644-651.

MAY, P. (1970): Origins of Hydraulic Mining in California. Calif.: Holmes Book Co.

MEADE, R.H. (1982): Sources, sinks, and storage of river sediment in the Atlantic drainage of the United States. - *J. Geol.* **90**:235-252.

__ (1988): Movement and storage of sediment in river systems. - [In] LERMAN, A. & MEYBECK, M. (Eds.):

Physical and Chemical Weathering in Geochemical Cycles: 165-179. Kluwer Academic Publishers.
MEADE, R. H., DUNNE, T., RICHIE, J. E., SANTOS, U.M., & SALATI, E. (1985): Storage and remobilization of suspended sediment in the Lower Amazon River of Brazil. - *Science* **228**:488-490.
MENDELL, G. H. (1880): Mining debris in Sacramento River. *House Doc. 69, 46th Congr., 2nd Sess*.
__ (1881): Protection of the navigable waters of California from injury from the debris of mines. *House Doc. 76, 46th Congr., 3rd Sess*.
__ (1882): Report upon a project to protect the navigable waters of California from the effects of hydraulic mining. *House Doc. 98, 47th Congr., 1st Sess*.
PHILLIPS, J. D. (1986): The utility of the sediment budget concept in sediment pollution control. - *Prof. Geographer* **38**:246-52.
PIEST, R. F.; KRAMER, L. A.; & HEINEMANN, H. G. (1975): Sediment movement from loessial watersheds. - [In] Present and Prospective Technology for Predicting Sediment Yields and Sources: 130- 141. Wash., D.C.: Agric. Res. Serv. Pub. ARS-S-40-61-65.
PYNE, S. (1975): The mind of Grove Karl Gilbert. - [In] MELHORN, W. N. & FLEMAL, R. C. (eds.): Theories of Landform Development: 277-298. Pubs. in Geomorph., Binghampton, N.Y.: St. Univ. N.Y.
RENFRO, G. W. (1975): Use of erosion equations and sediment-delivery ratios for predicting sediment yield. - [In] Present and Prospective Technology for Predicting Sediment Yields and Sources: 33-45. Wash., D.C.: Agric. Res. Serv. Pub. ARS-S-40-61-65.
ROEHL, J. W. (1962): Sediment source areas, delivery ratios and influencing morphological factors. - [In] *Internat. Ass. Hydrol. Sci. Publ. **59***:202-213.
ROHE, R. E. (1985): Hydraulicking in the American West: The development and diffusion of a mining technique. - *Montana, Mag. Western Hist*. **35**:18-35.
. - *Geogr. Annlr.,* **49A**:385-395.
SCHUMM, S. A. (1977): The Fluvial System. N.Y.: J. Wiley & Sons.
SCHUMM, S. A.; MOSLEY, M. P.; and WEAVER, W. E. (Eds.) (1987): Experimental Fluvial Geomorphology. New York: J. Wiley & Sons. 413 pp.
SWANSON, F. J.; JANDA, R. J.; DUNNE, T.; and SWANSTON, D. N. (Eds.) (1982): Sediment Budgets and Routing in Forested Drainage Basins. U.S.D.A. Forest Serv., Pacific NW Forest & Range Exp. Sta. Gen. Tech. Rpt PNW-141.
TRIMBLE, S. W. (1974): Man-induced soil erosion on the Southern Piedmont, 1700-1970. - *Soil Conserv. Soc. Am*.
__ (1975): Denudation Studies: Can We Assume Stream Steady State? - *Science* **188**:1207-1208.
__ (1977): The fallacy of stream equilibrium in contemporary denudation studies. - *Am. J. Sci.* **277**:876-87.
TURNER, F. C. 1891. Reports of Mr. F.C. Turner,.. of reconnaissance of Feather, Yuba, Bear and American rivers... and of deposits of mining gravel subject to hydraulic process... *House Doc. 1, Part 2, 52nd Congr., 1st Sess.*: 3041-3087.
WALLING, D. E. (1983): The sediment delivery problem. - *J. Hydrology* **65**:209-237.
__ (1988): Erosion and sediment yield research - Some recent perspectives. *J. Hydrology* **100**:113-141.
WARD, P. R. B. (1984): Measurement of sediment yields. - [In] HADLEY, R. F. & WALLING, D. E. (Eds.): Erosion and Sediment Yield: Some Methods of Measurement and Modelling: 37-70. Norwich, U.K.: Geobooks.
WHITNEY, J. D. (1880): The auriferous gravels of the Sierra Nevada. - *Memoir Museum Comp. Zoology* **6**:569.
WISTAR, I. J. (1914): Autobiography of Isaac Jones Wistar, 1827-1905; Half a century in war and Peace. N.Y.: Harper Bros. Pubs.
WOLMAN, M. G. (1967): A cycle of sedimentation and erosion in urban river channels