Sustained Storage and Transport of Hydraulic Gold Mining Sediment in the Bear River, California

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Abstract. Large deposits of hydraulic gold mining sediment remain in main channels of the Bear River more than 100 years after the cessation of mining. This study examines these deposits and reevaluates Gilbert's (1917) classic model of sediment transport in a symmetrical wave that is based on hydraulic mining sediment primarily in the Yuba Basin. Sustained storage and transport of hydraulic mining sediment in the Bear Basin are documented and a revised model of sediment transport is proposed.

In the lower Bear Basin, subsurface coring indicates that about 106 million cubic meters of mining sediment remain stored. This volume is more than double previous estimates of storage in the lower basin, and is greater than any previous estimate of storage in the entire basin, even though it excludes a large volume of mining sediment remaining in the mountains. More than 90 percent of the lower basin deposit remains in storage. In the upper basin, surface dimensions of the deposit, measured from cross-sections, reveal depths of erosion and the storage of an extensive but unknown volume of mining sediment.

Field and historical evidence is presented of the continued reworking of mining sediment. Frequent flows are competent to move channel-bed material derived from mining sediment. Sediment erosion, transport, redeposition, and lack of dilution document sustained remobilization of mining sediment. Sediment loads are now greater than pre-mining values, which were constrained by bedrock-dominated channels. This sustained transport is in contrast to Gilbert's symmetrical wave model that predicts a rapid return of sediment loads to pre-mining levels.

The empirical foundation of the symmetrical wave model is biased. Channel incision in the Sacramento Valley has been promoted by several factors in addition to decreased sediment loads and does not confirm the return of sediment loads to pre-mining levels. A revised, skewed sediment wave model is proposed for basins with a large component of long-term channel storage. This conceptual model is in better harmony with growing evidence of the importance of sediment storage in and near channels to long-term sediment loads. The persistence of anthropogenic sediment in fluvial systems may be much greater than implied by Gilbert's model.

Key Words: fluvial geomorphology, historical alluvium, placer gold, channel storage, stream pollution, Sierra Nevada, Gilbert's Sediment Wave Model.

IN the decades following the California gold rush, large volumes of sediment were deposited in stream channels of the Sierra Nevada foothills. This sediment was delivered to channels by the mining of placer deposits with pressurized water in conjunction with blasting. Channel aggradation caused by this hydraulic mining was so devastating to navigation and agriculture downstream that most hydraulic mining was enjoined in 1884 (Woodruff v. Bloomfield 1884; Kelley 1954). Sediment remaining in the system prompted the federal government to commission surveys in the late 19th and early 20th centuries (Mendell 1880, 1881; Heuer 1891) including the classic work of G. K. Gilbert (1914, 1917).

Movement of hydraulic mining sediment from the Sierra Nevada foothills through the Sacramento Valley into San Francisco Bay was interpreted by Gilbert (1917) as transport by propagation of a *sediment wave*. Gilbert's model and the evidence from which it was derived

Annals of the Association of American Geographers, 79(4), 1989, pp. 570–592

are evaluated here and contrasted with modern sediment studies and theories. Gilbert (1917) constructed three time series of low-flow stage elevations: for the Yuba River at Marysville, the Yuba River at the Narrows, and the Sacramento River at Sacramento (Fig. 1A). These low-flow stages were equated with channel bed elevations that were, in turn, equated with sediment loads at the respective gauging sites. Based on this evidence, Gilbert likened the movement of mining sediment to a series of storm water waves issuing from the various basins:

> "... the flood of mining débris is analogous to a flood of water in its mode of progression through a river channel. It travels in a wave, and the wave grows longer and flatter as it goes. Where the channel is too small to contain it, the water wave spreads out over adjacent lands, and the volume thus escaping from the channel is temporarily stored, so as to regulate the flow at points below. The débris wave differs from the water wave in the fact that part of its overflow volume is permanently lodged outside the river channel, and in the additional fact that the material of the wave is not homogeneous ..." (Gilbert 1917, 31).

Citation of Gilbert's data and wave model in prominent textbooks, papers, and planning studies warrants reconsideration of the concept and its empirical foundation (Mackin 1948, 488, 493; Lane 1955; Leopold et al. 1964; Meade 1982, 1984; Graves and Eliab 1977; Graf 1988). The implication that sediment loads rapidly return to pre-mining levels following episodic sedimentation is of particular concern. The distributions of low-flow stage elevations at Sacramento and the Narrows are nearly symmetrical in respect to time. This symmetry prompted Gilbert (1917) to predict a rapid passage of the Yuba River wave past Sacramento within about fifty years (*circa* 1967) and to predict a return of channels to approximately pre-mining conditions after most mining sediment was gone.

Two studies update Gilbert's low-flow stage data (Jones 1967; Graves and Eliab 1977) and document the return of channel beds to pre-mining elevations; the Sacramento River by 1930 and the lower Yuba River by 1950 (Fig. 1B). The latter study apparently accepts Gilbert's postulated sediment load analogy:

> "The hypothesis indicated by this plot is that the passage of mining sediment at these two river locations is directly related to the low water elevations ..." (Graves and Eliab 1977, 23).

Such reasoning implies that, following large ep-

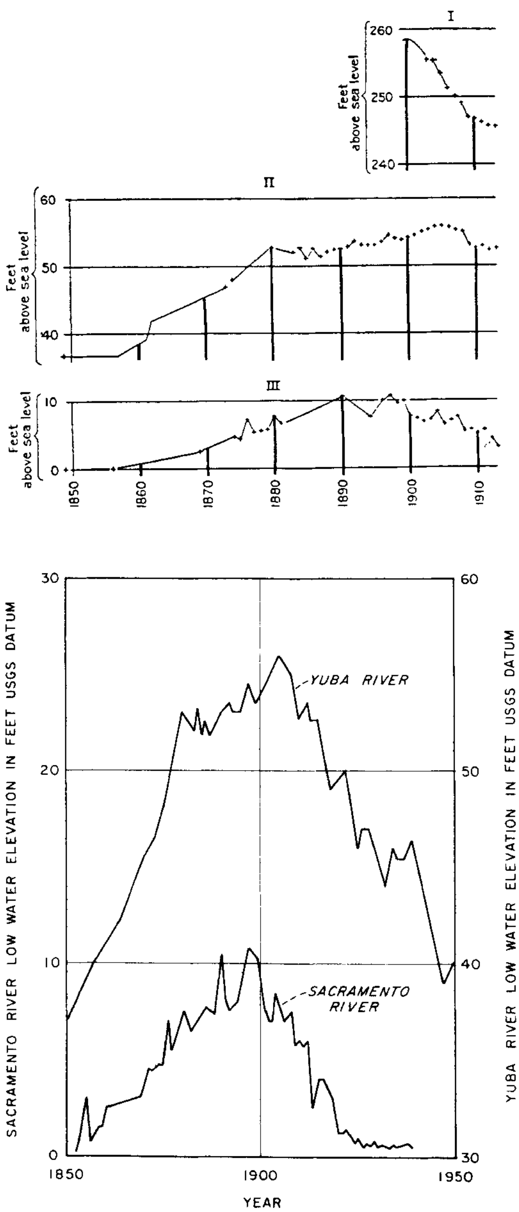

Figure 1. Time series of annual low-flow channel bed elevations. (A) Gilbert's (1917) original classic plot showing the Yuba River at the Narrows [I] and at Marysville [II], and the Sacramento River at Sacramento [III]. Gilbert inferred from these curves that sediment travels as a wave. (B) A recent time series plot for the Yuba River at Marysville and the Sacramento River at Sacramento. Graves and Eliab (1977) inferred from these plots that sediment loads have returned to pre-mining levels. Both figures are reproduced directly from the original government documents.

isodic sedimentation events, sediment loads will rapidly return to pre-event levels. There are two areas of potential misunderstanding in these interpretations. First, decreased sediment loads since the 1930s at these sites are due in large part to detention of sediment behind dams and levees. This is acknowledged by both modern reports but must be considered for a general geomorphic or sediment transport model. Second, equating sediment transport rates with bed elevations is of questionable validity. Low-flow stage is a valid proxy for channel bed elevation if water depth remains constant, but changes in channel bed elevation are not necessarily proportional to sediment loads.

Recovery of channel bed elevation or other forms of channel morphology does not necessarily represent return of sediment loads to pre-mining levels. Channel morphology tends toward a stable model state through the mutual adjustment of a number of variables in addition to sediment load, including channel width, depth, velocity, roughness, slope, and planimetric form (Leopold and Maddock 1953). These hydraulic variables were not held constant in Sacramento Valley channels during or after the mining era. Levees were constructed and enlarged throughout the Sacramento Valley during this period (Gilbert 1917, 26), particularly near the stream-flow gauges at Sacramento and Marysville (Kelley 1956). Levees resulted in straighter, smoother channels with increased flow depth, competence, and capacity. Thus, incision of Sacramento Valley channels to pre-mining levels at these stations is a biased indicator of sediment loads that does not prove a symmetrical distribution of sediment loads through time. The complex interrelationship between hydraulic parameters and channel morphology (including predicted effects of levees) was fully appreciated by Gilbert (1914, 1917, 28), who may not have intended the symmetrical sediment wave model to be rigorously applied. Modern citations of the model, however, often attribute considerable validity to the concept without examining the underlying assumptions.

In its present form, Gilbert's symmetrical wave model implies a rapid return of sediment loads to pre-event levels. A growing body of evidence from modern studies in many basins, however, demonstrates that sediment storage and remobilization is an important component of sediment transport on a variety of time scales and in a wide range of environments. Although exceptions have been noted (Lambert and Walling 1986), sediment transport in most fluvial systems is intermittent with temporary storage playing a vital role in the conveyance of alluvium (Roehl 1962; Hadley and Shown 1976; Schumm 1977; Walling 1983; Miller and Shoemaker 1986). In fact, sediment in most channel systems spends much more time in storage than in transport (Meade 1982) which results in decreasing sediment yields and delivery ratios in the downstream direction (Hadley and Schumm 1961, 182; Boyce 1975; Robinson 1977; Knox 1979a, 29; Walling 1983).

Sediment yields in large basins are dependent in large part upon remobilization of the sediment stored in and near channels. On average, channel erosion provides an estimated 26 percent of the total sediment load in streams of the United States (Robinson 1977). For example, a large volume of 19th-century anthropogenic sediment deposited in North American stream channels is now subject to erosion by lateral planation and gullying (Trimble 1974; Knox 1977, 1987a; Barnhardt 1988). Although long-term sediment yields generally decrease downstream due to net storage, this trend can reverse at times when upland sediment sources stabilize and channels begin to erode. During such periods sediment production can be greater from main channels than from uplands (Johnson and Hanson 1976).

These recent studies of protracted sediment storage and mobility are in direct contradistinction to the rapid relaxation of sediment loads and permanence of deposits postulated by Gilbert's symmetrical wave model. This study examines mining sediment storage and mobilization in the Bear River, more than 100 years after the cessation of large-scale mining, in an attempt to resolve this conflict by testing the validity of Gilbert's model. The high degree of sustained storage and mobility documented here is consistent with other modern sediment studies and suggests that the symmetrical wave model is inappropriate for the Bear River, a sub-system of the type-locale from which the model was derived.

Physiography and Sediment Production

The Bear River drains a basin of about 1300 km^2 extending from the Sierra Nevada foothills

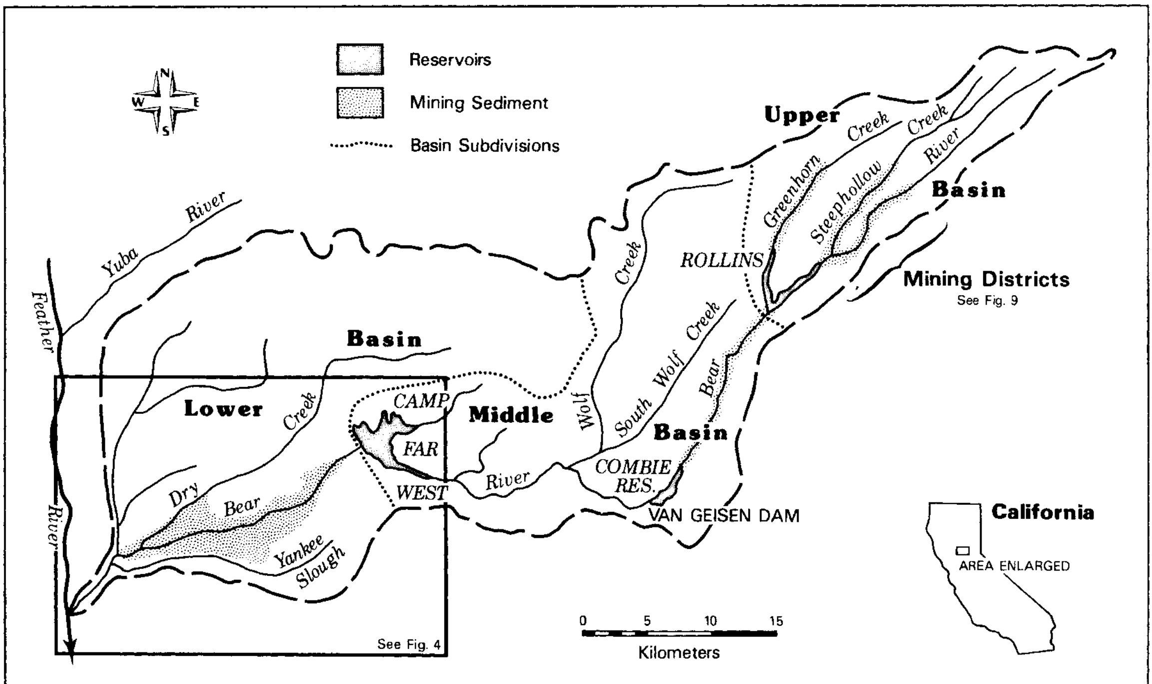

Figure 2. The Bear River Basin and sub-basins.

westward to the Sacramento Valley (Fig. 2), adjacent to the Yuba Basin, which was studied in detail by Gilbert (1917). Climate, vegetation, and soils vary considerably between the mountainous mining districts and the Sacramento Valley. The Mediterranean climate is characterized by warm, dry summers and mean annual precipitation ranging from 50 cm in the Sacramento Valley to 160 cm at higher elevations. The Bear River heads at a relatively low elevation of 1770 m, so snow-melt is not a dominant source of runoff in the basin.

Three divisions of the Bear River Basin are delineated: the *upper basin* above Rollins Reservoir, the *middle basin* between Rollins and Camp Far West reservoirs, and the *lower basin* below Camp Far West Reservoir. The upper and middle basins comprise the *foothills* portion of the basin. The Bear River and its tributaries, Steephollow and Greenhorn creeks, flow in deep valleys through the heart of the northern mining districts, where gold occurs in upland Tertiary channels striking north–south across ridge crests (Lindgren 1911; Yeend 1974).

During the late 19th century, hydraulic mines generated large volumes of sediment with no attempt to restrain tailings. In fact, down-valley sediment transport was encouraged in order to maintain steep local gradients and facilitate sluicing. Sediment production began slowly around 1853 as the hydraulic mining technology began to be developed in the Bear and South Yuba basins (Kelley 1954; May 1970; Rohe 1985). These initial deposits remained in and near the mines until 1862 when a large flood delivered the first substantial volume of sediment to main channels (Keyes v. Little York Gold Washing Co. et al. 1878; Mendell 1881, 2489). Sediment production from mines increased through 1866, but decreased in the late 1860s as easily-removed upper gravel deposits were exhausted (Keyes v. Little York Gold Washing Co. et al. 1878, 391; Paul 1963, 90; Rohe 1985). Production increased again in the early 1870s with technological developments that facilitated the mining of coarse, cemented lower gravel (Keyes v. Little York Gold Washing Co. et al. 1878; Paul 1963; Loyd and Bane 1981; Rohe 1985).

Most trunk channels in the Bear Basin aggraded throughout the 1870s. Overbank flooding became very destructive in the lower basin during this period as channels suffered a series of avulsions in spite of attempts to contain them

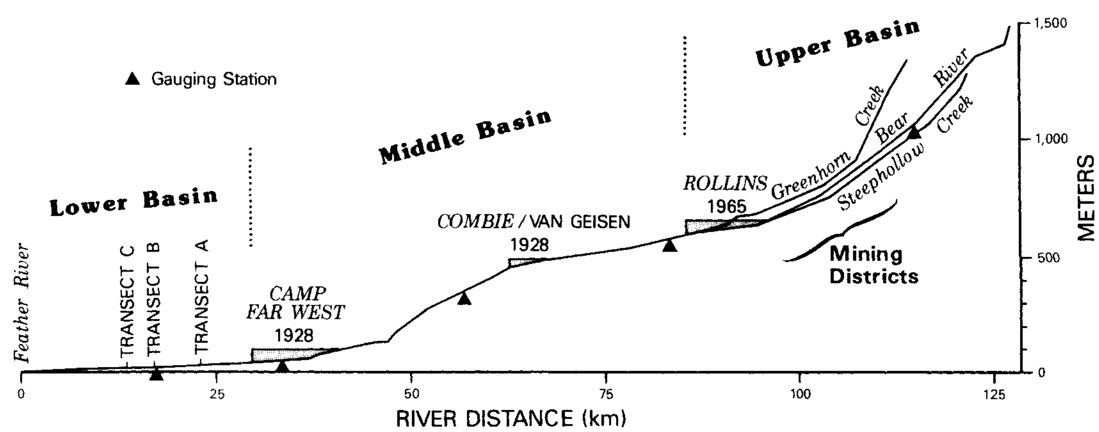

Figure 3. Bear River longitudinal profile with two concave-upward profiles separated by a structurally controlled break in slope. Reservoirs are shown with dates of construction. Steep gradients and narrow gorges below Van Geisen Dam discouraged sediment deposition, even during the peak period of sediment production. (Vertical exaggeration 60:1.)

with levees. Litigation was initiated in the 1870s and, after a decade of intense debate, miners were enjoined in 1884 from freely discharging sediment to channels flowing into navigable waters (Woodruff v. Bloomfield 1884; Kelley 1956, 1959). The few remaining large hydraulic mining operations were ended in 1890 by a large flood that destroyed miles of canals and waterworks servicing the mines (Kelley 1959).

Main channels of the lower Bear had apparently begun to degrade by 1890, although some overbank deposition probably continued in unleveed reaches (Von Geldern 1891). In the late 1890s, resumption of hydraulic mining on a much smaller scale was predicated upon the construction of small dams to restrain tailings. Most of these dams were too small and ephemeral to detain sediment for more than one or two decades, but sediment produced during this period was less than 2 percent of total volumes delivered earlier (James 1988a). Closure of Van Geisen and old Camp Far West dams in 1928 cut off mining sediment deliveries to the lower basin.

Mining Sediment Storage

When most mining ceased in 1884, immense deposits of sand and gravel remained stored in channels and continued to be reworked by floods. Much of this sediment is still lodged in narrow valleys from the mining districts downstream to Van Geisen Dam (Combie Reservoir) and in wide, flat valleys of the lower basin from Camp Far West Dam to the mouth of the Feather River (Fig. 2). Storage is most extensive in the mining region and at sites corresponding with low gradients. The double concave-upward longitudinal profile of the Bear River has had great bearing, therefore, on spatial patterns of sediment deposition (Fig. 3). The middle basin below Van Geisen Dam is dominated by steep, narrow gorges in which little alluvium was stored even during the peak mining period. As a first step in evaluating Gilbert's Sediment Wave Model, this study documents the large extent of mining sediment remaining in the Bear River and compares it with earlier estimates.

Historical Sediment in the Lower Basin

Mining sediment in the lower basin overlies older fine-grained alluvium with well-developed soils, in contrast to the upper basin where it overlies bedrock, boulders, colluvium, and thin pockets of alluvium. Surface areas and mean depths of the deposit along the lower Bear River (between the Feather River and the diversion dam below Camp Far West) are used to calculate mining sediment volumes.

Surface areas of the deposit were delineated

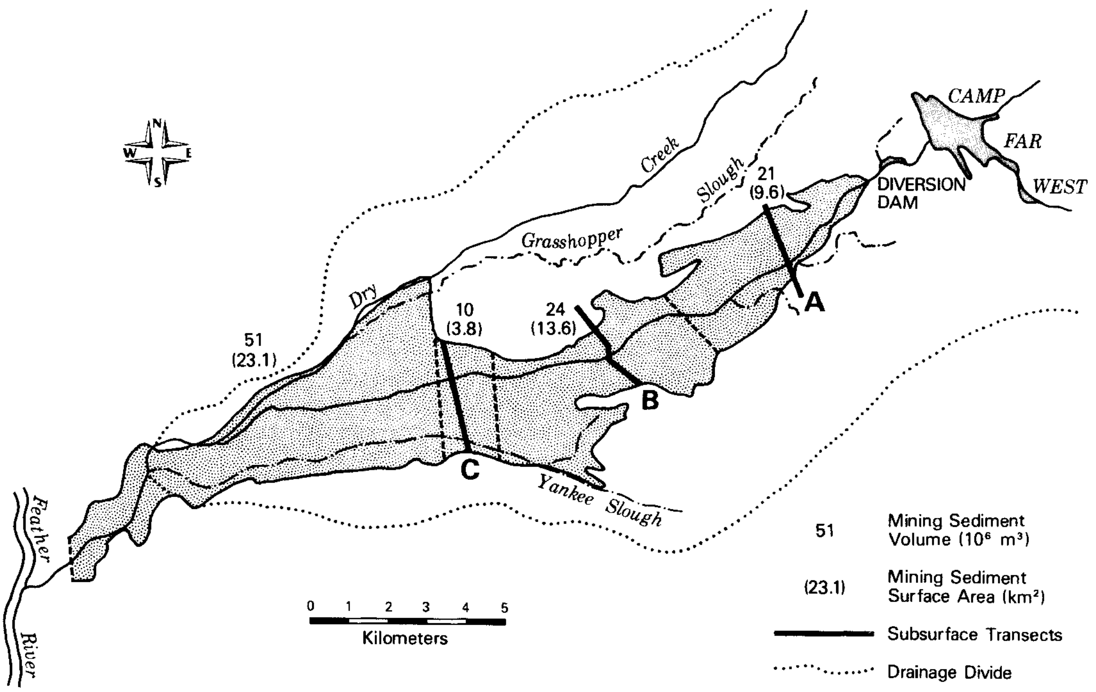

Figure 4. Mining sediment (stippled) and three valley transects in the lower Bear River. Present volumes of mining sediment are shown by sectors (10^6 m^3). Surface areas of mining sediment (km^2) are shown in parentheses. The total present volume is about $106 \cdot 10^6$ m^3 and the total surface area is about $50 \cdot 10^6$ m^2. The drainage divide shown excludes Reed's Creek, a tributary from the north, joining the Bear River near its mouth.

using soil surveys from Placer, Yuba, and Sutter counties (Rogers 1980; Gowans and Lindt 1965; Herbert and Begg 1969; and Lytle 1988). Identification of soils developed on mining sediment was based on (1) published correlations between soil series and geomorphic surfaces, (2) soil order, (3) presence of argillic or silicic horizons in soil series descriptions, and (4) geomorphic position (James 1988a). Several soil series in Yuba County are formally defined on the basis of hydraulic mining-sediment parent-material (Herbert and Begg 1969). Soils classified as Xerofluvents or Riverwash are assumed to be developing on mining sediment, but soils with advanced pedogenic development are not.

The resulting map of mining sediment deposits (Fig. 4) was spot-checked in the field and is comparable with a 19th-century map generated by a survey of fresh deposits (Mendell 1880). Surface areas of mining sediment were determined by planimetering areas on the map (Fig. 4; Table 1). Mining sediment in the lower basin covers about 50.1 km^2 (5010 hectares). This estimate is 40 percent greater than Hall's (1880) estimate. Relative to Von Geldern's (1891) areal estimates, it is 27 percent greater than lands "destroyed" in 1889, 6 percent less than lands "destroyed" plus lands "injured" in 1889, and 22 percent less than total lands affected by the 1890 flood (Von Geldern 1891).

Subsurface coring of the mining sediment was possible in the lower basin, because mining sediment is fine textured. In the summers of 1983, 1984, and 1985, more than 125 sediment cores were extracted with a 2-cm diameter silt-probe along three transects extending 2 to 3 km across the valley (Fig. 4). Coring proceeded into a distinct buried soil that stratigraphically defines the pre-mining surface. Sediment textures and mineralogic compositions were described from cores (James 1988a), and surface topography along each transect was surveyed with a rod and level. At many sites, thick sequences of laminated silt and fine sand indicate that overbank deposition from suspension was the dominant depositional process away from

Table 1. Lower Bear River Historical Sediment; Surface and Subsurface Dimensions

Transect	Cross section area (m^2)		Top width (m)	Mean depth (m)		Historical sediment				Pure mining sediment[a] volume	
						Surface area (m^2 10^6)	Volume (10^6 m^3)		Percent eroded		
	P*	F*		P*	F*		P*	F*	%	P*	F*
A	4247	4871	1992	2.13	2.38	9.6	21	23	10	17	19
B	2940	3232	1655	1.78	1.95	13.6	24	27	9	20	22
C	7854	8087	2880	2.73	2.81	3.8	10	11	9	8	9
D	—	—	—	2.21[b]	2.38[b]	23.1	51	55	7	42	46
Mean	5014	5397	2176	2.21	2.38	—	—	—	9	—	—
					Total	50.1	106	116	—	87	96

Minimum volume = 89·10^6 m^3. Maximum volume = 141·10^6 m^3. P* = Present (1985). F* = Former (circa 1900).

[a] Pure Mining Sediment volumes assuming 17 percent of total historical deposit is non-mining sediment.

[b] Average of mean deposit depths along the three transects.

main channels. In contrast, sedimentation along Transect C south of the present channel was dominated by fine-to-medium sand. Large-scale trough-set cross-stratified sand, exposed between the levees near Transect B, indicates deposition by the downstream migration of dunes (Harms and Fahnestock 1965). These dunes apparently spread out across the valley in the vicinity of Transect C where the early levees ended in sandy, braided stream deposits and intermittent channels (USGS 1910).

Cross-sections derived from the three transects reveal the subsurface topography and processes of sedimentation in the lower basin (Fig. 5). The pre-mining surface beneath the transects is buried by as much as 5.1 m of mining sediment. Channel locations prior to avulsions in the 1870s correspond to county lines on all three transects. Channels aggraded, migrated southward, and incised through the mining sediment into the pre-mining surface. The sediment covers most of a low pre-mining surface with dark soils that averaged abut 2.4 km wide and was described by early settlers as the *lower bottoms* (Keyes v. Little York Gold Washing Co. et al. 1878, 7, 75). Former locations of sloughs under Transect B support early accounts that the pre-mining channel was anastomosed (Keyes v. Little York Gold Washing Co. et al. 1878, 7, 14, 28–29, 95; Pixley, Smith, and Watson 1865). Terraces between existing levees are higher than adjacent land surfaces beyond the levees, provide a source of sediment for transport, and indicate that aggradation continued after levee construction.

Mean depths and volumes of the mining sediment deposit were calculated from the valley transects. Vertical cross-section areas were planimetered and top widths were measured from large-scale transect plots. Two estimates of mining sediment cross-section areas and depths are presented for each transect (Fig. 6) (Table 1): (1) *present areas* (1985) exclude all areas of eroded sediment, and (2) *former areas* (at the time of peak aggradation) exclude areas of eroded pre-mining alluvium but include areas of eroded mining sediment estimated by linear extension of terrace tops and contacts across modern channels. Mean mining sediment depths, calculated as the ratio of cross-section area to top width, range from 1.8 to 2.7 m in the present deposit and from 2.0 to 2.8 m in the former deposit. Sedimentation in the lower basin began with the 1862 flood and, based on observations of channel incision by Von Geldern (1891) and Turner (1891), is assumed to have been largely completed along leveed channel reaches by 1900. Based on this assumption, mean rates of aggradation ranged from 4.7 to 7.4 cm yr^{-1}, averaged across the valley transects over this 38-year period. At the maximum observed depth of fill (5.1 m) on the Transect C, aggradation rates averaged about 13.4 cm yr^{-1}. By comparison, decadal rates of sedimentation generated by agriculture and mining in southwest Wisconsin reached as high as 4 cm yr^{-1} (Knox 1987a), but these rates were not sustained for such a long period. Mining sediment aggradation rates were probably much higher in the lower Bear during the period 1862 to 1884.

Mining sediment volumes in the lower basin were calculated as products of surface area and mean depths of deposits (Fig. 4; Table 1). Sub-

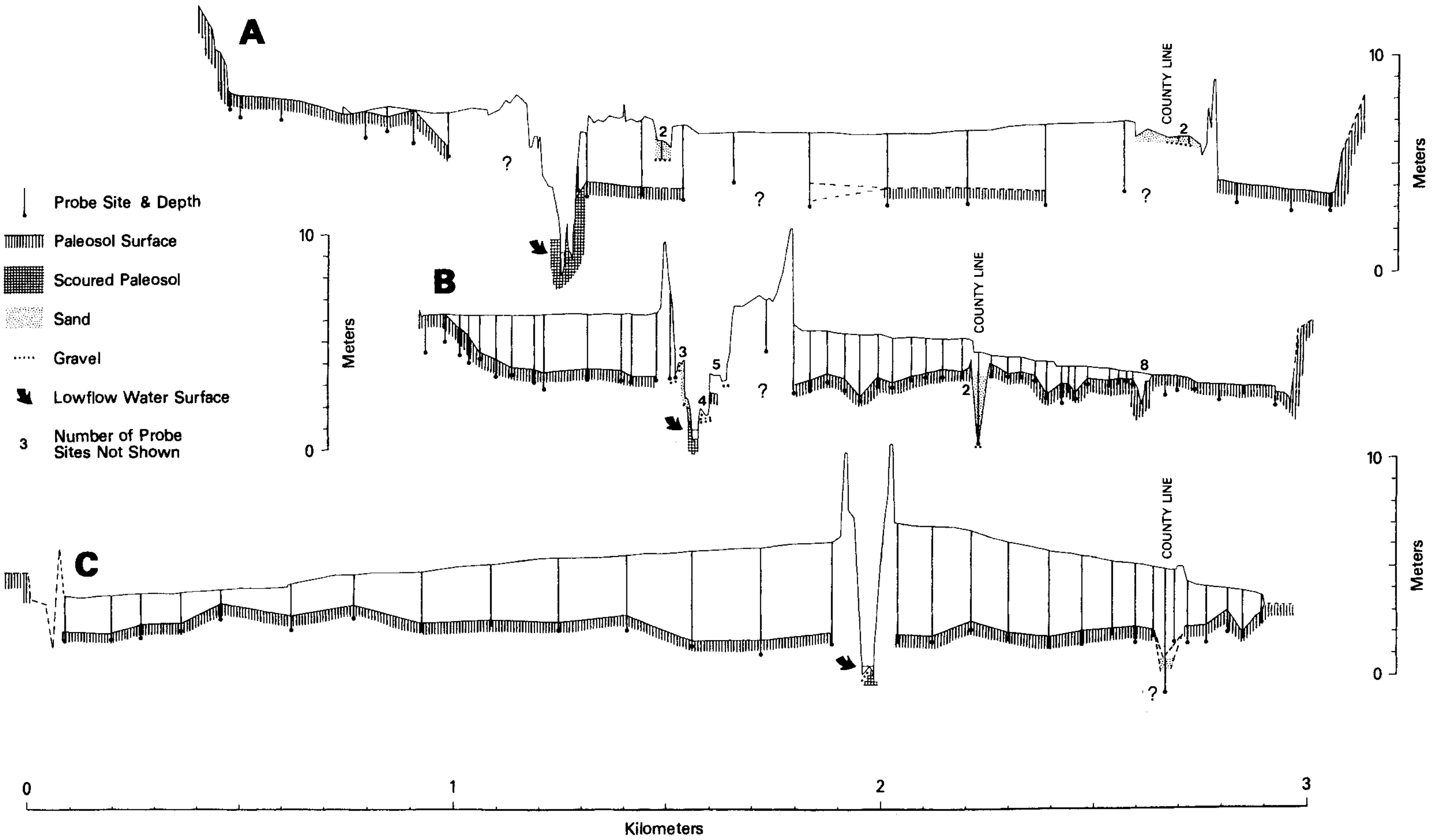

Figure 5. Valley transects in the lower Bear River surveyed between 1983 and 1985. Core-holes are shown by vertical lines, the pre-mining soil surface by vertical hachures.

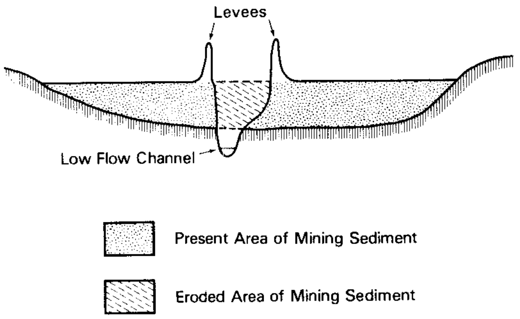

Figure 6. Hypothetical valley cross-section showing the method for determining cross-section areas of mining sediment. The former area of mining sediment is assumed equal to the present area plus the eroded area.

surface data are lacking for the sector furthest downstream, so mean depths were assumed to be the average of the three observed mean depths. This provides a conservative estimate for deposits near the Bear River mouth, where sedimentation continued long after levees were constructed on upstream reaches, and base levels were raised by more than 1.5 m of aggradation along the Feather River (Hall 1880). Depth-area products indicate that the present and former volumes of historical sediment stored in the lower Bear are about $106 \cdot 10^6$ m^3 and $116 \cdot 10^6$ m^3, respectively. Thus, less than 10 percent of the original deposit has been eroded from the lower basin. This preservation of more than 90 percent of the lower basin deposit may be due largely to the maintenance of levees.

Two extreme values of sediment volumes in the lower basin (from the Feather River to the diversion dam) were calculated to establish plausible upper and lower limits. Products of total surface area and the smallest and greatest mean depths of mining sediment encountered in any of the transects yield minimum and maximum volumes of 89 and $141 \cdot 10^6$ m^3, respectively (Table 1).

The lower Bear historical deposit is not entirely composed of mining sediment. Gilbert (1917, 46) estimated that non-mining activities such as lumbering, agriculture, and roads contributed about 23 percent of the sediment in Sacramento Valley streams during the mining period. Based on a sediment mixing index derived from quartz concentrations of mining and non-mining sediment (James 1988b), a value of 17 percent non-mining sediment was calculated for the lower Bear River deposit indicating that approximately $88 \cdot 10^6$ m^3 of undiluted mining sediment was stored there in 1985 (Table 1). Most non-mining historical sediment sources were intimately related to mining activities, and previous storage estimates were unable to distinguish between mining sediment and other contemporary sources. Therefore, the entire historical deposit will henceforth be referred to as mining sediment.

Previous Estimates of Mining Sediment Production and Storage

The results of this study show that the volume of historical sediment stored in the lower Bear Basin is more than twice as large as the largest previous estimates ($48 \cdot 10^6$ m^3; Table 2) which have been considered authoritative (Mendell 1880; Gilbert 1917). Some aggradation may have continued after those estimates were made until 1928, when two dams were closed upstream, but the discrepancy is much too large to be explained simply by 20th-century aggradation. Most of the difference is due to underestimation attributable to the calculation methods employed by earlier studies.

Previous studies lacked subsurface information or cut-bank exposures and estimated sediment storage largely as a proportion of sediment produced in the basin. Unfortunately, early estimates of sediment production by mines in the Bear Basin were conservative and led to low estimates of storage, ranging from 78 to $113 \cdot 10^6$ m^3 (Table 2). Sediment production (P) was conventionally estimated as the product of water used by a mine (Q_m) and the *duty* (D) of the mine. The duty is an assumed measure of sediment erodibility for the mine, expressed as sediment volume moved per unit water-use (Benyaurd et al. 1891, 3007):

$$P = Q_m \cdot D \qquad (1)$$

Manson (1882, 93) surveyed the upper Bear Basin and argued that the assumed duty for Bear River mines was too low, because they were determined from coarse, cemented, lower gravel exposed around 1880. The upper gravel, mined earlier, was finer and more erodible, so more material would have been moved with a given volume of water in the first fifteen years of mining (Keyes v. Little York Gold Washing

Table 2. Early Estimates of Sediment Volumes Produced and Stored in the Bear Basin (10^6 m^3)

Source	Total production	Bear River Basin storage volume: Lower basin	Bear River Basin storage volume: Foothills	Bear River Basin storage volume: Total basin	Volume/ area[a]	Yuba River: Total	Yuba River: Volume/ area[a]
Keyes v. Little York Gold Washing Co. et al. (1878)		28	66	93	123		
Mendell (1880)		48	66	113	150	110	32
Benyaurd et al. (1891)		28	51	78	103		
Uren (Turner 1891)			68				
Turner (1891)	179		51				
Gilbert (1917)	271					302	87
Gilbert readjusted[b]	194	46	46	92	121		
This Study previous		116					
This Study present		106					

[a] Total storage per unit drainage area (10^3 m^3 km^{-2}).

[b] Readjusted by Gilbert down from his initial adjustment (see text).

Co. et al. 1878, 377–78, 391). This led Manson to conclude that contemporary estimates of mining sediment produced and stored in the Bear Basin were too low. It is unfortunate that Manson's analysis has not been incorporated in other studies.

Gilbert (1917) improved estimates of hydraulic mining sediment production by plane-table mapping mine pits in the Yuba Basin to determine production volumes. Comparison of these volumes with earlier sediment production estimates led Gilbert to infer that previous estimates needed to be increased by a factor of 1.51. Application of this ratio to production in the Bear Basin raised Turner's (1891) estimate from 179 to $271 \cdot 10^6$ m^3 (Table 2). Gilbert had few measurements of mine pits in the Bear Basin and lacked confidence in his initial approximation. When confronted with very small storage estimates in the lower Bear, Gilbert (1917, 48) lowered his production estimate to $194 \cdot 10^6$ m^3 (Table 2) to achieve a sediment delivery ratio comparable with other basins. Thus, early underestimates of storage in the lower Bear led to underestimation of sediment production in the basin, which, in turn, justified low estimates of storage volumes.

Mining Sediment Stored in the Foothills

Hydraulic mining sediment continues to comprise a large component of channel sediment in the Bear River above Van Geisen Dam. Quartz concentrations facilitate the identification of mining sediment and indicate that deposits within the mining districts are composed primarily of undiluted mining sediment (James 1988b). Depths and volumes of fill in the foothills could not be reliably estimated, but topographic surveys of surface morphology reveal magnitudes of eroded sediment and terrace dimensions and suggest the large reserves of sediment remaining in 1985.

Valley cross-sections were surveyed at 22 sites to measure width, depth, and cross-section area of eroded mining sediment. The greatest erosion has occurred near tailings fans, which formed at confluences where tributaries draining mines joined main channels (Fig. 7A). Large volumes of mining sediment have also been eroded from channel reaches between tailings fans (Fig. 7B). Measured depths of incision into the mining sediment above Van Geisen Dam average about 10 m and range to more than 27 m. Little or no erosion has occurred in steep, narrow gorges where deposits were negligible, or near Rollins Reservoir where post-mining aggradation has dominated.

Cross-section plots provide a qualitative measure of the large volume of sediment remaining in main channels of the Bear River foothills (Fig. 8). This volume is greater than along comparable lengths of the Yuba or American rivers for a number of reasons. The Bear River heads only 15 km upstream from the mining districts, so discharges in main channels near the mines are much smaller than in the Yuba or American rivers, which head at high elevations (Manson 1882, 90). In addition, the total volume of sediment produced in the Bear Basin, when scaled to basin area, is considerably

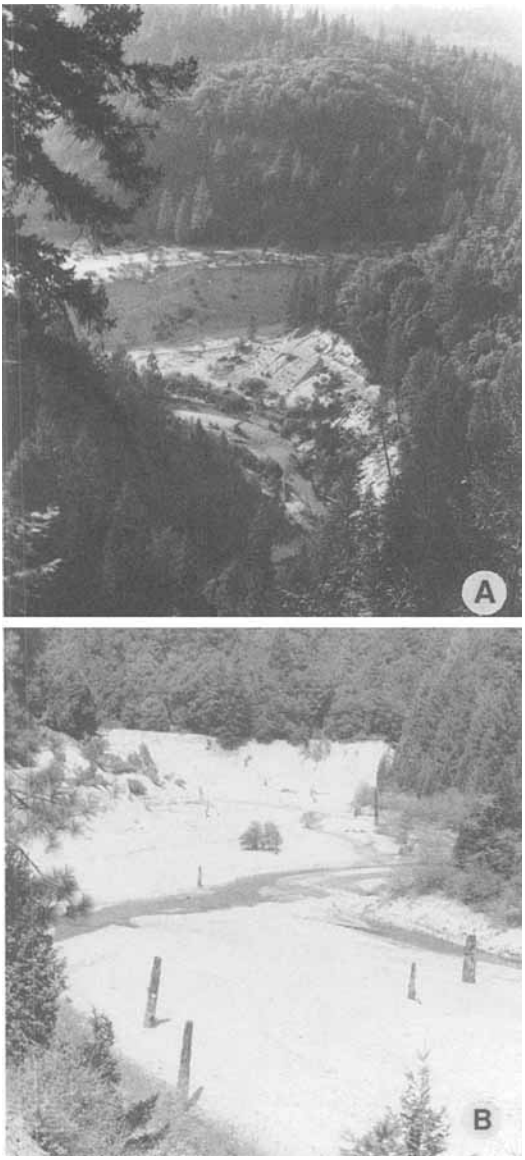

Figure 7. Views of the upper basin mining sediment deposits. (A) The tailings fan-dam at Wilcox Ravine has been incised by Steephollow Creek (flowing from lower right to middle left). The Red Dog-You Bet Mine (beyond upper right corner) discharged into Wilcox Ravine (joining Steephollow Creek from middle right). (B) The tailings at Buckeye Ford in Greenhorn Creek have been eroded, leaving terraces and revealing a partially exhumed pre-mining forest.

greater than in the Yuba or American basins (Table 2). Finally, field evidence indicates that the upper South Yuba River was captured from the Bear Basin, probably as a consequence of late Quaternary ice-damming. This stream capture may have led to underfit channel conditions providing more channel storage capacity than in the Yuba or American rivers.

In short, the Bear River Basin was overwhelmed with sediment, much of which remains in storage. There is some doubt about the volume of sediment produced by hydraulic mining in the Bear Basin, and apparent underestimates of production may explain the underestimation of storage volumes by previous studies. In the lower basin, mining sediment deposits are more than twice the volume of previous estimates and substantially greater than previous estimates of storage in the entire basin. In the upper basin, a large but unknown volume of sediment remains in and near the active channel, beneath the bed, and in massive terraces. Further research is needed to determine upper basin volumes, total basin storage, and sediment delivery ratios, but foothill deposits are clearly vast. The addition of foothill deposit volumes to lower basin volumes will result in storage greatly in excess of previous estimates (Table 2). These vast reservoirs of stored sediment provide potential sediment sources for future channel erosion. According to Gilbert's model, the Bear River deposits should now be permanent, but this premise needs to be examined.

Sustained Sediment Transport in the Basin

Gilbert's symmetrical sediment wave model implies that sediment loads have returned to pre-mining levels. This hypothesis was tested by calculating the competence of flows to entrain channel bed material and by examining mountain deposits for evidence of recent reworking. Evidence of flow competence and vigorous sediment mobility supports the hypothesis that present sediment transport rates are greater than pre-mining rates. Although pre-mining sediment concentrations are unknown, they were constrained by the limited amount of fine-grained sediment available for transport. Pre-mining Sierra foothill channels were

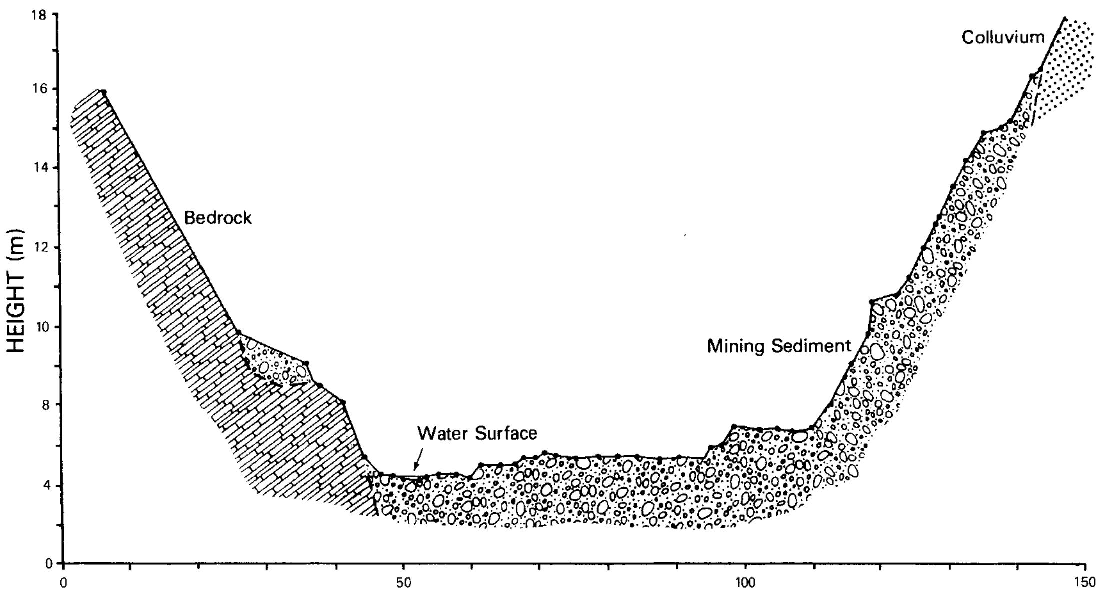

Figure 8. A representative valley cross-section in the upper basin at Buckeye Ford on Greenhorn Creek (see Fig. 7B). The cross-section area of mining sediment eroded from this site is between 1528 and 1881 m^2. There is a large but unknown volume of sediment remaining. (Vertical exaggeration 4.3:1.)

dominated by bedrock and had relatively low sediment supplies (Rohe 1983, 10).

> "... before the advent of white man the [Sierra Nevada] streams at nearly all points rested on the rock bottoms of the canyons and were engaged in deepening them.... The rivers continued to the western base of the range with steep descent and rocky beds, but at the base their habit was abruptly changed, the slopes of the beds becoming gentle and the material of the beds changing to gravel and sand" (Gilbert 1917, 15).

This statement not only supports an argument for low sediment availability in pre-mining channels, but also establishes that Gilbert postulated a return to pre-mining sediment transport rates based on bed-rock controlled valley bottoms. In the Bear River, shallow gravel bars were the earliest source of gold but were limited in extent and could not have supplied much sediment for transport. A description of the placer gravel along Greenhorn Creek in 1849 reveals the paucity of alluvium present prior to aggradation:

> "The gold bearing gravel is contained and only found in a small 'bar', rarely more than a few feet wide and not over two feet [0.6 m] deep to the solid or bed rock, and is so filled with boulders or detached rounded masses of all dimensions, that the wash-gravel is probably less than a fourth or fifth part of the mass" (Wistar 1914; cited in Lloyd 1985, 278).

Under channel conditions dominated by bedrock and coarse colluvium, much flow energy is dissipated and sediment transport capacity is lowered accordingly.

Low pre-mining sediment deliveries can also be inferred from a lack of sediment accumulation on modern terrace surfaces. Many flat terrace treads abutting steep slopes have been stable for more than 100 years. The small amount of colluvium or alluvium at contacts indicates that rates of hillslope erosion have been modest. The vigorous channel erosion and sedimentation documented in this section, therefore, are assumed to represent an increase in sediment transport rates over pre-mining conditions.

Flows Required to Entrain Bedload

This section examines the competence of flows to entrain bed material present in 1985.

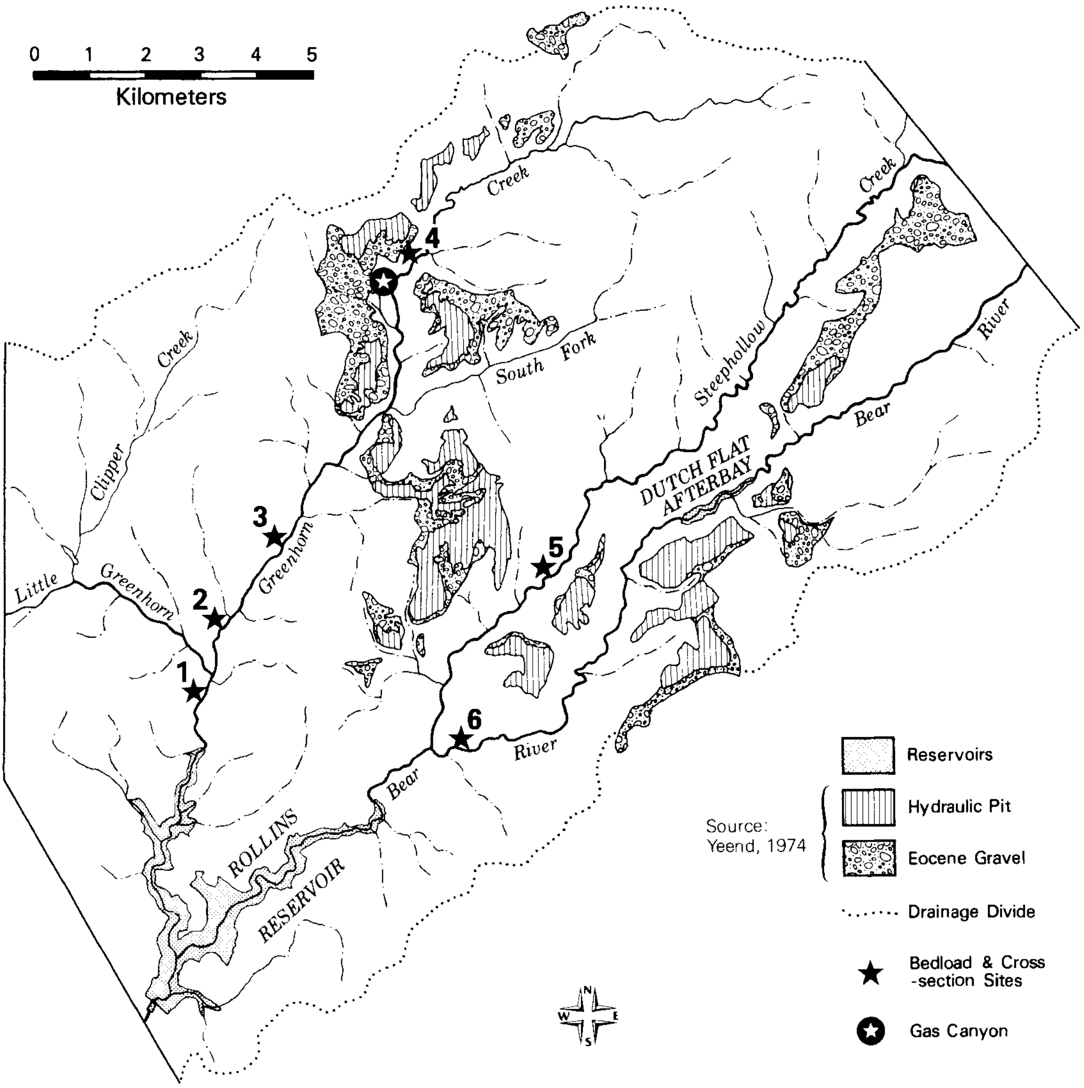

Figure 9. Upper Bear River cross-section and sample sites used in the competence and flood frequency analysis. The seventh site is located at Taylors Crossing about 2 km downstream from Rollins Dam. Mines and upland Tertiary gravel deposits illustrate the proximity of sediment sources. Gas Canyon is the site of an earthflow discussed in text.

Mining sediment bed material, distinguishable from non-mining sediment by mineralogic composition (James 1988b), is significantly finer ($\alpha = 5$ percent), better sorted, and more spheroidal than non-mining bed material (James 1988a). Mining sediment, therefore, forms weaker armor than pre-mining sediment, and a given flow moves more sediment from beds dominated by mining sediment than from beds dominated by coarser pre-mining sediment.

A series of empirical hydraulic equations indicates that bed material in the upper basin can be moved by frequently occurring flows. Channel-bed grain intermediate-axis dimensions were sampled in 1985 throughout the basin (James 1988a), using a stratified random grid

Table 3. Flows Required to Entrain Coarsest 90 Percent of Bedload[a]

Site[b]	Basin area km^2	Slope %	D_{90} mm	Dmax[c] m	A m^2	Width m	R m	D_{84} mm	n	Vel. m s^{-1}	Q m^3 s^{-1}
1	97	0.50	96	0.51	27.1	48.6	.565	84	.036	1.3	36
2	60	0.50	76	0.38	3.1	18.0	.258	66	.038	0.75	2.3
3	57	1.54	94	0.26	3.6	18.0	.195	74	.043	0.97	3.5
4[d]	24	2.31	431	1.32	10.8	10.8	.864	380	.059	2.3	25
5[d]	51	1.59	295	1.03	15.7	18.7	.837	257	.050	2.2	35
6	69	1.21	179	0.66	12.2	20.2	.744	149	.042	2.2	26
7[d]	274	0.65	161	0.83	24.7	55.0	.398	144	.047	0.92	22

[a] Abbreviations are defined in text, p.583.

[b] Site locations are identified on Figure 9.

[c] Competent maximum depth of cross section: $D_{max} = 0.0001 \cdot D_{90mm}{}^{1.21} \cdot S^{-0.57}$ (Knox 1987b).

[d] Coarse pre-mining lag exposed; mixed with mining sediment.

method (Wolman 1954). This analysis is confined to seven sites in and near the mining districts where cross-sections were also surveyed (Fig. 9). Quartz concentrations indicate that mining sediment dominates four of the sites, which are within the mining districts, and relatively coarse pre-mining lag deposits are partially exposed at the other three sites near the upstream margin of the mining districts and below Rollins Dam (Table 3).

Depths of floods competent to move the mining sediment were calculated using an expression of channel cross-section maximum depth (D_{max} in meters) as a function of bedload particle size and slope (Knox 1987b, c):

$$D_{max} = 0.0001 \cdot D_{90mm}{}^{1.21} \cdot S^{-0.57} \qquad (2)$$

where D_{90mm} is the size (mm) of the particle corresponding to the coarsest 10 percent of bedload and S is dimensionless water surface slope. The physical basis for this equation is the strong relationship between size of grains entrained and tractive force of the competent flow (Baker and Ritter 1975; Knox 1979b; Costa 1983). Slopes were estimated from valley-bottom slopes measured on 1:24,000 topographic maps. These calculations indicate that competent flow depths at the thalweg are less than 1.4 m at all sites and less than 0.7 m at the four sites dominated by mining sediment (Table 3).

Discharges (Q) associated with competent flow depths were calculated using the Manning equation:

$$Q = A \cdot n^{-1} \cdot R^{0.67} \cdot S_e^{0.5} \qquad (3)$$

where A is channel cross-section area (m^2), n is channel roughness, R is hydraulic radius (m), and S_e is the dimensionless slope of the energy grade line (Leopold, Wolman and Miller 1964). Cross-section areas and hydraulic radii were measured from channel cross-section plots at stages of maximum depths calculated with Equation 2. Topographic maps were used to measure valley-bottom slopes to approximate the energy grade line. This method of slope determination may overestimate the energy grade line for unsteady, non-uniform flows (Magilligan 1988), so estimates of discharges required to move bed material may be somewhat high. Sample sites are straight and lack vegetation or substantial bedforms, so flow resistance is assumed to be primarily a function of grain roughness. Therefore, an empirical equation of flow resistance, developed for northern California gravel-bed channels (Limerinos 1969), was utilized to calculate Manning's roughness:

$$n = \frac{0.113R^{1/6}}{7.16 + 2\log\left(\frac{R}{D_{84mm}}\right)} \qquad (4)$$

where D_{84mm} is the particle size (mm) representing the 84th percentile on the particle-size frequency distribution. Calculated roughness values cluster around 0.04, the value commonly assumed for gravel-bed streams (Chow 1964), except at sites dominated by coarse pre-mining lag materials, which are rougher (Table 3). Competent discharges at the seven sections range from 2 to 36 m^3 s^{-1}, suggesting that mining sediment is transported by relatively small flows.

Flood frequencies were calculated using a three-parameter lognormal probability mass

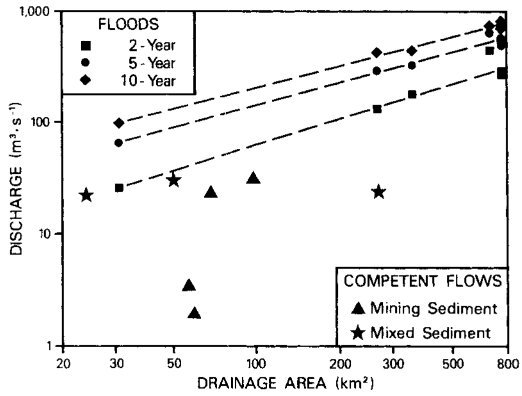

Figure 10. Flood frequencies at five stream-flow gauges in the Bear Basin plotted as a function of basin area. Discharges required to entrain bed material at seven sample sites are plotted for comparison. Competent flows occur relatively frequently, so even the coarse fraction of bed material should be mobile.

function (Hydrology Subcommittee 1982) to reveal the frequency of competent discharges. Annual maximum flood data from five streamflow gauges were applied to this function using Consolidated Frequency Analysis, a Fortran 77 flood-frequency analysis program (Pilon et al. 1985). Flood discharges of various recurrence intervals were calculated (Table 4) and plotted against drainage area to show values of 2-, 5-, and 10-year floods at various locations within the basin (Fig. 10). Floods with recurrence intervals of two years or more are competent to entrain bedload at all seven sample sites. Thus, competent flows recur at relatively frequent intervals and bed material of all sizes up to the coarsest 10 percent moves relatively frequently. The frequency and volume of sediment transport will be maximized at the relatively fine-grained sites dominated by mining sediment.

Field Evidence of Sediment Mobility

Having established the competence of flows to move channel material, this section describes field evidence that mining sediment is moving. There are few quantitative measurements of sediment concentration in the basin, so indirect evidence of sediment mobility is evoked, including scour and fill at channel cross-sections, lack of dilution of mining sediment in channel beds, freshly eroded terrace scarps, delta progradation into reservoirs, and channel lateral migration.

Changes in channel cross-sections through time provide evidence of sediment transport in the upper Bear, because channel-bed aggradation and degradation at a site represent net sediment transport into and out of the reach, respectively. Channel cross-sections were derived from stream-flow velocity measurements made by the U.S. Geological Survey at its cableway downstream from Rollins Dam during moderate magnitude discharges with recurrence frequencies of less than five years (Fig. 11). The cross-sections document a series of scour and fill events from 1964 to 1974 that are plotted on the 1985 cross-section and stratigraphy, surveyed by hand-level. Deep channels during high discharges in 1964, 1966, 1969, and 1974 are in contrast with relatively high bed elevations and flat cross-section shapes during moderate discharges in 1964, 1965, 1967, 1970, and 1972. These sequences of channel scour and refilling cannot be used to quantify sediment transport rates, but they clearly indicate

Table 4. U.S. Geological Survey Stream-flow Data, Descriptive Statistics, and Recurrence Intervals

Station name	Basin area km²	Water years	N	Mean cms	σ_{n-1} cms	Flood discharge (cms), RI = 50	20	10	5	2
Van Trent	686	1905-28	23	428	250	900	817	740	642	446
Wheatland	756	1929-86	58	351	270	1180	908	716	531	285
Near Auburn[a]	363	1941-67	27	222	157	732	560	440	327	180
Rollins[b]	272	1964-86	22	185	160	833	587	428	290	133
Drum[c]	32	1967-86	20	39	50	181	132	98	66	26

[a] At Hwy 49.
[b] Near Colfax.
[c] Below Drum Afterbay.

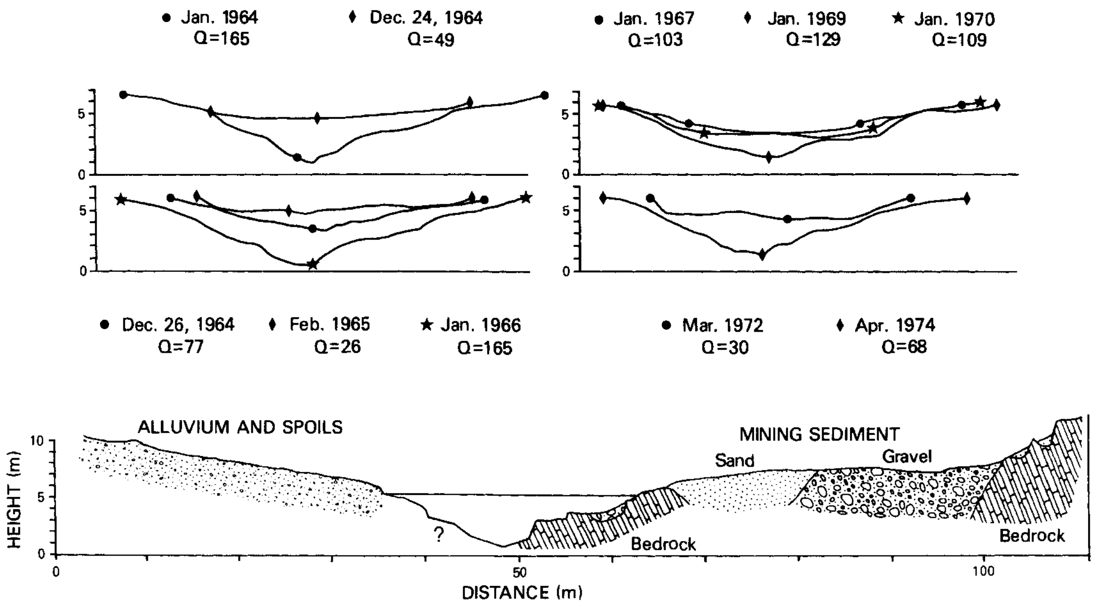

Figure 11. Channel cross sections at the U.S. Geological Survey stream flow cableway below Rollins Dam. Episodes of scour and fill between 1964 and 1974 document transport of sediment into and out of the reach. Discharges (Q) are given in $m^3 s^{-1}$. Unpublished data from U.S. Geological Survey, Sacramento.

sediment transport into and out of the reach following dam closure in 1965. From 1972 to the present, channel refilling has been negligible, because sediment supplies are cut off by the dam, and storage between the dam and the cable site has been depleted.

Channel scour below Rollins Dam may have been exacerbated by dam closure, but similar scour and fill occurs at sites above the dam. Complete removal of two low terraces on Greenhorn Creek and erosion along Steephollow Creek occurred in response to a moderate magnitude flood in 1980 (Wildman 1981). A channel cross-section at the You Bet Bridge on Greenhorn Creek, surveyed in 1975 by the California Department of Transportation, was resurveyed in 1985, indicating up to 1 m of change in channel bed elevations in that period (James 1988a). The channel near the bridge has aggraded more than 2 m since the 1940s (Hanson 1985) and a very small dam a few hundred meters downstream from the bridge, photographed around 1939 (Fig. 12), is now buried by reworked mining sediment.

Mining sediment is being reworked to such an extent in the mining districts that it dominates sediment loads and prevents substantial dilution of low-flow channel sediments. Sediment compositions indicate that mining sediment constitutes more than 80 percent of the sediment in Bear River low-flow channels in the mining area in spite of other important sources of sediment, such as logging and road construction (James 1988b). Negligible dilution of mining sediment in active channels and deltas of the upper basin indicate that mining sediment must be the dominant sediment source.

Deposits in upper basin terraces are generally much less stable than the pre-mining colluvium that they cover, so sediment produced by terrace scarp erosion is much greater than pre-mining deliveries from the same localities. In some narrow valleys within the mining area, the present channel is more than 20 m below terrace tops. Vertical terrace scarps are so unstable at some sites that micro-scale mass wasting events were observed during calm summer afternoons. Terrace scarp retreat in the upper basin is exhibited by fresh talus cones and by undercut and fallen trees at terrace edges (Fig. 13A). In contrast, colluvial slopes are less steep, covered with vegetation and residual organic

Figure 12. Dam on Greenhorn Creek, photographed around 1939. The dam is now completely buried by mining sediment indicating a substantial influx of sediment since that time. (Photograph by U.S. Army Corps of Engineers.)

matter, and often dominated by bedrock. At some locations, actively eroding terrace scarps are adjacent to bedrock-floored channels indicating that delivered sediment does not accumulate but is transported downstream.

Delta sedimentation behind Combie and Rollins reservoirs documents high rates of mining sediment transport in the upper Bear. About $1.2 \cdot 10^6$ m^3 of sediment was deposited in Combie Reservoir from 1928 to 1935 (Brown and Thorp 1947). Spring floods annually refill excavations made by a commercial aggregate mining company in the Combie delta (Dupras and Chevreaux 1984; Chevreaux 1985) and in the Rollins deltas. Quartz concentrations of sediment in the Rollins Delta on Greenhorn Creek (Fig. 13B) indicate that the delta is composed of from 70 to 85 percent mining sediment (James 1988a).

In the lower Bear River, channel incision has lowered the channel onto pre-mining alluvium, and transport of mining sediment from the foothills has been arrested by dams since 1928, so the presence of mining sediment in modern bed material indicates reworking of local deposits. Quartz concentrations of a gravel bar at Transect B (Fig. 4) indicate that it was composed of about 35 percent mining sediment in 1985. Between Transect B and the diversion dam, channels are vulnerable to lateral migration which delivers sediment down-

Figure 13. Views of upper Bear River showing evidence of sediment transport. (A) Terrace scarp along Greenhorn Creek showing typical erosion of tailings next to bedrock-floored channel bed. Lack of sediment accumulation indicates sediment transport out of the reach. (B) Large delta forming in Rollins Reservoir at the mouth of Greenhorn Creek. Lithological compositions indicate that the delta is comprised primarily of mining sediment. (C) Eroding bank at bend in the lower Bear River (1985). Severe erosion was observed at this site between 1983 and 1986. Mining sediment contributes a substantial portion of the sediment load. The contact between mining sediment and the underlying pre-mining soil is shown at the arrow.

stream to navigable waters of the Feather and Sacramento rivers. From 1983 to 1986 a high cut-bank 200 m upstream of Transect A rapidly retreated, eroding a large volume of mining sediment (Fig. 13C).

Sediment loads in the mountains may be augmented by interactions between fluvial and hillslope systems. Mining sediment deposits extending to depths between 45 and 60 m (Turner 1891) raise water tables, mechanically buttress hill slopes, and attenuate sediment contributions from mass wasting of pre-mining material. Stabilized colluvium represents a dormant sediment source that can be reactivated by channel incision, thus prolonging high sediment loads. A recent large slump and earthflow in the Greenhorn Basin near Gas Canyon was apparently due to channel incision into mining sediment at the toe of the slide. Sediment production in Gas Canyon is now augmented by the earthflow.

The field evidence outlined above records a large volume of mining sediment remaining in the Bear River that continues to be reworked and is slowly progressing down-valley through repetitive erosion and resedimentation. Sediment loads in the mountains have not returned to levels during the pre-mining era when channels were dominated by bedrock and coarse colluvium. Protracted storage in main channels of the upper Bear Basin is in contrast to main foothill channels of the Yuba and American rivers, upon which many generalizations about hydraulic mining sediment have been drawn (Gilbert 1917). In regards to hydraulic mining sediment in the Sierra Nevada, Meade (1982, 244) has written:

> "The time required to remove sediment from storage on the floodplain is apparently much greater than the century that was required to remove debris from the main channels . . . the process of lateral erosion of the flood plains must proceed at a substantially slower rate than the vertical readjustment. . . ."

In the upper Bear River, not even the vertical readjustment is complete; vast deposits remain in main channel valley bottoms. Although most sediment from the mountains is now prevented by dams from reaching the lower basin, this would not be true of unaltered basins. Although most deposits in the lower Bear River are now protected by levees, unprotected deposits are eroding, and this deposit is not entirely permanent. A geomorphic interpretation of episodically introduced sediment should consider the import of channel storage to sediment transport throughout the basin.

Sediment Transport in an Asymmetric Wave

Gilbert's belief that the mining sediment remaining in storage after fifty years would be permanent is not born out by observations in the Bear River. The Bear River sediment wave has not been symmetrical but is substantially skewed in respect to time. This skewness is due to slow, sporadic, but prolonged sediment releases that are confirmed by sustained storage, competent flows, and active erosion and deposition. A revised sediment wave model is proposed here for basins like the Bear River, where long-term sediment storage and remobilization is an important component of the sediment budget.

Sediment deliveries do not necessarily occur abruptly in response to environmental changes. Biogeomorphic responses to sudden climate change include gradual decreases in non-point source sediment production that asymptotically approach new steady-state conditions (Knox 1972). Depletion of historical alluvium has also been described as an asymptotic process (Trimble 1983). The *rate law* provides a general geomorphic model of the return of disturbed geomorphic systems to new equilibrium states at a negative exponential rate:

> "Just as decaying isotopes approach new stable isotopes at continuously decreasing rates, so gullies erode toward equilibrium lengths at continuously decreasing rates. . . . If the negative exponential form provides the best fit for the data, a negative feed back loop is operating to dampen the effects of disruption, resulting in a decreasing rate of change that approaches some steady state" (Graf 1977, 183).

In accordance with the rate law, episodically increased sediment loads may return to pre-event levels at an ever-decreasing rate as potential energy and sediment availability gradually decrease.

Evidence of decreasing rates of sediment remobilization over millennial time scales is provided by erosion of many Quaternary or older alluvial deposits (e.g., Knox 1972; Baker and Penteado-Orellana 1978). Potential for sedi-

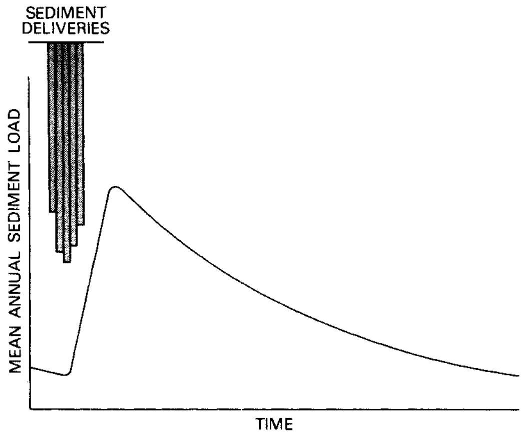

Figure 14. Hypothetical skewed sediment wave for the upper Bear River Basin. This model of sediment transport rates through time is in accord with modern concepts of long-term sediment transport following an episodic introduction of sediment. The right-skew is a result of remobilization of sediment stored in and along channels. Sediment deliveries to upstream channels are shown (not to scale) preceding peak sediment loads at a point downstream.

ment reactivation is largely dependent on accessibility to channels. A stochastic model developed by Kelsey et al. (1986) indicates that sediment can enter stable deposits and remain there for thousands of years. Sediment residence times in Redwood Creek range from 9–26 years for active storage sites in and near the channel to 700–7200 years for stable sites largely in isolated terraces covered by old-growth forest (Madej 1984). In steep, mountainous channels, little storage is absolutely permanent, because isostatic uplift in response to erosional unloading ultimately results in denudation of the entire landscape. Thus, fine-grained, unconsolidated alluvium has a low preservation potential over millennial time periods, and its introduction to bedrock channels will augment average sediment loads as long as it remains accessible. In channels with broad valley bottoms and much floodplain storage, erosion of deposits by channel lateral migration will tend to decrease asymptotically due to decreasing accessibility (Trimble 1984). Unless channel migration is inhibited or deposits become inaccessible, therefore, sediment loads will remain higher than pre-sedimentation loads.

Gilbert's symmetrical wave model can under-predict future sediment loads following major sedimentation events, because, in many basins, it underestimates the importance of sediment storage to long-term sediment budgets. With slight modification, however, the sediment wave model remains valid as a conceptual paradigm and better depicts observed environmental responses to the sudden influx of sediment. The revised model does not rigorously equate channel-bed elevations with sediment loads, so it allows increased sediment transport rates to be sustained following channel incision. As a result, the revised sediment wave model is right-skewed in respect to time (Fig. 14).

Fluvial sediment transport is often episodic (Schumm 1977), so a sediment wave may have a "saw-toothed" curve superimposed upon it due to inter-annual irregularities in water and sediment discharges and threshold responses. The smoothed trend, however, is likely to be an asymmetrical wave with the receding limb approaching pre-event levels asymptotically. The degree of skewness is dependent on the proportion of sediment stored in the basin and its release rate.

More research is needed to identify the factors determining the shape of sediment waves in various basins under various conditions. Many of the same factors that determine the shape of hydrographs in a basin may be relevant to sediment waves, but there are at least two fundamental differences complicating the modeling of sediment waves. First, due to long periodicities, difficulties of measurement, and lack of discrete sedimentation events, there is a paucity of data that precludes accurate model calibration. Unlike stream-flow hydrographs, which can be averaged, scaled to unit hydrographs, and synthesized by empirical techniques, comprehensive data for the duration of sedimentation events are rarely available for even a single large event. Second, due to morphological changes attendant upon both temporary and permanent storage, subsequent sediment waves are not independent of antecedent events. For example, overbank deposition may raise channel banks and decrease storage potential in that part of the basin. Our ability to predict sediment loads is contingent upon an understanding of long-term sediment transport that can best be attained through the study of well-documented deposits.

Conclusion

Spatial and temporal patterns of sedimentation are relevant to such diverse practical concerns as flood-frequency evaluation, reservoir sedimentation rates, channel stability, water pollution, aquatic habitat management, interpretation of the geologic record, and erosion of bridge abutments, levees, and other engineering works. Hydraulic mining sediment provides an outdoor laboratory in which a fairly well-documented experiment was initiated more than 100 years ago. This study measured deposits and documented sustained storage and mobility of mining sediment in the Bear River to evaluate the outcome of this experiment in long-term sediment storage and transport.

Coring and mapping reveal that the mining sediment deposit in the lower Bear River has mean depths between 2.0 and 2.8 m and covers about 5010 hectares (50 km^2). Most of the deposit was emplaced between 1862 and 1900, so rates of aggradation during that period ranged from 4.7 to 7.4 cm yr^{-1} when averaged across valley transects 2 to 3 km in length. About $106 \cdot 10^6$ m^3 of the mining sediment remains stored in the lower Bear Basin below Camp Far West Reservoir. This estimate is more than double previous estimates, which lacked subsurface information and were probably based on underestimates of sediment production in the basin. During the peak period of aggradation, the lower basin storage volume was about $116 \cdot 10^6$ m^3, so less than 10 percent of the lower basin deposit has been eroded.

Topographic surveys of valley-bottom cross-sections in the foothills indicate that erosion of the mining sediment from main channels has been greatest near tailings fans. Measured depths of incision into mining sediment in the upper and middle Bear average about 10 m and range up to 27 m at tailings fans. In contrast to main channels in mining districts of the Yuba and American rivers, a large volume of sediment remains in main channels of the upper Bear River. This distinction is apparently due to greater sediment production per unit basin area, lower flood discharges than in mining districts of the Yuba or American river basins, and possible differences in the geomorphic history of the Bear Basin.

Sediment loads have not returned to pre-mining levels in the upper Bear River. Prior to mining, mountain channels had only thin patches of alluvium and were dominated by bedrock and coarse, bouldery material. Long-term storage of mining sediment has been substantial, and this sediment is readily available and easily reworked by the active channel. Frequently occurring flows are competent to entrain bed material derived from mining sediment. Sustained high transport rates are documented by field evidence of erosion, deposition, and sediment mobility, including erosion and deposition at channel cross-sections, terrace-scarp erosion, sedimentation in deltas, erosion downstream of modern reservoirs, lateral channel migration, and lack of mining sediment dilution in low flow channels. These high sediment transport rates are greater than pre-mining rates which were constrained by the limited availability of fine-grained sediment.

The sustained storage and delivery of mining sediment in the Bear River calls for a revised conceptual model of downstream responses to episodic sedimentation. Protracted high sediment loads indicate that the sediment wave passing through the Bear River has not been symmetrical in respect to time as visualized by Gilbert. The sediment wave is skewed to the right, representing a gradual decrease in sediment loads with time as the result of protracted releases of stored sediment. Channel-bed elevations, presented by Gilbert as evidence for sediment loads, can vary independently of sediment loads through changes in channel hydraulic properties. Incision of Sacramento Valley channel beds was encouraged by levee construction at stream-flow gauges that increased flow depths and competence.

The skewed sediment wave-form has important implications to the persistence of human impacts on the environment. Such persistence has been recognized across the North American continent, where the introduction of European agricultural practices exacerbated upland erosion and floodplain aggradation by sediment that is now prone to further down-valley migration. These modern observations need to be reconciled with Gilbert's model of sediment transport, which may underestimate the time period at which fluvial sediment remains active. The revised asymmetrical sediment wave model implies that impacts of episodic sedimentation may be persistent, and that human impacts to fluvial systems may have long-enduring consequences.[1] In many areas of the United States, this appears to be the rule rather than the exception.

Acknowledgments

I would like to thank my father, Laurence B. James, who made this research possible by providing field work, logistical support, and encouragement. Special thanks are also due to Ben James for field assistance, Dave and Pat Beach for providing summer quarters, James C. Knox for field equipment and editorial comments, the U.S. Geological Survey for stream-flow sounding data at Rollins Cable, and four anonymous reviewers of an early draft for suggestions that led to substantial improvements. Graphics were done by the University of South Carolina Cartography Lab.

Notes

1. A National Science Foundation grant (SES 8822436) was recently received to continue this research in the upper Bear River Basin and to extend it into the South Yuba Basin where much of Gilbert's work was centered. It is hoped, therefore, that additional documentation of the sustained nature of sediment reworking will be forthcoming.

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