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Time and the persistence of alluvium: River engineering, fluvial geomorphology, and mining sediment in California

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Abstract

River managers need to understand fluvial systems as they change through time. Many river systems are presently in a state of flux as a result of substantial anthropogenic changes to water and sediment regimes and channel hydraulics. Yet, historical approaches to understanding river systems rarely receive adequate attention because historical methodologies are not conducive to the application of quantitative analysis. While there is limited precision in most historical reconstructions, the information derived from these studies constrains other interpretations and is essential to a full understanding of the behavior of fluvial systems. Geomorphology provides a perspective on river systems in which time — at various scales — is interwoven into practical and theoretical aspects of scientific inquiry. Thus, geomorphology is important to our understanding of not only physical systems but also fundamental concepts of time.

This study examines channel morphological changes in the Bear and American basins brought about by two episodes of sedimentation from hydraulic gold mining. The primary event was the production of more than 1 billion m^3 of sediment throughout the northern Sierra Nevada from 1853 to 1884 which caused aggradation in many channels across the Sierra foothills and Sacramento Valley. Assumptions by both engineers and geomorphologists that morphologic responses to this event were ephemeral, that sediment loads have returned to previous levels, and that deposits have stabilized, are not borne out by field and historical data in the Sacramento Valley. A secondary sedimentation event, not previously studied, was the production of at least 24 million m^3 of sediment during a period of licensed mining from 1893 to 1953. This episode of sedimentation has been largely overlooked as a geomorphic, hydrologic, or water quality event. Yet, channel morphologic responses in phase with mining during this period are demonstrated. Systematic changes in stage–discharge relationships reflect channel morphological changes that are relevant to flood risk assessments, stability of engineering structures on floodplains, and geomorphic interpretations. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: physical system; channel morphology; hydraulic gold mining; river management

1. Introduction

Two scientific traditions have evolved around the study of river channels in Great Britain and the United States: river engineering and fluvial geomorphology. Although differences between these disciplines may become blurred by collaborations and exchanges of ideas, a contrast persists that should be understood to facilitate communication and to appreciate various approaches to river management. Traditional differences between river engineering and fluvial geomorphology reveal that (1) both are valuable

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disciplines, (2) each has much to learn from the other, and (3) a fundamental difference exists in the perception of time and, therefore, of fluvial processes.

Engineering design theory has approached high levels of precision for many common structures, but the geological environments in which these structures are placed are highly irregular in ways that are difficult to anticipate or model (James and Kiersch, 1991). Understanding the complexities of these environments requires considerable training in the geological sciences. Yet, the importance of geological science is often underestimated due to the difficulty of precisely specifying parameters in quantitative form. Stratification of 20th century science has resulted in an implicit ranking of pure quantitative science (physics, chemistry, and math) at the top, natural sciences in the middle, and social sciences at the bottom of a perceived hierarchy (Baker, 1996; Moores, 1997). Through uncritical applications of this ranking, a study using sophisticated mathematics and technology may be considered rigorous even if conventional scientific methods such as hypothesis testing or model validation are not employed. Conversely, a well-conceived and thoroughly researched study with hypothesis testing and validation of results may be regarded as less rigorous if it does not employ advanced mathematical or technological methods. This cultural perception of the quality of science has led to a growing emphasis on quantitative methods and a deemphasis on changes of environmental systems through time.

Most problems in river management are four dimensional in nature, while numerical models of surface–water systems are rarely developed beyond two dimensions. Limitations to the dimensionality of numerical models have recently led engineers to further de-emphasize time. In contrast, geomorphologists have traditionally sacrificed some of the precision and clarity of quantitative methods in order to include the historical nature of systems. The inability of most numerical approaches to adequately incorporate full dimensional representation of processes at any scale, let alone over extended time periods, leaves those methods susceptible to extreme errors of judgement and overestimates of precision regarding long-term processes if not tempered by independent information. Resulting uncertainties in river engineering calculations often call for the inclusion of 'margins of safety' (e.g., levee freeboard or reservoir surcharge storage) that can be quite arbitrary, thus defeating the purpose of the methods.

Ignoring historical information may result in questionable assumptions of static conditions over time in spite of clear evidence of extreme environmental and climatic changes during the Late Quaternary and substantial changes during historic time (Johnson, 1982; Knox, 1983; NRC, 1995). For example, unchanging probabilities (independence) of climatic events are routinely assumed in flood frequency analysis although persistence is commonly acknowledged (e.g., during El Niño events or conditions of the 1930s dust bowl in the western USA). Information afforded by historical studies, although often disregarded as fuzzy, incomplete, and of limited relevance, may provide constraints and insights into processes and rates that can prevent the commission of major blunders (Baker, 1996). This paper describes fundamental differences between river engineering and fluvial geomorphology, reviews a few time-related geomorphic concepts, and argues for an increased use of historical geomorphology in river management. It finishes with examples of how underestimates of the magnitude of natural phenomena over time have led to erroneous judgements about flood control and channel geomorphic conditions in northern California.

2. Background: traditions, time, effectiveness, and sediment waves

2.1. River engineering and fluvial geomorphology traditions

Although scientific transfers of knowledge have been proceeding rapidly in recent decades between engineers and geomorphologists studying river systems (e.g., Thorne and Osman, 1988; Hey, 1990), many basic differences remain. River engineering evolved largely from studies of fluid mechanics, hydraulics, and regime theory. Due to emphasis on factors relevant to channel hydraulics and structural competence, engineering studies have traditionally focused on channel gradients, channel and floodplain topography (including bedforms), roughness ele-

ments, and the geotechnical properties of materials (Lacey, 1930; Blench, 1952; Chow, 1959; Shen, 1971, 1976; Chang, 1988). Because engineers often work in a pragmatic environment with governmental institutions, consultants, and contractors, there has been an emphasis on practical solutions and symptoms more than underlying processes (Sear et al., 1995), thus an emphasis on relatively short time periods.

Geomorphology has evolved largely in research-oriented environments (e.g., universities, professional associations, and geological surveys) from physiographic studies that could be divided into descriptive methods (geomorphography) and genetic or historical methods (geomorphogeny) (Baker, 1988). At the turn of the century, the genetic approach dominated and geomorphic research was largely concerned with landform evolution over millions of years (Davis, 1902). An alternative approach based on equilibrium theory developed slowly from the work of Gilbert (1877) and led to such concepts as grade, dynamic equilibrium, and landform entropy with a greater emphasis on prediction through the identification of process–response linkages (e.g., Mackin, 1948; Hack, 1960; Leopold and Langbein, 1962; Leopold and Maddock, 1953; Leopold et al., 1964; Morisawa, 1985).

Mainstream geomorphology shifted toward process studies in the mid-twentieth century with concern for time-independent theories of landform development and the widespread adoption of quantitative methods. This trend was hastened along by the adoption of the dynamic equilibrium concept with relatively short response times as an alternate model of landscape evolution to the prevailing Davisian cycle of erosion (Hack, 1960; Tinkler, 1985). The use of statistical and mathematical methods also encouraged a move toward data which were readily available in numeric form such as cartographic data for morphometry and instrumental data for hydraulic geometry. Quantitative methods are more difficult to apply to stratigraphic and other historical records, and traditional concerns with landform evolution fell out of favor. Combined, the dynamic equilibrium model and quantitative methods led many modern geomorphologists away from the quest for historical causality to an emphasis on practical scientific and engineering methods over relatively short periods of time (Baker, 1988). While these studies have made many important contributions to the understanding of geomorphic processes, there are limits to what analyses of short-term records can achieve toward an understanding of long-term fluvial adjustments.

Sediment erosion, transport, and storage is the fundamental mechanism controlling channel stability and morphological change. An understanding of the behavior of fluvial sediment is at the heart of both engineering and geomorphic studies of physical river systems. Yet, due to different objectives, methods and perspectives regarding alluvium differ considerably between river engineering and fluvial geomorphology. River engineers typically focus on interactions between bedforms and hydraulic roughness, erosion-resistance, and sediment transport parameters such as the particle incipient motion and numerical methods for calculating transport rates (Meyer-Peter and Muller, 1948; Einstein, 1950; Shen and Julien, 1993). While many of the same sedimentary features are measured by geomorphologists as by engineers, they have traditionally been observed differently by also emphasizing fabric, structure, lithologic provenance, and facies models to identify genesis and linkages between form and historical processes (e.g., Baker 1977; Reineck and Singh, 1980; Miall, 1982).

2.2. Geologic time and historical methods

In spite of the shift of modern geomorphology toward methods more similar to engineering, important differences remain between mainstream geomorphologists and river engineers, and the perception of time is a defining characteristic of this dichotomy. River engineers are typically concerned with a design period on the order of 50 years; a time period over which static equilibrium and graded conditions of fluvial systems are commonly assumed (Johnson, 1982). In contrast, fluvial geomorphologists often consider a range of periods from a few years or decades (graded time) to periods of landform evolution lasting millions of years (cyclic time). The understanding and appreciation of time is one of the most important contributions that geomorphology makes to river management studies. Many geomorphic concepts are concerned with some element of time; e.g., equilibria, grade, landscape entropy, and magnitude-frequency analysis (Thornes and Bruns-

den, 1977). Explicit measures of time are needed to specify rates, frequencies, risks, and effectiveness of events, as well as to establish the stability of a river system. Time scales determine which hydrologic and morphologic variables are independent or dependent (Schumm and Lichty, 1965). In short, time concepts such as effectiveness and gradualism vs. catastrophism have generated debate within the geological sciences for hundreds of years, and these concepts are essential to a full understanding of fluvial processes and river management.

The value and methods of documenting historical changes to rivers have been demonstrated by several studies (Schumm and Lichty, 1963; Schumm, 1968; Knox 1972, 1977; Lewin et al., 1977; Patton et al., 1979; Bravard and Bethemont, 1989). Fortunately, long historical records tend to be available along rivers which act as arteries of travel, commerce, and settlement, and where wet soils facilitate the preservation of archeological relics (Petts, 1989). Unfortunately, many scientists and engineers are reluctant to use historical methods because the evidence may be anecdotal, incomplete, and less quantifiable than records derived from recent instrumental measurements. Nevertheless, placing modern processes into a long-term context requires knowledge of past process rates and changes which should be validated by historical data. The need for this validation grows rapidly when rates and processes are considered beyond a few decades.

As western geomorphologists turned to process–response studies in the mid-19th century, it was often asserted that knowledge of processes would ultimately resolve the landform evolution issues of classic geomorphology. Process studies alone will not lead to an understanding of landform evolution, however, because the time over which processes are instrumentally recorded is much shorter than the period over which landforms develop (Church, 1980). Long periods of measurement are required to characterize slow, episodic, or highly variable processes, so the likelihood of capturing appropriate information on instrumental records decreases when such events are effective. Just as the optimism of logical positivism in physics was damped by the uncertainty principle, so optimism about resolving landform evolution questions with process studies has been blunted by realizations of the amplitude, frequency, and sudden nature of Late Quaternary environmental changes and of process uncertainties such as thresholds, chaos theory, and complex response. Historical geomorphic and stratigraphic studies are needed to resolve questions of landform evolution.

The shift of geomorphology toward engineering methods has many benefits, but geomorphologists should not forget their roots or reject the value of the historical perspective. For geomorphology to be relevant to the central body of geologic thought, it is not sufficient to merely understand modern processes, but also to understand process rates and the history of form generation within the context of a broader Earth history (Baker, 1988). The need to consider events and processes acting over time scales greater than 50 years is particularly important now that equilibrium theory is being questioned; as non- and multi-equilibrium systems, thresholds, and episodic changes are being recognized (e.g., Phillips, 1992). While river engineers need not be concerned with landform evolution over cyclic time, they should recognize the value of historical viewpoints and methods and consider theories concerning long-term trends, responses to perturbations, and disequilibria in fluvial systems that such perspectives provide.

2.3. Effectiveness of aggradation events

A traditional time-dependent concern in geomorphology has been the effectiveness of events acting on the landscape, that is, how enduring are landforms created by a given hydroclimatological event? Conversely, effectiveness may be examined to determine what type of event is responsible for given landforms. The concept that moderate magnitude events are the dominant formative agents of many geomorphic features has a long tradition that can be traced back to uniformitarianism and the Fluvialist school of Hutton and Playfair (Chorley et al., 1964). Building on this notion, Wolman and Miller (1960) argued that the cumulative work performed by a given size event over time is the product of work done by the event and its frequency. For channels, they defined the effective discharge as the flow with the maximum magnitude-frequency product because it transports the most sediment over time. On this basis, they argued that the effective discharge for

large alluvial channels in humid climates is of moderate magnitude and occurs relatively frequently (every few years). This principle was corroborated in large alluvial basins in the subhumid eastern United States where rapid channel recovery from extreme floods and a high frequency of bank-full discharges were demonstrated (Jahns, 1947; Wolman and Eiler, 1958; Costa, 1974).

The concept of effective discharge has two distinct definitions: the discharge that transports the most sediment versus the discharge responsible for channel morphology (Wolman and Gerson, 1978; Harvey et al., 1979; Kochel, 1988; Jacobson et al., 1989). The effective sediment-transporting discharge, which integrates basin-wide rainfall-runoff and sediment delivery factors, is often measured by the magnitude-frequency product if suspended sediment concentration data are available. In contrast, the effective channel-forming event, which may vary from site to site with channel conditions, can be defined by the frequency of bank-full discharge or by erosion and recovery from floods (Dury, 1977; Harvey et al., 1979; Andrews, 1980). Understanding of the channel-forming event is complicated by difficulties associated with identification of bank-full stage (Williams, 1978), and because channel-erosion criteria depend on thresholds surpassed only during transient maxima rarely measured directly (Baker, 1977; Kochel, 1988). Differences in the two definitions of effectiveness can be illustrated by a stable channel reach that is eroded only by extreme floods, yet conveys high suspended sediment loads from upstream during moderate events.

Factors that decrease the frequency of moderate magnitude events such as arid climates or small drainage areas, may shift the effective discharge toward a larger magnitude and lower frequency (Baker, 1977; Wolman and Gerson, 1978; Kochel, 1988). This was understood by Wolman and Miller (1960) who noted that: ''the smaller the drainage area, the larger will be the percentage of sediment carried by the less frequent flows''. The concept of effectiveness has also been modified and expanded to accommodate intrinsic factors such as thresholds of stability imposed by coarse sediment, resistant bank materials, vegetation, etc. In fact, a neocatastrophist school has emerged which recognizes the importance of extreme events to channel morphology and sediment budgets under many circumstances (Baker, 1977; Kochel, 1988).

Recovery times from perturbations are implicitly included in the concept of effectiveness. Relaxation of channel morphological changes following a flood tends to proceed rapidly at first, then decreases, and it may become intermittent or subtle in later stages (Graf, 1977). Recovery times are longer where resistance to change is greatest (Thornes and Brunsden, 1977), so levees, riprap, and other protective measures may simply protract geomorphic responses if not built to withstand extremely large and rare events. The time required for readjustment of rivers to human alterations is not well understood because it generally exceeds 40 years (Petts, 1989), and because such alterations can seldom be isolated. For time periods of such durations, historic evidence, including stratigraphic, cartographic, instrumental, and documentary records may be needed to characterize changing rates of channel adjustments and to identify multiple perturbations.

The persistent effects of anthropogenic sediment on channel morphology is an example of geomorphic effectiveness which is relevant to sediment budgets, channel stability, and flood risks. The sudden introduction of large volumes of sediment to a fluvial system is typically followed by a period of relaxation in which channels recover to their previous form or to a new form representing a balance between the load of water and sediment through time. Some studies have shown that the introduction of sediment can be followed by relatively rapid returns to pre-event conditions. For example, Wolman (1967) showed a rapid return of sediment yields in small eastern US streams following a high episodic point-source loading caused by urban construction. In larger watersheds, Gilbert (1917) and Lambert and Walling (1986) indicated a relatively rapid transport of sediment through channels. The distinction should be made, however, between transport of sediment confined to bank-full channels, and sediment stored on floodplains, fans, or deltas, which may involve long residence times and protracted changes in sediment budgets. The latter component involves consideration of channel systems over a longer time period than is typical of most studies based solely on recent instrumental records. Long-term sediment storage is an essential element of sediment budgets as is evi-

denced by the tendency for sediment delivery ratios to be less than one (Roehl, 1962; Meade, 1982; Walling, 1983, 1988).

2.4. Gilbert's symmetrical sediment–wave model

In the first two decades of the 20th century, G.K. Gilbert became involved in the study of mining sediment deposits in the Sierra Nevada and published two classic monographs that have had a lasting impact on our understanding of fluvial processes (Gilbert, 1914, 1917). Gilbert not only developed a conceptual model of sediment transport, but also began a long tradition of geomorphologists adapting methods of river engineers to larger scales of time and space. Gilbert's model is based on changes in low-flow stages at three Sacramento Valley streamflow gages in response to the influx of mining sediment (Fig. 1). Production and reworking of sediment from the 1850s to 1880s delivered mining sediment to downstream reaches which aggraded, causing a rise in low-flow stages. After mining was enjoined in 1884, channel beds began to incise, and low-flow stages decreased. Gilbert inferred from these systematic changes in stage that sediment loads had increased and decreased accordingly and he envisioned sediment transport in a 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 the fact that part of its overflow volume is permanently lodged outside the river channel....'' (Gilbert, 1917)

Subsequent work using Gilbert's methods indicates that, as Gilbert predicted, channel-bed elevations had returned to pre-mining levels by the 1960s; that is, they rose and fell in a sequence which was symmetrical in time (Graves and Eliab, 1977). Thus, the model describes a symmetrical wave. Gilbert's wave model has been highly influential and is commonly cited by geomorphic papers and textbooks (e.g., Leopold et al., 1964; Richards, 1982). Recently, Madej and Ozaki (1996) presented a large amount of field data collected since 1973 following large floods on Redwood Creek in 1964 and 1972 which produced an episodic load of gravelly sediment. They clearly document lowering of channel beds and describe the process as passage of a sediment wave, although their data indicate substantial volumes of erodible gravel stored in terraces along the channel.

It may be correct to assume that sediment loads reach a maximum at a site when the channel bed has aggraded to its highest level, but it is dangerous to assume that sediment loads are linearly related to and can be estimated from low-flow bed elevations. Nor should we assume that all recent sediment has been either removed or permanently stored simply because low-flow stages have returned to their original level. Yet, Gilbert's model has been the guiding principle by which many modern engineers in California believe that channel morphologic responses to 19th century aggradation are complete. It continues to be evoked by geomorphologists and engineers alike, to argue erroneously that historical alluvium and channel morphologies have stabilized in the region.

If sediment loads are inferred from channel low-flow stages as is the common interpretation of Gilbert's model, then the unavoidable conclusion would be that reworking of historical sediment and channel morphologic adjustments are negligible after a relatively short period of time. This would imply that a massive sediment event such as 19th century hydraulic mining is geomorphically ineffective beyond about 100 years. However, lowering of low-flow channel beds in the Sacramento Valley does not indicate the depletion or complete stabilization of historical alluvium in the system because (1) it represents only the vertical dimension of channel adjustments, and (2) several hydraulic engineering changes have artificially encouraged channel incision.

Channel-bed elevations may be biased indicators of sediment loads. It is common for channels to respond to lowered base levels or decreased sediment loads, first by incision, then by widening (Schumm et al., 1987). It would be more precise to describe channel-bed lowering to pre-mining levels in the Sacramento Valley as a return to *grade*, which does not require sediment loads to have returned to background levels, particularly if flood depths and unit stream powers are elevated. For example, channel incision at two of Gilbert's three gage sites (at Sacramento and Marysville) was encouraged by ex-

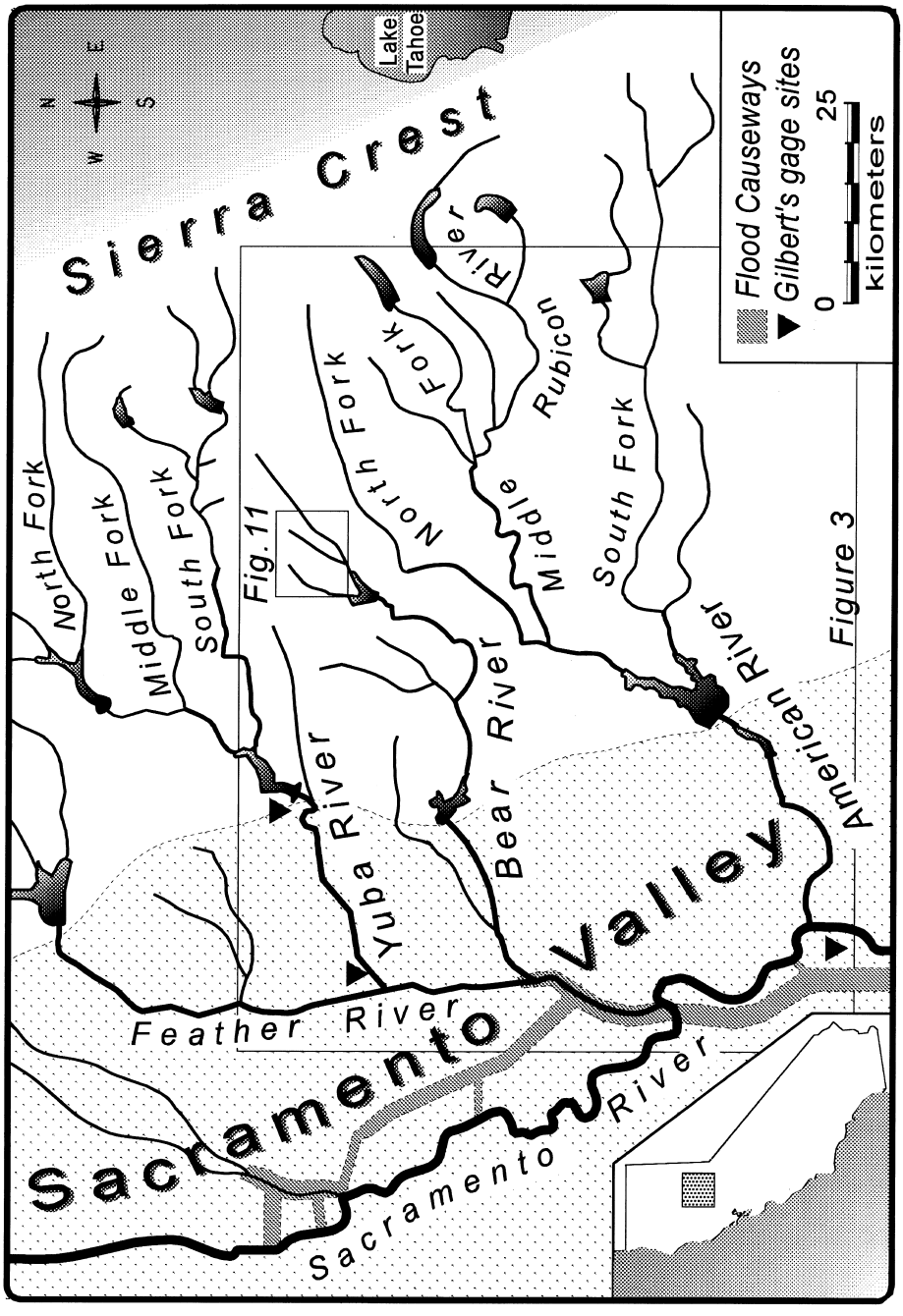

Fig. 1. Lower Sacramento Valley and northwestern Sierra Nevada foothills.

tensive levee construction which deepened flows and encouraged bed erosion independently of sediment loads (James, 1993, 1997). Gilbert's third site, the Yuba River Narrows, was a bedrock gorge. In addition, channel incision on the lower Sacramento River system was encouraged by the construction of jetties

and other hydraulic works at Newtown Shoal near the mouth of the river which resulted in more than 3 m of flow deepening around the turn of the century (Kelley, 1989). Similarly, dredging across Horseshoe Bend from 1913 to 1916 allegedly removed more sediment than was removed from the Panama Canal. Both of these operations removed a major constriction at the Sacramento River mouth and encouraged channel incision independently of sediment loads. Finally, the construction of large dams in the mountains and foothills from the 1920s through the 1960s arrested the down-valley transport of sediment to the Sacramento Valley.

G.K. Gilbert was a pioneer for modern geomorphology by adopting empirical, quantitative, and inductive methods oriented toward the testing of multiple hypotheses (Pyne, 1980). Gilbert's approach has been described as largely non-historical (Thorne, 1988) and was more in keeping with engineering methods than most of his contemporary geomorphologists who were preoccupied with landform evolution over cyclic time. Yet, Gilbert was deeply ensconced in historical geology as is demonstrated by three of his four classic monographs (Gilbert, 1877, 1890, 1917). His *Report on the Geology of the Henry Mountains* (1877) was concerned not only with the emplacement of a Cenozoic laccolith, but also introduced classic laws of drainage which became canons of fluvial and hillslope evolution. His Lake Bonneville monograph (1890) detailed shoreline processes and isostatic crustal deformation based largely on the Bonneville and Provo shorelines, relicts of Quaternary pluvial events. His last monograph, *Hydraulic-mining debris in the Sierra Nevada* (1917), is a comprehensive view of geomorphology that weaves together concepts of long-term landform evolution with processes operating on an immediate basis. When the spatially broad perspective of this study is combined with his flume analysis of the mechanics of grain transport (Gilbert, 1914), Gilbert's mastery and comprehensive view of landform processes becomes clear. There can be no doubt that Gilbert regarded the response of channels to the influx of mining sediment with a mind that was honed on geologic time. It is this historical perspective that has made his work so influential in the Sacramento Valley where few others (e.g. Bryan, 1923; Shlemon, 1972) have provided the perspective of historical geomorphology. It is unfortunate that Gilbert used the phrase ''permanently lodged'' to describe sediment remaining in the basin following channel-bed regrading, because this has been interpreted literally in spite of clear field evidence to the contrary. The remainder of this paper reviews the nature of flood control in Sacramento Valley and the effects of episodic 19th century mining sediment and previously undocumented 20th century mining on channel morphology of the Bear and American Rivers.

3. Geomorphic and engineering developments in Northern California

Rivers in the region flow from crystalline and metamorphic rocks of the northern Sierra Nevada westward through the mining districts to the alluvial plain of the Sacramento Valley where they join the Feather and Sacramento Rivers (Fig. 1). Mining took place in the upper foothills between 700 and 1200 m elevation where channels flow in steep, narrow valleys. Small pre-mining channels in the mountains were dominated by bedrock and boulders with local areas of alluvium. In larger mountain channels, considerable depths of alluvium collected in reaches of gentle gradient while steep reaches were floored by bedrock and large boulders. As tributaries from the Sierra Nevada enter the Sacramento Valley, their gradients and sediment textures decrease considerably. Channels cross broad basins that were prone to annual flooding prior to the construction of levees, and were deeply alluviated when mining sediment arrived.

3.1. Introduction of hydraulic mining sediment

Sedimentation by hydraulic gold mining dominated fluvial systems and exacerbated flood hazards throughout the lower Sacramento Valley and northwestern Sierra Nevada foothills. The advent of hydraulic gold mining in the 1850s was followed by rapid and voluminous sediment production and widespread channel aggradation, which is well documented by historical evidence (reviewed in James and Davis, 1994). Sedimentation was so extreme and rapid, and occurred so early in the history of the State that it largely predates Federal land surveys. Extensive litigation over hydraulic mining between

1878 and 1884, however, produced detailed expert testimony describing channel conditions before and during the hydraulic mining era (Keyes, 1878; Sawyer, 1884). Contemporary government surveys by engineers and geologists provide reliable descriptions and measurements of deposits (Hall, 1880; Mendell, 1882; Heuer, 1891).

Hydraulic mining produced more than 1 billion m^3 of sediment from 1853 to 1884 when mining was enjoined. Sediment production volumes were estimated by Benyaurd (Heuer, 1891) based on records of water use, and were revised by Gilbert (1917) based on topographic surveys of selected mine pits. The largest volume of sediment was produced in the three forks of the Yuba River, but the Bear River received more than any of the individual Yuba branches (Fig. 2A). The Bear Basin also received the most 19th century mining sediment per unit drainage area, representing denudation on the order of 23 cm (Fig. 2B). Since most mining took place from 1858 to 1884, this represents a denudation rate of almost 1 cm per year across an area greater than 1000 km^2. Denudation of neighboring basins ranged from 2 to 21 cm for the 19th century mining period.

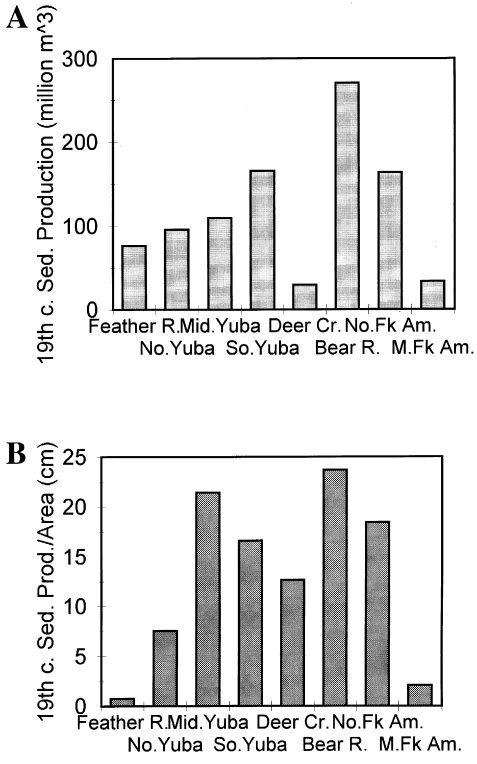

Fig. 2. Sediment production by 19th century hydraulic gold mining. (A) Volumes based on Benyaurd (Heuer, 1891) adjusted by the 1.5 coefficient of Gilbert (1917). (B) Depths of denudation calculated as volume/drainage area.

During the 1850s most mining sediment remained in tributaries, but in 1862, two large floods delivered this material to main channels throughout the lower Sacramento Valley causing widespread channel aggradation and increased flooding thereafter. Fine sediment was delivered downstream to the Sacramento Delta, the San Francisco Bay, and beyond the Golden Gate (Gilbert, 1917). Sediment impacts on flooding and navigation in the Sacramento Valley led engineers to seek measures to arrest sediment in the mountains and encourage its passage through the lower system. By the 1880s, these efforts had led to a sophisticated knowledge of several aspects of river hydraulics but an underestimate of flood risks.

3.2. 19th century flood-control measures in the Sacramento Valley

Extreme floods in the Sacramento Valley result from orographic uplift of Pacific storms tracking from the southwest over the northwest-trending Sierra Nevada. High interannual precipitation variability of the Mediterranean climate, thin soils, and sparse vegetation result in high proportions of surface runoff at low to moderate elevations. Mountain channels are narrow and steep so the delivery of runoff downstream can be quite rapid (NRC, 1995). These conditions were not fully appreciated by the early settlers, and flood-control planning in the Sacramento Valley historically has suffered from underestimates of long-term flood variability. Late 19th century flood control was flawed by several additional factors: (1) lack of centralized coordination, (2) a fragmented levee system, (3) conversion of flood conveyance to a single-channel system, (4) aggradation of main channels by several meters of mining sediment, and (5) failure to detain sediment from the mountains with dams. Several methods of coordinating flood protection were considered during the late 19th century but lack of central authority prevented large-scale solutions from being implemented. Throughout this period, a series of competing levees maintained by individual farmers and drainage districts resulted in flooding, sedimentation, and litigation (Kelley, 1989).

Due to underestimation of flood risks and the need to maintain navigation, flood-control planning in the 19th century was dominated by a single-channel policy which attempted to contain all flood waters within main channels. Prior to European settlement, the Sacramento Valley had consisted of a series of back-swamp basins that were separated from the main channel by natural levees and flooded extensively during most winters (Gilbert, 1917). To encourage conveyance of mining sediment out of the system, the entire line of flood defense was focused on confining within a narrow channel, large floods that had previously been conveyed across much of the marshy Central Valley with flows many kilometers wide. To accomplish this task, the US Army Corps of Engineers (Corps) advocated the use of levees and other structures downstream to deepen flows, and dams upstream of navigable rivers to prevent further sediment deliveries.

The Corps advocated levees on large navigable channels to constrain channel widths, deepen flows, encourage self-scouring of channels, and move sediment through the lower system. Topographic surveys in 1870, 1879, and 1889 had indicated both filling and deepening of the lower Sacramento River. An average fill of 18 cm over 130 km of channel represented net filling of 19 million m^3 over this period (Heuer, 1891). The contrast between bed scour at narrow reaches vs. bed aggradation at wide reaches was recognized and wing dams were recommended to deepen flows and encourage channel scour:

> ‘‘...the greater shoaling occurred where the river was exceptionally wide and, ...the greater scouring occurred in localities where the river was below the average width... [The] depth of water can be effectively increased by a contraction in width of the low water channel, and this is the method which the Board recommends in the treatment of the river. To accomplish this object it is recommended that brush mattresses be used, projecting from the bank towards the channel as far as may be required....’’ (Heuer, 1891: 3014–3015)

This use of wing dams was correct in principle insofar as narrowing induced bed scour, but sediment deliveries were excessive and the variability of flood magnitudes was greatly underestimated, so levees frequently failed. The practice of encouraging channel-bed scour by constraining channel widths later influenced geomorphic concepts of fluvial sediment transport, however, when Gilbert (1917) adopted this recommendation, and it has become standard engineering practice.

Farmers and agricultural engineers in the Valley attempted to control the aggrading rivers with levees and opposed the construction of dams in the eastern Sacramento Valley which they believed would aggravate local flooding and sedimentation. In spite of popular pressure, the Corps built two brush dams in 1880 to detain sediment on the lower Yuba and Bear Rivers before it reached the navigable Feather and Sacramento Rivers. This strategy failed in the first year, but not before the Yuba and Bear River brush dams filled with 137,000 and 27,000 m^3 of sediment, respectively, as shown by topographic resurveys in October, 1880 and August, 1881 (Mendell, 1882).

The movement toward coordinated river management in the Sacramento Valley was initiated by the Manson–Grunsky report (CCPW, 1895). This State flood-control plan departed from the prevailing single-channel plan by proposing a series of flood weirs and by-pass channels (causeways) that would mimic the natural basins but would be leveed to contain flows parallel to the main channel meander belt. This proposal was in stark contrast to the prevailing philosophy of levee-based main-channel flood control along the Sacramento and Mississippi Rivers and was not implemented for two decades. It received little support from 19th century Corps engineers who believed that diversion of flows to causeways would not provide sufficient scouring of mining sediment from the main channel to support navigation. The ultimate movement toward a by-pass system was in part necessitated by decreased main-channel flood capacities due to the levees and wing-walls which deepened thalwegs but constricted channel widths, and to mining sediment deposits along channel margins.

3.3. 20th century flood control measures

The Manson–Grunsky Plan was largely incorporated into the Jackson Plan (CDC, 1911) which was

implemented in 1917. By this plan, major by-pass channels designed to carry flood flows every few years were constructed along the Sacramento River more than 300 km to its mouth (Fig. 1). The system includes a cross-over where flows from the Sutter Bypass enter the Sacramento River and, on the opposite side of the river, pass through the Fremont Weir to the Yolo Causeway (Fig. 3). The plan combined a narrow, leveed main channel to encourage scour of mining sediment with extensive leveed overflow channels to convey flood waters. The restriction of land use in by-pass channels to farmland anticipated by 50 years limited land-use policies adopted by the National Flood Insurance Program. While the by-pass system, in principle, has proven to be superior to a single-channel system, the causeways were not large enough to contain the large-magnitude floods that ensued. From the onset, flood control in the Sacramento Valley has been plagued by ever-increasing estimates of the frequency of large magnitude floods.

Flood risks on the Sacramento River were initially based on a period with few large floods. In the 1890s, the probable maximum flood (PMF) for the lower Sacramento River was estimated by many engineers to be much less than 8500 m^3s^{-1}, but following a large 1907 flood two years after the installation of the first stream-flow gages, however, the PMF was raised to 8500 m^3s^{-1} (Kelley, 1989). On the lower American River alone, one of many tributaries to the Sacramento River, regulated flows

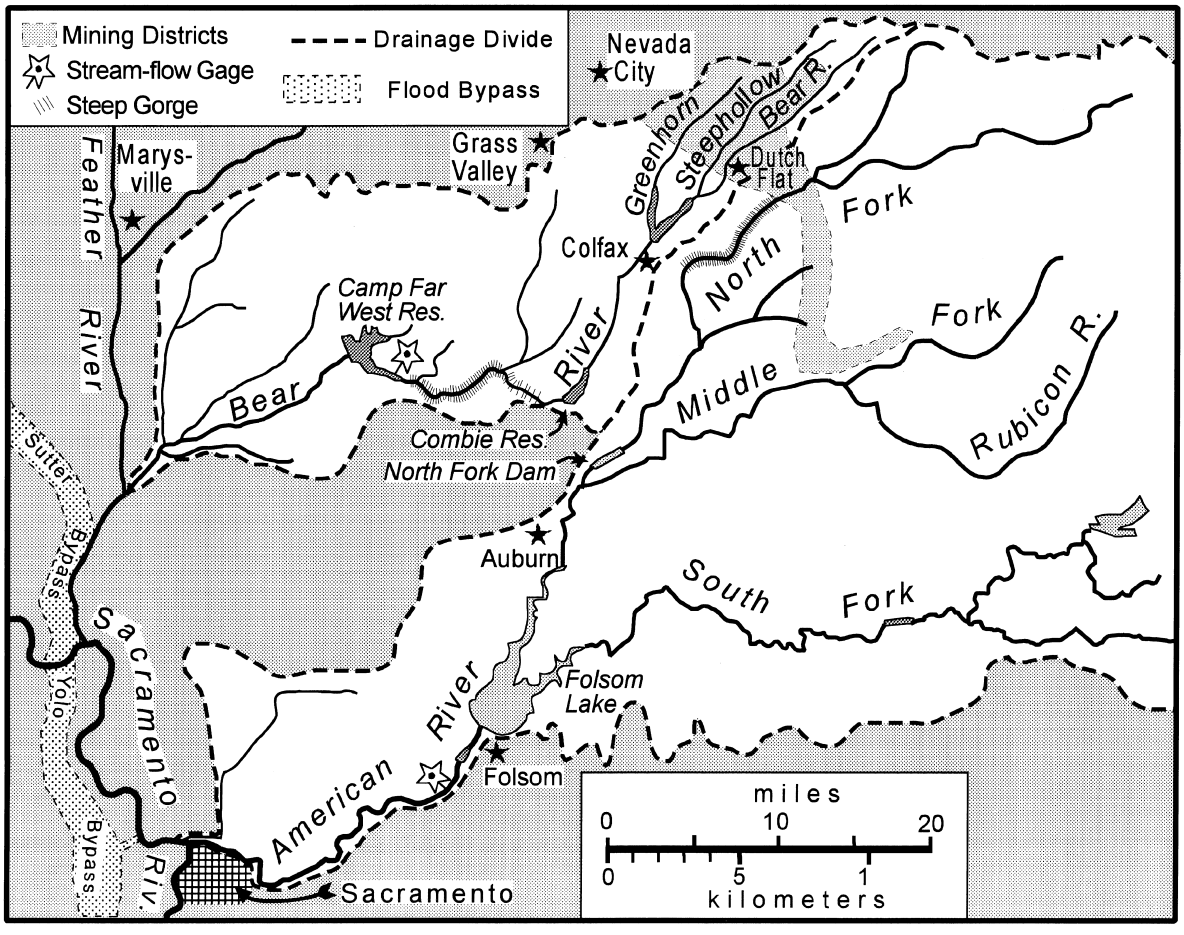

Fig. 3. Bear and American River Basins.

from the design flood (100-year return period) doubled from 3260 to 6520 m^3 following the 1986 flood of record. Folsom Dam was designed in the late 1940s to manage an event on the lower American River initially thought to have a recurrence interval of 250 years. By 1961, following large floods in the 1950s, this estimate was lowered to 120 years, and further reduced to only 70 years by 1993 following the 1986 flood of record (Fig. 4) (USACE, 1991). The 1997 flood at Folsom had a 3-day volume identical to the 1986 flood of record, and is likely to further lower this estimate of the return period to below 70 years.

Little historical geomorphology has been included in Sacramento Valley flood planning. Early work by Gilbert (1917) and Bryan (1923) was followed by a series of stratigraphic studies (Olmsted and Davis, 1961; Shlemon, 1971, 1972; Marchand and Allwardt, 1981; Busacca, 1982), but little has been done to close the gap between Pleistocene stratigraphy and modern processes. Late Quaternary stratigraphers have largely avoided the lower Yuba, Bear, and American valleys due to burial by historical deposits. Local engineering has lacked the geomorphic tradition that has characterized the lower Mississippi River (Fisk, 1944; Saucier, 1994), and has adopted the early predictions of Gilbert (1917) of sediment behavior uncritically, without field validation. Vast deposits of historical alluvium have not been mapped

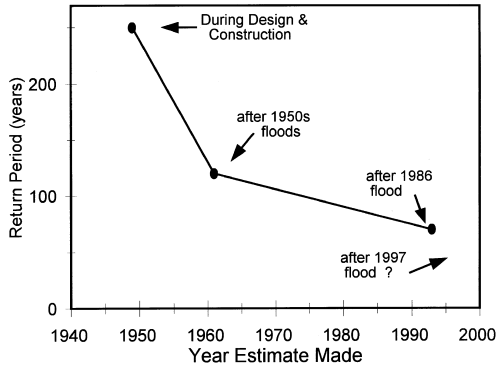

Fig. 4. Decreasing estimates of design flood recurrence interval at Folsom Dam on the lower American River. Each large flood lowered estimated return period, indicating need to include historical information in flood-frequency analysis (Data: USACE, 1991; cf. NRC, 1995).

except in 1879 along the lower Yuba and Bear Rivers while sediment was still being delivered (Hall, 1880). The importance of this sediment to modern channel processes continues to be downplayed as being either above dams or behind levees.

4. Sediment storage and transport in the Sierra Nevada

The importance of geomorphic history to fluvial systems is exemplified by the episodic production of hydraulic gold-mining sediment in the late 19th and early 20th centuries in northern California. The remainder of this paper concentrates on effects of sedimentation in the Bear and American Rivers, two of the three major basins that received the most sediment (Fig. 3). Previous viewpoints of both geomorphologists and engineers have underestimated the effectiveness and duration of channel morphologic changes caused by hydraulic mining sedimentation in valleys of the northwestern Sierra Nevada. This is due largely to the erroneous assumption that rapid vertical regrading of channels represents the removal of all active historical sediment from channels. Yet, return of channels to pre-sedimentation base levels can be explained by hydraulic changes largely independent of sediment loads and does not necessarily represent a removal of all sediment from the inner channel, let alone storage on floodplains and other sites. In spite of accelerated channel erosion below dams, substantial historical deposits remain, and they are actively eroding.

4.1. On-going sediment reworking

Field and historical evidence documents sediment production, sustained storage, and on-going mobility in the Bear River (James, 1989, 1993). Aggradation exceeded 60 m in some mountain reaches and vast deposits of mining sediment remain along main channels of the Bear River and its main tributaries, Greenhorn and Steephollow Creeks (Fig. 5). These deposits are readily distinguished from other sediment due to their lithology which is so distinctively quartz rich that it is possible to estimate sediment

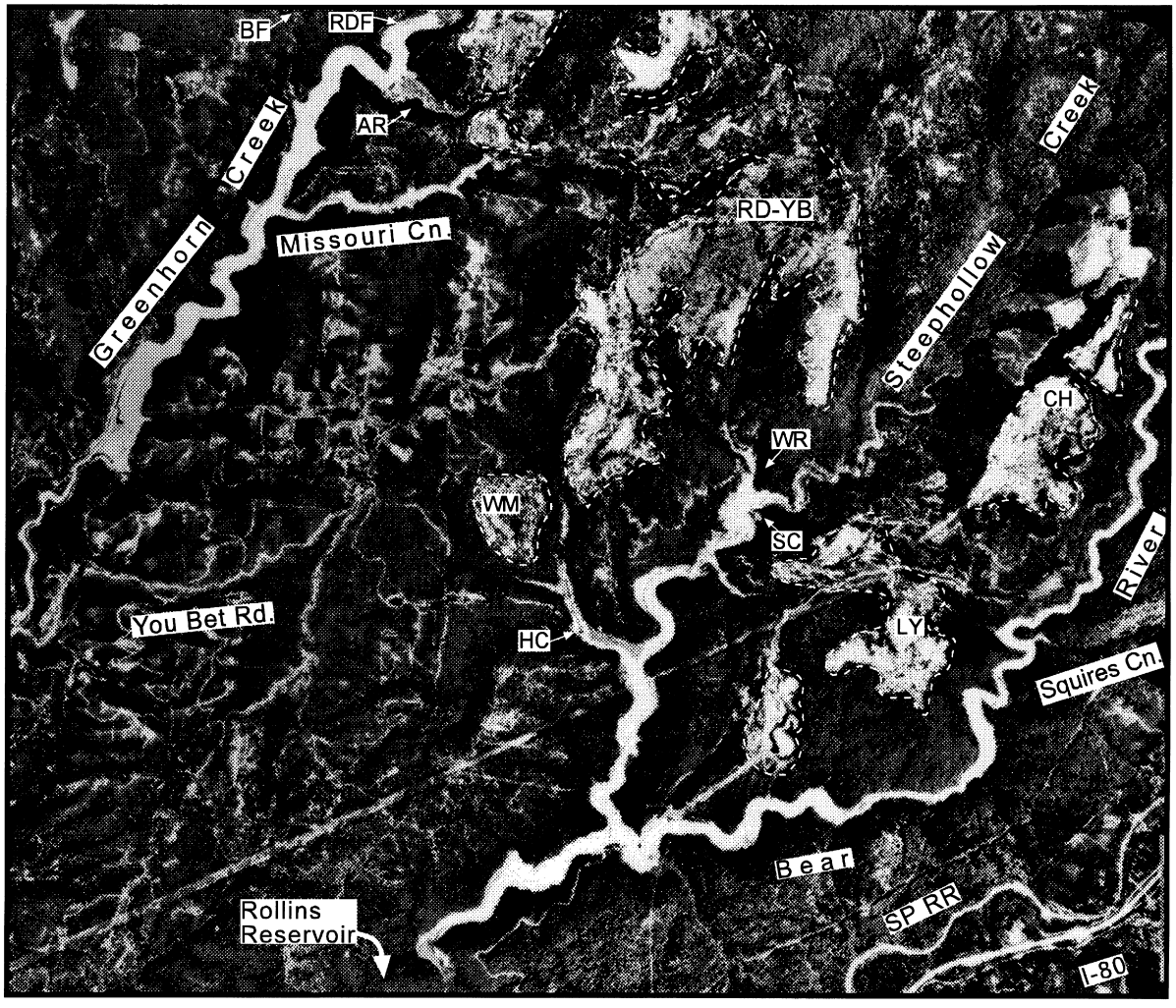

Fig. 5. Aerial photograph (1987) showing mines and extent of mining sediment in upper Bear Basin. Major mines highlighted by dashed lines. AR = Arkansas Ravine, CH = Christmas Hill Mine, HC = Hawkins Canyon (a.k.a. Birdseye Cn), LY = Little York Mine, RD-YB = Red Dog-You Bet Mine, SC = Steephollow Crossing, WM = Waloupa Mine, WR = Wilcox Ravine.

mixing from pebble counts (James, 1991b). Erosion of historical alluvium has left flights of terraces, the higher of which grade up to large mines through tailings fans such as those in Wilcox Ravine, Hawkins Canyon, and Missouri Canyon. These terrace and fan deposits continue to erode and supply reworked mining sediment, and channels continue to avulse and incise during and after large floods (Fig. 6). Similar deposits can be found in selected mountain tributaries of the South Yuba River. Limited but substantial quantities of mining sediment remain stored along the North Fork American River above North Fork Dam (Laddish, 1996). Prior to closure of dams in the foothills between 1928 and 1940 (Table 1), sediment was freely transported downstream to the Sacramento Valley, but large multipurpose dams now arrest most sediment deliveries from the mountains.

In the Sacramento Valley, more than 5 m of 19th century aggradation has been measured at places in the lower Bear River (Fig. 7). Field reconnaissance indicates substantial mining sediment deposits along the lower American River near Sacramento (NRC,

Fig. 6. View up Hawkins (a.k.a. Birdseye) Canyon across Steephollow Creek (foreground), showing channel avulsion from 1997 flood. Tributary in Hawkins Canyon has incised 11 m into tailings fan from hydraulic mines. Steephollow channel was forced to left bank (toward viewer) by sediment from tailings fan which grades across and covers old channel. (Photo July, 1997).

1995) and along the lower Yuba River near Marysville. While much of this sediment is stored under and behind levees, substantial deposits in terraces, islands, and channel bars are not protected and are subject to episodes of erosion following large floods. Large volumes of historical sediment in the Sacramento Valley below the dams continue to erode as has been shown in the lower Bear River by repeated topographic surveys (James, 1993).

Table 1
Early large dams arresting sediment transport in the Yuba, Bear, and American Basins

Dam	River	Date
Combie (Van Geisen)	Bear	1928
Old Camp Far West	Bear	1928
Englebright,	Yuba	1928
North Fork (Lake Clementine)	NF American	1940

Monitoring of mining sediment deposits with repeated topographic surveys indicates that channel erosion continues in the upper Bear River. For example, at Buckeye Ford on Greenhorn Creek, there was 85 m^2 of cross-section erosion between 1985 and 1989, attributable primarily to the 1986 flood and 195 m^2 between 1989 and 1996, primarily due to the 1996 flood (Fig. 8A). Erosion has lowered the entire channel bed from valley wall to valley wall except for terrace remnants 22 m high on the right bank (cf. James, 1993). This section appears to be representative of the reach, so it is estimated that 280,000 m^3/km of sediment was produced from this part of Greenhorn Creek by channel-bed lowering from 1985 to 1996. Similar erosion occurred on Greenhorn Creek downstream at Red Dog Ford where 35 m^2

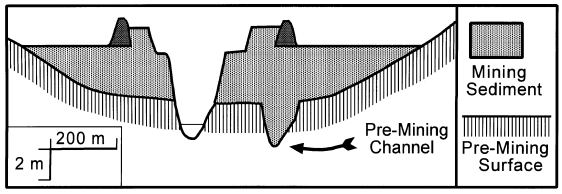

Fig. 7. Ideal cross-section across lower Bear River showing extent of mining sediment, location of pre-mining channel prior to avulsion, and superpositioning of levees on top of historical sediment. Schematic based on sediment coring (James, 1989).

was eroded from a cross-section between 1985 and 1989 and an additional 85 m^2 from 1989 to 1996 (Fig. 8B). This represents 120,000 m^3/km of sediment produced from this reach from 1985 to 1996. Most of a 4 m high middle terrace was eroded from the left bank by the 1986 flood although a broad 8 m high terrace remains on the right bank. Additional erosion caused by the 1997 flood at both sites has not yet been surveyed. Although the down-valley transport of this sediment is now arrested by reservoirs, the implications of vast active sediment deposits to geomorphic theories of sediment waves and effectiveness should not be overlooked.

The effective discharge in these stream channels has increased following episodic aggradation. In the initial stages of readjustment, gradients were steep-

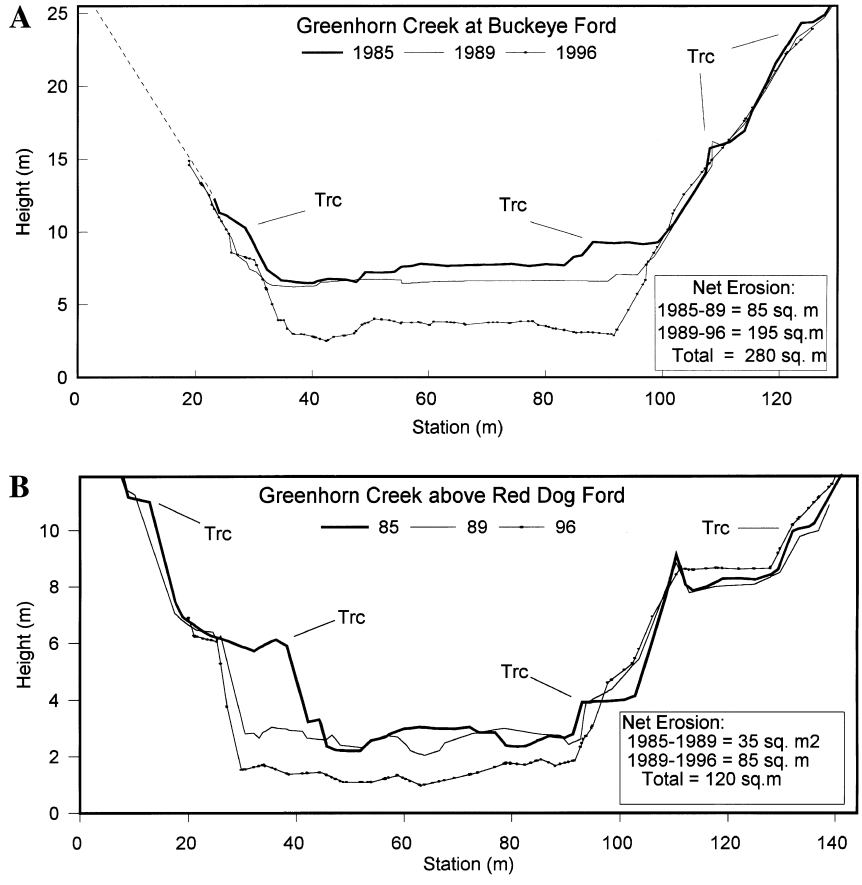

Fig. 8. Cross-sections on Greenhorn Creek from repeat topographic surveys showing erosion from 1985 to 1996 due to floods in 1986, 1995, and 1996. Results of a large 1997 flood not shown. Extensive deposits of mining sediment remain at both sites along valley sides and beneath bed. Trc = crest of mining sediment terraces. (A) Buckeye Ford experienced 4 to 7 m of channel incision across most of valley bottom representing 280 m^2 of net erosion across the section. (B) Red Dog Ford experienced 1 to 4 m of channel incision plus removal of a 3 m high terrace along the left bank.

ened and abundant sand and fine gravel was available in the bed, so sediment was readily entrained and channels were modified by frequent flows (James, 1988, 1989). Textures of mining sediment in terrace deposits along the upper Bear River are much finer than the present bed material at the same locations indicating that channel armoring has occurred. Where exposed, pre-mining bed material in mountain channels is considerably coarser than armor developed in mining sediment. In the Sacramento Valley, incision through mining sediment reveals channel beds armored by clay cemented gravels (James, 1991a). In addition to the development of channel lags, the establishment of vegetation, isolation of deposits above low-flow channels, and development development of engineering works (dams, levees, and revetment) also stabilized sediment. From this it can be inferred that modern bedload transport rates in areas of mining sediment are greater than pre-mining rates (James, 1989, 1993), and that mode rate magnitude events have produced less sediment and done less geomorphic work through time. Eventually, most deposits became stable enough that now only large floods (e.g., the 1986, 1996, and 1997 floods) can initiate periods of sediment remobilization and channel morphological changes substantially above background rates. Thus, in channels readjusting from episodic aggradation, the magnitude of the effective discharge, by both the sediment transport and channel morphological definitions, has increased with time, and sediment loads are returning asymptotically to background levels.

In spite of a decreased frequency of sediment transport events, field observations and measurements through 1997 indicate that historical sediment continues to be remobilized not only from within low-flow channels, but also from net erosion of banks and high terraces. This represents the on-going removal of mining sediment stored in these basins. Furthermore, historical evidence indicates that maximum aggradation in the Bear River had peaked by 1880 when incipient channel incision was noted in the basin. This early geomorphic response presumably corresponds approximately with the period of maximum sediment deliveries. In short, sediment loads can be summarized as (1) rapid attainment of peak sediment transport rates in the 1880s, (2) decreasing sediment transport rates since then due to stabilizing factors, but (3) mining sediment transport rates remaining well above pre-mining background levels through the 1990s. These factors indicate that if sediment transport following episodic sedimentation are to be conceptualized as traveling in a wave, the waveform should be a skewed sediment wave, and elevated sediment yields should be expected long after the channel bed has returned to where it was prior to aggradation (Fig. 9). As higher discharges are required to entrain sediment later in the sediment-wave sequence, sediment-producing events become more episodic. Field evidence of sediment storage and mobility in the Bear River after major flood events indicates qualitatively that sediment loads are behaving in this manner.

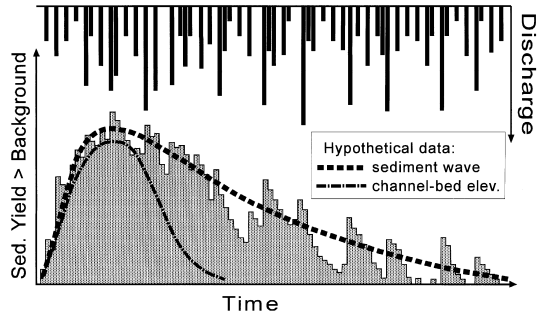

Fig. 9. Hypothetical skewed sediment wave model showing elevated sediment yields long after channel has returned to grade (ideal data). Channel-bed elevations define a symmetrical time series, but this does not necessarily mean sediment loads have relaxed, particularly if other hydraulic changes have occurred such as leveeing or lowering of base levels downstream.

5. Twentieth century licensed hydraulic mining

Following the injunction against hydraulic mining in 1884 and a brief period in which no legal mining took place, several decades ensued in which limited mining was permitted (Hagwood, 1981; Kelley, 1989). The 1893 Caminetti Act legalized hydraulic mining if sediment could be detained, which usually required construction of a dam. The California Debris Commission (CDC) was authorized to issue licenses to mine specified gravel volumes and to conduct inspections of reservoirs. The early dams

were small, ephemeral, log structures in deep, narrow valleys, creating small reservoirs with low trap efficiencies. None are known to remain intact. Several substantial dams were constructed from 1928 to 1940 (Table 1) and a flurry of mining took advantage of the storage behind them.

Records of mining volumes after 1905, based on CDC estimates of fill behind dams, are available in archives. Prior to 1905, records are incomplete due to the San Francisco fire, but they indicate sediment production at several mines. The CDC sediment production volume estimates are minimum values since they were based primarily on sediment stored in reservoirs with small trap efficiencies and do not include sediment that passed over dams or was stored temporarily above reservoirs. Licenses were revoked when reservoirs filled or failed, but there was no allowance for decreasing trap efficiencies as capacities decreased. In addition, illegal practices such as unlicenced mining or sluicing sediment through reservoirs would have produced more sediment than was recorded.

Most mines operated briefly and produced little sediment, so the volumes and geomorphic effects of 20th century hydraulic mining sediment have previously been assumed negligible. Over the 60-year period from 1893 to 1953, however, at least 24 million m^3 (averaging 400,000 m^3 $year^{-1}$) of licensed hydraulic mining sediment was produced in the northern Sierra Nevada with 2/3 of this in the Yuba basin (CDC records). Large volumes of sediment were produced in some years (Fig. 10). The total production of sediment by licensed hydraulic mining in the Sierra Nevada was only about 2.4% of the total billion m^3 estimated by Gilbert (1917) to have been produced by hydraulic mining from 1853 to 1884. Most of the 20th century sediment (15 million m^3) was produced before the first large permanent dams were constructed in 1928, and could have been freely delivered downstream to the Valley.

Three centers of sustained sediment production can be identified in the Bear Basin (Fig. 11); mines tailing to Bear River near Dutch Flat, the Birdseye mines near You Bet tailing to Steephollow Creek through Hawkins Canyon and Wilcox Ravine, and the You Bet mines tailing to Greenhorn Creek through Missouri Canyon. From 1893 to 1936, at least 2.3 million m^3 of sediment was produced in the

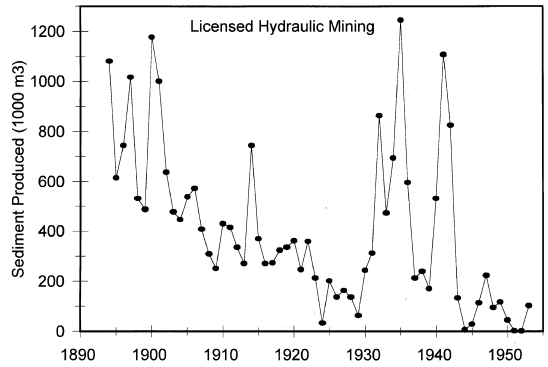

Fig. 10. Time series of 20th century mining sediment production in the Sierra Nevada. Partial records prior to 1905. (Data from CDC archives).

Bear Basin and 1.1 million m^3 of this was before the 1928 dams. This minimum estimate of sediment mined from 1893 to 1935 is only about 0.9% of the production during the peak mining period based on the high estimate of Gilbert (1917), so it is volumetrically a minor event relative to 19th century mining. Yet, 2.3 million m^3 of sediment represents a denudation of 1.0 cm across the upper basin above Rollins Reservoir. Furthermore, sediment was produced in pulses including volumes on the order of 90 or 100,000 m^3 $year^{-1}$ in 1914, 1919, and 1921 (Fig. 12C).

Records of detention structures in the basin are incomplete but document the filling or failure of several small dams including the Sailor Flat, Nevada Tunnel, and Swamp Angel dams in the Bear Basin (Table 2). A dam in Missouri Canyon below the Nevada Tunnel Mine lasted five years during which time 127,000 m^3 of sediment was produced. Brown's Hill Dam, a high concrete wedge at Steephollow Crossing, lasted only two years, but not before 29,000 m^3 of sediment was produced. Given the steep terrain and lack of major dams before 1928, much of the sediment that got past the small detention structures would have been transported downstream to the Sacramento Valley and beyond. For this reason, annual volumes of 20th century hydraulic mining in the Bear and North Fork American Rivers were compared with downstream stream-flow data to test the effects of licensed mining on flow stages and channel morphology in the Sacramento Valley.

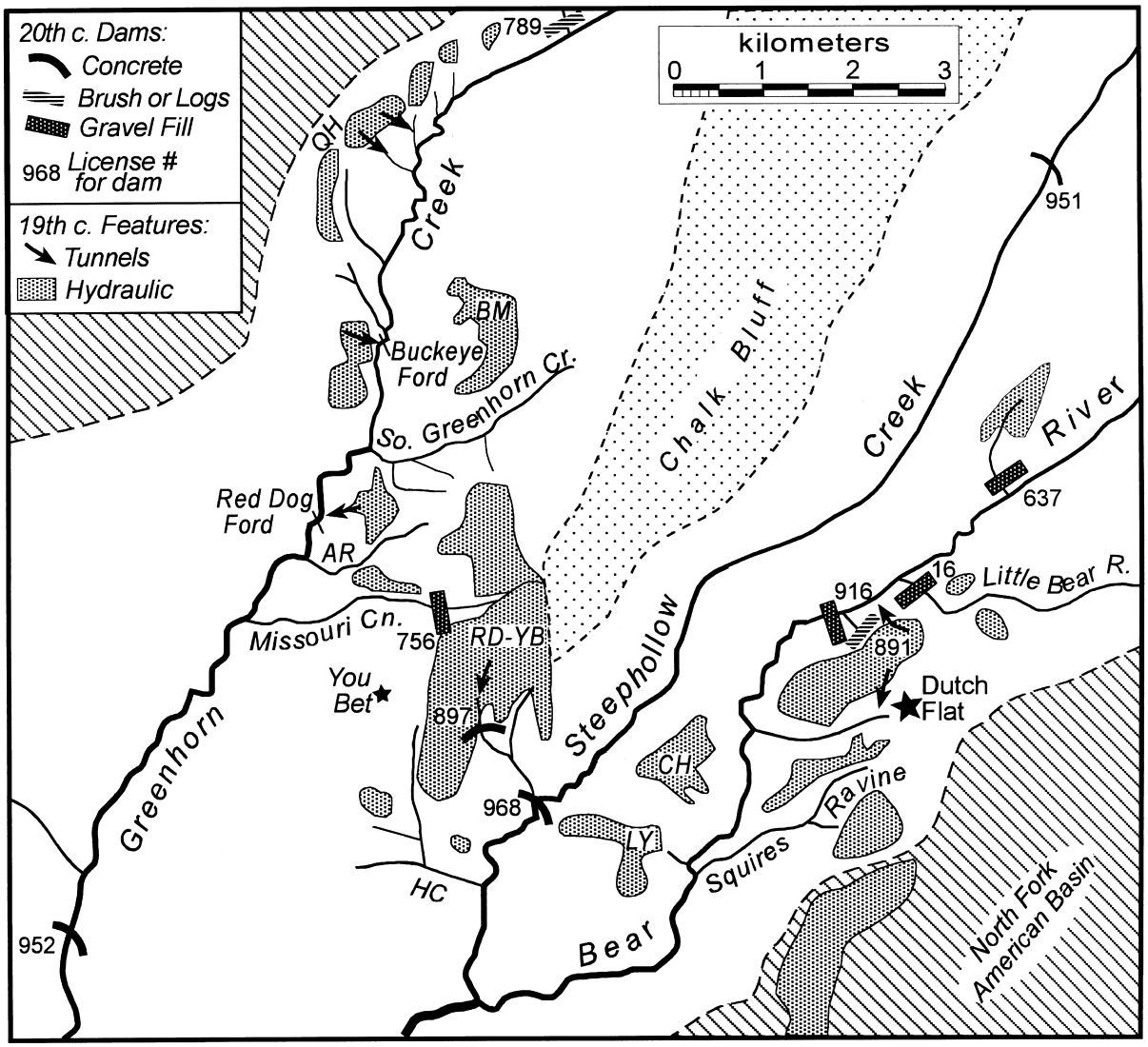

Fig. 11. Hydraulic mines and tunnels in upper Bear Basin from 19th century mining with some 20th century sediment detention structures. License numbers relate to Table 2; abbreviations defined in Fig. 5 except QH = Quaker Hill, BM = Buckeye Mine, and NM = Nichols Mine.

5.1. Channel responses to 20th century licensed mining

Historical stream-flow measurement data from archived US Geological Survey records reveal changes in flow stages and channel morphology since the turn of the century that is related to sediment production by licensed mining. On the lower Bear River, a few kilometers below where the river emerges from a bedrock-controlled canyon, the Van Trent stream-flow gage operated from 1905 to 1928, prior to the construction of major dams (Fig. 3). This site, now inundated by Camp Far West Reservoir, was near a mill where about 3 m of aggradation occurred in the 1870s (Keyes, 1878). Sediment production and storage have been negligible between

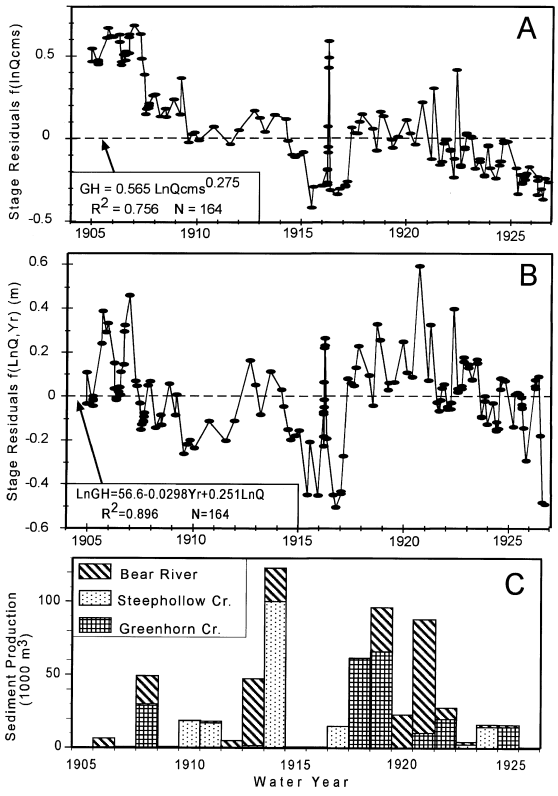

Fig. 12. Statistical analysis of flow stages at the Van Trent stream-flow gage on lower Bear River. (A) Residuals from regression of stage on log discharge, showing long-term lowering of stages interpreted as slow, progressive channel degradation. (B) Residuals from bivariate regression of log stage on log discharge and year, showing high frequency variation in channel bed not explained by discharge or the time trend showing in A. (C) Time series of hydraulic gold-mining sediment produced in the Bear River. Stream-flow data from US Geol. Survey archives. Sediment volumes from CDC archives.

Combie Reservoir and the Van Trent gage site due to a steep narrow gorge, and prior to 1928, there were no major obstacles to sediment transport from the mining region to the gage site. Hydrographers repeatedly noted channel instability at this site between 1907 and 1927. Rating-curve changes were noted in most years from 1914 to 1927, and in 1909 were specifically attributed to movement of ''mining debris''. Plots and regression analysis of variance in width, depth, and velocity with discharge suggest that stage changes were accompanied by channel morphological changes (James, 1988). The channel was narrow and deep in 1915, rapidly widened and shallowed in 1916 suggesting aggradation, deepened and narrowed from 1919 to 1921, and maintained an intermediate shape from 1921 to 1926. In 1927, flows deepened and slowed due to backwater ponding during reservoir construction, so data from 1927 were omitted from further analysis.

Statistical examination of covariations in flow stage with discharge reveals historic channel morphologic changes at the gage site. Stage variations were standardized for discharge by linear regression of stage using standard methods (cf., Knighton, 1977; James, 1991a, 1997). Regression residuals reveal a long-term decrease in flow stages at a rate of 4 cm year^{-1} at the Van Trent gage (Fig. 12A) which is attributed to the progressive erosion of 19th century mining sediment. Short-term stage variations superimposed on the long-term lowering trend reveal channel morphological changes. The most rapid stage changes occurred up to 1915, presumably in response to channel incision as is suggested by deep narrow channels. Stage lowering averaged 14 cm year^{-1} from 1905 to 1909 perhaps due in part to large floods in 1907 and 1909, although large floods in 1911 and 1925 had little effect. Interruptions in the long-term degradation trend occurred in 1913 and from 1917 through the early 1920s. In a similar position at the Narrows on the Yuba River, Gilbert (1917) showed that low-flow stages had peaked by 1900 and had stabilized by 1912. At Van Trent, where the channel was not as narrowly confined, long-term stage lowering was continuing through 1926 when the record was interrupted.

To isolate high frequency changes in stage independent of the long-term progressive degradation, logarithms of stage were regressed on both log discharge and time in quarter years. These two variables explain 90% of the variance in stage ($N = 164$). The bivariate regression line is shown on Fig. 12B as a dashed horizontal line surrounded by residuals which represent variations in stage that are not explained by discharge or progressive long-term degradation. Neither annual runoff nor annual floods were significantly related to these high frequency stage fluctuations at Van Trent (James, 1988). Residuals from the bivariate regression have similar patterns to the time series of 20th century sediment production (Fig. 12C); that is, residual stage changes are approxi-

Table 2
Debris dams and dump sites in Bear Basin. Sources: Calif. Debris Comm. archives (Corps of Engrs., Sacto. Div.) and State Mineralogist Reports

Mine	License #/ Year	Location[a]	Dam Type	Dam Height (m)	Reservoir Capacity (1000 m^3)	Volume Mined (1000 m^3)
Polar Star	16/1894	Little Bear R.	Stone and gravel		463	
	637/1904	Stump Cn., upper Bear Trib	Earth			
Nevada	756/1907	Greenhorn Cr. 0.8 km. NE of You Bet	Crib	9.1	28	26.4
Isabel	776/1907	1.6 km N Lowell H. in Steephollow Cr.	Crib	9.1	18	1.5
Southern Cross	786/1907	Hills Cn, Bear R. 0.4 km NE Dutch Flat	Brush			18.7
Sailor Flat	789/1908	3.2 km NE Quaker H. in Greenhorn Cr. failed Jan. 1909	Log crib with rock walls	6.1	12	2.3
Neece and West	843/1909	Steephollow Cr. 1.6 km SW You Bet	Brush and earth			35.2
Birdseye	897/1913	Steephollow Cr., 0.4 km S. of You Bet	Old mine pit			102
Queen City (Birdseye)	915/1913	2 1/2 km NE Dutch Flat (also #897)	Old mine pit			14.5
Liberty Hill	916/1917	Bear R., 0.4 km below Little Bear R.	Log crib and hydraulic fill	60	46	140
Nevada Tunnel	924/1918	Missouri Cn. 1.2 km below mine; failed in 1923;	Gravel fill; w/ bedrk spillway	10.7	2300	127
Swamp Angel	951/1922	Steephollow Cr. 0.8 km NNE Dutch Flat 1.2 km below mine	Concrete arch	10.4	18	2.3
Old Red Dog	952/1922	Greenhorn Cr. 0.8 km below bridge	Concrete	4.6	8	19.9
Browns Hill	968/1924	Steephollow Crossing; failed Feb., 1925	Concrete wedge	76	37	29.1
Tom and Jerry	1026/1931	Greenhorn Cr. 4 km E Scots Flat	Van Geisen Dam Large concrete arch	23		4.4
Liberty Hill	1027/1931	Bear R. 4 km N + 1.6 km E Dutch Flat	Van Geisen	23		479
You Bet	1084/1933	Steephollow Cr.	Van Geisen	23		688
Remington Hill	1130/1934	Steephollow Cr. 9 km S Washington	Van Geisen	23		14.7

[a]Some locations may be of mines, not of dams.

mately in phase with mining-sediment production upstream. Large volumes of sediment were produced in the Bear Basin from 1913–1914 and from 1918–1921, periods that correspond with relatively high flow stages at Van Trent. Multiple regressions using sediment production data at one-year time lags to predict channel-bed changes revealed a significant correlation ($r^2 = 0.70$) between gravel production up to 6 years prior to channel responses. Thus, annual licensed mining sediment production can explain much of the high-frequency variance in flow stage. This suggests process–response linkages between mining and channel-bed changes. Interannual stage changes are interpreted as responses to channel-bed aggradation and degradation during and following periods of mining, respectively (James, 1988).

A similar statistical analysis of stage-discharge data was performed on stream-flow data for the lower American River (NRC, 1995; James, 1997). Comparison of those regression residuals with 20th century mining sediment production for the American basin, suggests a correlation between sediment production and channel aggradation in the lower American River (Fig. 13), although no record of licensed mining has been found to account for aggradation in the 1920s. At least 300,000 m^3 of sediment was produced in the North Fork American Basin between 1907 and 1908 which was followed by a decade of increased flow stages on the order of 30 cm at the Fair Oaks gage site on lower American River. Stage increases from 1923 to 1937 began too soon to be simply related to sediment production in the mid-1930s and could represent other non-mining sediment sources, non-licensed mining sediment, remobilization of stored mining sediment, lack of large floods in the 1930s, or changes in local hydraulics at the gage site. The end of aggradation in the late 1930s appears to be strongly related to closure of North Fork Dam in 1940. In the first decade after dam closure, stages lowered 1 m at the Fair Oaks gage and 1 m downstream at the H Street gage in the City of Sacramento where stages lowered an additional meter in the following decade (James, 1997).

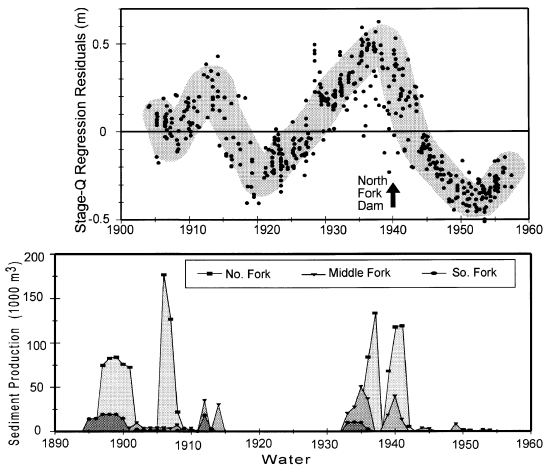

Fig. 13. Statistical analysis of flow stages at Fair Oaks stream-flow gage on the lower American River. (A) Residuals from regression of stage on a second order function of discharge, showing fluctuations in flow stages interpreted as channel aggradation and degradation. (B) Time series of hydraulic gold-mining sediment produced in the American River. NF = North Fork, MF = Middle Fork, SF = South Fork. Stream-flow data from the US Geol. Survey archives. Sediment volumes from CDC archives.

Prior to closure of the North Fork Dam, no major barriers existed between the mining districts and the lower American River, and sediment passing through small detention dams would be rapidly transported down the steep narrow canyons to the lower river. The dam controlled the upper North Fork where large volumes of hydraulic mining sediment were produced in both the 19th and 20th centuries, but did not control the Middle or South Forks which received relatively little mining sediment (Fig. 13). The upper American watershed is a glaciated, bedrock controlled, and sediment starved basin, so mining sediment dramatically increased sediment budgets in the North Fork. Stage lowering in the lower American River following dam closure, therefore, is interpreted as a response to channel degradation resulting from detention of mining sediment behind the dam.

Although 20th century licensed mining sediment production was one or two orders of magnitude less than production during the 19th century, enough sediment was transported more than 50 km to have a measurable effect on flow stages and channel morphology in both basins. These linkages reveal the sensitivity of channel morphology to 20th century mining activity prior to construction of large dams. Stage changes in phase with hydraulic mining support the historic and field evidence that debris dams were ineffective in detaining sediment, presumably

due to low trap efficiencies, reservoir filling, and dam failures. Thus, CDC estimates of 20th century sediment production were low to the extent that much sediment was transported downstream without being accounted for. The importance of this sedimentation episode has been overlooked, because the effects were subtle, ephemeral, and of shorter duration than the 19th century sediment event. This sediment was presumably transported within channels and stored on low floodplains between large terraces of earlier historical sediment, so morphologic changes attributable to this late episode of sedimentation should not be confused with the massive channel changes and sediment storage in high terraces from the earlier period. Yet, they clearly affected channels and flood stages in the 20th century.

6. Conclusion

A long history of successful hydraulic engineering works is in stark contrast with our relatively recent scientific understanding of the most basic elements of the hydrologic cycle and landform evolution. Extensive levee systems, dams, canals, aqueducts, and water power developments characterize early civilizations in China, Mesopotamia, India, Egypt, Rome, and elsewhere. Yet, up until the 17th century, atmospheric processes such as rainfall were considered inadequate to produce streamflow. Instead, rivers were believed to emanate from extensive subterranean caverns known as hydrophyllacia (Meinzer, 1942; Biswas, 1970; Krinitsky, 1988). Nor were basic principles of landform evolution or geologic time understood until relatively recently. It was not until the early 19th century that basic geomorphic principles had advanced to the point where it was understood that most valleys are the result of erosion by the rivers that flow within them. Revelations about the vast extent of geologic time and the relative brevity of human experience on Earth represented a revolution in human thought in the 18th century on par with the Copernican Revolution (Albritton, 1980). Yet this epistemological development has received relatively little attention from the engineering community or the classical sciences of chemistry, physics, and mathematics.

The reason why hydrologic and geomorphic sciences have lagged 2000 years behind hydraulic engineering is to some extent the same explanation for why present river engineering in the Sacramento Valley emphasizes local main-channel hydraulics. Practical solutions to immediate problems take precedence over a search for causality in nature. The dire, ever-growing need for flood control has compelled engineers in California to concentrate on complex hydraulic aspects of rivers, dams, and levees in the Sacramento Valley without a full understanding of long-term, on-going morphologic adjustments of the fluvial system to mining sediment and other changes. Unfortunately, fluvial systems — particularly the risks and effectiveness of extreme flood events — cannot be fully understood without the proper perception of historical and geological time. Studies of fluvial systems should include a long-term perspective toward channel change over geological time based on field evidence and over historic time based on both field and documentary evidence. Historical methods should not replace quantitative scientific analyses but should be combined with them in a multi methodological approach to characterize fluvial systems.

The traditional geomorphic concern for problems of time is important to river management, because the concept of time is essential to earth science and hazard mitigation. Differences in perceived hydrologic and geomorphic process rates call for an exchange of ideas between engineers and geomorphologists that should recognize the validity of geomorphic and historical methods of documenting environmental change. Principles of event magnitude-frequency, gradualism vs. catastrophism, relaxation times, and effectiveness are diverse philosophical frameworks for interpreting fluvial responses related to time. Recent instrumental records are important but should be augmented by and correlated with historical evidence from field and documentary records.

The historical belief in low inter-annual flood variability, ephemeral alluvial deposits, and enduring small crib dams in northern California suggests an innate human belief in the relative ineffectiveness of nature that is in conflict with evidence of extensive past fluvial changes. Although hydraulic processes have long been understood by river engineers in the

region, long-term geomorphic process rates and hydrologic probabilities have not. The effects of human-induced alluvial deposits have continued much longer than anticipated, and rates of transport of historical alluvium out of the Sacramento Valley continue to be overestimated. Based on inferences from low-flow stage elevations, most engineers assume that historical alluvium rapidly left the Valley as part of a past sediment wave or is permanently stored and of no consequence. Yet, Sacramento Valley flood-control was specifically engineered with a leveed and wing-walled single-channel conveyance system to maximize incision of main channel beds. Not only did this induce bed scour independently of sediment loads, but it also encouraged the long-term storage of anthropogenic sediment along channel margins and decreased channel capacities which ultimately required a shift to an innovative channel-bypass flood control system.

The use of dams to detain sediment upstream and levees to encourage scour on navigable channels downstream in the 19th century was sound in terms of principles of sediment transport, but contemporary dam-construction technology was inadequate and long-term flow variability was grossly underestimated. Both of the large 19th century sediment-detention dams constructed in the Sacramento Valley failed shortly after their construction, as did tailings dams and most small 20th century detention structures in the mountains. In the 1890s, the assumption that detention structures in mountain canyons would reliably store sediment led to renewed hydraulic mining well into the 20th century. Concepts of reservoir trap efficiency had not been developed, and the passage of sediment through these narrow reservoirs was underestimated. Furthermore, most of the dams quickly failed releasing sediment downstream. Records of 20th century mining sediment production and downstream channel responses indicate that mining was associated with contemporary channel adjustments and increased flood hazards, and demonstrate the geomorphic effectiveness of this late stage of mining.

In spite of extensive geomorphic changes, a rich body of historical evidence, and extensive engineering research on the hydraulics of the system, there has been little understanding of the importance of historical alluvium to on-going channel changes by planners and engineers. Vast deposits of 19th century mining sediment continue to influence flooding and sediment yields in the mountains and Sacramento Valley. Levees are constructed on top of the unmapped historical alluvium which continues to be eroded by floods. In some mountain valleys, extensive sand and gravel deposits persist with terrace scarps more than 20 m above the valley bottom which continue to erode and produce sediment.

Maximum aggradation from the larger 19th century mining sediment event occurred by the 1880s, within a decade of the cessation of mining. Yet, reworking of this sediment continues to produce substantial volumes of sediment more than 100 years after the cessation of mining. Decreasing rates of sediment production due to stabilization of deposits are accompanied by increases in magnitudes of the effective discharge. Yet, large floods continue to initiate episodes of mining sediment remobilization. These factors indicate that the rising limb of a sediment wave can be much steeper than its receding limb and that sediment effects can be protracted in time in spite of rapid recoveries of channel-bed elevations. In other words, large sediment waves which involve storage outside of the main channel can be strongly skewed in respect to time. Elevated rates of sediment production during the receding limb may be masked by need for large discharge events to initiate erosion; that is, after sediment has become relatively stable, the discharge required to initiate transport may become larger and less frequent leading to the perception that the system has recovered. These findings are contrary to some prevailing concepts of fluvial sediment behavior and should be considered carefully in planning and mitigation studies concerning episodic sediment events.

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