Geomorphology xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Invited review

A centennial tribute to G.K. Gilbert's Hydraulic Mining Débris in the Sierra Nevada

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ARTICLE INFO

Keywords:
G.K. Gilbert
Fluvial geomorphology
Sediment budget
Sediment waves
Nonequilibrium

ABSTRACT

G.K. Gilbert's (1917) classic monograph, *Hydraulic-Mining Débris in the Sierra Nevada*, is described and put into the context of modern geomorphic knowledge. The emphasis here is on large-scale applied fluvial geomorphology, but other key elements—e.g., coastal geomorphology—are also briefly covered. A brief synopsis outlines key elements of the monograph, followed by discussions of highly influential aspects including the integrated watershed perspective, the extreme example of anthropogenic sedimentation, computation of a quantitative, semidistributed sediment budget, and advent of sediment-wave theory. Although Gilbert did not address concepts of equilibrium and grade in much detail, the rivers of the northwestern Sierra Nevada were highly disrupted and thrown into a condition of nonequilibrium. Therefore, concepts of equilibrium and grade—for which Gilbert's early work is often cited—are discussed. Gilbert's work is put into the context of complex nonlinear dynamics in geomorphic systems and how these concepts can be used to interpret the nonequilibrium systems described by Gilbert. Broad, basin-scale studies were common in the period, but few were as quantitative and empirically rigorous or employed such a range of methodologies as PP105. None demonstrated such an extreme case of anthropogeomorphic change.

1. Introduction

Gilbert's (1917), *Hydraulic-Mining Débris in the Sierra Nevada*, U.S. Geological Survey Professional Paper 105 (PP105), was written late in his life, and it shows the maturity of a master scientist approaching a complex and urgent problem that had challenged engineers for > 30 years. The PP105 monograph presents several novel methods and concepts, including integrated watershed science, anthropogenic changes, legacy sediment, sediment budgets, sediment waves, and examples of rapidly changing channels in disequilibrium. The problem of hydraulic mining sediment (HMS) presented Gilbert with challenging new physical environments, such as a rapidly changing fluvial system that was clearly out of equilibrium and a coastal system with a strong tidal component unlike his experience with Lake Bonneville. He was also thrust into a working environment that was largely new to him, i.e., an applied problem in immediate need of practical solutions that was surrounded by rancorous political and economic controversy. Although these challenges were daunting, the HMS issue gave Gilbert an opportunity to apply his renowned skills at comprehending and synthesizing extremely large-scale, multivariate, open systems. This paper reviews the historical context of PP105, presents a brief synopsis of PP105, outlines some of its major contributions, and concludes with a modern geomorphic perspective of the work.

1.1. Historical context of PP105

Hydraulic mining was invented in California in the early 1850s when placer miners located gold-bearing paleochannels high above the modern canyons and learned to apply water under pressure to wash those gravels into the canyons below. The process was environmentally devastating and produced > 1.1×10^9 m^3 of hydraulic mining sediment (HMS) (Gilbert, 1917). The HMS filled valley bottoms throughout the Sacramento Valley and into the bays in the vicinity of San Francisco Bay, where it destroyed agricultural land and impeded navigation. From 1861 to the 1880s, production of HMS was a leading political issue in California until hydraulic mining in watersheds draining to navigable streams was enjoined by a federal court in 1884 (Kelley, 1989). However, the HMS had already been introduced and rivers had aggraded by that time. Substantial efforts to control the sediment, reduce flood risks, and restore navigation were ongoing in 1905 when

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http://dx.doi.org/10.1016/j.geomorph.2017.04.004
Received 1 December 2016; Received in revised form 29 March 2017; Accepted 5 April 2017

Please cite this article as: James, L.A., Geomorphology (2017), http://dx.doi.org/10.1016/j.geomorph.2017.04.004

Gilbert was asked by Charles Doolittle Walcott, Director of the U.S. Geological Survey, to begin a study of the Sacramento débris problem (Pyne, 1980a).

The PP105 monograph was the final publication Gilbert completed during his lifetime, although his *Studies of Basin-Range Structures* was published ten years after his death (Gilbert, 1928). The research and writing of PP105 occurred over an extended period due to a combination of (i) an interlude to conduct flume experiments in Berkeley for his other treatise on HMS (Gilbert, 1914), (ii) work on the 1906 San Francisco earthquake, and (iii) delays brought on by two years of ill health following a stroke in 1909 (Pyne, 1980b). During this hiatus, Gilbert contributed a section on the "*Quantity of Mining Débris*" to Lindgren's (1911) monograph on the *Tertiary Gravels of the Sierra Nevada*. This section was essentially reproduced verbatim in PP105 in the first three pages of Chapter 6. Gilbert's (1914) treatise on the *Transport of Débris by Running Water* is a contrast in scales of space and time with the PP105 monograph. The *Transport* monograph—based on flume studies at Berkeley—generated insights and a wealth of experimental data on the forces and shear stresses associated with grain entrainment. Gilbert summarized what was known of the hydraulics of transport, tested those ideas, and added many new formulations. The narrow flume in Berkeley could not be adjusted for slope, however, so Gilbert was unable to test for influences of slope, sinuosity, or planform adjustments to discharge, that often mutually adjust and change the nature of shear stress and sediment transport (Leopold, 1980). Nevertheless, those experiments produced a trove of entrainment data that are still widely used.

The 1914 monograph largely satisfied Gilbert's inclination to conduct experiments and produce formal functional mathematical explanations of the fine-scaled sediment transport processes involved with HMS transport. This freed him in PP105 to present and interpret massive amounts of data in a more synthetic style, while continuing to work inductively from an empirical basis. It also enabled him to develop broad theories of sediment behavior at the scale of large watersheds and beyond. Gilbert's viewpoints in PP105 were broad and incorporated an integrated watershed perspective of sediment production, transport, and storage that is not readily conducive to experiment or specific hypothesis testing. He had often taken the broad view in the past; e.g., the Henry Mountains report (Gilbert, 1877) and the Bonneville report (Gilbert, 1890), but his usual research style was to intersperse detailed examinations of mesoscale processes into his interpretations. Here, however, many of those details had been covered in his 1914 *transport* monograph, so he was at liberty to think broadly. Field work, as always, was an important aspect of his research, and he visited the mines in the mountains and visited the deposits that extended from the mountains through the Sacramento Valley to the San Francisco Bay many times, especially between 1907 and 1908. Over the years he filled several field books with detailed notes, some small segments of which were transcribed by the first author at the U.S. Library of Congress in 1992. The geographic scale of hydraulic mining was so vast that it took years to develop an empirical knowledge of the mines, the HMS deposits in the rivers and bays downstream of the mines, and erosion rates in areas that were not mined.

Much of Gilbert's published work is concerned with process rates or ages of systems that are on the order of millennia or greater. This was in keeping with the dominant line of geologic and geomorphic inquiry in the late nineteenth century after the old age of the Earth had been recognized by scientists and topographic and geologic maps of new western regions were being interpreted at a broad scale. Later, however, as settlement and resource extraction began to change natural systems, geomorphic research in the USA began to shift to modern process rates and resources management (e.g., Bryan, 1923; Strahler, 1952). The PP105 monograph represents a personal shift of Gilbert from the traditional geologist to a more contemporary environmental scientist. His field notes indicate, however, that he maintained the long-term perspective. For example, while observing mass wasting from the vertical wall of a hydraulic mine pit, he described faults that he felt may explain Basin and Range structures (Gilbert, 27 April 1908, *p.31*, *field book #3506*). The work in PP105 is largely focused on the issue that confronted Gilbert: explaining and seeking a remedy for $> 1.1 \times 10^9\ \mathrm{m}^3$ of HMS that had been introduced to the rivers of the Sacramento Valley.

1.2. How the research was accomplished

As Gilbert began studying and conducting field work for PP105 in 1905, he was already well established as one of the great minds of nineteenth century geologic science. Gilbert (Fig. 1) had achieved fame and recognition much earlier for his monographs on the Henry Mountains (1877) and Bonneville Lake (1890), as well as for prominent papers on scientific methods (1885), isostasy, planetary geology, and other topics (Pyne, 1980a). By the time PP105 was published in the year before he died at age 74, Gilbert was extremely well respected by his scientific contemporaries. He had been elected president of the Geological Society of America twice and of the Association of American Geographers. No other individual has served twice as GSA president (Pyne, 1980b; Hunt, 1988). Gilbert's work and career have been honored and analyzed elsewhere (Pyne, 1980b; Yochelson, 1980), but

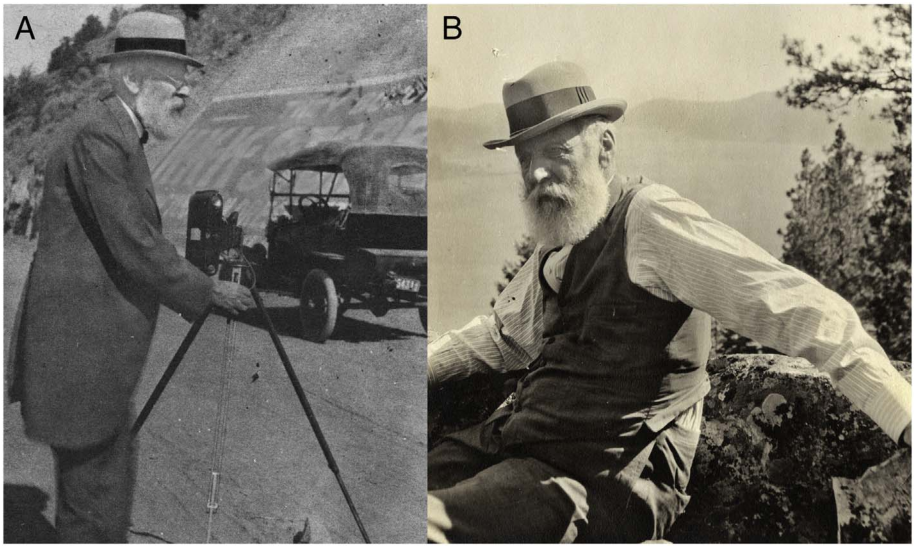

Fig. 1. G.K. Gilbert (1843–1918). (A) Photographing slickensides on a fault surface south of Klamath Falls, Oregon, 1916. Published in Wallace (1980). (B) Presumably in Klamath County, 1916. Buwalda papers, 1907–1981, Cal Tech.
Both photographs by John P. Buwalda.

most attention to his prior work has been on his other publications. For instance, two prominent papers represent Gilbert's work on fluvial sediment transport in the Sierra Nevada in larger compendia, and both focus on Gilbert's (1914) *Transport of Debris* monograph (Leopold, 1980; Keller, 1999). The PP105 monograph is often cited for its reference to sediment waves, but other novel aspects of this work are often overlooked. An exception is Pyne (1980b), who presents a balanced historical perspective on PP105. Gilbert's many other works are unquestionably important and well worthy of the praise they have received. Moreover, his earlier work built a foundation upon which his keen perceptions of geologic and geomorphic processes were based. For example, Gilbert's (1877) *Report on the Henry Mountains* established the laws of slope, structure, and divides and heralded the concepts of equilibrium and grade, which collectively guided his interpretations of the evolution of concave-upward headwater fluvial systems. Later, he expanded this reasoning to include creep and mass-wasting processes to explain frequent convexities of hilltops (Gilbert, 1909).

The majority of Gilbert's earlier projects were conducted in regions with, at best, a modicum of previous study by others and little political or economic scrutiny of the findings. The Henry Mountains remain one of the most isolated areas of the lower 48 states, much of the Lake Bonneville shorelines are in desert areas, and glaciation of the Sierra Nevada was in the high country. By the turn of the twentieth century, however, the Sacramento Valley and foothills of the Sierra Nevada were quite different. The rivers were lined with levees, the mines were closely guarded, and the issue of HMS remained controversial. Ellis (1939), former mayor and levee commissioner at Marysville, a city that was severely damaged by HMS, showed 'Professor Gilbert' around the lower Yuba, Feather, and Bear rivers for several weeks and advised him to be careful in visiting the mines. Gilbert was initially amused by the caution but informed Ellis later that he had been accosted by a man with a rifle at one of the mines and had to make a rapid retreat. The HMS had been a leading political issue in northern California for 20 years up to 1884 (Kelley, 1954, 1989), and a key scientific and engineering problem for another 20 years before Gilbert began to study it. As a consequence of working on such a well-studied phenomenon, it is sometimes difficult to distinguish Gilbert's original ideas from established contemporary concepts. For example, the alluvial basins that form the geomorphology of Sacramento Valley (Fig. 2), preliminary estimates of storage volumes of HMS, and the self-scouring of leveed channels, were well known to professionals working in the Sacramento Valley. Even with the preexisting knowledge, however, Gilbert combined his genius at field observation and synthesis with clear, succinct prose to summarize, elucidate, and expand upon ideas in an unprecedented manner. Furthermore, he added many new concepts that extended the domain of thought and filled in missing elements. Concepts such as sediment waves and sediment budgets enhanced the scientific basis of HMS, whereas including agriculture, roads, trails, and grazing into contemporary and future sediment budgets filled an important void in contemporary studies of the HMS problem.

Gilbert worked for the U.S. government for much of his career, first as a member of the Wheeler Survey, then under Major John Wesley Powell, and finally, he was asked by Charles Walcott to undertake this study for the U.S. Geological Survey to find an answer to the HMS problem in California. The HMS issue presented an immense practical problem and in turning his scientific genius to that problem, Gilbert anticipated a key new direction of the future of geomorphology: the development of theoretical bases and geological perspectives for practical problems that had challenged civilizations for millennia and engineers for centuries—human-induced aggradation and degradation of fluvial systems. With the HMS, however, the stark freshness and rapidity of processes were extreme. The opportunity to observe rapid river morphogenesis was not wasted on Gilbert who produced another masterpiece—this time with broad, practical implications.

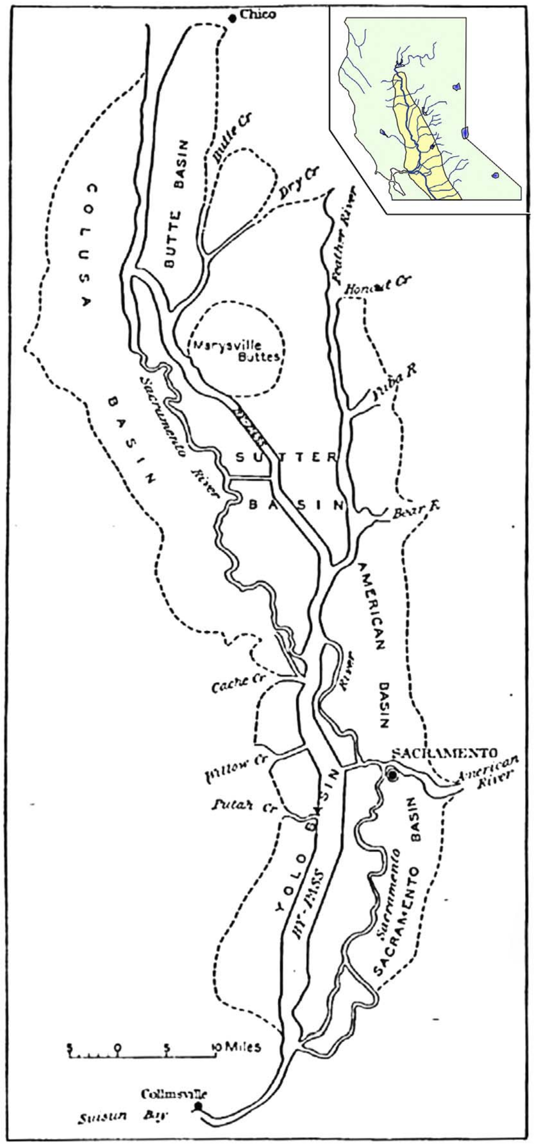

Fig. 2. Gilbert's (1917) map of natural basins in the Sacramento Valley showing the flood bypass system, which was being designed. Inset map of northern California added.

2. Synopsis of PP105

The breadth of PP105 is so considerable that it is beyond the scope of this paper to cover all its wealth of topics. The monograph begins with a brief regional history of mining and flooding and the nineteenth century institutional and political developments surrounding the débris issue. The importance of HMS to flooding is outlined, along with engineering efforts to control sedimentation and flood risks. A brief description of the hydrology and geomorphology of the Sacramento Valley provides an introduction to the area prior to the changes caused by HMS. Given the importance of anthropogenic change, this description of the physical setting at the outset reveals Gilbert's geomorphic perspective and approach to the problem. In Chapter 3 Gilbert describes detailed evidence of former lower sea levels around San Francisco Bay and the Sacramento-San Joaquin Delta, an immense inland wetland at the confluence of the two major rivers of the Central Valley. Gilbert describes the delta including deep peat deposits with underlying bedrock sloping westward. He explains the evidence for former lower sea levels in the Bay Area as being caused by 'crustal changes' and 'land subsidence.' This interpretation agrees with conclusions drawn by Lawson (1894), but the analysis provided abundant new evidence.

Holocene sea level rise was not commonly recognized by scientists in the region until Louderback (1951) applied the glacial-melt theory of sea-level rise, and it is now generally recognized that tectonic subsidence and sea level rise are important (Atwater et al., 1977). Gilbert's thorough analysis of the evidence is exemplary of his multivariate empirical approach to science based on a wide variety of field evidence and measurements.

The crux of Gilbert's analysis of fluvial geomorphology and the production, transport, and storage of HMS from the mountains and through the Sacramento Valley to the bays around San Francisco is presented in Chapters 4 through 7. Particular attention is given to HMS in the mountains, the lower Yuba River, and the bays below the Sacramento River. Chapter 4 provides qualitative descriptions of the spatial and temporal aspects of production, transport, and storage of HMS deposits in the mountains, canyons, piedmont, and Sacramento Valley. These deposits are contrasted with negligible deposits in the San Joaquin and upper Sacramento valleys. Twelve photographic plates illustrate conditions of rivers and mines with extensive deposits of HMS in small mountain streams below the mines and wide piedmont reaches of the Yuba River. Gilbert introduces the highly influential sediment wave analogy, which is based on an analysis of low-flow bed elevations. His interpretation of bed waves as sediment waves led him to underestimate the long-term persistent remobilization of HMS in rivers draining the mines (James, 1999, 2006). Nor did he anticipate the large volume of HMS that would be trapped in the mountains by dams built in the second half of the twentieth century. However, the descriptions in PP105 fully capture and summarize the enormity and dynamic nature of this massive anthropogenic sedimentation event.

Having established the nature and scale of the problem, Gilbert turns his attention to the timing of HMS delivered to Suisun, San Pablo, and San Francisco bays (Chapter 5). His time series of sediment production and deliveries to the bays shows the rates and relative proportions of sediment in the system (Fig. 3). Gilbert concluded that HMS deliveries were already in decline as is shown by the delivery of HMS to the bays (Curve D) cresting ca. 1895. This conclusion was reinforced by hindcast simulations of sediment loads based on decadal rates of bay infilling by HMS, which found that deliveries to the bays peaked ca. 1880 (Ganju et al., 2008). Gilbert also presented (i) changes in the bathymetry of the bays determined from pairs of repeat soundings in the 1850s–1860s and 1880s–1890s, (ii) volumes of deposition in the bays computed for the periods between surveys, and (iii) volumes of deposition for the entire period from 1849 to 1914 (Table 1).

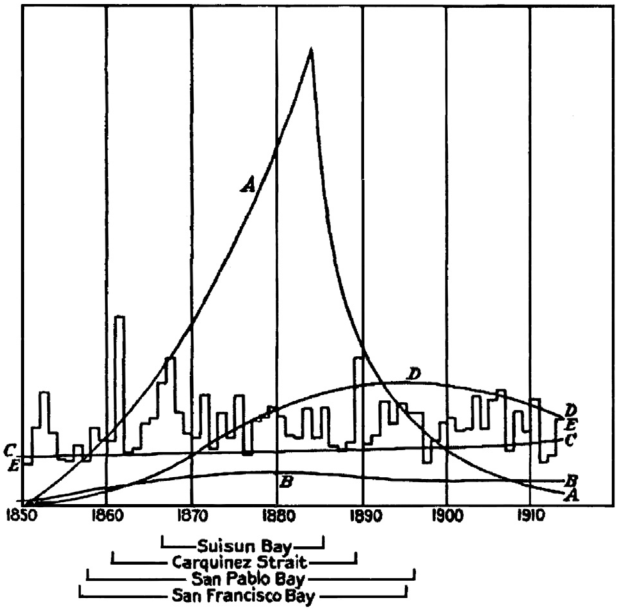

Fig. 3. Gilbert's (1917) Fig. 5 showing the timing of HMS production (A), soil erosion (B), percentage of fines not deposited on inundated lands (C), delivery of HMS to the bays (D), and precipitation (E). Delivery to the bays is shown as cresting in 1895, which reflects Gilbert's observations that decline had already begun long before the time of his writing. Although soil erosion (B) is small compared to HMS production and delivery, by 1910 it was producing more sediment than HMS production and was predicted to overtake HMS deliveries to the bays in the future. Times of the bay surveys are shown by brackets at the base of the figure. The second survey in each pair coincides with the period of maximum HMS delivery.

Table 1
HMS volumes deposited in the bays.
Source: Gilbert, 1917; Table 5).

Water body	Survey dates	Deposited between surveys ($\times 10^6$ m^3)	Deposits 1849 to 1914 ($\times 10^6$ m^3)
Suisun Bay	1867–1886	49	153
Carquinez Strait	1861–1890	31	38
San Pablo Bay	1857–1897	280	436
San Francisco Bay	1856–1896	150	249
Total:			877

Sedimentation of the bays resulted in reduction of the tidal flux and contraction of bays along their margins where HMS deposits were stabilized by vegetation (Fig. 4). Bathymetric surveys of the bays have been repeated and sediment volumes have been recomputed using modern geospatial techniques to interpolate and difference the bathymetric data. For example, Capiella et al. (1999) computed 61 × 10^6 m^3 of sediment deposition in Suisun Bay from 1867 to 1887 compared to Gilbert's estimate of 49 × 10^6 m^3. Jaffe et al. (2007) computed 270 × 10^6 m^3 of sediment deposition in San Pablo Bay from 1856 to 1898 compared to Gilbert's estimate of 280 × 10^6 m^3.

Although soil erosion during the nineteenth century mining period was minimal compared to HMS production and delivery, by 1910 production of HMS had greatly diminished and HMS deliveries to the bays was beginning to decline (Fig. 3). By that time, Gilbert estimated that sediment production by soil erosion was already greater than production by hydraulic mining and he predicted that deliveries from soil erosion would soon overtake HMS deliveries to the bays. This forecast appears to have been accurate with regard to San Francisco Bay. A comparison of fluvial suspended sediment loads to the Bay from the Central Valley and small local, urban tributaries to the Bay that contain no HMS, found that the local tributaries contribute 61% of the suspended sediment, although they comprise only 7% of the drainage area (McKee et al., 2013). Another study showed that, although 85% of the suspended sediment entering the delta comes from the Sacramento River, 67% of the sediment entering the delta is deposited and does not reach the bays (Wright and Schoellhamer, 2005). Gilbert's forecasts of increased sediment loads from soil erosion and other anthropogenic activities have been demonstrated in many other major rivers and in global sediment budgets (Milliman et al., 1987; Syvitski et al., 2005; Walling, 2006).

Gilbert's PP105 next focused on the mountains and piedmont for a systematic, quantitative accounting of HMS production volumes based on topographic surveys of a sample of mines in the Yuba Basin (Chapter 6). Measurements of the volumes exhumed by 28 of the major mines or combinations of mines led Gilbert to increase a previous estimate of HMS production (Turner, 1891) by a factor of 1.51 and this ratio was applied to hydraulic mines throughout the region. Most of that analysis was also published by Gilbert earlier, as a section in Lindgren (1911). Gilbert concluded that hydraulic mining throughout the Sierra Nevada produced 1.18 × 10^9 m^3, that all mining in the Sacramento Basin produced 1.06 × 10^9 m^3, and that all mining to Suisun Bay produced 1.27 × 10^9 m^3. To put these numbers into perspective, 1.0 × 10^9 m^3 is 1 km^3 of sediment, or 1 m of sediment spread over 1000 km^2. These volumes represent mine-pit volumes and are not adjusted upward for decreased bulk densities of exhumed sediment. Gilbert's budget also

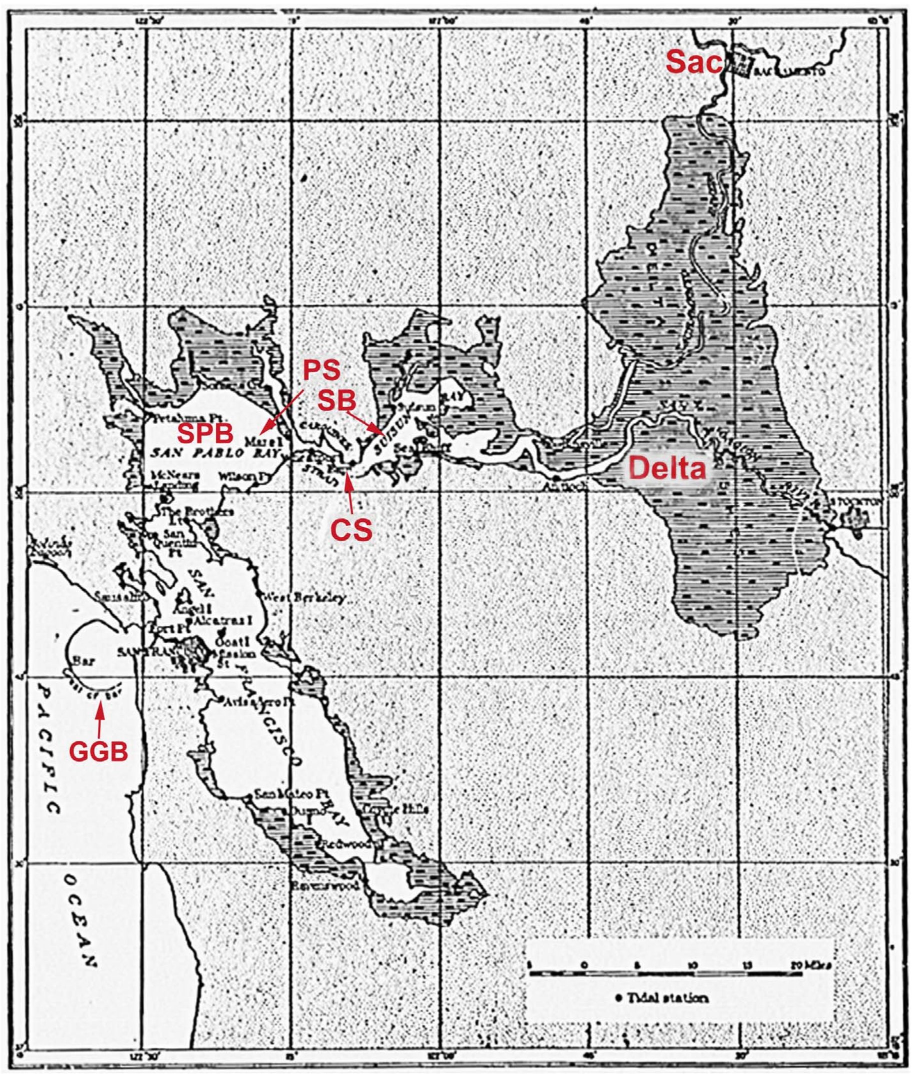

Fig. 4. Gilbert's (1917) map of the San Francisco Bay and Sacramento-San Joaquin Delta. Annotations (added): CS = Carquinez Strait, GGB = Golden Gate Bar, PS = Pinole Shoals, Sac = city of Sacramento, SB = Suisun Bay, SPB = San Pablo Bay.

includes estimates of additional sediment from non-mining erosion based on the nature of ground cover. Little data or methods existed for such computations, so Gilbert was forced to make approximations based on reasoning. For example, he assumed that sediment production from farmlands was proportional to area and period of occupation and that erosion from roads, trails, and overgrazing was proportional to population. Eighteen contemporary photographic plates of non-mining sources show remarkable images of rills and gullies not generally associated with northern California during this period (Fig. 5). The result of this multimethodologic analysis is a quantitative estimate of vast HMS storage volumes in the mountains, canyons, piedmont fans, Sacramento Valley rivers, and lateral basins and marshes of the Sacramento Valley that contrast with modest sediment volumes from other sources. These volumes, along with deliveries to the bays, are described further in the section on sediment budgets.

The lower Yuba River (LYR) is the focus of detailed consideration including direct observations and photographs (Chapter 7). The LYR had deeply aggraded and continued to respond rapidly to the influx of HMS, dam construction, and dredging at the time Gilbert was writing, Attempts to control HMS with dams on the lower Yuba were underway and Barrier Dam No. 1 had been built in 1904. Gilbert observed the dam being raised by 2.4 m, filling with sediment the following year, and breaching in early 1907. His descriptions are the best account available of this episode of reservoir filling and failure of Barrier Dam 1. Topographic surveys in 1905 and 1906 show extensive scour below the dam and $1.29 \times 10^6\ \mathrm{m}^3$ of fill between the surveys. Daguerre Point Dam and downstream training walls are mapped and described, including changes in channel gradient and rapid sedimentation upstream. Dredge spoils are described as having expanded volumes because interstitial clays were deposited first and the coarse matrix material was subsequently piled over the top of them. Gilbert documents sediment mobility and lateral channel changes at Timbuctoo Bend above the Daguerre Point Dam with a series of four sequential maps between 1898 and 1908.

The Sacramento Valley flood control project is inseparably intertwined with management of HMS in the Valley. The flood-control project is unique in the USA in that it utilizes broad high-water bypasses through the large, low alluvial basins of the Sacramento Valley (Fig. 2). Gilbert describes the system and predicts decreasing HMS deliveries and offsetting increases in sediment deliveries from agriculture and roads that will ultimately exceed natural erosion rates (Chapter 8). He also describes the mobility of HMS in the mountains and provides four photographs of brush dam and rock-filled log-crib dams that show the ephemeral nature of HMS storage at the time. These photographs are extraordinary because few if any unbreached brush or crib dams remain in the region, photographs are scarce, and modern environmental managers are searching for the dam sites as potential sites of stored sediment with high concentrations of mercury. Gilbert notes that most of these dams had failed or were failing at the time, which reinforced his conclusion that HMS would move quickly through the system.

An analysis of HMS movement through and beyond the Golden Gate inlet to Golden Gate Bar, a large, submerged, semicircular offshore bar,

Fig. 5. Gilbert's (1917) Plate XVII-A showing gullies on hillslope grazed by sheep.

is the largest section of PP105. Approximately half of the total pages of PP105 are devoted to Chapter 9 and three appendices on currents, tides, and harbor surveys. Tidal prisms are defined as well as tidal oscillations that may occur in large, extensive bays and estuaries. Gilbert describes an equilibrium between waves shoaling on the seaward side of Golden Gate Bar and tidal currents acting from the landward side that controls the position and morphology of the bar. Further, he postulates that reductions in tidal volumes and tidal currents caused by bay filling with HMS explain the observed landward migration and reduced depth of the bar. He analyzes the bay and estuarine bathymetry, tidal prisms, effects of encroachment, currents, and competence of flows to carry bed material, and the provenance of sands sampled from Golden Gate Bar. A grain-size analysis and microscopic examination compares sands from Golden Gate Bar with sands derived from neighboring beaches and from the bed of main tidal channels through Suisun Bay, Carquinez Strait, and San Pablo Bay. Gilbert concludes that Golden Gate Bar sands were derived from local beaches and were nonHMS. Conversely, he concludes that sand samples from the tidal channel through Suisun Bay and Carquinez Strait were river sand from the mines because they lacked the stained quartz that is distinctive in nonHMS sands:

> ‘That channel, which was remodeled and contracted by the invading débris from the mines, is unquestionably lined by sand and gravel from the [Central Valley] rivers, and the material of its bed epitomizes the composition of sands from the two rivers and their tributaries.’ Gilbert, 1917; p. 92

From this observation, Gilbert concludes that Pinole Shoal, which lies below the mouth of Carquinez Strait where flows decelerate into the upper opening of San Pablo Bay, was beyond the downstream limit of fine sand transport during the mining period and before. This conclusion does not preclude the transport of fines across Pinole Shoal into the San Francisco Bay and beyond.

Finally, in ‘The Outlook for Hydraulic Mining’ (Chapter 10), Gilbert recommends that hydraulic mining should not be conducted in a manner injurious to either land owners or navigation. He identifies a growing need for soil conservation and concludes that reductions in deliveries of HMS alone would not resolve issues with navigation associated with shoaling of the bays. Instead, he predicts that a growing amount of sediment from soil erosion will gradually replace the reworking of HMS as the primary source of sediment to the bays, encroach upon tidal areas, reduce tidal currents, and generate deposits in the bays, all of which will contribute to inhibiting navigation. In this way, Gilbert does not take sides in the long-standing debate between miners and farmers but notes that both occupations were threatening navigation and commerce (Pyne, 1980b). Although Gilbert underestimates the longevity and persistent reworking of HMS (James, 1999), his recommendations anticipated the U.S. soil conservation movement by two decades.

3. Key innovative fluvial aspects of PP105 with implications beyond California

Gilbert's treatise presents novel perspectives on fluvial sediment and methods for its study that were prescient of future geomorphic and hydrologic thinking. For example, Gilbert adopted an integrated watershed perspective, based on multidisciplinary, multivariate, and spatially distributed methods. From that perspective he documented a major anthropogenic disruption to a fluvial system and the legacy sediment that it produced. The PP105 monograph was written half a century after Marsh (1865) had raised awareness of human capabilities as a geomorphic agent, and it became the quintessential geomorphic example of anthropogenic change in the western world. Gilbert also demonstrated the use of quantitative sediment budgets and presented the concept of sediment waves. Interestingly, Gilbert only peripherally addressed the classic concepts of equilibrium and grade that he had anticipated in earlier works, so their conspicuous omission is worthy of consideration. This section briefly examines these key fluvial concepts of PP105.

3.1. Integrated watershed science

One of the greatest achievements of PP105 is that it introduced an integrated watershed management perspective to river research and recognized the growing need for soil conservation. Integration may take many forms including multidisciplinary, multivariate, and spatially distributed methodological structures. River science and management has historically been conducted in a fragmented manner with regard to disciplinary approaches, i.e., engineering, geologic, biologic, social, political, and economic analyses conducted separately by different teams of specialists. This disciplinary fragmentation results in the development of knowledge in isolated clusters and intelligible only to specialists. The breadth of study in PP105 is noteworthy as Gilbert was primarily a geomorphologist and geologist, but he worked with engineers on flooding and sedimentation problems, the Coast Guard on navigation and tides, and many others to address multiple factors in this report. Integrated watershed perspectives also consider spatial connectivity in which the location and interactions between phenomena are important. Gilbert provided a famous example of a broad spatial perspective by considering the basinwide dimensions of sediment transport and by following the débris from the mountains to the sea. He set an example for watershed-scale evaluations that is exemplary for a variety of purposes including soil erosion as an environmental impact of land use, forensic evaluations of episodic sedimentation, quantitative sediment budgets, and management of basins for sediment control.

3.2. Anthropogenic changes and legacy sediment

Gilbert's PP105 may be the first detailed, quantitative, watershed-scale study to document fluvial responses to episodic inputs of legacy sediment in the New World. This section describes modern studies of anthropogenic sediment for which PP105 is a precursor. Legacy sediment—anthropogenic sediment that primarily occurs as post-settlement alluvium or colluvium (James, 2013)—includes historic vertical accretion deposits that bury pre-settlement soils on floodplains (Knox, 1972, 1977, 1987, 2006; Costa, 1975; Griffiths, 1979; Trimble, 1981, 1983; Trimble and Lund, 1982; Jacobson and Coleman, 1986; Xu, 2003; Lang et al., 2003; Olley and Wasson, 2003; Houben et al., 2006). The movement and storage of legacy sediment has implications for channel and floodplain morphology, downstream sediment supply, channel-floodplain connectivity, water quality, and river restoration.

3.2.1. Interactions between legacy sediment and fluvial morphology

The deposition and storage of legacy sediment has direct and indirect effects on fluvial systems through alterations of channel and floodplain morphology. Anthropogenic changes are often driven by changes in land use and land cover that alter the magnitude and frequency of flood flows and produce severe episodes of upland erosion that supply legacy sediment to downstream areas (James and Lecce, 2013). At the watershed scale, aggradation-degradation episodes (James, 2010; James and Lecce, 2013) may ensue whereby sediment transported from uplands during a large erosional episode produces channel aggradation, followed by the eventual reduction of upland erosion and subsequent channel incision. The focus and examples used here are drawn primarily from work in the upper Midwest and mid-Atlantic regions of the USA, recognizing that this necessarily excludes a large number of relevant studies in other regions.

Gilbert's PP105 clearly recognizes that sediment transport can be influenced by hydraulics induced by changes in channel morphology, as illustrated by the training walls at Daguerre Point that increased the sediment transporting efficiency of the Yuba River by restricting channel width and deepening the flow. Similarly, the deposition of legacy sediment on floodplains not only alters floodplain topography and buries terraces, but it also directly affects channel morphology by increasing bank heights, which can lead to a sequence of process-form interactions. For example, Lecce (1997a, 2013) showed that increased flow depths may induce channel enlargement by increasing in-channel shear stress and stream power. The morphologic response to changing energy conditions and reduced sediment deliveries in the degradational phase enlarges channels through incision, widening, or lateral migration. As the capacity of this enlarged channel increases, it becomes capable of containing increasingly larger flow magnitudes. This progressively decreases the frequency of overbank flows, and with it, rates of vertical accretion of legacy sediment. In cases where channel enlargement is accomplished primarily by lateral channel migration, a negative feedback operates; whereby widening of the meander belt causes a decrease in power per unit area and, therefore, decreased rates of lateral migration (Lecce, 1997b). In some places, the capacity of the meander belt cross section is large enough virtually to eliminate inundation of early historical floodplains, converting them into terraces (Knox, 2006) that Pizzuto et al. (2016) described as ‘legacy alluvial terraces.’ These terraces also have feedbacks on channel and floodplain hydraulics such as the downstream attenuation of flood waves (Woltemade, 1994).

These processes can be time transgressive so that upstream parts of the watershed behave differently than downstream areas. In the Driftless Area of Wisconsin, USA, Knox (1972, 1977, 1987, 2001, 2006) and others (Happ et al., 1940; Happ, 1944; Magilligan, 1985, 1992; Woltemade, 1994; Lecce, 1997b, 2013; Faulkner, 1998; Lecce and Pavlowsky, 2001, 2004) showed that the development of enlarged meander belts in tributaries is characteristic of most watersheds in the region, which is the direct consequence of legacy sedimentation on the presettlement floodplain surface that began first in tributaries. As meander belt enlargement progressively decreased the frequency of overbank flows and rates of floodplain sedimentation upstream, the sediment conveyed by these flows was routed farther downstream to lower in the watershed. These downstream main valley locations generally lack enlarged meander belts because of low gradients and low stream power (Lecce, 1997a), especially where base level is controlled by larger downstream rivers (Knox, 2006). Depths of overbank sedimentation are highest in the downstream locations, yet almost all of this legacy sedimentation occurred much later than that for the tributaries (Knox, 1987, 2006; Lecce and Pavlowsky, 2001).

The behavior of HMS in the Sierra Nevada was different from behavior in most of the watersheds documented by later studies in several aspects. Longitudinal connectivity was disarticulated with high storage potential near the mines and in low-gradient reaches of Sacramento Valley but negligible in steep, narrow canyons of major rivers that separated these areas (James, 2006). In the mining districts, sediment was coarse and channel planforms were braided, so braid bars often extended from valley wall to valley wall without a meander belt. Later as channels incised, terraces formed and flow widths, energies, and transport capacities increased. The time-transgressive tendency, i.e., downvalley progression of terrace formation and floodplain widening was largely obscured in these channels by (i) sporadic and spatially irregular episodic production of HMS, (ii) rapid delivery of HMS over long distances through the gorges, (iii) extensive leveeing in the Sacramento Valley, and (iv) construction of dams. Gilbert (1917) faced the formidable task of interpreting and describing the spatial and temporal complexities of fluvial responses to HMS over an entire region about thirty years into the event.

3.2.2. Impacts of legacy sediment on aquatic environments

Understanding the factors that influence sediment dynamics is critical to achieving management goals associated with reducing sediment loads and improving water quality (Phillips, 1986b; Hupp et al., 2013). The majority of the material exposed in some channel banks may be composed of legacy sediment (Costa, 1975; Jacobson and Coleman, 1986; Walter and Merritts, 2008; Hupp et al., 2013), so remobilized legacy sediment often plays an important role in supplying downstream suspended sediment loads (Gellis et al., 2009; Schenk and Hupp, 2009; Donovan et al., 2015; Lyons et al., 2015). Furthermore, this sediment may often be contaminated (Horowitz, 1991) so that legacy sediment remobilized from floodplain storage has the potential to substantially influence toxicity levels in aquatic systems (Macklin et al., 2006; Miller and Orbock Miller, 2007). In the eastern USA, legacy sediment stored in tens of thousands of mill ponds poses a substantial threat to water quality and downstream estuaries such as Chesapeake Bay due to contamination by fertilizers, pesticides, herbicides, trace metals, and polyaromatic hydrocarbons (Walter and Merritts, 2008; Pizzuto and O'Neal, 2009; Schenk and Hupp, 2009; Niemitz et al., 2013). Gilbert does not indicate whether he knew that HMS contains high concentrations of mercury (Hunerlach et al., 1999, 2004; May et al., 2000; Alpers et al., 2005; James, 2010; Singer et al., 2013). Sediment Hg toxicity complicates mitigation strategies that normally seek to enhance lateral connectivity by encouraging meander belt widening through removal of terraces and bank protection (James, 2015).

The fate of legacy sediment eroded during anthropogenic disturbances is influenced by connectivity in the system (Fryirs et al., 2007; Fryirs, 2013). Schenk and Hupp (2009) showed that increases in floodplain elevation in response to the deposition of 1–2 m of legacy sediment left the floodplain relatively disconnected from the channel. Alternatively, Pizzuto et al. (2016) showed that many floodplains in the mid-Atlantic region have continued to accrete vertically (albeit at lower rates than the period immediately following European settlement) and are fully connected to their rivers. This suggests that postsettlement alluviation has not necessarily reduced channel-floodplain connectivity and that they are not legacy alluvial terraces. Another way that legacy sediment influences floodplain-channel connectivity is through its influence on vegetation. For example, James (2006) suggested that thick accumulations of legacy sediment on floodplains may increase depths to water tables and lower soil moisture. Thus, the burial of floodplain wetlands may lead to the expansion of forests on floodplain surfaces that become disconnected from the river (James, 2006). High channel banks produced by thick sequences of legacy sediment also influence bank retreat processes because the lower portion of the bank may be below the root zone of riparian vegetation that stabilizes the bank (Wynn et al., 2004; Rood et al., 2015). Reestablishing channel-floodplain connectivity is a desirable goal of restoration efforts because of the water quality, flood peak reduction, and habitat benefits of wetlands.

Although Gilbert underestimated the persistence of HMS (James, 1999), recent studies of dam removals provide the means to estimate timescales over which legacy sediment can be expected to remain stored in valley bottoms (Pearson et al., 2011). Dam removals produce benefits associated with recreational opportunities and improved fish habitat and passage, but they can also produce large and persistent pulses of remobilized legacy sediment that threaten downstream estuaries (Schenk and Hupp, 2009). James (2006) suggested that dam removal may not necessarily achieve the desired result of restoring salmonids to the upper Yuba River if erosion ultimately removes the legacy sediment. Removing the large reservoir impounded by Englebright Dam may not successfully provide long-term spawning grounds if fine gravel derived from stored HMS is being depleted (James, 2006). Renshaw et al. (2013) suggested that while legacy sedimentation on floodplains can affect the composition and productivity of riparian ecosystems (Bornette et al., 1998; Steiger et al., 2005), it can also produce ecological disruptions that enhance ecological diversity (Grime, 1973; Connell, 1978).

This brief review reveals the complexity and diversity of problems associated with legacy sediment. The PP105 monograph opened the door to what has become a central issue in fluvial geomorphology. The mountain and piedmont deposits of HMS described in PP105 demonstrate the importance of within-channel legacy sediment, not only on local channels but also on downvalley conveyance. The HMS overwhelmed most channels downstream and continues to influence low-gradient channels near mines and in the Sacramento Valley, where lateral connectivity, aquatic habitats, riparian vegetation, soil water, and other environmental systems have been altered.

3.3. *Sediment budgets*

Quantitative sediment budgets are a relatively recent concept in the history of western Earth science, because of the late acceptance that land surfaces were dominantly formed by terrestrial processes. Until the early to mid-nineteenth century, debates continued about the importance of uniformitarian fluvial and terrestrial processes relative to catastrophic marine and Noachian flood hypotheses (Chorley et al., 1964). Very rapidly after the rejection of catastrophism, concepts of terrestrial denudation emerged and attempts followed to identify sources and to quantify rates and amounts of sediment redistributions. From this perspective, the late appearance of sediment budget analyses is not surprising and represents the first attempts to compartmentalize and quantify various sources, paths, and fates of sediment. Gilbert's sediment budgets for the Sacramento River and San Francisco Bay system are some of the earliest quantitative budgets known to geomorphology. Their influence on subsequent sediment budgets is hard to determine because the effects may have been largely subliminal. Few early sediment budget studies cited Gilbert as an example, yet Gilbert's study was very widely known. Later in the twentieth and twenty-first centuries, numerous volumes and conferences have been devoted to sediment budgets (Glymph, 1954; Swanson et al., 1982; Bordas and Walling, 1988; Abrahams and Marston, 1993; Horowitz and Walling, 2005; Walling and Horowitz, 2005).

A watershed sediment budget quantitatively expresses the sources and fate of sediment; that is, the volume or mass of sediment production and storage in a drainage basin and the sediment yield to locations downstream (Reid and Dunne, 2016). Sediment budgets can be at any scale of space and time for which accurate data are available. Thus, denudation studies over geological eras are feasible as are sediment budgets at time steps of a few minutes derived from a spatially distributed watershed simulation model. Two types of sediment budgets can be identified (Phillips, 1986b). Both types of budget ideally measure inputs (sediment erosion and production within the watershed) and outputs (sediment yield). However, input-based budgets are primarily concerned with determining the transport and fate of sediment produced throughout a watershed, whereas output-based budgets focus on the source of sediment at the site of deposition or export, e.g., an estuary. Both types of budgets may result in a spatially lumped (averaged) or distributed (geographically specific) estimate of sources. Gilbert provided examples of both types of budget by computing an input-based budget for sediment production and an output-based budget focused on sediment deliveries and storage in the bays.

Spatially lumped budgets partition sediment sources and sinks by geomorphic criteria such as hillslope, colluvium, floodplain, channel, fan, delta, and deep sea sites (Shi and Zhang, 2005; Notebaert et al., 2009). Sediment sources potentially include (i) hillslopes eroded by sheet flow, rilling, gullying, or mass wasting; (ii) terrace and colluvial floodplain margins; and (iii) floodplain and within-channel sources that experience channel widening, lateral migration, bed scour, floodplain erosion, or channel avulsions. Sediment budgets generally emphasize computations of suspended loads, although bed loads can be important. Budgets that include dissolved loads have been less common, with a few notable exceptions (Gibbs, 1967; Dietrich and Dunne, 1978). Budgets vary from elaborate and comprehensive accountings to simple input-output comparisons in which inputs come from soil-erosion models and outputs are from reservoir surveys or transport rates at gauge sites. Budgets may be in the form of tabular data or schematic maps. Storage, which represents the volumetric difference or lag time between production and yield, involves complex interactions between geomorphic, hydraulic, and sediment grain-size characteristics, but in the extreme, budgets may collapse complex processes into a single value such as the sediment delivery ratio (SDR) (Renfro, 1975).

Gilbert's (1917) sediment budgets were developed volumetrically in multiple steps (Chapters 5 and 6) assuming conservation of mass and without compensations for changes in bulk density. He computed HMS production on a mine-by-mine basis and lumped production within a few large watersheds: the Yuba, Feather, Bear, and American rivers and Deer Creek. The production data were for all hydraulic mining between 1849 when mining began and 1909 when his field mapping ended, but he recognized that most of the production took place before 1884, when hydraulic mining largely ceased. From the input-based HMS production budget, Gilbert moved to a lumped approach to compute an output-based budget for the entire region. Total sediment production (P) was initially calculated for mines (M), agriculture (A), roads (R), trails (T), and grazing (G), as a spatially lumped, output-based budget for a subset study area of the Yuba basin:

$$P = M + A + R + T + G \tag{1}$$

Gilbert computed total production in this way for the subset area and scaled volumes up to the larger Sacramento basin. He derived storage volumes of HMS in the mountains, canyons, and piedmont from preexisting studies and compared them with production values. He used differences between total volumes of sediment production and storage to estimate sediment deliveries to the delta, San Francisco Bay, and out to sea through the Golden Gate.

Quantitative estimates of HMS production and storage in the major river basins had been developed earlier by engineers, who partitioned storage into mines, canyons, and valley deposits (Hall, 1880; Mendell, 1880; Benyaurd et al., 1891; Heuer, 1891; Turner, 1891). Gilbert painstakingly checked these estimates against topographic surveys of mine pit volumes and increased HMS production by 51% to reconcile the differences. Gilbert did not confine his budgeting methods to field surveying and computations. In characteristic fashion, he carefully considered large-scale processes and evaluated the results against logical factors. For example, when the ratio of total HMS produced in the Bear River basin to HMS stored in the lower Bear River gave a larger proportion than in other basins, he lowered his estimate of production in the Bear Basin. It turned out, however, that the estimate of storage in the lower Bear River that he had adopted from two previous studies (Mendell, 1882; Benyaurd et al., 1891) was substantially too low, that his original estimate of sediment production for the Bear River had been correct (James, 1989), and that his method of comparing ratios was appropriate. Interestingly, Gilbert's consideration of proportions predates the concept of sediment delivery ratios by several decades and illustrates his keen understanding of the importance of storage at the basin scale. It also demonstrates his penchant for using ratios in analyses (Pyne, 1980b).

Gilbert presented sediment production volumes as totals summed over the Feather, Yuba, and American basins. Applying his 1.51 adjustment to previous production estimates (Benyaurd et al., 1891; Turner, 1891) gives HMS production volumes for the individual branches of the Yuba and American basins and corroborates Gilbert's methods by reproducing the same totals reported in PP105 (Table 2). A schematic map of HMS production with widths proportional to production illustrates the dominance of the Yuba Basin as the primary source of HMS (Fig. 6).

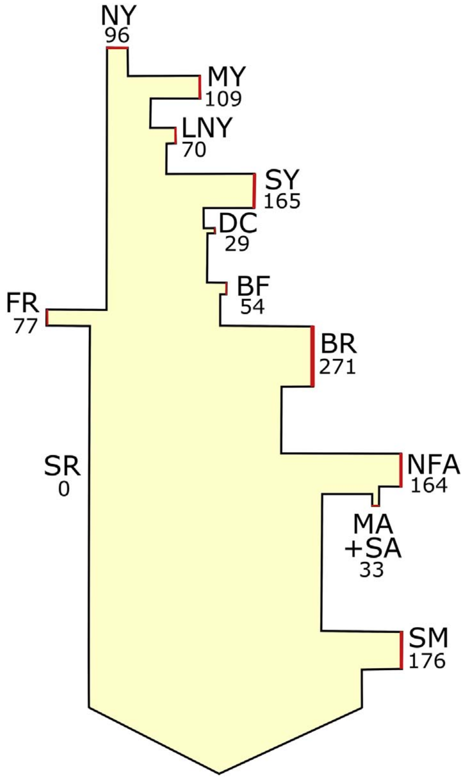

Fig. 6. Schematic sediment budget showing volumetric ($m^3 \times 10^6$) HMS production from 1849 to 1914 by catchment based on data from Gilbert (1917; Table 7) and Benyaurd et al. (1891). NY = North Yuba, MY = Middle Yuba, LNY = lower North Yuba, SY = South Yuba, DC = Deer Creek, BF = Below forks of the Yuba (below Deer Creek), FR = Feather River, BR = Bear River, NFA = North Fork American, MA + SA = Middle and South Forks American, SM = southern mines including Consumnes, Mokelumne, and Toulumne rivers. Sacramento River (SR) contributed no HMS but transported it below the Feather River.

Table 2
Hydraulic mining sediment production volumes (10^6 m^3); these are volumes of mine pits, so corresponding volumes of sediment produced were likely larger because bulk densities decreased when sediment was removed.
Adapted from Gilbert, 1917).

	B & T, 1891[a] × 1.51 $m^3 \cdot 10^6$	Gilbert $m^3 \cdot 10^6$
North Yuba	95.6	
Middle Yuba	109.2	
Lwr No Yuba (btwn MY & SY)	69.9	
South Yuba	165.1	
Deer Creek	29.5	
Below the forks	53.7	
Yuba River Total:	523.0	523.4
Feather River at Yuba City	76.5	76.5
Bear Basin	271.1	193.0[b]
North Fork American	163.5	
Middle Fork American	33.3	
American River Total:	196.6	196.6
To lateral basins		23.0
Total HMS SacV:		1090.3
Southern mines		176.0
Total HMS prod:		1266.3
Placer Mining		45.9
Quartz Mining		38.3
Drifting		23.0
Total other mining:		107.1
Non-mining waste from Sac Valley		321.4

[a] Benyaurd et al., 1891; Turner, 1891.

[b] Gilbert revised his initial estimate for HMS production in Bear Basin downward from 270.9 to 193.0 m^3, which is what he used in his totals. His initial estimate was probably correct, however, and is preferred (see text).

Gilbert also estimated storage volumes in the mountains, canyons, valleys, and bays based on combinations of previous estimates and bathymetric-change computations. By subtracting Gilbert's storage from production volumes, sediment deliveries to the San Francisco bays can be constructed (Table 3). This overall budget of sediment deliveries shows Gilbert's estimates of 1090 × 10^6 m^3 of HMS produced from the Yuba, Bear, American and Feather basins, of which 650 × 10^6 m^3 was stored and 440 × 10^6 m^3 was delivered downstream to the Delta. Subtraction of Gilbert's computed volumes of storage in the bays from deliveries to the bays generates a budget of deliveries through the bays and out to sea (Fig. 7). He estimated an additional 107 × 10^6 m^3 of sediment was produced by placer and quartz mining and 321 × 10^6 m^3 of non-mining sediment was produced in the Sacramento Basin. He also estimated 176 × 10^6 m^3 of sediment was produced by the southern mines, 143 × 10^6 m^3 of this was stored, and the remaining 33 x $10^6 m^3$ was delivered to the Delta south of the Sacramento River. The adjusted totals result in a net delivery of 902 × 10^6 m^3 to Suisun Bay, but the budget indicates that only a small amount of this (38 × 10^6 m^3) passed through San Francisco Bay to the ocean. It appears, however, that no non-mining sediment for the San Joaquin Valley or local tributaries below the Sacramento River were included in the budget, so it's possible that fluxes to the ocean were larger. In addition, expansion of HMS likely occurred when it was mined and adjusting for decreased HMS bulk densities would further increase estimated sediment production from the mines and yields to the ocean. Gilbert's HMS production volumes were computed from mine-pit volumes, but the tailings would

Table 3
Sediment delivery and storage (data from Gilbert, 1917 except as noted).

	1849–1909	1909	1914			
	HMS prod[a] $m^3 10^6$	Storage mtns $m^3 10^6$	Storage piedmont $m^3 10^6$	Storage bays $m^3 10^6$	Sed yield $m^3 10^6$	Cum sed delivery $m^3 10^6$
Feather River at Yuba City	77	11.5	19.1		46	46
Yuba River	523	49.7	252.5		221	267
Feather R below YC			20.5		− 25	247
Bear	271[b]	45.9	106.0[d]		119	365
American River	197	23.0	45.9		128	493
Sac R Storage below FR			53.0		− 64	440
to lateral basins	23		23.0		0	440
Total HMS SacV:	1090	130	520		489	
Other mine sediment	107				107	547
Non HMS to Sac Valley	321				321	869
Southern mines HMS	176	72.7	70.0		33	902
Total sediment prod:	1695	203[c]	590		902	
Suisun Bay				153.0	− 153	749
Carquinez Straight				38.3	− 38	711
San Pablo Bay				436.1	− 436	275
San Francisco Bay				249.4	− 249	25
Discharge to Ocean				38.3	− 38	− 13
Total				915.1		

[a] From Gilbert's values in Table 2.
[b] HMS production in the Bear Basin is set to Gilbert's initial estimate as the most accurate.
[c] Volumes and rationale for storage in the mountains are given in text of Gilbert on p.47.
[d] Storage in the lower Bear River (Piedmont) was greater than previously estimated. Volume of 106 $m^3 10^6$ is based on coring in 1988 (James, 1989).

have taken up a greater volume than the dense paleochannel gravels that were mined.

3.4. Sediment waves

Much has been written about Gilbert's analogy of HMS traveling in the Yuba and Sacramento rivers as a sediment wave. The concept has been applied to a wide range of scales and a variety of processes (Meade, 1985; Hoey, 1992; Nicholas et al., 1995; Lisle, 2008). Gilbert describes the downvalley translation of waves with attenuation, providing a time series of low-flow channel stages as evidence of changes in channel-bed elevations. Channel-bed elevations are not a direct linear indicator of sediment loads, however, and the symmetry implied by Gilbert's bed waves misled generations of river scientists and engineers into believing that most of the HMS had passed through the system and was gone or permanently stored (James, 1989, 2006, 2010). To distinguish between channel-bed changes and sediment loads, James (2006) recommended that waves documented by bed elevation changes (e.g., Gilbert's waves) be referred to as bed waves, whereas sediment waves should refer to rates of the passage of sediment. Channel-bed incision tends to occur relatively rapidly after a period of aggradation, so long-term remobilization of stored overbank sediment results in a tendency for, large-scale sediment waves to take longer to pass than bed waves. Gilbert applied the sediment wave concept to an analysis of sediment deliveries to Suisun Bay (Fig. 3). He showed peak deliveries occurred at approximately the same time as peak deliveries passed Sacramento (ca. 1895) and predicted that sediment deliveries from non-mining sources would ultimately exceed sediment delivered from HMS. A remarkable aspect of the sediment wave concept is Gilbert's ability to comprehend and recognize the large spatial and temporal scales of the phenomenon. Subsequently, sediment waves have been linked to sediment transport (Pickup et al., 1983; Gomez et al., 1989), longitudinal connectivity (Hooke, 2003), geomorphic change (Madej and Ozaki, 1996; Bartley and Rutherfurd, 2005; Hoffman and Gabet, 2006), and complex fluvial self-organization (Schoorl et al., 2014).

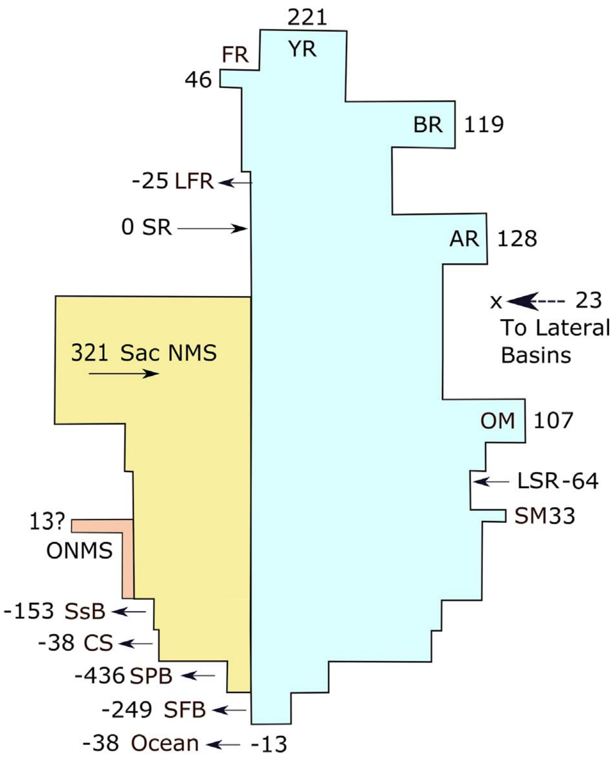

Fig. 7. Gilbert's (1917) budget of sediment deliveries shown by widths proportional to volume. Numbers represent volumes (10^6 m^3) of deliveries and storage (negative) primarily from Gilbert's data up through ca. 1914. Deliveries were computed by subtracting Gilbert's storage from production and upstream delivery volumes. Abbreviations: FR = Feather River, YR = Yuba River, BR = Bear River, AR = American River, LFR = lower Feather River below Yuba City, Sac NMS = non-mining sediment delivered from entire Sacramento Valley, LSR = lower Sacramento River, SM = southern mines, ONMS = other non-mining sediment, e.g., from San Joaquin Valley, SsB = Suisun Bay, CS = Carquinez Strait, SPB = San Pablo Bay, SFB = San Francisco Bay.

3.5. Equilibrium and grade

Although the concepts of grade and equilibrium are not important components of PP105, many scientists assume that the concepts are clearly expressed in the monograph due to Gilbert's prominence in their formulation. Discussions of equilibrium and grade are largely absent from PP105, which may reveal Gilbert's thinking on the subjects late in his career. The concepts can be traced back to Gilbert's (1877, p. 113) description of the processes resulting in a uniform grade and equilibrium of action in the land sculpture of badland slopes at the base of the Henry Mountains. It is interesting, therefore, that in PP105 he mentions equilibrium primarily in the context of the Golden Gate Bar that was composed primarily of non-HMS. Similarly, he does not use ‘graded’ to describe the channel and slopes of the HMS, which were rapidly changing. Instead, Gilbert describes graded slopes on tailing cones at the base of hydraulic mine pits (p. 50) and elsewhere uses the term ‘grade’ in a manner synonymous with slope or in reference to grain-size classes. In one important instance where he describes scour below the Daguerre Point Dam, Gilbert clearly defines the processes that establish a uniform grade as a balance between sediment, water, and slope similar to the description in his initial Henry Mountains report (Gilbert, 1877) 40 yr earlier:

> A stream flowing over a detrital bed adjusts the general slope of its bed, making it as steep as is necessary for the transportation of its bed load and no steeper. The adjustment of slope to load is accomplished, paradoxically, by means of a local adjustment of load to slope. Wherever the slope is too gentle for the load a part of the load is dropped, and the grade is thereby built up. Wherever the slope is steep enough to carry more load than the stream brings to it the stream increases its load by scouring the bed, and the slope is thereby pared down. (Gilbert, 1917, p. 58)

In PP105, Gilbert generally uses grade to refer to a uniform slope resulting from a balance between water, sediment, and slope, just as he did in his 1877 report. This differs subtly from the use of grade by Mackin (1948) 30 yr later as a *condition*. Nonetheless, the modern geomorphic sense of the graded river follows logically from the processes described by Gilbert in both accounts. In the Henry Mountain report, Gilbert (1877) goes on to link the condition of uniform grade to 'an equilibrium of action.' However, PP105 makes no mention of equilibrium with regard to the extensive sand and gravel deposits of HMS. The concept that streams tend to develop a slope of equilibrium had been recognized by European engineers since the late seventeenth century (Knox, 1976). However, in widely circulated papers, Davis (1899, 1902) redefined grade to include evolutionary implications by postulating that equilibrium and grade were only established in geologically *mature* systems. These added Davisian implications may explain why Gilbert used the concepts of grade and equilibrium sparingly in PP105. Alternatively, the obvious disequilibrium in fluvial systems below the mines, demonstrated by multiple young terrace sets of historical age and frequent avulsions, may have led Gilbert to avoid discussing equilibrium in PP105, except in the context of Golden Gate Bar. He clearly recognized that rapid adjustments in these rivers represented an imbalance between sediment loads and transport capacity, so avoidance of the terminology that he had introduced 40 yr earlier may have been deliberate in recognition of a nonequilibrium system.

4. PP105 from a modern perspective of complex nonlinear dynamics

Modern geomorphic theory has called for an expanded view in which equilibrium is a subset of a much broader array of potential system conditions. For example, complex nonlinear dynamical (CND) systems theory provides a framework in which stable equilibrium is only one possibility. G.K. Gilbert's seminal work on HMS highlighted the importance of sediment storage, transport lag times, and large imbalances between sediment supply and transport capacity. He apparently believed that under *normal* undisturbed conditions streams maintain an approximate balance between supply and transport capacity, but he also recognized that rivers are not merely steady-state conveyor belts. While Gilbert's work has, not unfairly, been cast as a forerunner of an *equilibrium* approach that dominated geomorphology in the late twentieth century based on normative steady-state attractors (see Sack, 1992), his work on anthropic sedimentation also clearly implies nonlinearity in geomorphic systems. This applies at the level of process mechanics, where thresholds (e.g., force or power vs. resistance) are critical, and at broader scales. Gilbert describes lag times and supply/transport capacity imbalances, which together with thresholds show that fluvial systems are nonlinear, as linearity is defined as outputs being proportional to inputs across the entire range of the inputs.

While nonlinear systems do not always exhibit complex behavior, they often do and have possibilities that cannot occur in linear systems. Like scientists in general, most geomorphologists did not fully recognize the implications of this through most of the twentieth century. Though antecedents certainly exist, most of the pioneering work on complex nonlinear dynamics in geography, geology, and other fields dates to the early 1980s. In geomorphology, much of this work was in reference to fluvial systems influenced by anthropogenic effects. Thus, it is interesting that Gilbert—who anticipated equilibrium theory—describes in great detail responses to anthropogenic nonequilibrium conditions in PP105. It would be too much, however, to expect Gilbert to make explicit references to CNDs > 50 years before the advent of such theory.

4.1. Complex nonlinear dynamics (CND) in fluvial geomorphology

This section briefly highlights work on nonlinear complexity in fluvial geomorphology. The focus is on work that explicitly addresses CND, as opposed to the much larger body of work relevant to CND, or where CND is a more peripheral issue. This excludes many studies showing nonlinear behavior in the form of thresholds, discontinuities, disproportionate responses to changes and disturbances, and various manifestations of nonsteady-state in fluvial systems. Focus is also on modern work specific to sediment transport and storage in fluvial geomorphology, recognizing that this is only a fraction of the work on CND in geomorphology more broadly. We do not claim Gilbert as a CND practitioner or advocate. Rather, the argument is that applications of CND in fluvial geomorphology are directly related to the presence of thresholds, storage, and lag effects, and that abundant examples of these factors and explicit attention to the latter can be traced to Gilbert and PP105.

Nonlinear dynamical systems—including fluvial systems—may exhibit discontinuities or bifurcations between alternate states. These bifurcations are closely related to geomorphic thresholds. Catastrophe theory can describe and model bifurcations, particularly in situations where the alternative evolutionary pathways may be controlled by a combination of factors such as sediment inputs, exports, and storage in a fluvial system. Graf (1979, 1988) proposed just such a catastrophe theory model for fluvial systems. Unstable behavior in ephemeral channels was modeled using a cusp catastrophe by Thornes (1980), based on the interactions of particle size (a ratio of mean particle size to sorting), stream power, and bedload transport. More recently Wainwright (2015) coupled catastrophe theory, dynamical (in)stability, and connectivity in an agent-based model of fluvially shaped Mediterranean landscapes. Responses to anthropic changes were shown to be highly nonlinear and strongly historically and geographically contingent. Thornes (1983) generalized notions of bifurcations, nonlinear dynamics, and dynamical instability to geomorphic evolution, using water erosion and unstable channels as two of his three examples. The *competition* between vegetation cover and water erosion was modeled as an alternative stable-state system (Thornes, 1985), and the relevance of complex nonlinear dynamics to paleohydrology was laid out by Thornes and Gregory (1991).

4.2. Sediment budgets and transport from a modern perspective

Trofimov and Moskovkin (1984) explored the potential for dynamical instabilities in geomorphic mass-flux systems by formally linking existing concepts of supply and transport limitations to CND. This laid the groundwork for Phillips' (1986a) work on fluvial sediment budgets, applying nonlinear dynamical systems (NDS) theory to the problem of estimating sediment budgets from sediment yield. This resulted in a formal demonstration that denudation models based on yield must over- or under-predict unless there is no change in storage (rather than simply no net change in sediment storage).

The stability of a watershed sediment budget can be evaluated based on the partitioning and fluxes of sediment among upland sediment sources (and colluvial storage), floodplain and channel storage, and stream flows. For the case of the Tar River, North Carolina, Phillips (1987) found the system to be dynamically unstable, implying that relatively small changes in any component are likely to persist and grow rather than recover to the previous state. Phillips (1992) obtained similar results for a more general geomorphic mass flux model. Large responses—river metamorphosis—were addressed for the Gila River, Arizona, by Hooke (1996), who showed that channel morphology may show disproportionately large or small responses to changes in discharge based on nonlinear feedbacks.

A common misconception, particularly in the early days of CND applications in geociences, was that a nonlinear, nonequilibrium approach implies that complex, nonlinear dynamical patterns are inevitable. This is not the case. Renwick (1992) showed that steady-state equilibrium, disequilibrium (steady-state may be approached but has not occurred yet), and nonequilibrium (no tendency toward equilibrium) landforms may occur simultaneously in the same landscape or at different times in the same location. He illustrated these principles with a model of stream profiles based on sediment inputs to the channel, sediment transport as a function of stream power, channel aggradation or degradation, and feedbacks on channel width/depth. Progress toward steady state, nonequilibrium, and all states in between may occur under realistic combinations of sediment supply and transport and of channel and profile morphology (Renwick, 1992).

Renwick's work showed that sediment loads may or may not be proportional to external forcings. Gaffin (2009) also explored these phenomena, showing that internal feedbacks of fluvial systems may either amplify or filter effects of sea-level changes as recorded in alluvial sedimentary basins. Jerolmack and Paola (2010) showed that the ubiquitous thresholds in sediment transport systems can obscure the role of environmental changes that drive transport. These thresholds may make transport a nonlinear filter that 'completely destroys ('shreds') environmental signals' (Jerolmack and Paola, 2010). Using a numerical model, they likened these dynamics to morphodynamic turbulence, showing that higher-frequency environmental forcing makes 'shredding' more likely. Coulthard and Van de Wiel (2013) further explored amplifying, filtering, and shredding phenomena in fluvial sediment transport and alluvial records. They used a landscape evolution model to explore the relative role of climate, tectonics, and drainage basin morphology on sediment yield. They found that the sediment signal from substantial rates of uplift may be lost in response to internal storage effects within even a small basin. In addition, in larger basins, tectonic inputs can be substantially diluted by regular delivery from non-uplifted parts of the basin. However, the signal from modest increases in rainfall was evident in increases in sediment yield. Schoorl et al. (2014) concluded that sediment waves are not necessarily caused by external changes but may result from destabilization of fluvial systems by self-organizing behavior of rivers in response to the relative amounts of available sediment and transport capacity.

Phillips (2003) explored the question of why sediment yields in some drainage basins may remain relatively consistent in spite of known changes in climate, land use, sea level, and tectonics. He found that the interrelationships among fluvial sediment yield, alluvial storage, regolith mass, and weathering could be dynamically stable if alluvium is always available for potential remobilization and if regolith development exerts negative feedback on weathering (i.e., weathering rates slow as soils and regoliths become thicker). As illustrated by a case study, under these circumstances environmental changes are mainly manifest as reorganizations within the fluvial system (e.g., variations between net increases and decreases in alluvial storage; changes in the spatial locus of deposition) rather than output at the basin outlet.

Complications induced by CND in interpreting sediment yields or alluvial archives are not insurmountable. For instance, several of the studies above explicitly identify circumstances under which effects of external forcings might be obscured or exaggerated—or not. Phillips and Gomez (2007) exploited this to interpret the offshore sediment record of the Waipaoa River, New Zealand. A mass balance stability model showed that the system was stable for much of the Holocene. However, anthropic change in this case resulted in a shift to dynamical instability, such that sediment exports became highly sensitive to land-use changes. Wang et al. (2011) specifically addressed these issues with respect to stratigraphic interpretation, finding that scale-dependent compensational stacking (the tendency to preferentially fill topographic lows) can help to distinguish between patterns generated endogenously to the drainage basin versus exogenous forcings. Archeological interpretations of fluvial deposits are also strongly influenced by complex nonlinear dynamics. Accordingly, Davies et al. (2016) applied an agent-based model to explore amplifying and filtering of alluvial deposits in an arid Australian stream. Patterns were more consistent with episodic geomorphic change than with changes in human activity.

More generally, CND in fluvial systems related to thresholds, lags, and feedbacks in sediment transport and storage have played an increasingly large role in explanation even where CND techniques are not directly employed (see, e.g., Jain et al., 2012). It is unlikely that Gilbert, who anticipated equilibrium theory (Gilbert, 1877), considered the notions of CND, but many of the disturbed, transient conditions he described fit into this framework better than to concepts of dynamic equilibrium.

5. Salient aspects of PP105

Several qualities of PP105 are worthy of further discussion. Striking characteristics of Gilbert's science include his multimethodological approach and the extensive use of empirical, field-based methods and historical data. In addition, the subject of PP105 is an important foray into anthropogenic change that was not common for scientific publications of the time.

Methodologically, PP105 is exceptionally broad and eclectic. The breadth of methods is appropriate for such a large-scale study—in time and space—in which Gilbert documents the production and transport of HMS from the mountains to the sea. This was extremely challenging and would not have been feasible without avoiding detail on local-scale processes. Gilbert's PP105 combines his genius for synthesis with his acumen for recognizing detailed process without getting distracted by detailed process discussions. Gilbert's multimethodological approach to science is rarely possible in modern studies that do not have the flexibility to employ such a wide array of methods. In fact, the modern tendency is to apply a method or two and write a brief report on the results, but this leads to fragmented analyses of a few isolated elements of systems and does not consider interactions between multiple components of fluvial systems. The many approaches to problem solving presented in this monograph demonstrate the creativity, resourcefulness, flexibility, and breadth of Gilbert's science. They also indicate that the methods were secondary—as long as they were accurate and logical—to the primary objective of finding answers to difficult questions. What drove Gilbert was discovering (i) how much and where sediment was produced, (ii) where it was located, (iii) how it behaved in a large complex system, and (iv) what were the geomorphic processes and consequences. These discoveries led him beyond to forecasts of future sediment behavior. Gilbert located all the reliable data that was available in whatever form and used his creativity as a scientist to develop analytical methods and make appropriate interpretations of that information.

Gilbert's penchant for empirical, field-based observations, interpretation, and verification is maintained admirably in PP105. His interpretations and theories are based primarily on keen analyses of observations and data. For example, low-flow data led to a theory of sediment waves and sedimentary and morphologic evidence led to a theory of equilibrium between wave and tide forces to explain evolution of Golden Gate Bar. This approach provides an important lesson for some modern scientists who may overemphasize interpretations drawn directly from conceptual and simulation models, rather than drawing process-based inspiration from the physical environment and using models *a posteriori* to expand upon or test those observations. An empirical field-based approach also implies some degree of place-based science, for which PP105 is exemplary. At the centennial of its publication, river managers and engineers in northern California continue to refer back to Gilbert's findings with regard to sediment and aquatic environments in the Sacramento Valley, the Delta, and the bays. The combination of contemporary data and logical interpretations form a compelling and irreplaceable view of the contemporary fluvial geomorphology and sediment transport in the region that are essential to modern fluvial management and forecasting.

Historical analysis is an essential means of understanding complex fluvial systems (Grabowski and Gurnell, 2016). The PP105 monograph demonstrates the importance of historical analysis in two ways. First, Gilbert used historical data in his analysis to bring out key new components of the HMS assessment. For example, data on water used by mines that were analyzed by Turner (1891) allowed recalculations of sediment production, low-flow data compiled since 1850 were analyzed to demonstrate a sediment wave, and sedimentation volumes from changes in bathymetric data were used in sediment budgets. The great success of PP105 as an enduring scientific study demonstrates the effectiveness of utilizing historical methods and Gilbert's stature as one of the leading scientists of his day adds credence to these methods. Second, the use of PP105 by others is an historical approach to science. The study may be used directly for data and knowledge of contemporary conditions or it may be used indirectly to understand contemporary methods. The abundance of data in PP105 makes it a valuable source of historical information.

Gilbert's PP105 has long been a well-known example of scientifically documented extreme anthropogenic change and legacy sedimentation. Production of more than a billion cubic meters of anthropogenic sediment over a period of 31 years and its spread downstream to the rivers and bays of northern California are clearly and indisputably recorded in an early, widely circulated publication. The topic of HMS has always been the obvious change noted by readers of PP105. Much more subtle are Gilbert's predictions of soil erosion from agriculture and road construction and the watershed view that was involved. Little has been made of Gilbert's early prognositication of the menace of soil erosion—long before H.H. Bennett (1928) announced this problem in the USA. Gilbert estimated that rates of sediment produced by soil erosion had already surpassed rates of HMS production at the time of its writing, but he also predicted that sediment produced by soil erosion would soon be the dominant source of sediment delivered to the delta. He arrived at that conclusion through a basinwide assessment of sediment production, transport, storage and yield. Gilbert was prescient in his forecast of increasing sediment production by ubiquitous land-use changes. As ever, he presented these projections without fan-fare as a matter-of-fact conclusion of his scientific report.

6. Conclusions

Hydraulic-Mining Débris in the Sierra Nevada, a capstone to the extensive body of work by a brilliant scholar, has a rightful place among the classic works of geology, geography, environmental science, and geomorphology. Gilbert's PP105 is an exemplary combination of applied and theoretical geomorphology and of field observations, secondary data, induction, and deductive reasoning. Themes highlighted by Gilbert (1917)—some for the first time—reverberate 100 yr later. The PP105 monograph was not the first example of applied geomorphology, but was certainly an early and influential instance of the explicit application of geomorphological concepts and reasoning to a high-profile environmental, engineering, and economic problem. Likewise, Gilbert did not pioneer the study of human impacts on the environment via sediment, but PP105 was critical in highlighting such impacts and in tracing their reach in space and time. The report is also an early example of an integrated watershed approach to river science.

Gilbert's work showed that sediment production, storage, and transport in fluvial systems does not act as a steady-state ‘conveyor belt’ moving sediment from source to sink. Rather, such movement is intermittent and episodic, incomplete, and characterized by long lag times. Further, presence of the sediment and its related forms has important feedback effects on the water and sediment conveyance capacity of the streams. Gilbert thus drew attention to the historical and time-transgressive aspects of anthropic sedimentation and the importance (in a geomorphic and a management sense) of what are now termed ‘legacy’ sediments.

While Gilbert's name is often associated with concepts of steady-state equilibrium and grade as normative conditions in geomorphic systems, PP105 implicitly treats the HMS problem as a nonequilibrium one, and does not predict or postulate a return toward any supposed steady-state condition. The PP105 study reflects a more referential (as opposed to normative) and nuanced view of (steady-state) equilibrium and grade, as compared to more general subsequent invocations in geomorphology and Gilbert's earlier publications. By implicitly dealing with a system in distinct nonequilibrium on its own terms (as opposed to treating it as an aberration), Gilbert brought out these features and processes for subsequent scientists to see. Although he does not specifically describe the role of thresholds, discontinuities in sediment fluxes, or the inherent nonlinearity of geomorphic systems—concepts that were developed later—PP105 provides examples of complex behavior such as lag times in sediment delivery. Thus, while Gilbert (1917) cannot be claimed to foreshadow studies of complex nonlinear dynamics in geomorphology, the latter did arise later from the increasing recognition of the nonlinear phenomena first underscored in PP105.

Gilbert's PP105 explained and predicted future impacts of hydraulic mining debris using a sediment-budget approach. By the late twentieth century, sediment budgets had become a standard tool for analysis of human impacts (and environmental changes in general) on fluvial systems and for management and analysis of soil conservation and sediment-control issues. While more general approaches to mass budgets (e.g., nutrients and other pollutants) are difficult to attribute directly to Gilbert, PP105 presaged the use of such budgets in hydrology, ecology, geomorphology, and watershed management. Furthermore, by concluding PP105 with a recommendation for soil conservation, Gilbert made the transition from a nineteenth century focus on geomorphic mapping and explanation to a twentieth century focus on geomorphic explanation for the purpose of land and river management.

Acknowledgements

The authors are thankful to three anonymous reviewers who provided a variety of insights and constructive comments that led to improvements throughout the manuscript. We take full responsibility for the content of the study, but benefitted greatly from these inputs.

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