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Secular Sediment Waves, Channel Bed Waves, and Legacy Sediment

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Abstract

The concept of sediment waves is reviewed and clarifications are proposed for nomenclature concerning vertical channel responses to large fluvial sediment fluxes over a period of a decade or longer. Gilbert's (1917) original sediment waves are re-evaluated at their type locale and used to develop a consistent set of definitions. A 'sediment wave' represents a transient sediment flux that includes but is not necessarily identical to a 'channel bed wave' that represents the rise and fall of the bed in response to sedimentation. A large-scale sediment wave results when a major sediment-delivery event generates an aggradation–degradation episode (ADE). It may leave a legacy of sediment deposited on valley bottoms. Gilbert's classic sediment-wave model was empirically based on changes in bed elevations but was described as a sediment flux. He described downstream translation of an attenuating symmetrical wave although it was too large and disjointed to have a coherent waveform. Rapid return of bed elevations to pre-sedimentation levels in Gilbert's wave should not be mistaken for exhaustion of sediment. The common concept of a symmetrical sediment wave representing the time series of sediment loads is not accurate for large-scale sedimentation events that store and slowly release sediment on floodplains. Large sediment waves composed of relatively fine material and limited bed armoring tend to be right-skewed owing to rapid vertical readjustments relative to lateral recruitment of stored sediment. A revised right-skewed conceptual model of large sediment and bed waves is presented that fits modern observations and incorporates stochastic elements of flood events. Large sediment waves may be linked to legacy sediment; that is large repositories of anthropogenic alluvium stored on valley bottom floodplains, wetlands, mill ponds, and reservoirs. This illustrates the ubiquity and importance of secular sediment waves to river management.

Introduction

Understanding the behavior of large masses of episodically delivered sediment in river systems is of increasing importance owing to the need to assess and mitigate the effects of global environmental change and climate warming on river systems, flood hazards, water quality, and aquatic or riparian ecosystems. This article is concerned with large episodic sedimentation events occurring over decades or many centuries (10^1–10^3 years), which may be generated by natural, tectonic, hydroclimatic, or anthropogenic factors. Natural and tectonic factors include volcanic eruptions, tectonic events, landslides, vegetation changes associated with fire, pestilence or climatic events. Hydroclimatic and anthropogenic factors include storms, vegetation disruptions by droughts, land clearance, or fire, dam removal, and land-use/land-cover changes. Once a sediment wave is initiated, its passage generates a transient spike in sediment transport at a point and increases storage at various locations in the drainage network (Lisle and Church 2002). Passage of a sediment wave may cause increased flood stages and the homogenization of local channel variability, because pools and microenvironments are buried. Loss of habitat diversity reduces

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biodiversity and may persist until the last of the sediment has been removed so that recovery lags long after passage of the wave peak (Bartley and Rutherford 2005a; b). Channels do not necessarily re-establish the same morphology but may return to a new stable condition balancing sediment loads and transport capacity (Madej et al. 2009).

In spite of their importance to fluvial forms, flood hazards, and aquatic and riparian biodiversity, inconsistent definitions and misconceptions about large sediment waves have frequently led to a fundamental misunderstanding of how massive, episodic sedimentation events behave and underestimation of their persistent effects (James 1989, 1999, 2006). This article seeks to clarify definitions and address linkages between secular sediment episodes associated with large sediment waves and the vast repositories of legacy sediment that they may leave behind.

Definitions of sediment waves and associated phenomena

Many different phenomena have been described as sediment waves and many alternate and overlapping expressions have been employed. Explicitly defining these features is essential to an unambiguous clarification of the concept of sediment waves. Definitions of terms are reviewed along with distinctions between their spatial and temporal scales, textures, and processes of propagation. This is followed by a discussion of basin-scale sedimentation events that may accompany secular waves. The history of the sediment wave concept is reviewed by revisiting Gilbert's (1917) type locale and a distinction between sediment and bed waves is made. The fluvial features and processes described here are not the same as marine bedforms described as sediment waves (Wynn and Stow 2002) or changes in sediment concentrations observed during a storm (Bull 1997).

ALTERNATIVE DEFINITIONS AND TERMINOLOGY

Definitions and interpretations of fluvial sediment waves have varied greatly as have the names for related wave features (Table 1). Categories of sediment waves have been reviewed by several workers (Hoey 1992; James 2006; Lisle 2008; Nicholas et al. 1995). Various alternate terms have been used such as bed waves, bed material waves, bed-load sheets, sediment slugs, and sediment pulses (Kasai et al. 2004; Lisle et al. 2001; Madej 2
et al. 2009; Wathen and Hoey 1998). 'Sediment slug' was preferred by Nicholas et al. (1995) owing to difficulties that often arise in identifying coherent waveforms. Lisle (2008) objected to the use of 'slug' because it implies that recruited ambient sediment is not included. Additional references to sediment waves or related phenomena can be seen in many different contexts (Ashmore 1991; Bartley and Rutherford 2005a; Doyle et al. 2000; Erskine 1994; Gomez 1991; Gomez et al. 1989; Griffiths 1993; Iseya and Ikeda 1987; Knighton 1989; Legleiter et al. 2003; Madej 2001; Madej and Ozaki 1996; Meade 1985; Miller and Benda 2000; Sutherland et al. 2002; Weir 1983). Some definitions of waves are explicitly tied to changes in channel-bed elevations (Gilbert 1917). For example, sediment waves are described as 'transient zones of sediment accumulation in channels' and 'a propagating disturbance in bed elevation and sediment properties' (Sutherland et al. 2002, p;. 1036). Most definitions imply a bed response, but some definitions focus on sediment storage and do not explicitly require thalweg aggradation. For example, sediment waves have been defined as zones of increased sediment storage (Benda and Dunne 1997; Hoey 1992; Hoey and Sutherland 1991; Wathen and Hoey 1998).

Waves have been categorized by scale on the basis of size or duration; for example megaslugs for bar assemblages larger than 1 km, or super slugs for the even larger features

Table 1. Systems of sediment-wave classifications (Adapted from James 2006; which drew heavily upon Hoey 1992 and Nicholas et al. 1995).

Type of response to an aggradation–degradation Episode; James (2007)
1. Bed waves –the rise and fall of the channel thalweg in response to an episode of high sediment deliveries.
2. Sediment waves – total sediment flux associated with a bed wave.
Scale (two overlapping classification systems based on magnitude)
1. By spatial scale of bed wave; Hoey (1992), Nicholas et al. (1995), Wathen and Hoey (1998)
Mesoforms (individual bedforms): 10^{-1}–10^{2} m
Macroforms or macroslugs (unit or complex bars): 10^{1}–10^{3} m
Megaforms or megaslugs (bar assemblages): >10^{3} m
Secular waves, Gilbert waves, or ADE (superslugs) (basin-scale valley-floor adjustments)
2. By temporal scale of wave persistence; Nicholas et al. (1995)
Annual or seasonal periodicities Meade (1985)
Large flood responses: 10^{1}–10^{2} years
Catastrophic sedimentation: 10^{2}–10^{3} years
Sediment source and fate (two overlapping classification systems based on source or extent of sediment)
1. By sediment source; Hoey (1992), Nicholas et al. (1995), Wathen and Hoey (1998)
endogenous waves from within channel (autopulses; endoslugs)
exogenous waves from catchment sources (allopulses; exoslugs)
2. By sediment storage processes; Nicholas et al. (1995)
within-channel storage only
overbank deposition with long-term floodplain storage James (2007)
Sediment character (based on grain size); Cui et al. (2003b)
wave material coarser than bed
wave material similar to bed
wave material finer than bed
Wave propagation process; Cui et al. (2003) Lisle et al. (2001), Sutherland et al. (2002)
Translation
Dispersion

described in this article that lack measurable wavelike morphologies. Given that the history of the sediment wave can be traced to immense channel aggradation events described by Gilbert (1917), it seems inappropriate to refer to the large secular waves emphasized in this article as 'super slugs,' which connotes an ephemeral phenomenon (if not a B-grade horror film about giant gastropods). Sediment waves or slugs can be generated by a variety of processes. Bartley and Rutherford (2005b) describe slugs as anthropogenic, but this restriction is not universal. Waves can be described as exogenous (allopulses) when generated by external sediment supplies or endogenous (autopulses) when generated from within-channel sources (Wathen and Hoey 1998). Semantic difficulties arise from the conflation of two distinct processes. Sediment waves are frequently used to describe both changes in channel-bed elevations and sediment flux, but the two phenomena are not identical and not necessarily synchronous. Furthermore, the sediment flux involved may be defined as total sediment loads or bed material loads.

The definitions of bed waves and sediment waves that are the focus of this article are derived from the original concept of secular waves advanced by Gilbert (1917), but they distinguish between the timing of channel bed changes and the timing of the passage of sediment, respectively. These distinctions may be difficult to observe in studies at the reach-scale or in experimental flumes, which rarely include remobilization of stored overbank sediment and operate over relatively short periods. Meso-scale bedforms or macro-scale unit bars and bar complexes behave differently than the much larger sediment waves described by Gilbert (1917). It is recommended that smaller meso- or macro-scale bed features be referred to as bedforms, and the associated sediment fluxes be referred to as sediment pulses or slugs. Ideally, 'sediment waves' would refer to major sediment fluxes as originally described by Gilbert (1917). This practice may not be universally accepted, however, so the scale of smaller sediment waves should be clearly described as meso or maco (e.g. Nicholas et al. 1995).

AGGRADATION–DEGRADATION EPISODES (ADE)

Channel aggradation is caused when sediment deliveries exceed the transport capacity of a channel resulting in deposition. Aggradation ceases when sediment loads decrease, channel gradients increase (Mackin 1948), or other hydraulic variables adjust (Leopold 1980) to increase transport capacities. Channel incision generally follows when sediment deliveries return to normal levels (Gilbert 1917). Decreased sediment deliveries and adjustments of hydraulic variables may be responses to human engineering attempts to control flooding, such as dams upstream or levees. Prior to a sedimentation event, the channel may be 'graded' so that equilibrium conditions pertain (Davis 1902); that is vertical adjustments are slow to the point of being negligible over modern time scales. With increased sediment loads the equilibrium is disrupted and channels fill or 'aggrade,' and with decreased sediment loads channels downcut or 'degrade' (cf. Leopold and Bull 1979; Mackin 1948). The rise and fall of the channel bed in response to a period of elevated sediment deliveries can be referred to as an *aggradation–degradation episode* (ADE). An ADE is a morphodynamic process involving both channel form and sediment dynamics with an emphasis on the vertical dimension of channel response. Rivers may adjust to an episodic sedimentation event in a variety of other ways, including changes in flow width, depth, velocity, and roughness (Leopold 1980), but aggradation and degradation of the inner channel are of critical importance owing to their effects on floods, floodplain connectivity, and habitat diversity. By definition, an ADE represents sediment storage and removal within the channel, but it may also store substantial amounts of sediment in adjoining floodplains and terraces which can later be released. While this article largely emphasizes secular aggradation lasting for decades or centuries, major ADEs occurring over longer periods such as a glacial cycle, other climate changes, volcanic eruptions, or tectonic events are recorded in the geologic record and may be accompanied by floodplain metamorphosis (Schumm 1968). Understanding such process-response systems is important for anticipating potentially rapid fluvial changes associated with climate change and anthropogenic disturbances such as agriculture, deforestation, or mining.

GILBERT'S ORIGINAL CONCEPT OF SEDIMENT WAVES

Sediment wave theory was first introduced in Gilbert's (1917) treatise on hydraulic mining debris in the Sierra Nevada. Gilbert described immense sediment waves generated by mining in the mountains that were passing down the Yuba, Bear, and North Fork American Rivers in the eastern Sacramento Valley (Figure 1). The sediment waves described by Gilbert were associated with sequences of rise and fall in the channel bed in response to a long period of elevated sediment production. They were initiated by 31 years of hydraulic mining from >50 mines that generated over a billion m^3 of sediment in large river basins. They currently are maintained by an ongoing period of reworking of stored mining sediment >125 years after the cessation of mining.

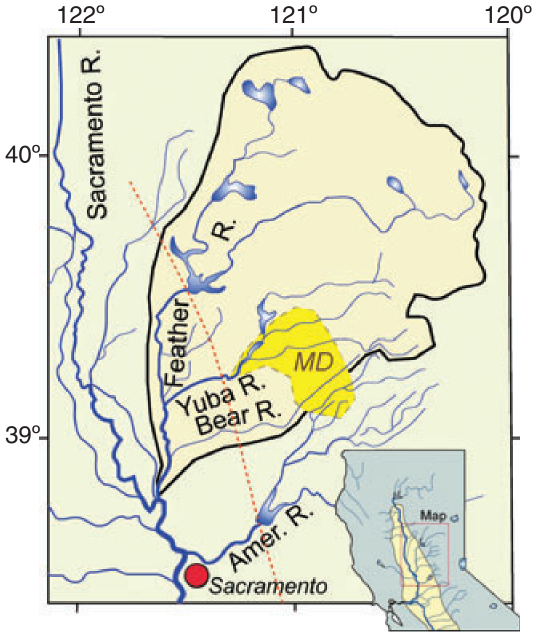

Fig. 1. Feather River Basin. Hydraulic gold mines operated on ridge tops, especially in the Yuba and Bear River basins. Large sediment waves flowed out of Middle and South Yuba, Bear, and North Fork American Rivers. Much mining sediment remains stored in the foothills on ridges near the mines and in the Sacramento Valley (west of dashed line). Little storage was possible along main foothill canyons owing to high stream powers and lack of accommodation space. MD, hydraulic mining districts.

Gilbert's original sediment wave concept included both (i) the rise and fall of the channel bed which formed the empirical basis of the model (Figure 2), and (ii) a sediment flux that behaved like a long-term flood hydrograph:

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

Gilbert predicted that channel lowering would reach pre-mining levels by the mid-twentieth century, and updated plots of low-flow stages at the gauges corroborate his forecast (Figure 3). Thus, the Gilbert waves defined by bed elevations were symmetrical with respect to time. Gilbert's hydrograph analogy clearly indicates that he visualized the rise and fall of the channel as a measure of sediment transport, and the shape of the bed-elevation time series has compelled many workers to conflate bed adjustments with sediment loads. The timing of at-a-station channel-bed adjustments, may differ from the sediment flux at that location, however, and the implication of symmetrical waves that sediment loads recover rapidly from episodic sedimentation events can lead to gross misinterpretations of floodplain dynamics and misdirected river management policies.

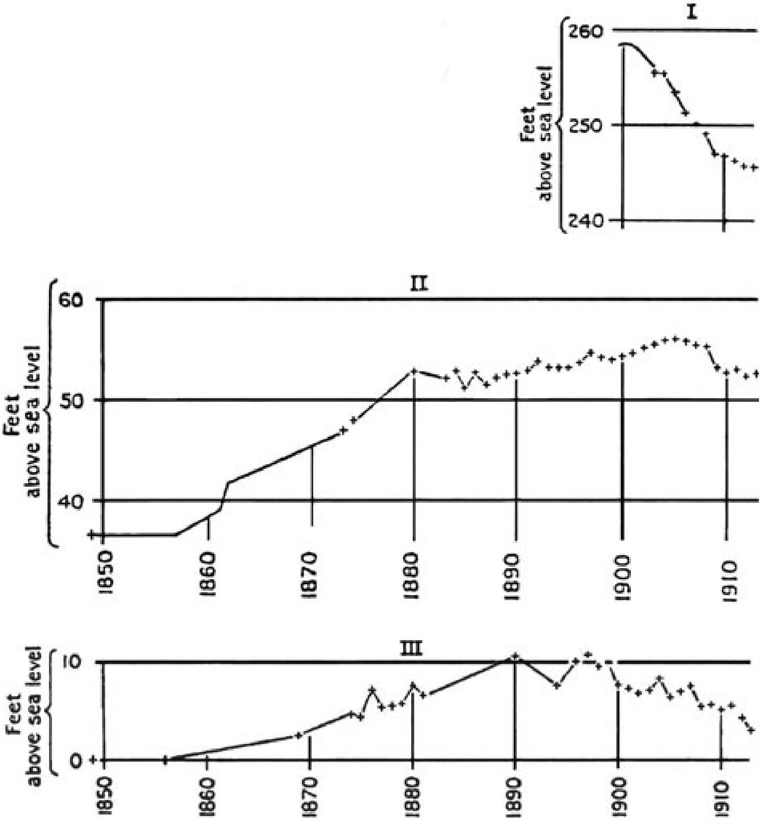

Fig. 2. Time series of changes in low-flow stages at three river gauges were the basis of the original sediment wave concept. Water heights on the Yuba River at the Narrows (I) and at Marysville (II), and on the Sacramento River at Sacramento (III) show systematic responses to the aggradation–degradation episode (ADE) generated by hydraulic mining (Source: Gilbert 1917; Figure 4).

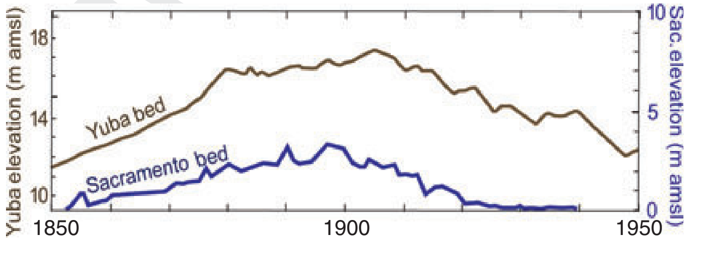

Fig. 3. Updated low-flow stage plots for the Yuba River at Marysville and the Sacramento River at Sacramento. Channel beds had largely recovered at the two gauge sites by 1950 as predicted by Gilbert (1917), implying a symmetrical response with respect to time. Adapted from Graves and Eliab (1977).

SEDIMENT WAVES VERSUS CHANNEL BED WAVES

The vertical changes in Gilbert's wave were defined by low-flow river stages, which recorded within-channel aggradation and degradation. Gilbert acknowledged sediment storage on floodplains and noted that some floodplain storage is 'permanent,' but he did not address the possibility that the bed and sediment flux responses could be asynchronous, because he emphasized aggradation, degradation, and changes in slope as the primary response to changes in sediment loads:

> ''If a stream which is loaded to its full capacity reaches a point where the slope is less, it becomes overloaded with reference to the gentler slope and part of the load is dropped, making a deposit. If a fully loaded stream reaches a point where the slope is steeper, its enlarged capacity causes it to take more load, and the taking of load erodes the bed. If the slope of a stream's bed is not adjusted to the stream's discharge and to the load it has to carry, then the stream continues to erode or deposit, or both, until an adjustment has been effected and the slope is just adequate for the work.''
> ''Any change of conditions which destroys the adjustment between slope, discharge, fineness, and load imposes on the stream the task of readjustment and thus initiates a system of changes which may extend to all parts of the stream profile.'' (Gilbert 1917: pp. 26–27).

This statement of the graded stream profile alludes to key concepts Gilbert had advanced as a young scientist (Gilbert 1877) and led to the influential concept of grade later postulated by Mackin (1948). By emphasizing vertical adjustments, however, Gilbert led others to neglect the multivariate nature of fluvial responses to changes in sediment loads. He recognized the importance of multivariate responses but maintained an emphasis on slope as the primary adjustment to sediment changes:

> ''An alluvial stream which is not confined by rigid banks shapes for itself a course made up of curves. The curves are not stationary but undergo continual changes. The curve pattern is large for a large stream and small for small one. In a variable stream the pattern is adjusted to the needs of the flood discharge. The general slope of a stream bed is determined chiefly by the magnitude of the load that travels at time of the larger floods.'' (Gilbert 1917, p. 27).

Subsequent theoretical findings in fluvial geomorphology (e.g. statistical hydraulic geometry or physically based regime methods) have shown that other variables, including width, depth, velocity, grain size and armoring, grain roughness, plan roughness, sinuosity, and bedforms, are involved in gravel-bed river morphologic adjustments (Chew and Ashmore 2001; Ferguson 1986; Gomez 1994; Griffiths 1981; Hey and Thorne 1986; Leopold 1980; Leopold and Maddock 1953). Furthermore, recent work has emphasized effects of sediment storage on transport capacity (Church et al. 1998; Dietrich et al. 1989; Lisle and Church 2002). For accurate and unambiguous definitions of sediment waves, therefore, it is critical for definitions to differentiate between rates of vertical channel-bed responses and sediment flux. Otherwise, the return of the bed to pre-event base levels can be misinterpreted as a return of sediment loads to pre-event levels. In the sediment wave type locale, for example, the symmetrical plots of Graves and Eliab (1977) were interpreted as evidence for evacuation or stabilization of hydraulic mining sediment below the dams and a return of sediment loads to pre-mining levels in the post-dam era. This was in spite of a dearth of sediment transport measurements. Subsequently, abundant field evidence has been shown of active reworking of stored mining sediment (James 1989, 1991, 1993; Singer and Aalto 2009; Singer et al. 2008).

Increased sediment loads may continue long after channel-bed elevations have recovered – especially where channel-margin and floodplain storage is substantial (Figure 4). To differentiate between bed and sediment flux changes the channel-bed responses described by Gilbert can be described as a channel bed wave, which represents a rise and fall in the channel bed, while his sediment hydrograph analogy – as a measure of sediment flux – can be describe as a sediment wave (James 2006). To be explicit, a large-scale

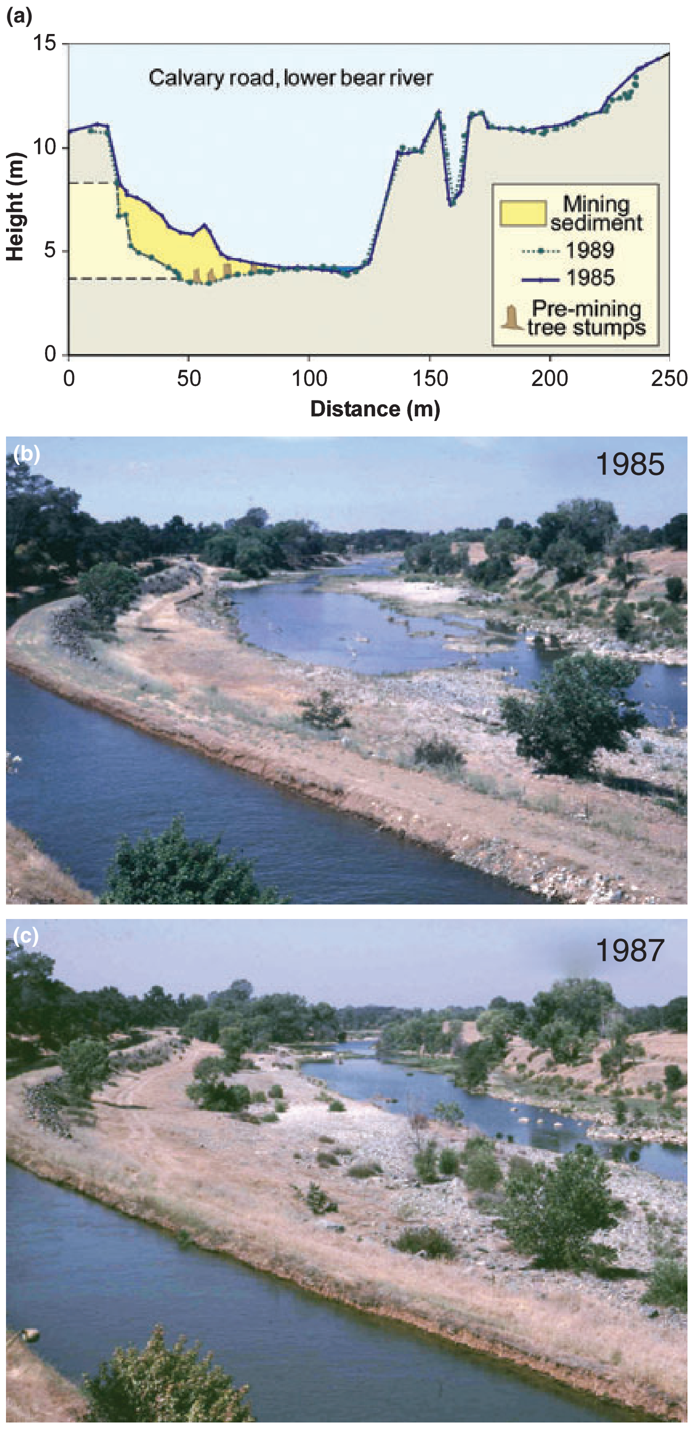

Fig. 4. Erosion of mining sediment on lower Bear River 1985–1989 in response to 1986 flood. Although channel thalweg had returned to approximate pre-mining levels by 1985 at this site, sediment recruitment continues. (a) Repeat channel cross sections measured by rod and level surveys. (b) Reach in 1985 showing gravel bar and low terrace of historical alluvium to left of low-flow channel. (c) Reach in 1987; gravel bar eroded exposing stumps at pre-mining surface. Remaining historical alluvium extends under levee on left bank (Adapted from James 1993).

Gilbert bed wave may be described as a 'secular bed wave' or 'aggradation–degradation episode' (ADE) to distinguish it from the meso-scale bedforms described in bed material transport studies (Gomez 1991; Meade 1985) and sedimentology (Best and Bridge 1992; Billi 2008; Bridge and Best 1997). Although they may be accompanied by a bed wave, a sediment wave represents a transient change in sediment fluxes. When considered from an at-a-station (Eulerian) frame of reference, a sediment wave is analogous to a long-term sediment hydrograph. When considered from a downstream (Lagrangian) frame of reference, bed and sediment wave peaks may migrate downstream if wave translation pertains.

The study of bed waves involves consideration of the temporal dimension of bed-load transport. At fine scales of time and space, transient bed changes can be linked directly to bed-load transport and to bedforms (Gomez and Church 1989; Simons et al. 1965). Temporal changes in bed-load transport rates were initially ignored due to the dominance of the Meyer-Peter and Müller (1948) and Einstein (1950) formulae, which assumed steady transport rates (Ergenzinger 1988), and owing to lack of confidence in samplers, which led to dismissal of observed time variance (Gomez 1991). A theoretical temporal distribution of bed-load transport was postulated by Hamamori (1962), and studies have found that this distribution compares fairly well to field and flume observations in sand-bed channels (Carey 1985; Gomez et al. 1989; Hubbell 1987). Spatial variability at this scale has also been an issue, especially in the presence of sand dunes (Gomez et al. 1990) or coarser materials (Hamamori 1962). Many of the relationships observed in small watershed, reach-scale, and flume studies, however, do not pertain to the large secular sediment or bed waves, which are the topic here.

Secular sediment waves, aggradation–degradation episodes, and legacy sediment

A large-scale sediment wave represents an episodic sedimentation event associated with a bed wave; that is an ADE. Previous concepts of symmetrical sediment waves underestimated the persistent effects of these episodes, which may leave persistent and extensive deposits in valley bottoms (Madej and Ozaki 1996, 2009) or geochemical changes. In a simple scenario with steep, V-shaped valley bottoms and relatively fine-grained sediment – where lag times of storage and recruitment are negligible (i.e. stream power is abundant and the system is supply limited) – both the bed and sediment waves could be symmetrical with respect to time and simple down-valley wave translation may pertain. In most cases, however, valley bottom sediment storage is substantial with large ADEs, periods of sediment remobilization are substantial, and recovery times are slower than initial response times.

SKEWED WAVES AND IMPLICATIONS TO PERSISTENCE OF SEDIMENTATION IMPACTS

In fluvial systems that have experienced a major ADE without substantial bed armoring and with abundant extra-thalweg storage, bed incision tends to precede the exhaustion of stored sediment. In this common case, channel-bed elevations return to pre-event levels prior to the return of total sediment flux to pre-event levels, because local sediment is recruited from bar, bank, and terrace alluvium. A right-skewed sediment-wave model accounts for this delayed recovery in sediment flux rates and contrasts with the symmetrical bed wave defined by bed incision (Figure 5). This conceptual model is based on extensive study of the type locale of Gilbert's wave model, conforms to the observed behavior of historical sediment fluxes, and accommodates long-term storage and reworking of sediment. It differentiates between bed lowering and sediment exhaustion, incor-

Fig. 5. Conceptual model of skewed sediment and bed waves in response to an aggradation–degradation episode (ADE). The sediment wave (time series of sediment fluxes) is strongly skewed to represent prolonged recruitment of stored sediment, implying a protracted period of recovery and floodplain residence time of legacy sediment. When introduced bed material is relatively fine and flows are narrowly confined, the bed may incise relatively rapidly resulting in a symmetrical bed wave. Where armoring is substantial or channels are free to migrate laterally, a skewed bed wave may result. Floods provide a stochastic series of triggering mechanisms that may initialize sediment remobilization events.

porates the stochastic nature of flood events as triggering mechanisms, and implies a more prolonged impact of legacy sediment than does the classic symmetrical wave model. At the three stream gauges studied by Gilbert, bed incision occurred relatively rapidly in spite of the persistence of enormous volumes of sediment adjacent to channels (Gilbert 1917; James et al. 2009). Vertical responses of the low-flow channel were not synchronous with the exhaustion of sediment from bar, floodplain, and terrace surfaces where deposition continued after the bed began to incise, and sediment recruitment from storage continues at the time of writing (James 1989, 1991, 1999, 2006; James et al. 2009). Initially, the relaxation of sediment flux was assumed to occur at an exponential decay rate assuming random processes of decreasing availability and recruitment (cf. Gomez 1991; Graf 1977; James 1989; Simon 1992). Lisle (2008) points out, however, that sediment availability may be non-uniform owing to the abandonment of channels by avulsions (James 1991), bed armoring (Lisle and Church 2002), and vegetative stabilization of banks (Simon et al. 2004). He suggests a gamma distribution as a more general probability density function for sediment storage depletion. The gamma distribution includes the exponential as a special case but is more flexible for varying conditions of sediment availability (Lisle 2008).

The skewed wave shown in Figure 5 allows for the possibility that bed waves may also be right-skewed in addition to the skewness of sediment waves. In fact, the three river-gauge sites that formed Gilbert's empirical foundation were not representative of the river as a whole (James et al. 2009). The Narrows was a narrow bedrock gorge, and the Marysville and Sacramento gauges were narrowly constricted by levees with channel dredging downstream. Levees south of Marysville completed between 1906 and 1909 constrained flood top widths to <600 m at the D Street gauge, a reduction of 3500 m (85%) from the broad flows 5 km upstream (Figure 6). In addition, historical maps of the lower Yuba and Feather Rivers and Gilbert's field notes indicate that a new channel was dredged below the Marysville gauge site ca. 1905 (James et al. 2009) (Figure 7). Extensive channelization by steam-powered dredges also was conducted on the Sacramento River below the river gauge at Sacramento (Thompson and Dutra 1983). Dredging below the gauges and levees that narrowed flood flows at the gauges encouraged the channel

Fig. 6. Levee spacings on the Yuba River narrow from 4100 m to 600 m at Marysville gauge (M). Narrow levee spacings on the Feather River were adopted to ensure that channels would self-scour and restore navigability (James et al. 2009). Base map from Google Earth.

incision shown in Gilbert's bed wave. Gilbert acknowledged the channel modifications but dismissed this as an important factor:

> "The mining débris disturbed the adjustment of streams by adding to their load. Reclamation by levees disturbs it by increasing the flood discharge in certain parts of the river channels." (Gilbert 1917: pp. 26–27).
>
> "At Marysville, where the Yuba joins the Feather, the record of low-water stages for the same period… shows a total lowering of 2.9 feet [0.9 m]. The sequence of levels is here less orderly than at the upper gaging station [at the Narrows], partly because the low-water stages for different years correspond to different discharges and partly because the local conditions have been modified by engineering works for the control of the rivers, but the two records are of the same general tenor. The maximum phase of the piedmont deposit has been passed, and the work of excavation has begun." (Gilbert 1917, p. 28).

While he was right to conclude that the maximum aggradation phases had passed, bed incision may have been much slower without channelization and levee constrictions. On other reaches of the lower Yuba and Feather Rivers the bed has not yet returned to pre-mining base levels (EDAW 2006; James et al. 2009). This contradicts the idea that a symmetrical bed wave passed through the lower river by simple translation. Instead, the timing of bed incision varied from place to place depending on local hydraulics, engineering works, and sediment characteristics. These complications do not invalidate the Gilbert wave concept or detract from its utility. They do, however, call for a more careful distinction between bed responses and sediment yields and a critical evaluation of large-scale symmetrical bed waves. Where sediment is fine and floodplain storage is substantial, systems that have experienced an ADE may be much slower to recover than is implied by a symmetrical wave. This is particularly important to evaluations of toxic sediment repositories, dam removal, and feasibility assessments of passive river restoration strategies.

RELATIONSHIPS BETWEEN SEDIMENT WAVES AND LEGACY SEDIMENT

Legacy sediment is primarily alluvium that was deposited following human disturbances in a watershed. The disturbance may have been in the form of deforestation, plowing agricultural land, mining, or other land-use changes. In North America and Australia, legacy sediments are ubiquitous and represent episodic erosion in response to the coloniza-

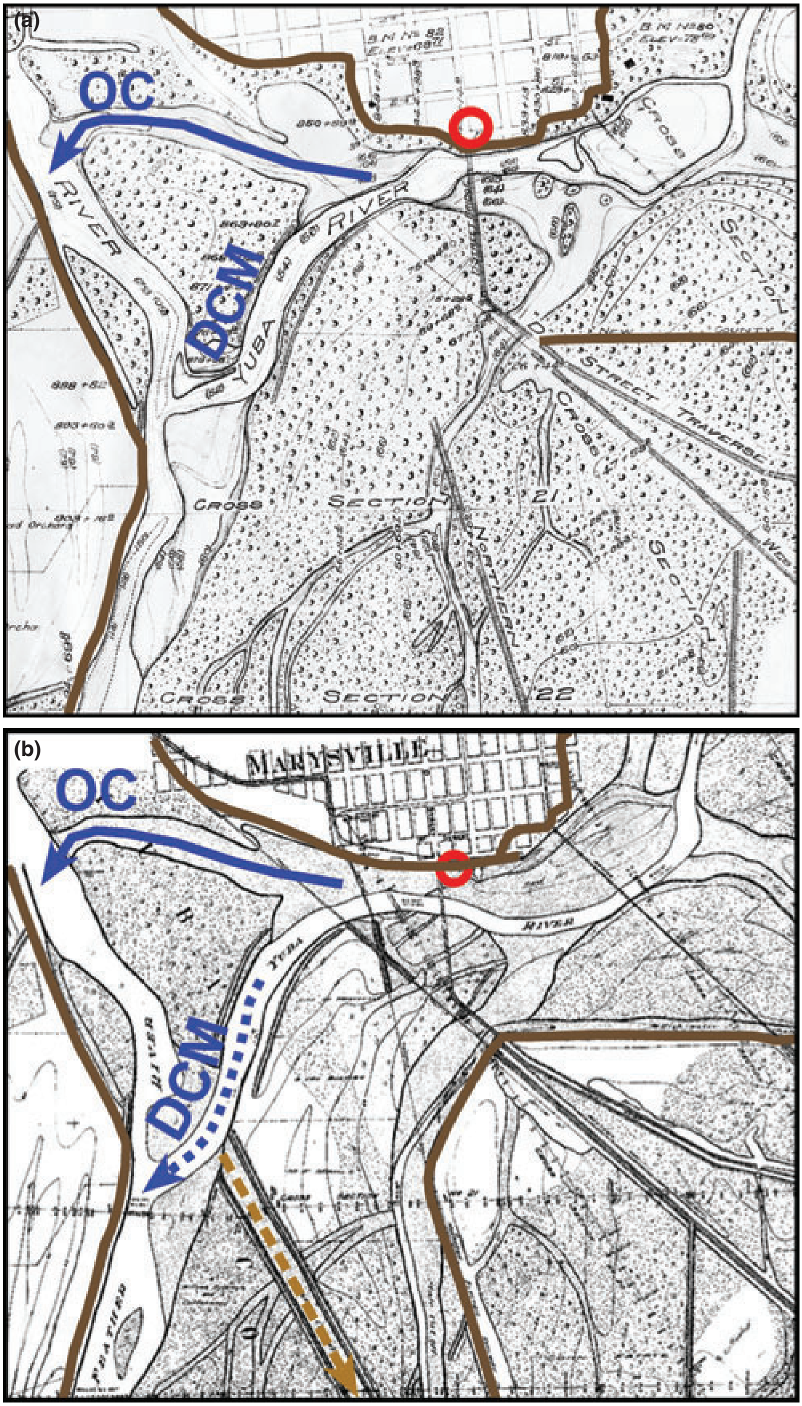

Fig. 7. Excerpts from 1906 to 1909 topographic survey maps. Annotations show USGS Marysville gauge at D Street bridge (red circle), old channel (OC) prior to 1905, and new dredged channel mouth (DCM) forming new confluence with Feather River. (a) 1906: south levee under construction; not yet completed past the gauge. (Source: CDC 1906) (b) 1909 after large 1907 flood: South levee completed; new dredged channel near confluence (below gauge) (Source: CDC 1912).

tion of land by European settlers who introduced Old World land-clearance technologies (e.g. steel tools and plows pulled by draft animals) and export economies. In these settings, legacy sediments are often described as post-settlement alluvium (PSA), which may cover entire floodplains and bury the pre-settlement soil with a thick mantle of relatively young stratified sediment (Griffiths 1979; Knox 1972, 1977, 2006). In Europe and Asia legacy sediment in a given watershed may have been generated by multiple ADEs including the Bronze Age, Roman occupation, Medieval, and later episodes resulting in a more complex anthropogenic alluvial stratigraphy (Dotterweich 2005; Macklin and Lewin 2008; Vanwalleghem et al. 2006).

Awareness of legacy sediment and legacy contaminants has grown in recent years owing to the implications of these deposits to lateral channel connectivity, sediment budgets, water quality, aquatic and riparian toxicity, and geomorphic theory. Legacy sediment left in numerous mill ponds dominates the floodplains of Brandywine River, Seneca Creek, Watts Branch, and Western Run in the mid-Atlantic Piedmont (Walter and Merritts 2008). Studies of these rivers were central to the development of mid-nineteenth century theories of fluvial geomorphology; especially theories of the processes by which meandering channels adjust (Leopold and Wolman 1957; Wolman and Leopold 1957). The realization that these floodplains went through a post-colonial metamorphosis in response to an ongoing ADE has caused a re-evaluation of the degree to which these channels represent 'natural' conditions (Montgomery 2008; Walter and Merritts 2008). Although this realization does not invalidate the fluvial theories developed in these watersheds, it does raise issues about what constitutes appropriate reference reaches for restoration projects.

Legacy sediment often contains contaminants that are important to assessing toxicity levels in aquatic systems, the chemical budgets of rivers and estuaries, identifying historical alluvium, and calibrating mixing models. Most studies of legacy contaminants have focused on metals in mining sediments (James et al. 2009; Knox 1987; Lecce and Pavlowsky 1997, 2001; Lecce et al. 2008; Leigh 1997; Marcus 1987, 1989; Martin 2000, 2004; Miller 1997; Wiener and Suchanek 2008), or pesticides and other organic chemicals (Lebeuf and Nunes 2005; Pereira and Hostettler 1993; Winger and Lasier 1998). Contaminants in legacy floodplain sediment can be an important secondary source of water pollution (Dennis et al. 2003; Hudson-Edwards et al. 2003; Turner et al. 2008).

MORPHODYNAMICS OF SEDIMENT SLUG PROPAGATION

Morphodynamics, the co-adjustment of form and process, is a growing field in geomorphology due to applications in numerical simulation studies. Much progress has been made on specifying the morphodynamics of smaller bed waves but secular waves lack wave coherence for such an analysis. Although Gilbert (1917) inferred wave translation and attenuation of waves based on the shapes of the at-a-station low-flow stage time–series plots at three locations in the Sacramento Valley, the waves had no discrete morphology – such as stoss or lee sides. In fact, Gilbert's waves were discontinuous in the longitudinal direction because they were initiated by deep deposits near the mountain mines (where much sediment remains today), passed through steep bedrock gorges of the Yuba, Bear, and North Fork American Rivers where sediment storage and bed aggradation was negligible, and reformed as thinner deposits in the piedmont at the Sacramento Valley margin (Figure 8). Wave propagation may be discontinuous through narrow zones lacking accommodation space or with high stream powers. The possibility of discontinu-

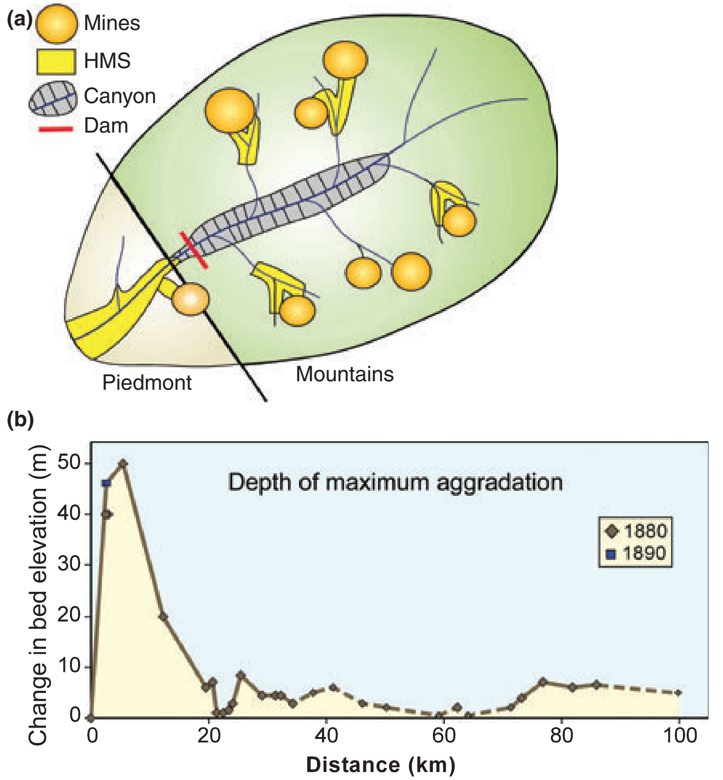

Fig. 8. Spatial heterogeneity of hydraulic mining sediment deposits indicating that Gilbertian bed waves were discontinuous in space. (a) Schematic map of deposits located near mines on ridge tops and in Piedmont in the Sacramento Valley. Little sediment persisted in steep, narrow gorges. (Adapted from James 2006). (b) Maximum historic changes in depths of deposits along the Bear River from mining districts through gorges to the piedmont. Data points for solid lines are from historical surveys (Heuer 1891; Whitney 1879) and field measurements by author. Dashed lines are estimates based on low sediment-storage potential and lack of field evidence of storage.

ous bed wave propagation through scoured canyons was recognized by Benda and Dunne (1997) and should be considered in interpreting the behavior of bed wave propagation based on observations from widely spaced cross sections.

Four types of transformation – or their combinations – are possible for bed waves: translation downstream, dispersion in place, interference at tributaries, and loss of mass by attrition (Benda and Dunne 1997). Research on how meso and macroslugs evolve has largely centered on whether the waves translate, disperse or both. Several studies of these features have not observed simple translation or have noted that that dispersion predominated (Hoffman and Gabet 2007; Knighton 1989; Lisle et al. 1997, 2001; Madej and Ozaki 1996; Roberts and Church 1986). For example, a 9-m-high dam formed by a landslide on the Navarro River in a steep, narrow, mountain valley demonstrated no measurable down-valley translation, although the profile flattened through time (Sutherland et al. 2002). Such behavior may be described by wave dispersion (Lisle et al. 2001; Sutherland et al. 2002). Mathematical models of wave translation and dispersion have been applied by a large number of studies (Kasai et al. 2004; Kelsey et al. 1987; Pickup et al. 1983; Weir 1983). Numerical simulation models have been developed for translation (Benda and Dunne 1997), translation with attenuation (Cao and Carling 2003), bores with a sharp front (Cao and Carling 2003; Needham 1990; Needham and Hey 1991), dispersion, or both translation and dispersion (Cui and Parker 2005; Cui et al. 2003a,b; Tassi et al. 2008). The Exner equation can be used to express changes in bed elevation with respect to time as a function of changes in sediment discharge in the downstream direction:

$$\partial\eta/\partial t = -(\partial q_s/\partial x)(1 - \lambda_p)^{-1} \quad (1)$$

where η is bed elevation, t is time, q_s is volumetric sediment discharge (flux) per unit stream width, and x is distance downstream, and λ_p is bed porosity (1 - λ_p = grain packing density) (Lisle 2008; Lisle et al. 1997; Parker 2009). This expresses bed wave amplitude as a response to changes in sediment discharge in the downstream direction owing to erosion or deposition. The Exner equation can be combined with a bed-load equation and the St. Venant equations for conservation of mass and momentum to derive an expression of bed wave evolution that incorporates both wave translation and dispersion (simplified from Lisle et al. 1997, 2001):

$$\partial\eta/\partial t = f(B)[\partial^2\eta/\partial x^2 + (\partial/\partial x(1 - F^2)) + \ldots] \quad (2)$$

where f(B) is an expression of bed-load transport, F is dimensionless Froude number, and the unspecified terms (ellipsis) are unsteady flow terms considered negligible for subcritical flows (F < 1). This approach incorporates the effects of grain size through the coupling with a bed-load transport model. It has been tested in flumes (Cui et al. 2003a) and field data from mountain rivers (Lisle et al. 2001; Sutherland et al. 2002). It was found that dispersion dominates in mountain stream environments with coarse sediment but that translation can be important when wave grain sizes are substantially finer than the pre-existing bed material (Cui et al. 2003a,b). The validity of the mathematics expressing bed-wave dispersion has been debated (Cao and Carling 2003, 2005; Cui et al. 2005). These issues go beyond the scope of this article, however, for which the focus is on secular bed waves.

Modeling the morphodynamics of bed waves will ultimately need to address complexities of multiple grain sizes and make distinctions between coarse-grained waves generated at a point (e.g. tributary junctions) and relatively fine-grained sediment generated from multiple sources. The transformations that accompany bed evolution during passage of a bed wave may involve temporal variations in bed material textures. Episodic introductions of sediment that initiate waves usually involve a variety of grain sizes – often relatively fine-grained material (Lisle 2008), which is preferentially transported. Coarse material left as lag deposits may armor bedforms and interact with geomorphic and sediment redistribution processes (Brummer and Montgomery 2006). Moreover, as proportions of grain sizes change, the competence of flows to erode the bed changes in a complex manner with interactions between grain-size mixtures. For example, sand contents between 10% and 30% in gravel-bed rivers enhance gravel transport (Wilcock et al. 2001), but sand and gravel may form patches rather than mix in the bed (Paola and Seal 1995). As sand is winnowed away, gravel transport may be enhanced and the critical grain diameter that can be transported by a given flow may decrease (Gran et al. 2006).

Hydraulic myopia versus Gilbert's vision of integrated watershed processes

The reluctance of the scientific and engineering communities to question the direct linear relationship between bed elevations and sediment fluxes – in spite of serious potential inconsistencies – represents a strong, persistent bias towards reach-scale and short-term river analyses. This 'hydraulic myopia' is deeply embedded in water science and is reflected by the disparity between the long history of hydraulic knowledge versus the young history of hydrologic science. The science of hydraulics can be traced back several millennia to the construction of levees, irrigation canals, and flood-control works of early irrigation societies (Rouse and Ince 1957). In contrast, the science of hydrology is <500 years old (Biswas 1970). The basic premise of the hydrologic cycle was considered blasphemous when Pallisy (1580) argued for rainfall as the source of rivers, and Perrault (1674) and Mariotte (1686) presented evidence for rain-fed rivers. Hydraulics can be practiced at the local scale without an understanding of basin-wide processes, but hydrologic understanding ultimately requires a spatial comprehension of watersheds. Overcoming the historically dominant hydraulic myopia remains a challenge to the adoption of modern approaches to integrated watershed management. Many hydrologists overlook the fact that that Gilbert's (1917) treatise was a pioneering effort on integrated river basin methods.

STANDING ON THE SHOULDERS OF A GIANT

Gilbert (1917) was arguably the most brilliant geologist of the late-nineteenth and early-twentieth century (Figure 9). To some geomorphologists, a critique of Gilbert's ideas would be regarded as a form of scientific blasphemy. Gilbert ushered in the modern era of quantitative process geomorphology and generated a shining beacon for its practice. His publications included brilliant studies in many of the systematic areas of geomorphology including fluvial, glacial, coastal, tectonic, and planetary geomorphology, in addition to important contributions to geophysics, hydrology, and hydraulics (Pyne 1980). His writings were logically reasoned and his theories were consistently based on a sound empirical foundation. In fact, Gilbert's methods ultimately inspired a post-Davisian revolution in geomorphic thought (Baker and Pyne 1978; Chorley et al. 1964; Tinkler 1985; Yochelson 1980) that led to the geomorphic emphasis on physical processes, although the typical characterization of Gilbert's work as directly antithetical to Davisian geomorphology may be oversimplified (Sack 1991). Modern subfields of geomorphology such as fluvial geomorphology, landscape evolution modeling, and morphodynamics owe their existence to this philosophical basis. Beyond his unparalleled accomplishments in science, in his youth, Gilbert participated in the exploration of the West, including Powell's navigation of the Grand Canyon, and he later supported the conservation movement. Gilbert performed several administrative roles in Washington, was a founding member of the Association of American Geographers, and served as its president in 1908. The clarifications of sediment wave theory presented here should, in no way, diminish the immense stature or scientific genius of Gilbert as a historic figure in the annals of geological science.

Gilbert's (1917) treatise was so far ahead of its time that many modern river scientists still fail to recognize the important contribution that it made to principles of integrated watershed management and sediment budgeting. Gilbert quantitatively estimated all substantial sources of sediment production in several large basins, the Feather – including the Yuba and Bear Rivers – and the American Rivers. Anthropogenic sediment was tracked from the mountain mining districts, down through the steep narrow Sierra canyons, across the flat alluvial Sacramento Valley, through the inland Delta region and San Francisco Bay, and ultimately through the Golden Gate where it formed subaqueous dunes on the shelf. By tracking sediment from source to fate, Gilbert used a Lagrangian

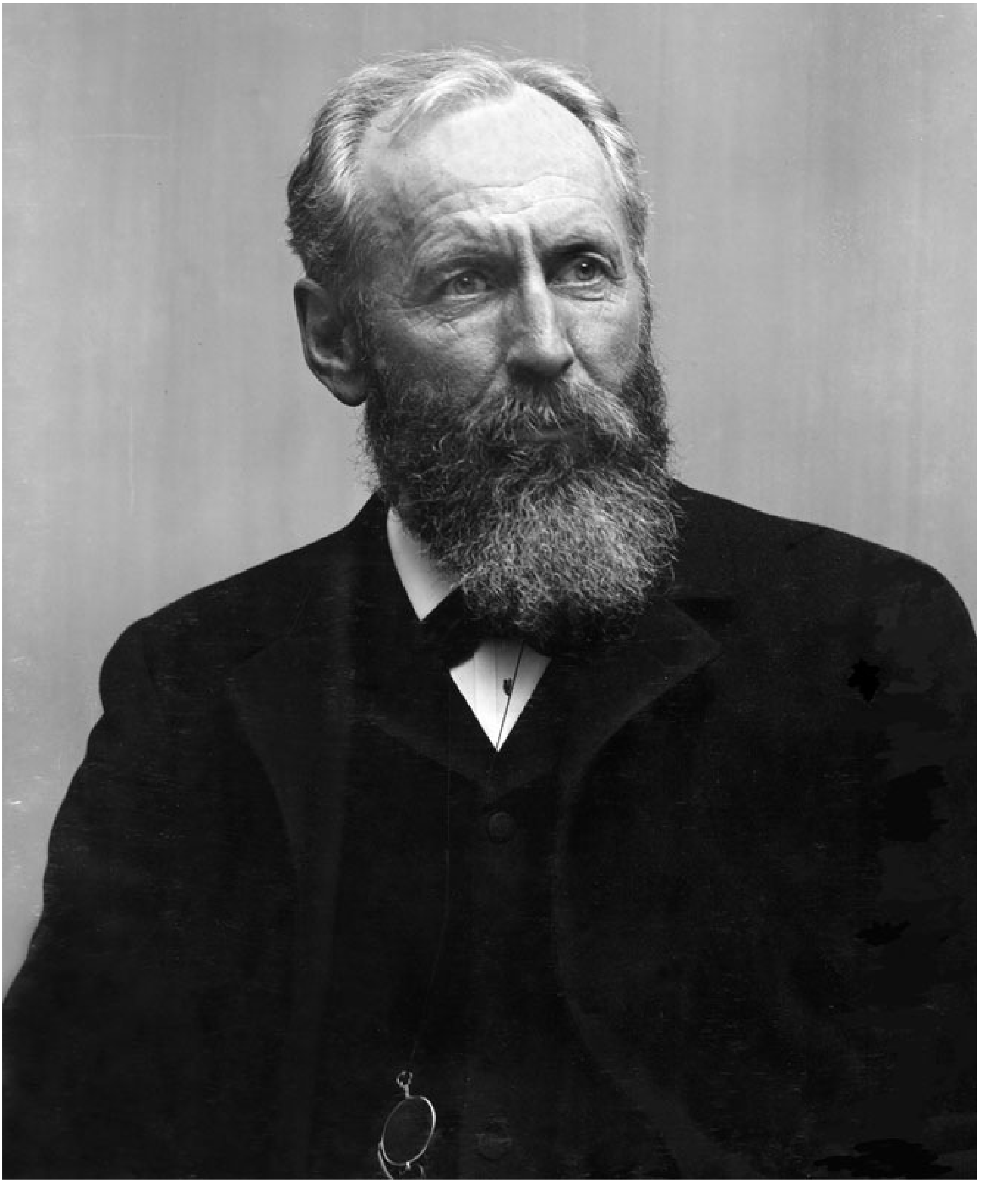

Fig. 9. Grove Karl Gilbert ca. 1910. US Geological Survey Photographic Library Portraits Collection 129 (port0129).

frame of reference and promoted the view of longitudinal connectivity that is essential to understanding river systems and integrated components of their watersheds. Gilbert's watershed perspective of is an important precursor to spatially distributed modeling. Modern simulation models of runoff and sediment generation are increasingly spatially distributed; that is, they employ physical characterizations that are geographical registered to specific locations. Modern science has not adequately recognized Gilbert's important role in pioneering the spatial view of river processes in an integrated watershed approach, or in developing quantitative sediment budgeting. Ironically, the focus of many river scientists has been on Gilbert's wave theory, which was based on evidence derived from three stream gauges; that is an at-a-station frame of reference.

Conclusions

The initial sediment waves defined by Gilbert were described as both bed elevation changes and changes in sediment flux. By using a sediment hydrograph analogy to equate bed elevation changes to sediment transport rates, Gilbert overemphasized vertical bed changes as the primary fluvial adjustment to changing sediment loads. To distinguish between bed and sediment flux responses to episodic sediment events, large transient bed elevation changes can be referred to as bed waves and the associated sediment flux as a sediment wave. Gilbert's definitive sediment waves were in response to a major ADE that resulted in irreversible channel and floodplain metamorphoses. Smaller fluxes may be referred to as meso or macroslugs or pulses and the associated bedforms (10^1–10^3 m longitudinally) can be referred to by their specific names (braid bars, unit bars, bar complexes, etc.). Large-scale waves are often composed of finer-grained sediment than the armored bed material they cover. With substantial storage of this alluvium, a sediment wave is likely to be right-skewed as high fluxes are maintained by recruitment of stored alluvium. Legacy sediment left by secular anthropogenic waves is ubiquitous in large river valleys and should be recognized as the vestiges of the late phase of an ongoing ADE. Following an episodic sedimentation event, the timing of sediment fluxes depends on local complexities of sediment storage potential and recruitment on valley bottoms. Specific responses will vary between watersheds so no one simple one-dimensional linear model will can provide a universal prediction. However, the sediment wave model provides an important conceptual starting point for watershed management and planning.

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