# Bed waves at the basin scale: implications for river management and restoration

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Abstract

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An extensive literature about fluvial sediment waves, slugs or pulses has emerged in the past 20 years. The concept has been useful in many respects, but has been applied to diverse phenomena using a variety of definitions. Moreover, inferred linkages between channel-bed changes and sediment loads are often not justifiable. This paper reviews concepts of large fluvial sediment waves at scales extending to several tens of kilometres. It points out constraints on the inferences that can be made about sediment loads based on changes in channel-bed elevation at this scale where channel sediment interacts with storage in floodplain and terrace deposits. The type area of G. K. Gilbert's initial sediment-wave concept is re-examined to show that neither wave translation nor dispersion occurred in the simple manner commonly assumed. Channel aggradation and return to graded conditions provide an alternative theory explaining Gilbert's observed bed-elevation changes. Recognizing the evidence and implications of the former passage of a large-scale bed wave is essential to the accurate diagnosis of catchment conditions and the adoption of appropriate river restoration goals or methods. Sediment loads, water quality, channel morphologic stability and aquatic ecosystems often reflect changes in sediment storage long after the channel bed has returned to grade. Copyright © 2006 John Wiley & Sons, Ltd.

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# Introduction

This paper examines semantic and conceptual issues associated with large-scale fluvial bed waves. It briefly reviews definitions commonly applied to these waves and the validity of using changes in bed elevation to infer sediment loads. Studies of channel-bed elevation changes often make assumptions about sediment loads that may be inappropriate, particularly for sedimentation events at the large basin scale. This limitation is elucidated by a re-evaluation of the bed wave generated in the Sierra Nevada of California where Gilbert (1917) described the original sediment-wave concept. This sedimentation episode differed in fundamental ways from smaller-scale waves and from commonly held concepts. After the passage of a bed wave, the production of sediment and pollutants from alluvium left in storage can be persistent and has great bearing on water quality, non-point-source sediment loads, channel morphology and aquatic habitat. These effects and their causes need to be fully recognized as vestiges of a past episodic sedimentation event for appropriate river management and restoration schemes.

In many parts of the world, perturbations caused by deforestation, intensive agriculture, mining, fire, road building or urbanization have resulted in episodic sedimentation that caused channel aggradation or floodplain burial. In some cases, such as the Waipaoa River in New Zealand, this is an ongoing process (Gomez *et al.*, 1998). In other cases, such as the Southeastern Piedmont of the USA, accelerated aggradation ceased when erosive land-use was reduced (Trimble, 1974). Such historical perturbations may have disrupted channel quasi-equilibrium conditions and initiated bed waves. Channels formerly bounded by broad, low floodplains may now be narrowly confined by high terraces. Attempts to return a river to pre-disturbance conditions require that historical characteristics and trends be accurately known. This includes a basin-wide comprehension of the spatial relationships between sediment storage components and their connectivity, as well as an understanding of the dynamics of the system on a historical timescale. Recognition of

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sediment buffers and barriers such as local base-level controls is an important first step in understanding fluvial adjustments to anthropogenic sedimentation (Brierly and Fryirs, 1998; Fryirs and Brierly, 2001). Restoration efforts may be ineffective if high rates of sediment production from historic alluvium are not recognized. If sediment loads are presently elevated due to former disturbances, they may decrease in the future causing morphological adjustments to the channel.

# **Bed Waves versus Sediment Waves**

A first step in understanding the nature of sediment waves is to differentiate between widely varying concepts and processes that may be referred to as sediment waves. In addition, a critical evaluation is needed of assumptions often made about the relationship between sediment loads and channel-bed elevations.

## G. K. Gilbert's initial concept: Gilbert waves

The concept of a sediment wave was first presented by G. K. Gilbert (1917) in a study of the production and fate of hydraulic gold-mining tailings introduced in California during the late 19th century. The empirical basis of Gilbert's initial sediment-wave concept was drawn from changes in at-a-station low-flow river stages as a proxy for channelbed elevations. As noted by Lisle *et al.* (2001), many sediment wave studies have been influenced to some degree by Gilbert's seminal work, so it is constructive to begin with that original thesis: 'The downstream movement of the great body of débris from the Yuba is thus analogous to the downstream movement of a great body of storm water, the apex of the flood traveling in the direction of the current. The apex of the débris flood, leaving the mountain canyon in about the year 1900 and the mouth of the Yuba River in about 1905' (Gilbert, 1917, p. 30).

This quote has been widely repeated, often in concert with Gilbert's time-series diagrams of channel low-flow stage elevation at three gauges in the Sacramento Valley: two on the lower Yuba River and one on the Sacramento River (Figure 1). The stage data indicate channel aggradation between 4 and almost 6 m on the lower Sacramento and Yuba Rivers, respectively (Figure 2). Degradation had begun by 1913 and channels have now returned to pre-mining levels. Gilbert quantified the volume of hydraulic-mining sediment produced in the Yuba, Bear and North Fork American Rivers to be c. 2·1 Gt in 31 years. It overwhelmed channel capacities causing aggradation.

No low-flow stage data are available between 1850 and 1873, so a smooth rising limb of the wave has customarily been assumed by linear interpolation. However, most mining sediment actually remained in small mountain tributaries throughout the 1850s until it was suddenly introduced to Sacramento Valley rivers by record floods in water year 1862: 'No one appears to have observed any considerable change in the bed or slopes of the streams until the great



Figure 1. Map of Sierra Nevada foothills, the type area of the Gilbert (1917) wave model shown in Figure 2. The three stream gauges that Gilbert used are shown. The oval area locates the upper Bear River long profile shown in Figure 8. This figure is available in colour online at www.interscience.wiley.com/journal/espl



**Figure 2.** Time-series plots of low-flow stages at three stream gauges in the lower Sacramento Valley. Data from Gilbert (1917) with exception of step at 1862 which is based on Mendell's (1881) observation of little sediment delivered prior to 1862 floods (see text). This figure is available in colour online at www.interscience.wiley.com/journal/espl

flood of 1862 had receded. Placer mining had been prosecuted by thousands of miners for thirteen years, and the gulches and water courses of the foot-hills had been receiving deposits of gravel and sand all these years . . . In all these years there had been no great flood. The prolonged and excessive high water of 1862 brought down such masses of material that they could not escape observation' (Mendell, 1881, p. 6). Hence, the rising limb of the Marysville and Sacramento bed waves shown in Gilbert's diagrams may have commenced with a sudden rise in 1862 (Figure 2).

In spite of missing details in the early record, the low-flow stage data accurately document substantial changes in channel-bed elevations in response to mining sediment production upstream. Gilbert (1917) predicted that the waves would pass Marysville and Sacramento by the mid-20th century, and subsequent work has confirmed that low-flow stages at the Sacramento and Marysville gauges returned to pre-mining levels by mid-century (Graves and Eliab, 1977). Flow stages at several other stream gauges in the region progressively lowered until the mid-20th century and became relatively stable thereafter (James, 1991, 1997; National Research Council, 1995). Large-scale bed waves resulting from episodic sedimentation events that overwhelm channels will henceforth be referred to as 'Gilbert waves'. These waves were not uncommon in recent history and can be identified in association with sedimentation induced by major landslides, mining, timbering or agricultural clearance.

## Modern concepts of sediment waves and bed waves

Channel-bed elevations have been the common basis for most sediment waves, although an alternative usage of sediment wave should be identified. Changes through time in at-a-station suspended sediment concentrations, better known as sediment hydrographs or sedigraphs, are occasionally referred to as sediment waves (Bull, 1997) due to similarities with the flood waves that they are often compared with. To avoid confusion with the older and more prevalent sediment waves. Sediment hydrographs are not considered further here as they represent an unrelated phenomenon at a relatively short timescale.

Systematic changes in channel-bed elevations that form an aggradation-degradation cycle have been referred to as sediment waves, bed waves, bed-material waves, sediment slugs and sediment pulses. Several comprehensive reviews of these concepts and relationships between bed elevation and sediment loads have been presented (Meade, 1985; Gomez *et al.*, 1989; Hoey, 1992; Nicholas *et al.*, 1995). Bed waves have been distinguished on the basis of spatial scale, temporal scale, sediment source, sediment storage processes, grain size, and by mode of wave propagation (Table I). In this paper, changes in bed elevation during aggradation-degradation cycles will be referred to as 'bed waves' to emphasize the bed-elevation changes upon which they are defined and to de-emphasize inferred changes in sediment loads that are less well established. Gilbert's (1917) wave model is based on the measurement of bed elevations, so it is best referred to as a bed wave rather than a sediment loads and bed elevations. Some studies (Nicholas *et al.*, 1995) prefer to describe these changes as 'sediment slugs' or 'sediment pulses' where transport of material as a coherent wave has not been adequately established. Some studies refer to 'bed-material waves' that imply a direct relationship between bed elevation and bed-material transport rates. Where this relationship is valid,

#### Table I. Systems of bed wave classifications

Classification	Reference
Scale (two overlapping classification systems based on magnitude) I. By spatial scale of waves mesoforms (individual bedforms): 10 <sup>-1</sup> –10 <sup>2</sup> m macroforms or macroslugs (unit or complex bars): 10 <sup>1</sup> –10 <sup>3</sup> m megaforms or megaslugs (bar assemblages): >10 <sup>3</sup> m superslugs or Gilbert waves (basin-scale with valley-floor adjustments)	Hoey (1992), Nicholas <i>et al.</i> (1995), Wathen and Hoey (1998)
2. By temporal scale of wave persistence annual or seasonal periodicities large flood responses:10 <sup>1</sup> -10 <sup>2</sup> years	Nicholas et al. (1995) Meade (1985)
catastrophic sedimentation: 10 <sup>2</sup> –10 <sup>3</sup> years	Gilbert (1917)
Sediment Source and Fate (two overlapping classification systems based on source or extent of sediment)	
<ol> <li>By sediment source endogenous waves from within channel (autopulses; endoslugs) exception waves from catchment sources (allopulses; exceptions)</li> </ol>	Hoey (1992), Nicholas et al. (1995), Wathen and Hoey (1998)
2. By sediment storage processes within-channel storage only	Nicholas et al. (1995)
overbank deposition with longterm floodplain storage	This study
<b>Sediment Character</b> (based on grain-size) wave material coarser than bed wave material similar to bed wave material finer than bed	Cui et al. (2003)
Wave Propagation Process	
Translation	Lisle et al. (2001), Cui et al. (2003)
Dispersion Migrating inflection point between aggrading and degrading zones	Lisle et <i>al.</i> (2001), Cui et <i>al.</i> (2003) This study

referring to bed waves as passage of a bed-material wave may be appropriate. Bed-material transport is greater than bed-load transport because it includes fine material that is not sampled by conventional bed-load samplers (Ashmore and Church, 1998).

## Translation versus dispersion

The mode of bed-wave propagation or morphologic transformation is generally assumed to be by wave translation, dispersion, or a combination of the two (Lisle *et al.*, 2001). Wave translation is the movement of the wave form down-valley without deformation or attenuation, and is often assumed to be the dominant means of wave movement. Bed-load transport in the East Fork River, Wyoming, was thoroughly and quantitatively described as small translating waves (Meade *et al.*, 1981; Meade, 1985; Weir, 1983). Wave translation is often inferred from Gilbert's wave data, although a rise and fall in channel-bed elevations observed at-a-station does not necessarily indicate passage of a wave by translation, as is often assumed. Wave dispersion, the flattening and spreading of a bed wave *in situ*, can produce a similar rise and fall of the bed through time (Lisle *et al.*, 2001). The importance of dispersion in gravel-bed streams was recognized early on by Pickup *et al.* (1983) who described dispersion as being encouraged by differences in particle velocities. Several recent studies have concluded that dispersion predominates over translation in gravel-bed rivers (Lisle *et al.*, 2001; Cui *et al.*, 2003). Lancaster *et al.* (2001) identified deposition zones in mountain streams that damp out sediment pulses and preclude translation of bed waves through the reaches.

Experimental work comparing dispersion and translation of bed waves is largely based on observations in flumes or small channels, and generally neglects overbank storage and re-release. Under these conditions wave evolution in gravel-bed channels is almost exclusively by dispersion (Lisle *et al.*, 2001). Combinations of dispersion with translation may be common in sand-bed rivers (Cui *et al.*, 2003). A one-dimensional numeric model for bed-wave elevation changes has been presented as a function of three terms: bed-load transport, rate of dispersion, and rate of translation (Lisle *et al.*, 2001). The dispersion term is expressed by the rate of change in local bed slope and postulates degradation near the apex and aggradation away from the apex where depth is increasing or decreasing most rapidly



**Figure 3.** Models of bed-wave motion (Lisle et al., 2001). Top: wave translation based on Froude number (F) where x is distance and h is bed elevation. Translation is negligible at high F (common in steep gravel-bed rivers). Bottom: wave dispersion based on second derivative of bed elevation in respect to downstream distance. This figure is available in colour online at www.interscience. wiley.com/journal/espl

(Figure 3). The wave translation term is a function of the Froude number (F). Under subcritical flows (F < 1), scour occurs on the upstream side of the wave apex where flows shallow and accelerate and F increases. Conversely, deposition occurs downstream of the apex. Translation ceases as flows approach critical (F = 1) (Lisle *et al.*, 2001).

#### Stream grade as a wave-propagation mechanism

Channel aggradation followed by re-establishment of channel grade provides an alternative mechanism that can produce the bed-elevation changes observed as Gilbert waves. Alluvial channel longitudinal profiles tend towards a graded condition in which slopes are delicately adjusted to provide the energy needed to carry all of the supplied load of sediment given the available water discharge (Mackin, 1948). When abundant sediment is introduced in the headwaters, aggradation occurs and the profile develops greater concavity in its upper reaches (Time 2 in Figure 4A). When sediment production decreases, channel incision begins in the high, steep reaches and continues until the slope is no greater than needed to carry the reduced load. In the case of headwater sediment sources, degradation will begin there while aggradation continues downstream (Time 3). With continued degradation, the inflection point where degradation shifts to aggradation migrates downstream (from A to B; Time 4). If at-a-station bed-elevation data are collected through time at various points (I, II, III and IV), the time series will show the signature rise and fall of a bed wave at a given location (Figure 4B). The wave apex will be highest and arrive first in the headwaters and will be lower and arrive later downstream. These bed waves, therefore, represent progressive bed aggradation until the inflection point of the regrading system approaches and degradation begins as it passes through the site.

The concept of stream grade accounts for adjustments between water, sediment and gradient. It subsumes interactions between storage outside of the low-flow channel and changes to local hydraulics. Changes in bed elevations may be encouraged by hydraulic changes in the reach; e.g. if incision creates a narrow confined channel. Disruptions in channel morphology are often associated with deviations in sediment transport capacities, with aggrading reaches generating less transport than predicted by transport-capacity calculations (Hoey and Sutherland, 1991; Nicholas *et al.*, 1995). Channel-bed changes associated with longitudinal profile adjustments may have been responsible for Gilbert's (1917) original sediment-wave concept and represent the passage of a bed wave. A wave can be defined as 'something that swells and dies away' (Merriam-Webster 9th Collegiate Dictionary). The rise and fall of the bed in response to longitudinal profile changes during a broad catchment-scale aggradation–degradation cycle fits this description even if it is not caused by the passage of a coherent wave of sediment.

## Relations between bed waves and sediment loads

Various aspects of sediment transport are sometimes inferred from channel-bed changes. The assumption that changes in bed elevation are proportional to total sediment load is generally flawed, however, unless important constraints can be assured. Bed elevations should only be used to estimate bed-material loads where sediment is contained within the channel. Overbank sediment storage and production may be independent of and out of phase with within-channel



**Figure 4.** Large-scale adjustments of channel grade can generate at-a-station bed-elevation changes identical to a Gilbert wave. (A) Ideal longitudinal profiles showing aggradation (Times I and 2) followed by degradation beginning in upper reaches and shifting downstream (Times 3 and 4). Maximum elevation of channel bed at a given point occurs when inflection point (A and B) passes and bed shifts from aggradation to degradation. Dashed lines, buried profiles; dotted lines, terraces; vertical lines, at-a-station bed-elevation stations (I to IV). (B) Changes in at-a-station bed elevations resulting from aggradation–degradation sequence. Rise and fall of bed describes passage of bed wave with attenuation downstream.

processes. An example of appropriate qualifying constraints in the use of the bed-wave concept is to limit inferences drawn from bed elevations to the transport of bed material within channels of gravel-bed rivers where exchanges between channels and their floodplains are negligible (Lisle *et al.*, 2001).

The erosion of sediment stored on floodplains and in terraces typically persists long after the channel has reestablished grade. During the aggrading phase of an overbank sedimentation episode, the channel may cover the entire valley bottom. During the degrading phase, however, incision is generally concentrated within the channel, and floodplain scour or planation are much slower processes. Moreover, bed incision is often accelerated due to constrictions by the historical terraces or by levees and bank protection that alter local hydraulics and retard floodplain reworking.

Ashmore and Church (1998) outline the history and intricacies of using channel-bed morphology to estimate bed-material transport. They use morphologic measurements in an inverse approach to calculating transport rates. Bed-material waves describe changes in bed elevation where bed-material transport is closely linked to bed elevation. They note that in the rivers studied, little bed material is lost to or derived from storage outside the low-flow channel. The propensity for long-term sediment storage on floodplains is often demonstrated by sediment delivery ratios (SDR) less than one and the decrease in SDR with drainage area (Walling, 1983). This decreasing trend, largely interpreted as the result of floodplain storage, supports the proposition that episodic bed waves that inundate valley bottoms will experience down-valley attenuation and will later contribute sediment after the bed wave has passed. Church et al. (1989), however, have demonstrated notable exceptions to the long-held SDR concept in mountain rivers in British Columbia where narrow valley bottoms restrict storage. In fact, they show a prevalence of SDRs greater than one that increase down-valley, and they attribute this increase to sediment recruitment from outwash terraces that constrict the mountain rivers. Under these special circumstances, the inverse method of using bed waves to infer bed-material loads may be feasible. Scale may also be a factor in the validity of assuming that sediment is contained within the channel as opposed to interacting with the floodplain (M. Church, personal communication). At short timescales or small geographic scales confined to a selected narrow channel reach, within-channel processes may dominate and floodplain storage may be assumed to be negligible. At the basin scale over long periods, however, floodplain storage is substantial during major sedimentation events.

Most bed-wave studies have been concerned with sand- or gravel-bedded flumes or streams at the reach or smaller scale. Moreover, most studies have been conducted under controlled conditions with no interactions between sediment transport and storage outside of the channel. At small scales under controlled, within-channel conditions, it may be possible to isolate direct linkages between bed elevation (bed forms) and bed load or bed-material transport rates (Gomez *et al.*, 1989). Where these special conditions are not met, however, such linkages should not be assumed. The assumption that total sediment loads are proportional to bed-elevation changes is not generally valid for basin-scale events that involve substantial amounts of overbank sedimentation. At this scale, the assumption of a direct relation-ship between sediment loads and bed elevations should be rejected unless it can be independently confirmed.

This paper concentrates on basin-scale bed waves that involve a substantial amount of overbank sedimentation. These Gilbert waves persist for long distances downstream, involve a massive amount of mixed sediment, and are not confined to within the channel. Long-term responses to such an event may be driven by sediment production from floodplain and terrace deposits. A few field studies have documented wave dispersion on large scales. For example, Sutherland *et al.* (2002) documented a landslide-dam failure that generated a bed wave in a gravel-bed river of northern California. They observed topographic changes 1.5 to 4.5 km downstream of the dam site for four years. They tested dispersion versus translation hypotheses based on field observations and concluded that the wave dispersed with no measurable translation. For episodic sedimentation events extending over several tens of kilometres, however, it is not clear whether or not sediment tends to be transported as a coherent wave and, if so, what is the nature of such a wave? To this end, re-examination of the Gilbert waves is of considerable interest.

# A Modern View of Gilbert Waves

The classic bed waves described by Gilbert (1917) should not be assumed to have been simple gravel waves generated by a discrete event and translated downstream in coherent wave forms. In fact, the sedimentation event involved a wide range of particle sizes introduced from many locations over a period of 31 years from 1853 to 1884 in several large catchments. The Gilbert waves were vastly larger and more complex and were dimensionally different from most modern wave studies (Table II). The Gilbert waves consisted of mixtures of particle sizes that varied through time and space, ranging from boulders down to large amounts of sand, silt and clay. These materials were quickly sorted and silts and clays were largely washed downstream to the Sacramento Valley. As production was on-going, however, deposits in the mountains include cobble channel lags inset into sand and gravel strata. Deposits in the valley range from gravels along the valley margin to silts and clays in the lower river.

While Gilbert waves may be symmetric in time, this does not mean sediment loads have returned to pre-event levels. Sediment loads and geomorphic impacts of hydraulic gold-mining have been far more persistent than would be predicted by the form of the bed-wave. Time series of total sediment loads following a large-scale sedimentation event can be described by a positively skewed distribution (James, 1999). Hence, in the type area where the sediment-wave concept was conceived, sediment wave theory seriously underestimates the time required for sediment stabilization, yield reductions and system recovery. This persistent response has important implications for river restoration. If the return of the bed to pre-sedimentation base levels is mistaken for a return to background sediment loadings, then the nature of pre-disturbance conditions may be misconstrued.

#### Gilbert waves are not dispersed or translated

Neither wave translation nor dispersion is compatible with the field evidence of how Gilbert bed waves were propagated in the type area. Wave translation represents a relatively short but pronounced rise in bed elevation followed by rapid relaxation, while wave dispersion prolongs moderately high bed elevations and extends them both upstream and downstream (Lisle *et al.*, 2001). Topographic conditions inhibited propagation of coherent waves from the mines to

#### Table II. Complexities of Gilbert's (1917) mining-sediment wave

I. Sediment production was extensive in time and space.

<sup>2.</sup> Wave dimensions were expressed as a function of time, not as a function of distance.

<sup>3.</sup> Grain-size distributions were mixed across a broad range.

<sup>4.</sup> Two major storage zones (upland and piedmont) are connected by a canyon with highly efficient sediment transport and little storage potential.

<sup>5.</sup> Protracted storage and remobilization of historical alluvium continues long after passage of the bed wave.

<sup>6.</sup> Propagation of maximum bed elevation was not by simple translation, but attenuated down-valley.



**Figure 5.** View down South Yuba River at Purdon Bridge. Many hydraulic mines and sediment storage sites are located on the flat upland surface of San Juan Ridge (middle distance) *c*. 300 m above the channel. Once sediment reached hanging tributaries at the ravine edge, storage was negligible until it reached the flat piedmont area of Sacramento Valley. This figure is available in colour online at www.interscience.wiley.com/journal/espl

the piedmont. Between the mountainous mining districts and the Sacramento Valley, main channels of the American, Bear and Yuba Rivers pass through deep canyons with low storage potential (Figure 5). Two categories of storage can be identified in these basins: local upland storage near the mines and downstream storage in low-gradient piedmont reaches (Figure 6). These canyons represent a high degree of connectivity; i.e. the efficiency by which sediment is transferred from one zone of the basin to another (Hooke, 2003). This connectivity is encouraged by relatively fine-grained mining sediment textures and high stream powers of flows through the canyons, and is evidenced by large volumes of mining sediment deposited downstream during the mining period. When channel surveys were conducted in 1890, little sediment was found in the main channels although vast deposits were noted in both the upper tributaries and piedmont deposits in Sacramento Valley. Once historical sediment reached the steep, narrow canyons, it was quickly delivered to the piedmont.



Figure 6. Idealized map of multiple sediment production and upland storage sites, gorge-like canyons, and large storage in lowgradient piedmont reaches at east margin of Sacramento Valley. This figure is available in colour online at www.interscience.wiley.com/ journal/espl



**Figure 7.** Schematic diagram (not to scale) of maximum terrace heights representing maximum bed-wave crest heights above predisturbance level. Decrease downstream rules out simple wave translation. Little sediment storage in canyons. Dashed line, profile in Gilbert's (1917) time with downstream shift of piedmont inflection point (open circle). Cn, Canyon; MD, Mining Districts; Pd, Piedmont. This figure is available in colour online at www.interscience.wiley.com/journal/espl

These topographic complexities in the spatial distribution of sediment production and delivery are difficult to reconcile with the notion of coherent waves being translated or dispersed from the mines down to the Sacramento Valley. Terraces of mining sediment stand more than 20 m above the modern channel in some mountain areas of the mines, and this represents the minimum wave amplitude in the mining districts. On entering the canyons, bed-wave amplitudes were clipped to a very small proportion of their heights. Moreover, wave translation was suppressed by high Froude numbers. Where channels emerged from the Sierra Nevada canyons out onto the upper piedmont, channels widened, deep aggradation occurred, and bed-wave amplitudes apparently increased to 4-6 m (Figure 2).

Gilbert's (1917) waves did not move by simple translation because the apex of the wave was much lower downstream in the Sacramento Valley than in the mountains (Figure 7). Furthermore, the bed waves have not yet completely exited all of the mountain catchments because channel beds in many rivers of the mining districts remain well above pre-mining elevations more than 120 years after mining ceased. Although Gilbert clearly implied wave translation through his analogy to a water wave, he also recognized attenuation of maximum bed elevations downstream: 'It travels in a wave, and the wave grows longer and flatter as it goes' (Gilbert, 1917, p. 31). Locally, where introduction of hydraulic mining sediment-built tailings fans dammed the main river, dispersion may have been involved as deposition extended a few hundred metres upstream (James, 2004). These dams had breached by 1890, and the upstream deposition is insignificant compared to rapid transport 50 to 70 km downstream to the piedmont. At the basin scale, sediment transport was dominantly down-valley and did not take the form of a single coherent wave.

The Gilbert wave prototypes are based on dimensions and processes that are fundamentally different from most modern bed-wave studies. Dimensionally, the Gilbert waves were presented as at-a-station time series while most modern bed waves are plotted using length dimensions in the downstream direction. The Gilbert waves could be plotted with distance dimensions by plotting terrace elevations to indicate channel-bed elevations at the time of maximum aggradation. Terrace heights above the modern channel indicate a dramatic decrease in bed-wave height downstream, as shown schematically in Figure 7. The progressive lowering of terraces downstream reveals down-valley attenuation of bed-wave amplitudes that precludes simple wave translation. In short, the sedimentation event that occurred in the hydraulic gold-mining regions of California – the type area of the sediment wave – was not propagated downstream by simple translation.

#### Channel grade as an explanation for Gilbert waves

The upper and lower deposition zones in the mountains and the piedmont should be considered separately because the mountain reaches are responding to local base-level controls. Aggradation followed by degradation in these two areas can explain the channel-bed elevation changes associated with Gilbert waves. The aggradation–degradation cycle in the Bear River mining districts can be seen on successive longitudinal profiles derived from historical surveys and topographic maps (Figure 8). This 25-km river segment was controlled at its lower end by Bear River Dam built in 1850 and on the upper end at the Liberty Hill Dam site where a pair of large tailings fans had existed since the early 1870s. Pronounced degradation in the upper reaches with subtle but distinct aggradation—degradation cycle approximately in phase with mining. Due to high stream powers and lack of armour, piedmont channels incised to premining base levels more rapidly than the mountain tributaries. In this interpretation, the observed rise and fall of



Figure 8. Long profiles of upper Bear River (location shown in Figure 1). Incision greatest in headwaters with subtle post-1878 aggradation below km 58. Pre-mining, 1878 and 1890 profiles from Heuer (1891). Topographic map profile from 1950 USGS Colfax quad. (1:62 500). This figure is available in colour online at www.interscience.wiley.com/journal/espl

channel-bed elevations documented by Gilbert's bed wave represent channel beds rising during the aggradational phase and incising as channels in the piedmont regraded. In accordance with Mackin's (1948) concepts, aggradation and degradation were quickest in the upper piedmont and slower downstream, so the inflection point migrated downstream through the piedmont. When viewed from an at-a-station frame of reference, this sequence of aggradation and degradation gives the impression of wave translation and attenuation in the downstream direction (Figure 4B).

#### Implications for River Management and Restoration

In the early stages of the environmental movements in North America and Europe, efforts were concentrated on cleaning up water bodies and improving water quality. These efforts were initially aimed at point sources, but it soon became clear that non-point-source (NPS) pollution was critical to both water quality and ecological viability. Given that rivers are primary sources, sinks and conveyors of NPS pollution, efforts to protect, maintain and restore river systems have gained much momentum. Aquatic restoration, *senso stricto*, involves returning all aspects of an aquatic system – including physical, chemical, and ecological factors – to a pre-disturbance state (National Research Council, 1992). This definition has raised the challenge for river restoration projects to understand the history and past processes of the fluvial system, recognize how it behaves as a dynamic system now, and anticipate how changes are likely to affect it.

Stream channels are dynamic and integrate processes acting throughout their upstream catchment and across their valley bottoms. If a channel reach is considered without regard to alterations in any of these dimensions, restoration to a stable natural channel is prone to failure. The alternative hard-engineering approach of installing fixed bank-protection structures that prevent lateral channel migration may not be desirable because it results in an unnatural channel with limited aquatic diversity. Moreover, the tendency for bank erosion may be translated downstream. In many cases, restoration projects should strive to design channels that are geomorphically stable and provide diverse aquatic habitat. Hence, knowledge of how channel processes and sediment storage and delivery systems operate both within the reach and upstream are critical to developing a sustainable, dynamic channel system. These objectives call for an accurate assessment of the sedimentation history that takes into consideration the nature of prolonged sediment storage. Conversely, knowledge of deep historical floodplain deposits may limit the feasibility of restoring a system to a pre-disturbance condition. Even if such a system could be restored, the present hydrologic regime may also have changed in response to land-use changes in the catchment. In such cases, more realistic rehabilitation goals or restoration to a non-pristine set of conditions may be called for.

The pre-disturbance condition of many rivers in North America and Oceania were severely altered some time after the arrival of European settlers and the introduction of logging and agriculture that often produced a bed wave and episodic floodplain sedimentation. As illustrated earlier in this paper, passage of a massive bed wave through a basin is typically followed by the relatively rapid return of the channel bed to pre-sedimentation elevations. This return to channel grade is often misconstrued as a return of sediment budgets and river systems to their previous conditions, without regard to deep floodplain deposits and the effects that they have on channel morphology, local sediment production, bottomland ecology, frequency of floodplain inundation, and other factors. Specifically, the modern channel may be deeply entrenched in historical terraces with the former floodplain perched high above frequently occurring flood stages. Sediment production from the high terrace walls may be orders of magnitude higher, the floodplain wetland may be buried and replaced by a xeric or mesic forest that is disconnected from the river, and aquatic diversity may be reduced accordingly.

One common strategy in river restoration is to identify a *reference reach* that is adopted as the target design for the restoration project. The reference channel reach has an appropriate morphology representative of stable conditions (Hughes *et al.*, 1986; Brookes and Shields, 1996). If restoration to a pristine condition is the objective, a relatively pristine reference reach should be sought. Unfortunately, in catchments that experienced large Gilbert waves, no representative pristine channel reaches may exist. Moreover, it may not be feasible to restore channels to pristine conditions. In this case, a reference reach may be sought that represents a newly adjusted configuration for the modern water and sediment regime (Fryirs, 2003). In catchments where bed waves have left deep floodplain deposits, these conditions should be recognized by experienced fluvial geomorphologists. Such channels may be in a state of long-term flux and if this is not recognized and compensated for, they would make a poor reference reach for stable channel designs. Adding to this problem is the common use of purely descriptive channel-classification systems to describe a reference reach (Juracek and Fitzpatrick, 2003). Most stream-channel classification systems used in the United States do not adequately account for systematic adjustments to channel morphology through time. Static channel descriptions do not facilitate the recognition of on-going adjustments to buried floodplains.

#### Two examples: implications of bed-waves to restoration

In the type area of the Gilbert wave, the Yuba River catchment has been identified as the primary candidate for restoration of salmonids in the Central Valley of northern California. Recent studies of the Yuba River have examined the feasibility of removing Englebright Dam and its large-capacity reservoir (86 Mm<sup>3</sup>) to restore salmonid spawning habitat. Recognition of prolonged reworking of hydraulic mine-tailings is important to dam removal in four ways: (1) downstream delivery of tailings from upland tributary storage; (2) release of 29 Mm<sup>3</sup> of tailings stored in Englebright Reservoir; (3) potential toxicity of mercury associated with mining sediment; and (4) sustainability of fine spawning gravel produced by erosion of mine-tailings. The prolonged reworking of mining sediment in these rivers has proved to be important in the evaluation of scenarios for treatment of Englebright Reservoir (James, 2005). The sustainability of spawning gravels has not yet received sufficient attention, however. Field studies and sediment transport models have determined the locations and suitability of modern bed materials for spawning habitat. These conditions have been assumed to be static without considering the likelihood that the fine gravels are largely supplied from mining sediment deposits in the upper basin. As storage of available fine gravel slowly dwindles, the supply of spawning gravels may prove to be unsustainable. Thus, the rationale for restoration of the upper Yuba River depends upon an understanding of the passage of the Gilbert wave and the dynamics of the historical sediment system.

A second example, drawn from the southeastern Piedmont of USA, also illustrates the importance of recognizing the passage of a bed wave prior to restoration efforts. In response to early 20th century cotton farming, extreme gullying and sheet erosion caused stream channels to aggrade. Fairfield County, South Carolina, experienced particularly severe erosion and sedimentation (Trimble, 1974). As a consequence, many small catchments were deeply aggraded as in the Storm Creek basin in Fairfield County (Figure 9). Valley-floor cross-sections cored through the floodplain of Storm Creek reveal a large volume of historical fill remaining after the channel incised back down to bedrock (Figure 10). The historical age of the thick sandy alluvium is based on weak pedogenesis, lack of bioturbation within the unit, uniform thin plane-bedded sedimentary structures throughout the exposure, and an abrupt, wavy contact with a low underlying soil catena ranging from thin brown forest soils (Alfisols) to wetland soils (Histosols). This interpretation is corroborated by a historical carbon-14 date ( $180 \pm 50$  carbon-14 years BP; Beta-12729) collected from a tree trunk buried in its upright growth position in a wetland soil at the base of the stratigraphic column. These relationships indicate that the floodplain had been broad, low and wet, but began to be buried during historical time, due to forest clearance and severe upland erosion with the sudden introduction of European-derived agricultural technology. In short, a Gilbert bed wave with an amplitude of more than 2 m passed through this reach.

The channel is deeply entrenched into the historical deposits so the terrace tread is now high above the channel and well drained (Figure 11). The historical alluvium in a representative section (Figure 9) has a mean depth of  $2 \cdot 2$  m above the pre-agricultural soil, a top width of 109 m, and a volume of 62 000 m<sup>3</sup> over a reach extending 260 m (Alexander, 1997). Channel erosion has removed only a small proportion of the stored alluvium which continues to be actively reworked (Figure 10). Since this site was first visited in 1995, considerable terrace-scarp erosion has occurred by tree tips, mass failures and gullies, as well as lateral enlargement of the floodplain inset below the level of the old



**Figure 9.** Map of Storm Creek catchment in Fairfield County, South Carolina. The letter A shows location of transect A in Figure 10. The arrow shows position of tunnel gully in Figure 12 and direction of that photograph toward main channel. This figure is available in colour online at www.interscience.wiley.com/journal/espl



**Figure 10.** Cores through historical sediment on a small stream in the lower Piedmont of South Carolina. The channel aggraded in response to erosion from cotton farming beginning in the late 19th century. Channel incised to bedrock after the 1920s when cotton farming failed and reforestation began. Vertical exaggeration *c*. 7×. Adapted from Alexander (1997). This figure is available in colour online at www.interscience.wiley.com/journal/espl

A-horizon. A tunnel gully system is developing in the historical terrace alluvium near the site of Transect A, demonstrating a new source of sediment production since terrace creation (Figure 12).

No evidence supports the passage of a coherent sediment wave through these reaches. Sediment production was from diffuse upland sources over a protracted period, so at the basin scale channel response is best regarded as aggradation due to elevated sediment loads followed by channel incision during the re-establishment of grade. The subsequent changes in bed elevation over time constitute a Gilbert wave and are representative of many catchments in the region. Efforts to restore such channels must be founded on the clear recognition of their on-going geomorphic



**Figure 11.** View downstream on Storm Creek through Transect A showing narrow entrenched channel with high banks of historical alluvium. Tree fall on right bank is representative of active bank erosion. Bedrock exposed in riffle at centre of photo indicates that channel has returned to pre-agricultural base level. Photo taken 8 January 2004. This figure is available in colour online at www.interscience.wiley.com/journal/espl



**Figure 12.** Sinkholes (arrowed) to tunnel gully in historical alluvium near Transect A. Gullying of terrace deposits represents elevated sediment production after passage of Gilbert wave. Tunnel gully surfaces into larger surface gully between the two trees and enters main channel in distance. Location of photo shown in Figure 9. Photo taken 8 January 2004. This figure is available in colour online at www.interscience.wiley.com/journal/espl

#### Bed waves at the basin scale

adjustments to the passage of a bed wave, episodic sedimentation of the valley floor, and on-going sediment production by reworking of historical alluvium. These channel reaches are now producing much more sediment and, presumably, have much less aquatic diversity than when they were riparian wetlands.

# Conclusion

Bed waves are defined on the basis of a rise and fall of the channel bed. They can be differentiated by scale, sediment source, grain size, overbank storage potential, and mode of morphologic evolution. Bed waves in gravel-bed rivers are not usually propagated by simple translation and are not necessarily the result of dispersion. At the large scale, they represent aggradation-degradation cycles. The large-scale bed waves described in this paper are quite different from most of the bed waves studied in recent years. The classic Gilbert wave is interpreted as the result of channel aggradation in the Sacramento Valley piedmont followed by the re-establishment of channel grade. Massive upland sedimentation events are often followed by aggradation in upper reaches that steepen longitudinal profiles until local channel slope is sufficient to carry the new load. When sediment loads are reduced, channel incision begins in the steepened reaches while aggradation continues downstream. The inflection point between zones of incision and aggradation migrates downstream as channel grade is re-established. Arrival of the inflection point represents the maximum elevation of the channel bed or the apex of the Gilbert bed wave. This sequence generates a rise and fall in channel beds that appears like the passage of a wave form when viewed at-a-station, but they do not involve translation or dispersion of coherent wave forms. Gilbert waves should be distinguished from smaller-scale bed waves that have quite different characteristics, processes and explanations. The proliferation of studies of small-scale bed waves has produced a wealth of knowledge about bed processes and bed-material transport. Benefits of these studies are likely to be compromised if confusion arises from attempts to reconcile the characteristics of small-scale coherent wave forms with the broad, episodic nature of Gilbert waves.

Recognition of the former passage of a Gilbert wave (large-scale bed wave) is essential to an accurate assessment of the condition of river systems. Large volumes of sediment recently stored on floodplains may have altered valleybottom morphology and may provide large amounts of sediment that was not present prior to the perturbation. The frequency of flooding and diversity of aquatic habitats tend to be reduced where passage of a Gilbert wave has left high, erodible terraces along the valley bottom. These considerations should be included in the designation of pristine reaches (if any) and the selection of appropriate reference reaches in river restoration projects.

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