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Management responses to pulses of bedload sediment in rivers

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A R T I C L E I N F O

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A B S T R A C T

Rivers can experience sudden pulses of sediment, from human and natural erosion processes, that can accumulate in the bed. Abundant studies have examined the sources and dynamics of sediment pulses, and problems caused by these pulses, particularly flooding, avulsions, and habitat simplification. Much less has been written about what managers can do about sediment pulses, and that is the purpose of this review. The first option for managers is to do nothing, and this decision can be informed by many case studies and by theory on the propagation and character of sediment pulses (their diffusion, translation, and celerity). Doing nothing should be informed by the secondary effects of sediment pulses on channels including; widening, avulsions, and tributary interactions. If managers decide that something needs to be done about the sediment, they have four options: (1) reducing the sediment supply at source, (2) trapping sediment in the channel (3) accelerating sediment transport through a reach, and, (4) directly extracting sediment. The most common of these actions is undoubtedly to reduce the supply at source, but there are few examples of the consequences of this for sediment pulses. There are even fewer examples of trapping, accelerating and extracting sediment. All of these options have great potential for managing sediment pulses, however, they also have the potential to trigger incision of tributaries and of the channel behind the passing sediment wave. Overall, the literature equips managers to understand the dynamics of sediment pulses, but it does not yet equip them to confidently manage these geomorphic events.

1. Introduction

Rivers can experience sudden pulses of sediment from human and natural processes. These pulses can accumulate in the stream bed, and move downstream, predominantly as bed-load. Sediment pulses occur naturally in streams, with the unusual volumes of sediment coming from gullying (e.g., Hancock and Evans, 2006), debris flows (e.g., Hoffman and Gabet, 2007), volcanoes (e.g., Gran and Montgomery, 2005; Pierson et al., 2011), collapse of natural dams (e.g., Hancox et al., 2005), or a series of large floods (Erskine, 1986; Madej, 1992). Human activities can enhance these natural processes. Examples are where land-use changes lead to a great increase in the frequency or magnitude of gullying, debris flows, or landslides. Human activities can also generate pulses of sediment that are outside the natural range of processes in channels. Examples are the extraordinary loads of sediment from mine tailings in California (Gilbert, 1917; James, 1989, 1991, 1999, 2006, 2015; James et al., 2009), in the Fraser River, Canada (Nelson and Church, 2012) and in the Ok Tedi River, Papua New Guinea (Parker et al., 1996; Cui and Parker, 1999). Another example is the sediment pulse that can be liberated by dam removal (Pizzuto, 2002).

Packets of sediment that migrate downstream following large inputs have been termed sediment pulses, sediment waves, bed waves and sediment slugs (Gilbert, 1917; Hoey, 1992; Lisle et al., 2001; Nicholas et al., 1995; Rutherfurd, 2001). These terms have often been used interchangeably across varied spatial and temporal scales. Nicholas et al. (1995) prefers the term *slug* due to its generality and the difficulty in identifying coherent waveforms. Additionally, James (2006, 2010) notes that the term *wave* has been used to describe sediment waves (of varying size and particle size distribution), bed material waves, and sediment flux interchangeably. Any of these terms would suffice, but this study uses the term *pulse* which better describes the discrete injection of sediment that is the focus of this review. The pulses considered in this review are periodic injections of sediment at the scale of entire river reaches and have been termed ‘superslugs’ by Nicholas et al. (1995) and “aggradation-degradation episodes” by James (2010). They are distinct from smaller, self-organized pulses of bed material (termed macroforms by Hoey, 1992) such as ripples, dunes, bars and bed-waves.

Sediment pulses have many impacts. They can raise bed levels, widen streams, and smother and simplify bed features such as pool-and-riffle sequences (Fig. 1) (James, 2010; Wohl, 2015). The rising bed, and

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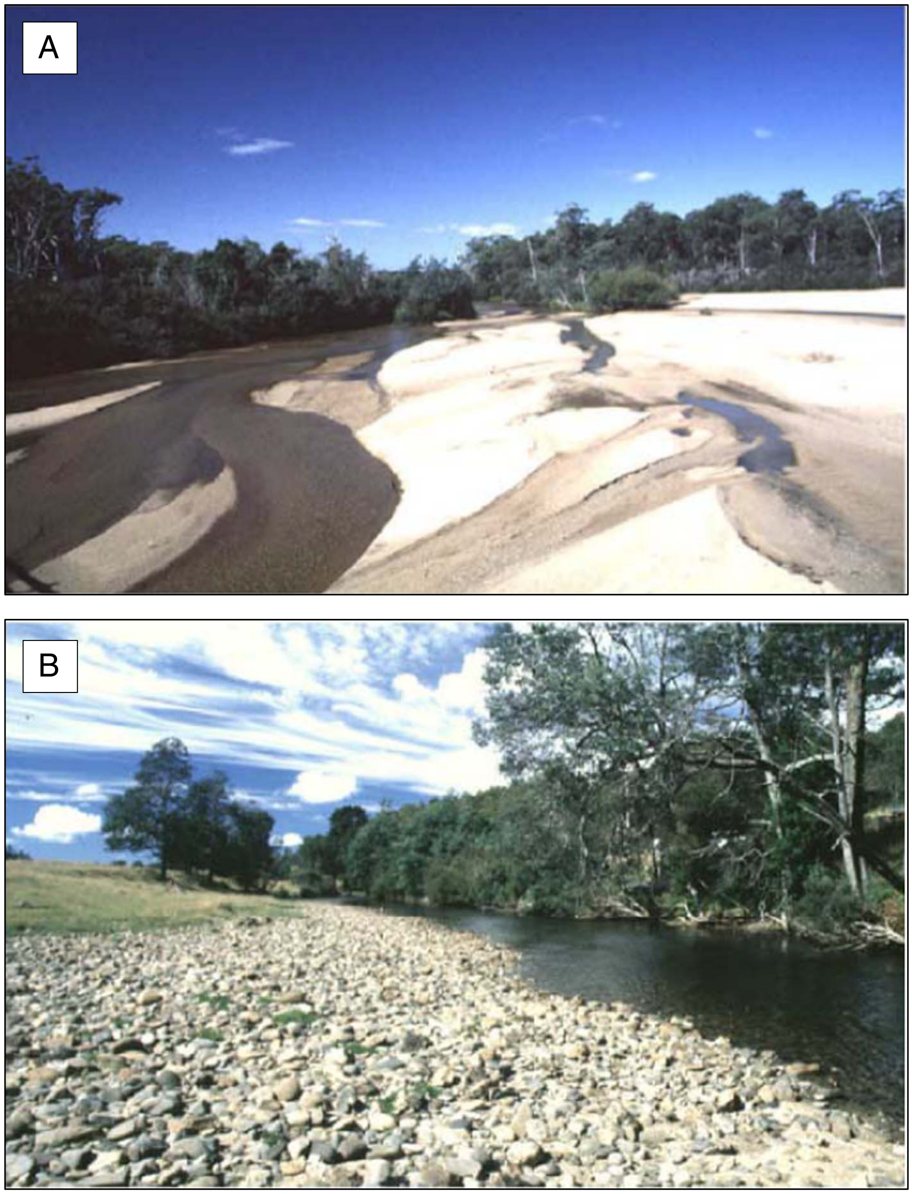


Fig. 1. (A) Mine tailings have filled a reach of the Ringarooma River that used to resemble the comparable un-impacted reach (B) upstream of the tributary inputs. (From Bartley and Rutherfurd, 2005a)

decreased channel capacity, can lead to increased flood frequency, more frequent channel avulsion, and restricted navigation. The sediment can also fill dams, reducing their function for flood mitigation and hydro-power production. Interventions aimed at managing these impacts are usually justified by way of protecting downstream reaches, re-establishing degraded habitat, increasing geomorphic complexity, or mitigating increased flood risk.

Gilbert's (1917) classic work on debris from gold mining in the Sierra Nevada was the first serious study of anthropogenic sediment pulses into rivers. He described the movement of many millions of tonnes of mine tailings in detail, as well as the resulting problems of flooding, navigation, and smothering of agricultural land. Gilbert also described some management options to mitigate the damage. He described the implications of doing nothing, levees that concentrate flow and scour the sediment, and a dam that could trap the sediment. As is so often the case, Gilbert's work continues to stand the test of time. In fact, despite the large body of work describing the degradation of river systems by unusually large, anthropogenically-triggered sediment loads (Gilbert, 1917; Knighton, 1989; Prosser et al., 2001; Kondolf et al., 2002; Bartley and Rutherfurd, 2005a; James, 2006, 1989; Simon and Rinaldi, 2006; James and Lecce, 2013; Wohl, 2015; Fryirs and Brierley, 2016) methods for managing their impacts have received less attention in the literature. In a recent example, in 2015, the Bento Rodrigues mine tailings-dam failed in Mariana, Brazil, releasing 60 million m^3 of iron-ore waste into the Doce River (Garcia et al., 2016) (Fig. 2F). Although commentators on the disaster suggest that there will be a huge cost for 'rehabilitation', they are by no means clear on what exactly managers can do to hasten that rehabilitation, apart from a suggestion to plough contaminated soils on the floodplain (Garcia et al., 2016). Despite an explosion of interest in stream restoration (Bernhardt et al., 2005), and many streams being affected by large sediment pulses, little literature summarises what management options are available to accelerate the recovery of these systems, or to reduce the risks presented by the sediment.

This paper uses case studies to review the five responses to sediment pulses that are available to managers. They can:

1. do nothing,

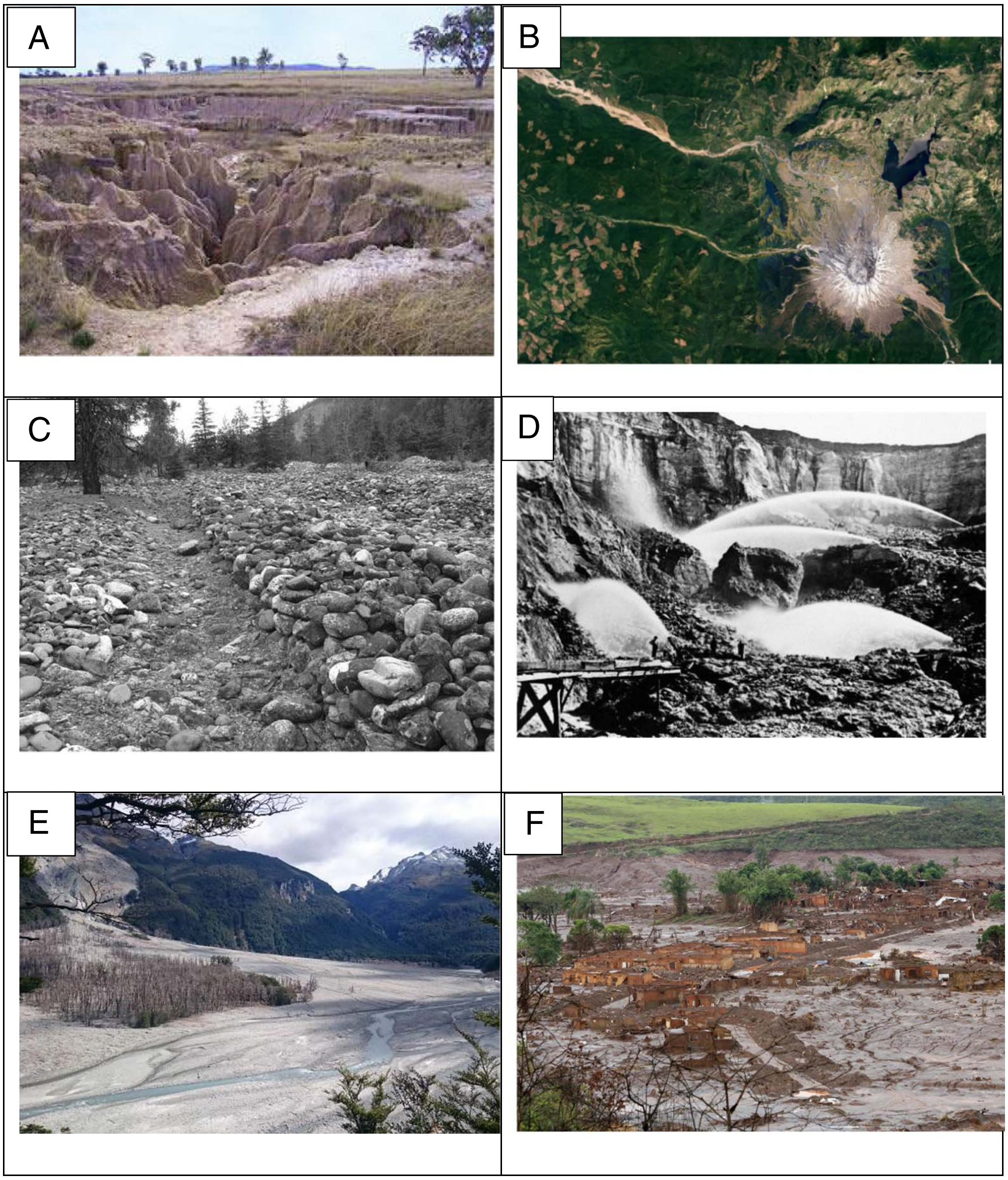


Fig. 2. Examples of Large sediment inputs: (A) severe gully erosion in New South Wales, Australia, (photo: B. Peasley/DECCW (obtained from Office of Environmental Heritage, NSW Government)) (B) Mt. St Helens, Washington, USA the sediment-laden Toutle River flows to the north east, (image: Google Earth) (C) lag deposits of coarse sediment liberated by placer mining near the confluence of the Fraser and Thompson Rivers, British Columbia (source; Nelson and Church (2012)), (D) hydraulic sluicing at the Malakoff Diggings, Sierra Nevada in the 1870s (source; USGS/Bancroft Library, University of California); (E) slip stream landslide and its debris fan, Dart Valley, New Zealand (photo; Alex Sims), (F) tailings deposited by the Bento Rodrigues tailings-dam failure in Mariana, Brazil (source; wiki commons).

2. reduce sediment supply at source,
3. promote in-channel storage,
4. accelerate sediment transport, and,
5. extract sediment.

Implementing options 2 to 5 will affect sediment continuity, so longer-term complex response is discussed involving channel incision and tributary interactions that may arise from manipulating sediment supply. The review concludes with an outline of a management framework that links the management options identified to different management goals. Managers can use the framework to help decide when to undertake different management activities.

While large sediment disturbances affect both the active channel and the floodplain, the focus here is on the active channel. It is also restricted to physical aspects of this issue, without considering biological issue, such as impacts on biota, or chemical contamination associated with the sediment. Before discussing the five management options, the dynamics of sediment pulses are reviewed.

2. The dynamics of sediment pulses

Before deciding whether to intervene, managers need to understand how sediment pulses are generated, how they disperse or translate through the channel network over time, and what controls their celerity. This understanding is the first step when deciding whether or not to intervene, and helps managers prepare for the consequences of sediment pulses in the absence of intervention. For example, Gilbert (1917) concluded that sediment pulses from gold mining move as an attenuating wave, so if managers did nothing he suggested that the pulse would potentially move through, and the stream would recover its natural morphology. Managers could wait for the pulse to move through, or act to accelerate this rate of recovery. In this section we examine how sediment pulses move through river systems, and characteristic recovery times.

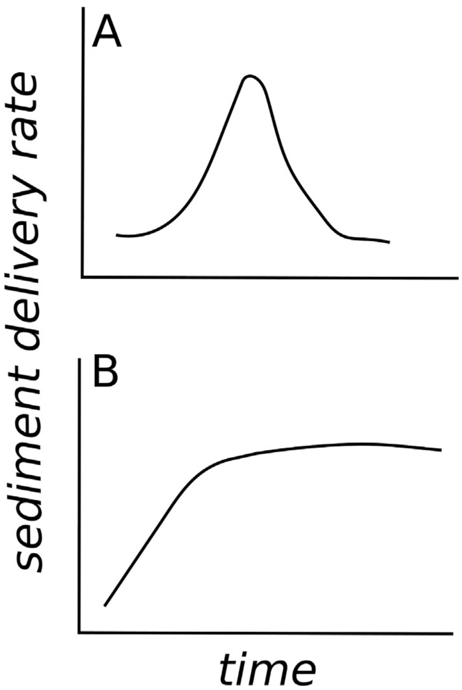


Fig. 3. Two types of sediment disturbance; temporally-discrete (A) and press (B), distinguished by their temporal trends in sediment delivery to the channel.
Source; Lake (2000).

2.1. How is sediment delivered to the channel?

The first step in predicting the type of sediment pulse that will result from an input pulse is to understand the volume, spatial distribution and calibre of sediment inputs relative to those normally experienced by the channel. These input characteristics will depend on the source of the disturbance, and are a key determinant of how the sediment pulse will be shaped.

Sediment pulses can be defined in space as being from diffuse or point sources (Phillips, 2009); and in time; as being either a prolonged press or discrete disturbances (sensu Lake, 2000). Point sources are inputs such as landslides, tailing dam failures, or bank collapse. Diffuse inputs are more widespread, such as sediment liberated from gullies, or multiple sites along the stream bed or stream banks (e.g., Benda and Dunne, 1997; Simon and Rinaldi, 2006). Importantly, inputs may be point sources at the reach scale, but diffuse at the catchment scale, e.g., the widespread occurrence of small landslides.

A temporally-discrete disturbance shows a clear rise, peak and fall of sediment inputs while a press disturbance is a more prolonged delivery that does not decrease with time (Fig. 3). Management of discrete inputs is primarily concerned with the evolution of the resulting sediment pulse (annual to decadal), while press inputs must also consider the ongoing delivery of sediment to the network (decades to centuries), which can undermine downstream remediation efforts.

Table 1 lists common sources of large sediment pulses, their style of delivery and typical impacts on channels. In general, sediment entering the channels in large pulses will have a longer residence time than their lower volume counterparts. Relatively large sediment pulses will reside in the channel network longer (either in the channel bed or in bars, islands or benches), especially when the larger, slow-moving sediment deposits are stabilised by vegetation. Interaction among channel deposits that enhance backwater effects (e.g., deposition behind tributary junction plugs) and a larger proportion of sediment being stored on the floodplain can also prolong sediment evacuation. Examples of these processes are given later in the paper.

Table 1
Summary of sediment pulses delivered to channels from natural and anthropogenic sources, whether the pulse is point source or diffuse (i.e., spread across the catchment), delivered as a temporally-discrete or press disturbances (sensu Lake (2000)), typical impacts on the channel, and studies describing the type of pulse.

Sediment source	Calibre of input	Point source/ diffuse	Pulse/ press	Typical impacts of the pulse	References
Landslides and lahars	Can be coarse or fine	Point	Pulse	Can dam channels, channel avulsion	Madej and Ozaki, 1996; Page et al., 1999; Pringle and Cameron, 1999; Montgomery et al., 2000; Sutherland et al., 2002; Korup et al., 2004; Huang and Montgomery, 2012; Nelson and Dubé, 2016
Debris flow	Slurry of mud carrying coarse material	Point	Pulse	Scour of steep tributaries, can dam channels, damage to infrastructure	Hoffman and Gabet, 2007; Lin et al., 2008; Stock and Dietrich, 2003
Rapid stream widening, meander bend cutoffs	Fine material	Point	Pulse	Further channel widening	Erskine, 1986; Hubble and Rutherfurd, 2010; Zinger et al., 2011; Saynor and Erskine, 2016
Avulsions	Floodplain sediments (fine and coarse)	Point	Pulse or press	Bed aggradation, further avulsions	Perignon, 2008
Gullying	Fines washed from eroding soil, & coarser material from rapidly incising gullies	Diffuse	Press	Loss of productive land, bed aggradation	Scott, 2001; Marden et al., 2005
Artificial channelisation	Coarse material from degrading bed, and fines liberated from undermined banks	Diffuse	Press	Bed aggradation	Simon, 1989; Simon and Rinaldi, 2006
Dam failure or removal	Initially fines as reservoir draws down, coarse material as bedload migrates past old obstruction	Point	Pulse	Smother habitat, increased turbidity	Pizzuto, 2002; Major et al., 2012; Wilcox et al., 2014; Warrick et al., 2015
Placer mining/hydraulic sluicing	Fines as a thick sludge/slurry, and coarse	Diffuse	Press	Constrain channel, increase flood risk	Gilbert, 1917; James, 1989; Nelson and Church, 2012
Tailings injection	material from waste piles	Point	Press	Smother habitat, inject pollutants	Knighton, 1989; Parker et al., 1996

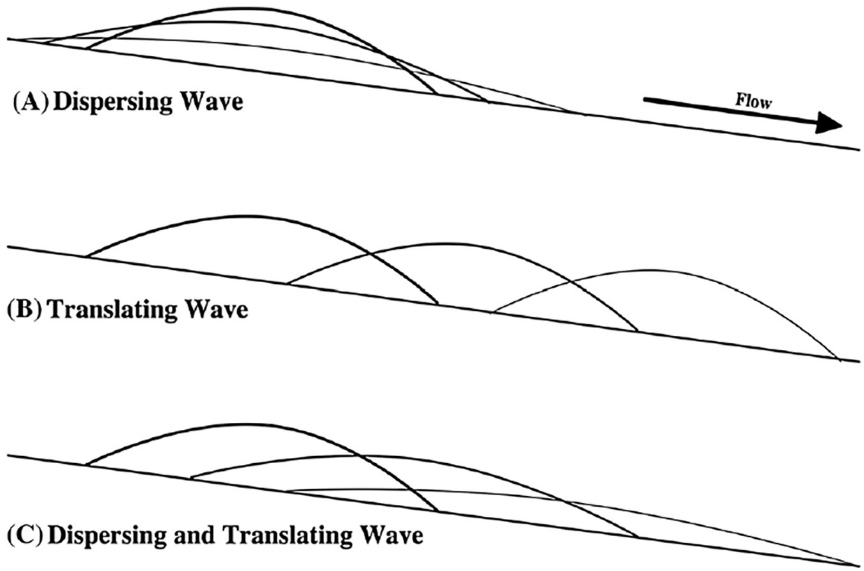


Fig. 4. Idealized types of bed material waves in profile. The heaviest line represents the original wave profile; successively lighter lines represent stages in wave evolution; n, bed elevation; t, time; x, channel distance.
Source; Lisle et al. (2001).

2.2. How do sediment pulses move through a river network?

The movement of sediment through a channel will be controlled by coupling between channel and hillslope, channel and floodplain and between channel reaches (Fryirs and Brierley, 2001; Hooke, 2003; Fryirs et al., 2007; Lamb et al., 2011). Downstream migration of sediment inputs along the channel bed is usually conceptualised as a moving wave (Gilbert, 1917). The 'shape' of such waves — measured as the temporal change of bed level at a reference site — is described as either dispersing or translating (Fig. 4), but individual pulses may have elements of both (e.g., Lisle et al., 2001; Czuba and Foufoula-Georgiou, 2014). *Dispersion* — a decrease in pulse amplitude and increase in period—has been shown to be the dominant mode of movement for discrete inputs that are large enough to perturb the local flow field (Lisle et al., 2001; Sklar et al., 2009). Dispersion is enhanced by size selective transport (which is strengthened where the pulse has a wide grain-size distribution) and deposition on the trailing edge of the pulse due to backwater effects (Lisle et al., 2001). The dominance of dispersion means that individual sediment pulses can quickly become difficult to discern from pre-existing bed topography (Lisle et al., 2001).

Translation – the downstream migration of the pulse peak, but without a change in pulse period — is most likely to occur when inputs are finer than bed material, transport capacity is high, the pre-disturbance bed is armoured, and Froude numbers and bed and bank roughness are low (Lisle et al., 2001; Cui et al., 2005; Sklar et al., 2009; Venditti et al., 2010). Thus, the degree to which a sediment pulse will disperse or translate depends on the calibre of sediment inputs relative to that of the pre-disturbance bed, the grain size distribution of input pulses, and the volume of inputs relative to stream transport capacity (Fig. 4).

Pulses may also amalgamate at tributary junctions, or low-gradient reaches downstream of inputs, a phenomenon termed *synchronisation* (Czuba and Foufoula-Georgiou, 2014; Gran and Czuba, 2017). Several smaller pulses can synchronise into a single, larger pulse when a pulse stalls at tributary junction, forming a barrier to sediment movement. The leading edge of an incoming pulse is deposited on the trailing edge of the stationary pulse. In this way a chain of overlapping pulses are deposited in an upstream direction. Alternatively, sediment pulses can move into sedimentation zones where they are deposited on the channel bed. Incoming pulses are deposited on top, but reworking by flows mixes the two together.

The movement of both fine and coarse sediment can be conceptualised as a waveform, but the different size fractions will move into different storage zones in the catchment (Fryirs et al., 2007). Fine sediment can be deposited on the floodplain during floods, or move into the interstices between larger sediment on the bed. Coarse sediment will migrate between bedforms (bars, benches and islands) or along the channel bed (Hooke, 2003).

2.3. What controls the pulse celerity?

How fast the peak of a pulse migrates downstream is the wave celerity. Pulse celerity is greater when inputs are small compared to transport capacity, and channel roughness is low. The relative dominance of dispersion, translation or concentration - coupled with pulse celerity - determines how long sediment pulses take to migrate downstream, and whether they are expressed as a subtle but long-lived change in bed level (dispersion) or a short-lived high magnitude change in bed level (translation).

Before considering how fast a pulse moves through a channel, it is worth asking; how can a manager judge that a pulse has passed? Assessing whether a sediment pulse has passed requires the use of some metric to measure recovery, the most common metrics are; return to pre-disturbance bed level (Gilbert, 1914; Knighton, 1989; Madej and Ozaki, 1996) return of the pre-disturbance thalweg, cross-section and sediment size variability (Knighton, 1999; Bartley and Rutherfurd, 2005b), establishment of stable features such as bars and benches (usually vegetated) (Erskine, 1996) or the return of pool-riffle sequences (Keene et al., 2008).

The celerity of the sediment pulse is controlled by the shape of the hydrograph (Humphries et al., 2012), the relative roughness of the channel (Kasai et al., 2004) and connectivity between reaches and with the floodplain (Fryirs et al., 2007; Fryirs, 2013). Sediment supply from many processes tends to decline over time. Gullies, for example, have a negative exponential erosion rate (Graf, 1977) and the supply of sediment from hillslope deposits and channel stores also tends to decline exponentially (Gran and Montgomery, 2005; Nelson and Dubé, 2016). A decline in sediment supply to pre-disturbance levels is required before the tail of the sediment pulse can begin to migrate downstream.

There can be a feedback between channel change caused by the sediment pulse and the transit time of the pulse itself. Sediment pulses fill pools and smother bedforms which homogenise the stream bed, reduces roughness and accelerates the passage of the pulse (Kasai et al., 2004). Conversely, a rise in bed level increases the frequency of flooding, which has two effects; storing fine sediment on the floodplain (decreasing pulse height by removing sediment from the channel), and decreasing downstream transport by distributing flow energy. Decreases in downstream connectivity, due to tributary plugs for example, will also slow the passage of the pulse.

Typical timescales for a return to pre-disturbance bed levels and reach morphology depends on the volume and calibre of inputs and transport capacity. In steep, high transport capacity environments the passage of sediment pulses from both single inputs (e.g., single landslides, Sutherland et al., 2002) or widely distributed inputs (e.g., earthquake induced landsliding throughout a catchment, Dadson et al., 2004; Lin et al., 2008; Hovius et al., 2011) tend to be at the rapid end, ranging from approximately five years to several decades (e.g., Gran and Montgomery, 2005). For example, a sediment wave in the Sandy River, Oregon was triggered by a sequence of lahars on the slopes of Mt. Hood between 1781 CE and 1793. Up to 10^8 m^3 of coarse sediment was deposited in its headwaters at this time. The wave travelled 87 km downstream and caused up to 23 m of aggradation in the lower reaches (Pierson et al., 2011). It took at least half a century for the river to reach its current bed level which remains at least 3 m above its former elevation (Pierson et al., 2011).

Madej (1992) describes how a 50-yr ARI flood in Redwood Creek in California increased the sediment stored in the downstream channel by 1.5 times. Sediment was stored in different areas of the system (Fig. 5), with the active channel having a residence time of decades, but this increased to thousands of years for sediment stored on terraces. Overall, Madej concludes that the influence of this single flood will persist on Redwood Creek for centuries.

Extremely large sediment pulses that amalgamate in lower gradient reaches can take decades to centuries to pass. Knighton (1989, 1999) predicted that it would take at least 50 yr after the cessation of mining in the 1980s, for the Ringarooma River to return to pre-disturbance bed levels, however, long sections of the river bed had already recovered their bed variability, relative to control sections, by the year 2000 (Bartley and Rutherfurd, 2005b). Gilbert (1917) used low-flow channel bed elevations to infer that large sediment pulses from hydraulic mining in the Yuba and Sacramento rivers, California, would pass through in approximately a century (Gilbert, 1917; James, 1989). However, James (1989) showed that transport rates remain elevated above pre-mining values for more than 40 yr after the bed returned to pre-disturbance levels. James suggested that the rise and fall of bed level is the period of grade adjustment but it does not signify the complete passage of the sediment pulse (James, 1989, 1991, 1999, 2006, 2010; James et al., 2009). Sporadic but persistent re-mobilisation of sediment stores, and ongoing supply from the Yuba's upper tributaries, mean that the total sediment pulse is right-skewed with respect to time (James, 1989, 2006). This important modification of Gilbert's original model tells managers that the return of bed level is not always synonymous with pulse evacuation and the destabilising effects of high sediments loads may persist decades beyond bed level adjustment (Fig. 6). Overall, examples in the literature suggest that sediment pulses seldom evacuate before decades or even centuries.

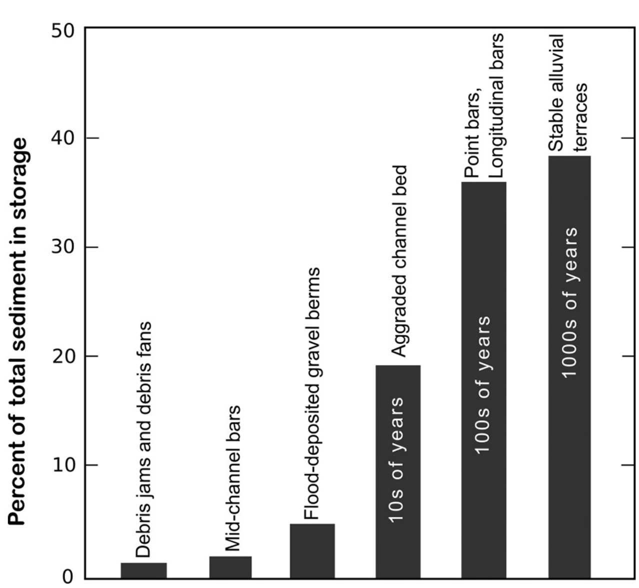


Fig. 5. Sediment storage in Redwood Creek following the 1964 flood, also indicating the estimated period of storage in different features (Madej, 1992, Fig. 13).

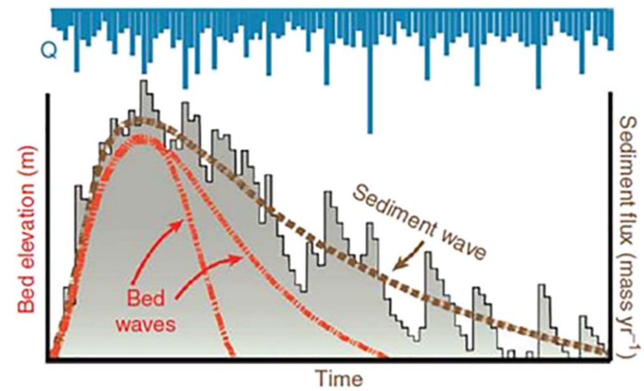


Fig. 6. Conceptual model of right-skewed sediment pulse (time series of sediment fluxes) and bed pulse (time series of bed elevations) to represent the movement of material into storage. The sediment pulse consists of the entire input pulse, some of which moves into long-term storage on the floodplain or in high terraces. The bed pulse is the component which travels on the channel bed causing a reach to aggrade then degrade. The passage of the bed pulse is not synonymous with the complete evacuation of all inputs, which may lag behind changes in bed level as stored sediment is recruited during flood events. Adapted from; James (2006).

Additionally, pulses may completely stall in low gradient reaches where transport rates are very low. An example is when large volumes of sand were deposited in the lower reaches of Creightons Creek, SE Australia, following flooding in 1916. The low gradient of the creek means that the sand has stalled in the channel moving little over decades (Davis and Finlayson, 2000).

This section has reviewed sediment pulse dynamics, namely; how sediment is delivered to a channel, how pulses change as they move through a network, the controls on pulse celerity, and typical timescales for a return to pre-disturbance bed levels. Managers can use an understanding of sediment-pulse dynamics to guide interventions. The five methods available to managers to manage sediment pulses are now described.

3. Option one: do nothing, and accept the impacts of the sediment wave in the channel

In order to make an informed decision to 'do nothing' managers need (a) a sound understanding of the consequences of doing nothing, and (b) to be prepared for the sequences of changes that will happen once the slug of sediment has passed, e.g., channel widening, bank erosion and a return to the pre-disturbance sequence of changes. As discussed above, the sediment pulse manifests as a rise in bed level, the filling of pools, smothering of bed features (e.g., riffles or LWD) and channel vegetation (James, 2006). In resistant or bedrock channels, the sediment can simply pass through, producing no substantial change in the channel morphology. Petts (1979) has couched the term 'accommodation adjustment' when a dam produces no appreciable change in downstream channel morphology. The same term could be used to describe the situation where a sediment pulse transits through a stream

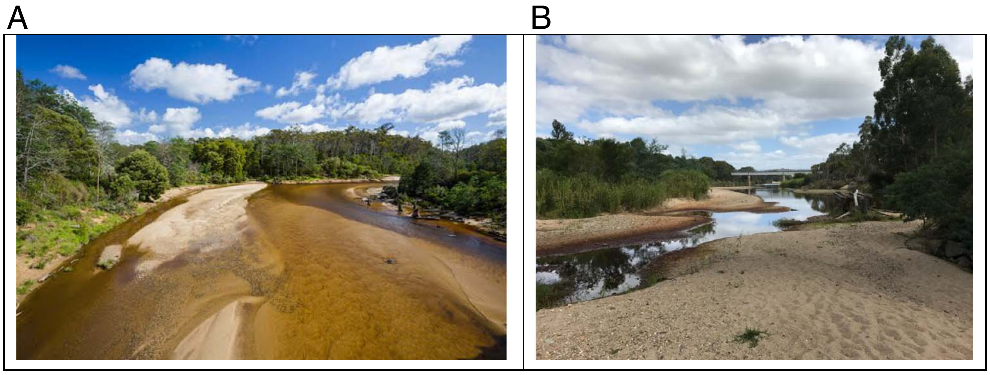


Fig. 7. (A) Ringarooma River above the township of Pioneer, Tasmania widened by the passage of a sediment pulse introduced by tin mining, and (B) Tambo River above the township of Bruthen, SE Australia, where a large pulse of sand has raised bed level by several metres but the stable banks have not eroded.
Photograph: Tambo photo by Ross Hardie.

reach with little impact on the channel. However, in many examples, the consequences of such dramatic increase in sediment load include widening, channel avulsions and tributary plugs. This section considers each of these changes.

3.1. Widening

Rivers confined by bedrock, or those that have banks with high clay contents and stabilising vegetation, are more stable and can remain unaltered as the sediment pulse migrates downstream (e.g., Rutherfurd, 2001). However, streams with less resistant banks commonly widen in response to rapid bed aggradation (e.g., Schumm, 1985; Simon, 1989, 1995). When mining sediments filled the Ringarooma River in Tasmania, the channel widened by between 15 and 65% in upstream reaches (Bartley and Rutherfurd, 2005b), and by over 300% in downstream reaches (Knighton, 1987) (Fig. 7). A slug of sediment into Creightons Creek in SE Australia led to a 25% increase in channel width (Bartley and Rutherfurd, 2005a). Downstream widening is common when sediment pulses are released by dam removal (Pizzuto, 2002). Stream widening also liberates additional sediment from the banks which can increase the volume of the sediment pulse (Rustomji, 2008). Significant widening and bed aggradation increase the ratio of storage to transport in a reach and forms zones of sediment accumulation (Hoey, 1992; Pryor et al., 2011). As these zones transition from aggradation to degradation, and the reaches switch from sediment sinks to sediment sources, the celerity of the sediment pulse changes. Pulse celerity will decrease as material moves into storage, and increase as it is liberated by degradation and flushed downstream (Pryor et al., 2011).

3.2. Flooding

A major impact of sediment pulses is that they can reduce hydraulic capacity of the channel, and increase overbank flood frequency and duration. Increased flood risk due to channel aggradation is one of the most common justifications for managing sediment pulses. In addition to the usual effects of flooding, the increased connection between the channel and the floodplain will place more sediment into long term storage on the floodplain, reducing the size of the sediment pulse in the channel (James, 2010).

3.3. Avulsions

Flooding can also accelerate deposition on levees; perching the channel, leading to avulsions (Brizga and Finlayson, 1994; Nanson and Knighton, 1996). The effect of an avulsion is to store sediment in the abandoned section of channel, and introduce a new pulse of sediment downstream from the avulsion channel itself. This represents a nice example of complex response sensu Schumm (1973). An example is the Suncook River in Epsom, New Hampshire, which, in 2006, scoured a new channel across its floodplain and deposited a pulse of approximately 100,000 m^3 of sand downstream (Wittkop et al., 2007; Perignon, 2008). The migration of the resulting sediment wave raised bed levels in downstream reaches of the Suncook River by over a metre, causing a second avulsion across a meander bend in early 2007 (Perignon, 2008). The probability of additional avulsions downstream will decrease as the sediment pulse disperses and bed levels lower. Similar avulsions have been triggered by pulses of sediment from landslides in the Southern Alps of New Zealand (Korup, 2004). Managers might be more likely to manage the sediment pulse if they suspect that it will trigger avulsions.

3.4. Tributary interactions

Sediment pulses interact with tributaries. If the pulse of sediment is moving down the trunk channel, it can block tributaries, producing a backwater lake. The lower Ringarooma, Tasmania is an example where trunk stream aggradation by a sediment pulse has blocked tributaries producing lakes that extend up to 2 km up the tributary (Knighton, 1989). If the sediment pulse is moving down a tributary, then it can similarly block the trunk stream. Several such 'tributary junction plugs' have formed across the Glenelg River in Western Victoria, Australia, where tributaries have deposited up to eight metres of sand in the trunk stream from gullying (Rutherfurd, 2001). In this case the blockage was enhanced by the more rapid arrival of tributary flood peaks relative to the more sluggish (and regulated) Glenelg River. Managers might decide to protect these new wetlands because they support a similar array of macroinvertebrates as downstream reaches (Lind et al., 2009).

To summarise, the first decision for managers faced with a sediment pulse is whether to do anything. This decision can be informed by predicting the celerity of the pulse, and whether it disperses or translates. In addition, the decision to act could be influenced by the consequences of the slug, namely flooding, widening, avulsions and tributary interactions. The four more direct management options are now considered.

4. Option two: controlling the supply of sediment at its source

Sediment inputs usually cease naturally as the source is eroded or becomes disconnected from the channel (e.g., landslide deposit) or activities driving the input, such as mining, stop. Cutting off the supply of sediment at its source can accelerate the recovery rate. This can convert a press disturbance into a pulse disturbance. The sediment pulse will then migrate downstream as its sediment supply is cut off.

Typical examples of eliminating or reducing point source sediment inputs are controlling the erosion rate of an artificial reservoir following dam removal (e.g., Randle et al., 2015) and stopping tailings deposition in channels (e.g., Knighton, 1987). Arresting supply from diffuse inputs includes reforestation (Kondolf et al., 2002; Marden et al., 2005) or gully stabilisation (e.g., Herzig et al., 2011). These interventions initially decrease sediment supply; initiating bed coarsening (e.g., Knighton, 1999), armour development (e.g., Lisle, 2008), or rapid incision and channel contraction (e.g., James, 1991). The net effect of these changes is to decrease the size of the pulse and accelerate dispersion and translation. Secondary effects of controlling the sediment supply at its source are discussed in Section 8.2. In places such as Japan and Taiwan small dams (called Sabos) are used in steep first- and second-order streams to interrupt debris flows and stop them from reaching the main channel and forming a coarse sediment pulse. Californian mining and reforestation in the North Island of New Zealand are now described which provide good examples of sediment control at source.

4.1. Cessation of hydraulic mining, Sierra Nevada, California

A good example of controlling sediment supply at its source is when a Federal Court in California in 1884 prohibited the discharge of mining debris into the Sacramento River and its tributaries, effectively ending all hydraulic mining in the region (Gilbert, 1917; James, 1991). The large sediment pulse that already occupied the channel continued to disperse downstream and the lower reaches of the Bear and Yuba rivers aggraded by as much as 5 m, and fine sediment was deposited across the floodplain of the Sacramento River (Gilbert, 1917; James, 1989; James et al., 2009). Ending mining effectively eliminated the supply of sediment to upper tributaries but the volume of material stored in piedmont streams remained a source of sediment to the lower Bear, Yuba and Sacramento rivers (James, 1989).

4.2. Reforestation in the Waipaoa River Catchment, New Zealand

The East Coast of the North Island of New Zealand is just 2.5% of New Zealand's land area but this disturbed landscape produces 33% of its annual sediment yield (Hicks et al., 2002). Forest clearing and conversion to agriculture in the late 19th and early 20th centuries accelerated gully development, landsliding and earthflows in the steep upper portion of the catchments (Herzig et al., 2011) and caused up to 7 m of aggradation in tributaries of the Waipaoa River (Gomez et al., 2003).

In an effort to control erosion the New Zealand government undertook extensive planting of exotic Douglas Fir (*Pseudotsuga menziesii*) in eroding gullies (Marden et al., 2005; Page et al., 2007; Herzig et al., 2011), which reduced annual sediment yield from treated gullies by 62% (Gomez et al., 2003). Furthermore, reforested areas showed remarkably few landslides during a 100-yr return period storm in 1988 (Page et al., 1999; Kasai et al., 2005) (Fig. 8).

While inputs from eroding gullies have declined, 48% of all material eroded in the catchment between 1950 and 1988 was stored in the lower 8 km of the Te Weraroa channel (Gomez et al., 2003). From the lower channel, the sediment is dispersing downstream and into the Waipaoa River where it is either deposited on artificial levees or across the adjacent floodplain at rates of $\sim$60 mm a^{-1} (Gomez et al., 1999). Levee deposition has led to channel narrowing and a steady (albeit slow) reduction in channel capacity.

The Te Weraroa and neighbouring catchments demonstrates the effectiveness of reforestation at controlling sediment supply. However, due to the catchment's naturally high sediment yields, and the large volume of material already stored in the upper tributaries of the Waipaoa River, it will take several decades for the benefits of reforestation to be felt downstream on the Poverty Bay flats (Gomez et al., 2003).

Controlling the supply of sediment promotes the dispersion of the sediment pulse by reducing the amount of material released into the channel, allowing the tail of the pulse to begin migrating downstream. Controlling the supply of sediment at the source should be prioritised so that the magnitude of the disturbance (and its impacts) can be minimised and no downstream remediation efforts are undone.

5. Option three: promoting in-channel storage

The sediment pulse can be trapped using in-stream structures such as check dams or by re-vegetation of bars or benches. Trapping the sediment pulse protects downstream reaches from high sediment loads.

Vegetation can naturally colonise channel deposits (e.g., Friedman et al., 1996a; Nelson and Dubé, 2016) but managers can undertake additional revegetation to accelerate the rate of trapping. Vegetation encourages deposition by shielding underlying deposits from erosion and by increasing channel roughness, which slows the flow and encourages further deposition (Rominger et al., 2010; Gurnell, 2014). In this manner, vegetation stores sediment in the channel. The colonisation of bedforms also influences channel morphology as bars are converted to benches and the channel contracts (e.g., Erskine, 1993; Erskine et al., 2012; Gurnell, 2014; Erskine, 2015). Because vegetation narrows channels and enhances incision (e.g., Friedman et al., 1996b), overall transport capacity is reduced which slows the passage of the sediment pulse. Revegetation has been used in the Genoa River, SE Australia to stabilise stream banks and trap large ‘sand slugs’ washed into the river during a series of floods in the 1970s (Erskine, 1993; Pearson, 2012) (Fig. 9).

In-stream structures, often called sediment detention dams, trap sediment by intercepting bedload, decreasing stream gradient, and encouraging deposition upstream (Fig. 10). Sediment accumulates

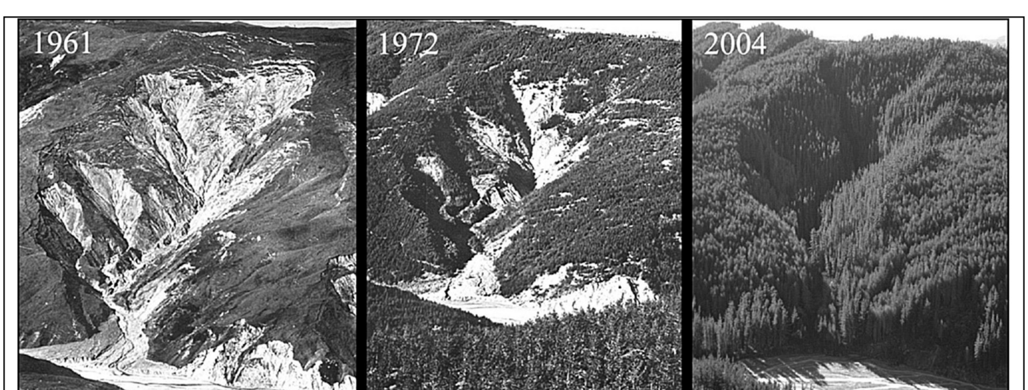


Fig. 8. Pre- (1961) and post-reforestation (1972, 2004) photography of a medium-sized gully in Te Weraroa Stream, Mangatu Forest, North east North island, New Zealand. Reforestation in this example reduced the area of active erosion from 7.6 ha to 0.8 ha between 1974 and 2004.
Source; Marden et al. (2005).

Fig. 9. Genoa River before revegetation of stream banks and channel sand deposits in 1979 (A) and after in 2009 (B).
Source: East Gippsland Catchment Management Authority.

behind the structures until it is either excavated or the structure fails (Wang and Kondolf, 2014). Several such small brush and log dams were constructed in the upper Yuba River in the early 20th Century to trap mining debris, and Gilbert (1917) documented their rapid in-filling and, in some cases, collapse. The much larger Englebright Dam (86 million m^3) was constructed in the Yuba Basin in 1941 for the same purpose. The dam is now being considered for removal in an attempt to re-introduce fine gravels into the Lower Yuba which provide critical spawning habitat for anadromous fish (James, 2005). In addition to trapping large sediment pulses in the trunk stream, smaller Sabo structures have seen widespread use in Austria, Japan and Taiwan as a means of trapping debris flows in steep tributaries (Ikeya, 1989; Chanson, 2004; Wang and Kondolf, 2014).

Without regular excavation these structures are a short-term solution and in rapidly eroding areas have a lifetime of several decades (Wang and Kondolf, 2014). Once dams have filled, sediment can pass directly over retention structures, so that managers will be forced to intervene again to control sediment. Filled dams can also fail catastrophically, unleashing secondary pulses of sediment as debris flows. For example, the Barlin Dam was one of a series of structures constructed along the Dahan River, Taiwan to trap and store sediment before it entered a downstream hydro-electric reservoir. The 38 m high structure was completely full by 2003 and failed during Typhoon WeiPa in 2007, releasing a 10.5×10^6 m^3 pulse of sand and gravel to the Dahan River (Tullos and Wang, 2014). For this reason, filled retention structures can pose a serious and ongoing hazard to downstream infrastructure. Deliberate breaching of filled dams in order to flush sediment downstream, is discussed in the next section.

6. Option four: accelerating sediment transport rate

Increasing the sediment transport rate accelerates evacuation of the sediment pulse and reduces recovery time. Removing sediment from affected reaches by increasing the sediment transport rate can be achieved in regulated rivers by increasing discharge (flushing flows) or in un-regulated systems by concentrating flows – usually by levee

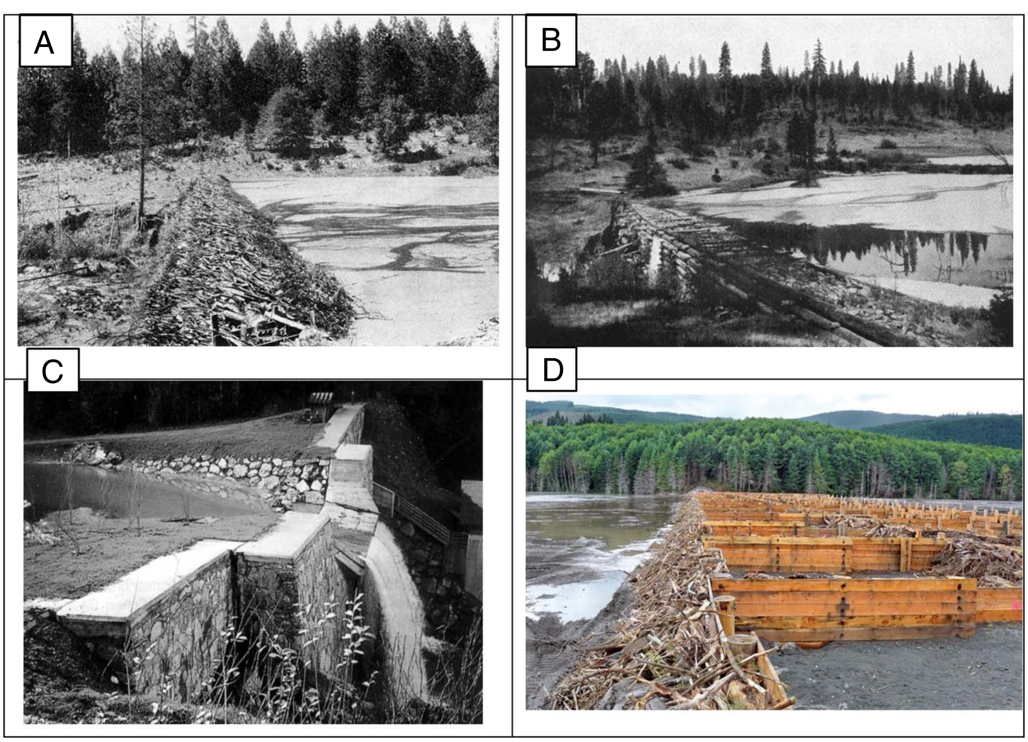


Fig. 10. (A) Brush dam below Murchie Mine in South Yuba basin in 1908, source Gilbert (1917; Plate 26A), reproduced from James (2005), (B) log-crib dam on Spring Creek below North Columbia mine in 1905, source; Gilbert (1917; Plate 27A) reproduced from James (2005), (C) sediment retention structure in Wagrainer Ache, Salzburg, Austria, source; Hubel and Fiebiger (2005), (D) a cross-valley structure designed to trap sediment moving down the north fork of the Toutle River, Washington, USA, source; US Army Corps of Engineers.

construction.

Targeted flow releases from dams have been used to flush bed sediments downstream. Flushing flows from dams are certainly used to maintain a particular channel form, and to turn-over bed material to reduce colmation (Kondolf and Wilcock, 1996; Wilcock et al., 1996). However, no evidence that managed releases from dams are used to specifically accelerate recovery of sediment pulses could be found. Acreman et al. (2000) in a comprehensive review of flushing flow releases from global dams, made no mention of releases to flush sediment downstream.

A similar strategy is that of 'store and flush' where sediment is deliberately trapped and stored behind detention dams during low flows, and is then rapidly flushed downstream during flood peaks. While the technique has been used to avoid generating a coherent sediment pulse during hydro-electric dam removal (e.g., Major et al., 2012) and to flush accumulated sediment from floodwater detention dams in urban stormwater systems (Yu and Tan, 2006), the authors are not aware of any examples where 'store and flush' has been used to specifically manage existing sediment pulses.

Concentrating flow within constructed levees is more common. This practice is often justified for flood protection because sediment has elevated bed levels. Engineers predicted that levees would have the dual-benefits of containing higher magnitude flows and increasing bed scour, historically making levee construction an attractive tool. For example, narrowly spaced levees constructed along the lower Feather River, California in the late 19th century were designed to accelerate transport of a pulse of mining debris being fed to the channel from the Bear River. Levee spacing was narrowest at the confluence of the Bear and Feather rivers, a site of historical deposition (James, 2010). The levees successfully encourage the bed to self-scour, accelerating sediment transport and maintaining navigable bed levels (James and Singer, 2008; James et al., 2009).

In some cases levee construction has had the effect of *increasing* bed levels, exacerbating flooding and increasing the likelihood of channel avulsion. For example, flood control levees built along the lower reaches of the Waiho River, South Westland, New Zealand have reduced the transport capacity of the bedload-dominated Waiho River and resulted in up to 5 m of aggradation since 1985 (Davies et al., 2003). The management response of periodically increasing the height of levees means that the river bed is now perched ~15 m above the adjacent Tartare River, and an avulsion is likely (Davies et al., 2013). The avulsion would cause a hiatus in aggradation in the Waiho for decades, after which sediment would fill the bed of the Tartare and aggradation would resume (Davies et al., 2013).

Flushing flows and concentrating flow are both options to accelerate the sediment transport rate. Flushing flows are not commonly used. Concentrating flow using levees works in some cases (e.g., along narrow sections of the Feather River, California) but may restrict transport capacity in high bedload rivers where avulsion is a threat.

7. Option five: extracting sediment

Probably the most radical response to a sediment pulse is to physically remove it from the channel. This can be achieved by extracting the material directly from the channel using excavators or by dredging.

Extraction induces an abrupt increase in channel accommodation space that interrupts the downstream passage of sediment until the bed discontinuity is either smoothed by degradation, or filled with incoming bedload (Lee et al., 1993; Rutherfurd et al., 2000). The deficit-induced erosion in the extracted reach is distributed upstream via knickpoint migration and downstream via 'clear water' effects (Lee et al., 1993; Kondolf, 1997; Wu and Wang, 2008). Extraction decreases the amplitude of the sediment pulse by removing material and dramatically reduces wave celerity.

The negative effects of commercial over-extraction are well documented (Kondolf, 1994, 1997; Rinaldi et al., 2005; Padmalal et al., 2014). Commercial extraction, which has the added benefit of providing economic as well as environmental value, may be an under-appreciated tool to preserve reaches downstream of migrating sediment pulses. However, no known comprehensive study has been made on the potential for commercial extraction to be used as a management tool in channels affected by unusually large sediment loads. Commercial extraction has been used as a management tool for the past two decades in the Glenelg River, SE Australia. In this case, extraction has primarily been used to prevent migration of the sediment pulse to non-degraded reaches. Studies to evaluate the effectiveness of this technique are currently underway. Below extraction in New Guinea rivers is described.

7.1. Examples of extraction of sediment pulses

There are several examples where dredging has been used to maintain navigation in rivers affected by sediment pulses including:

- the Colwitz River, Washington where a large sediment pulse from the eruption of Mt. St Helens is migrating downstream (USACE, 2010a),
- the Feather and Sacramento rivers in California, where a large pulse of hydraulic-mining debris is slowly being delivered by rivers draining the Sierra Nevada (Gilbert, 1917; James and Singer, 2008), and
- the confluence of the Wabash and Ohio rivers, Indiana, where an upstream bend cutoff in the Wabash River generated a large sediment pulse (Zinger et al., 2011).

Possibly the largest example is in the Ok Tedi and Fly rivers, which lie in the high rainfall highlands of Papua New Guinea's Western province. These rivers have been heavily degraded by inputs from mining since 1984. The Ok Tedi mine discharges approximately 150,000 mg day^{-1} of tailings (delivered as a slurry rich in fines) and overburden (coarse waste rock) to the headwaters of the Ok Tedi River (Markham and Day, 1994). The massive inputs amount to a forty-fold increase in annual sediment yields and have transformed the Ok Tedi River's channel, above its confluence with the Fly River, from being highly sinuous to a wide, braided channel (Parker et al., 1996) (Fig. 11). High abrasion rates enhance pulse dispersion as fine material is more rapidly flushed downstream, where it is either exported to the Fly River or deposited on the floodplain of the lower Ok Tedi and Fly rivers (Parker et al., 1996; Cui and Parker, 1999). Sand deposition in Ok Tedi's lower reaches has dramatically increased flood frequencies; causing the dieback of 1924 km^2 of floodplain vegetation (OTML, 2014).

Concern that siltation would restrict export of mined product by large ships navigating the Fly River, and a desire to reduce flood-induced forest dieback, led to a dredging program beginning in 1998 which continues today. Dredging occurs immediately upstream of the Ok Tedi – Fly River confluence (100 km downstream from the mine), removing approximately 18.8 Mt. of material per annum which is only 25% of annual mine inputs, but 85% of the sand load passing the dredge (OTML, 2014). Dredged sediment is pumped to engineered stockpiles on the adjacent floodplain where it remains in storage. The dredging program has succeeded in keeping the Fly River open to shipping, and has decreased the frequency of overbank floods and associated forest dieback. Dredging stops the sand component of the sediment pulse from travelling further downstream but fines are still deposited on the floodplain of the lower Ok Tedi and Fly rivers, where they are expected to remain in storage for centuries (Parker et al., 1996).

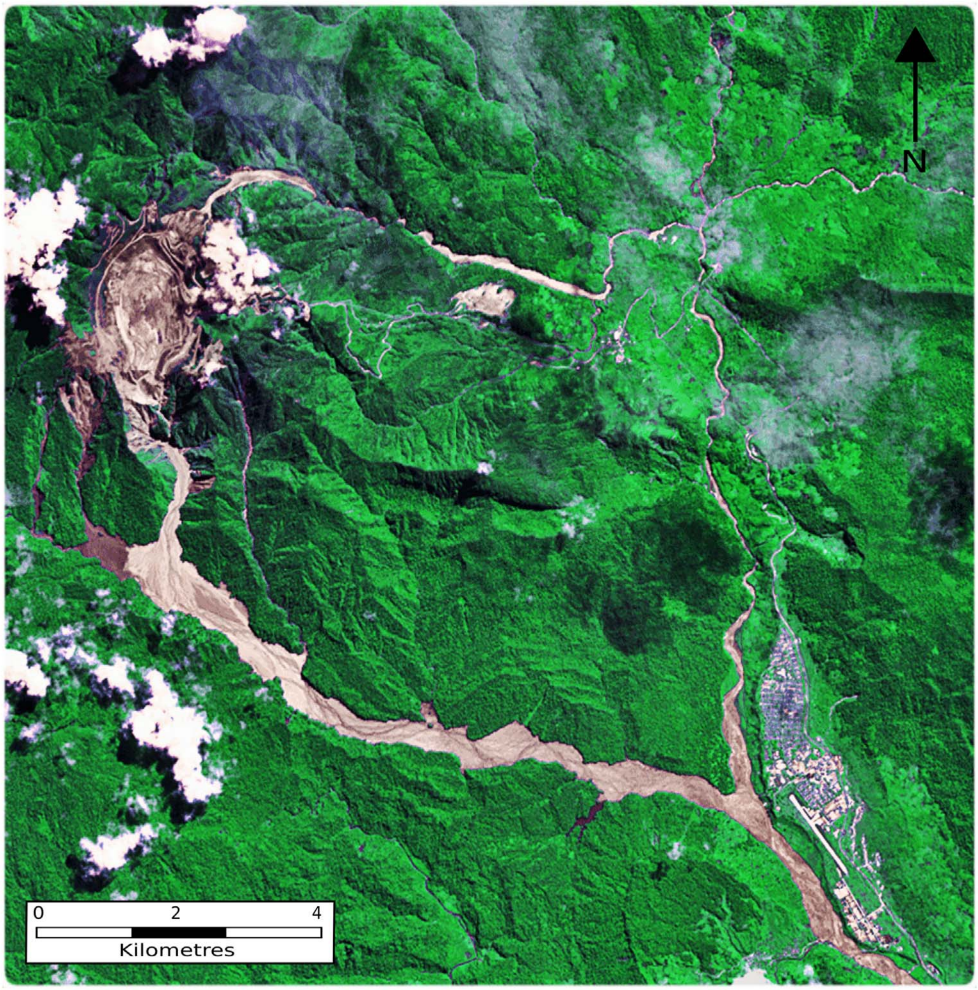


Fig. 11. Satellite view of the Ok Tedi mine which discharges mine tailings directly into the upper Ok Tedi River.
Source; Google Earth.

8. Longer term management; complex response & unintended consequences of intervention in sand pulses

All of the above options for managing sediment pulses in rivers will trigger secondary responses in the river. Catchment networks exhibit a complex response and their sediment yields continue to oscillate well beyond the initial disturbance (Schumm, 1973; Humphrey and Heller, 1995; Schumm and Rea, 1995). Interventions that alter the distribution of sediment, starving some reaches and storing it in others, also initiate a series of responses (e.g., Kondolf et al., 2002) that can lag behind interventions by decades. Three examples of complex response that managers need to consider are highlighted below: tributary rejuvenation, enhanced incision, and delayed incision.

8.1. Tributary rejuvenation: the Ringarooma River, Tasmania, Australia

The Ringarooma River and its tributaries in North East Tasmania, Australia, received over 40 million m^3 of mostly sand-sized waste from tin mining between 1875 and 1984 (Knighton, 1989). Mainstem aggradation blocked tributaries, and sediment moving down the tributaries was trapped and stored. As the sediment pulse in the Ringarooma River migrates downstream and the bed deepens, the large volumes of sediment stored in the tributaries will be released into the river as a second pulse of sediment (Knighton, 1989, 1991). As the pulse of sediment migrates downstream the upstream tributaries will be affected first, adding new sediment to the back of the sediment pulse, producing a complex sequence of sediment pulses over time. Attempts to trap or harvest sediment from the Ringarooma or its tributaries would affect the timing and sequencing of these tributary responses.

8.2. Enhanced incision

The morphological consequences of a reduction in sediment supply include; incision, channel narrowing, bed armouring and, in some cases, the transition from a braided to a single-threaded sinuous morphology (Schumm, 1985; Knighton, 1998; Surian and Rinaldi, 2003; Boix-Fayos et al., 2007). Whether or not such transformations are desirable depends on the context of the intervention and any target morphology. Such reductions in sediment supply have the potential to produce secondary, unintended consequences.

Natural regeneration of riparian vegetation, reforestation (37% increase in area between 1835 and 1988), the construction of check dams and historical extraction from some reaches led to a large reduction in sediment supply to the Drôme River, France over the 19th century (Piégay and Landon, 1997; Kondolf et al., 2002). In response, the channel has contracted by up to 60% and incised up to 5 m (Landon et al., 1998), and gravel bars have been colonised with woody vegetation (Kondolf et al., 2002). Drastic incision in the Drôme has had two consequences; lowering of the water table across the alluvial fan at its confluence with the Rhone – which support orchards and other high value agriculture - and migration of incision into tributaries, requiring additional grade-control structures to be built. Water-table lowering has led to the loss of an estimated 6 million m^3 of groundwater storage capacity formerly available for agriculture (Kondolf et al., 2002).

Fig. 12. View downstream of the incising bed of Bryans Creek, Victoria, Australia. A renewed phase of incision began in the late 1990s after a sediment pulse passed though. Photo: Glenelg Hopkins Catchment Management Authority.

Feedbacks between vegetation establishment (both on islands and as a riparian buffer), and reduced bedload have compounded the impacts of incision and have led to reduced diversity of riparian ecosystems (Landon et al., 1998).

8.3. Delayed incision

An interesting consequence of a sediment wave is that it can delay processes that are occurring in a stream. A major pulse of sediment migrated into tributaries of the Glenelg River in Australia. Several of these tributaries (Bryans Creek, Wando Vale Ponds, Chetwynd River) were in the process of incising (they are valley floor incised streams) when the sediment moved through in the 1940s. Now, nearly 70 yr later, the sand pulse has passed through, and the channels are returning to their delayed process of incision (Rutherfurd, 2001). Bryans Creek, for example has now incised over a metre since the sediment pulse passed in the late 1990s (Fig. 12).

9. A decision framework for managers

This section draws the management goals, sediment pulse dynamics, and the five intervention options together into a decision framework that managers can use. The framework helps managers decide when to undertake what methods when managing sediment pulses. The framework distinguishes between reaches yet to be affected by the sediment pulse, reaches being affected by the peak of the sediment pulse, and recovering reaches at the tail of the pulse. Each location will have appropriate management methods and managers often use a combination of methods across an affected catchment.

The decision framework (Table 2) links management goals to management actions. The management goals will depend on where the target reaches are in relation to the overall sediment pulse and the scale and celerity of the pulse being managed. Intervention methods can be used in combination, given managers may be dealing with multiple reaches that span all three zones of the sediment pulse. Importantly, if managers want to protect downstream reaches, they might have to opt for direct trapping or removal because reducing supply could take too long to have an effect. The variety of approaches is best illustrated by the use of two case studies, management of a large sediment pulse on the North Fork of Toutle River, Washington, USA, and the Glenelg River, Victoria, Australia (Table 3).

The decision framework can guide where different options are most appropriate in relation to the location of the sediment pulse. Managers will also face decisions about when the most appropriate time to use each intervention option is, the scale at which to implement each option, and where specifically to intervene. In this section insights from the case studies are used to provide guidance on this sequencing.

9.1. When and how can managers control sediment inputs?

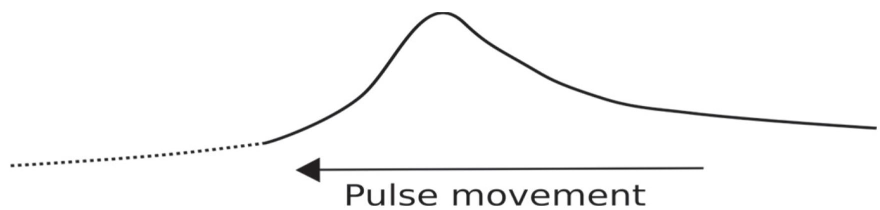
Controlling sediment at its source is the most commonly used method and provides the most long term benefit of the five options. In cases where the activity supplying material to the channel can be stopped, this should be a priority as doing so will limit the size of the resulting sediment pulse. Vegetation and erosion control measures are most effective for diffuse inputs at the catchment scale, but there will be a delay between intervention and reduced inputs. Vegetation takes decades to fully establish so managers can implement source control early and use other options to address the sediment pulse in the near-term.

9.2. How and where should managers trap the pulse?

When managers seek to protect downstream reaches, slowing or halting migration of the main body of the pulse is a priority. Trapping and storing, or extracting sediment at the leading edge of the pulse is one of the most effective and commonly used options to do so. Sediment can be trapped in lower value, upstream reaches where elevated bed levels do not threaten assets. Downstream barriers to sediment movement (which might be constructed first) can be used in conjunction with a sequence of upstream structures that enhance pulse dispersion - reducing the rate sediment is supplied to downstream reaches. By building detention structures in an upstream direction, downstream reaches are always protected and progressively more sediment is immobilised. Because the scale of trapping structures and the size of their storage basins will need to be large enough to trap a meaningful proportion of the sediment pulse, this option is more likely feasible for smaller pulses. However, when the value of downstream assets is high, interventions have been successful in trapping very large sediment pulses, e.g., along the North Fork of the Toutle River, Washington. If trapping sediment is not feasible managers could instead opt to

Table 2
Decision framework managers can use to select the most appropriate management method. The most appropriate method depends on the management goals, which in turn depend on the location of the sediment pulse.

Schematic of the pulse



Pulse stage	Downstream of pulse - not yet affected	Pulse peak	Tail of pulse	Source area
Management goal	Protection	Mitigation	Remediation	Reduce further inputs
	• Avoid damage to infrastructure. Protect restoration assets and high value reaches.	• Reduce flood risk • Reduce risk of avulsion • Maintain navigability • Limit habitat destruction	• Accelerate recovery	
Management actions	• Trap and/or extract at leading edge of pulse • Prepare for high sediment loading, projects to accelerate transport of approaching pulse.	• Accelerate transport, • Store and flush sediment • Trap and extract.	• Stabilise sediment sources • Limit mobility (trap and store)	• Stabilise sediment sources • Cease activity contributing sediment

accelerate transport through downstream reaches by constructing levees, or dredging sediment in high value reaches as the pulse passes through.

Once immobilised, sediment can either be stabilised by vegetation, or extracted from the channel. As with source areas, channel vegetation will take decades to properly establish and will be vulnerable to disturbance by floods and burial by further sediment inputs. Thus, revegetation of stored sediment should proceed in the opposite direction to sediment trapping, i.e., from upstream, where inputs are lower, to downstream. Managers could also use extraction to protect downstream reaches, in which case the annual volume of extraction needs to be as close as possible to the annual volume of sediment supplied to the storage reach.

9.3. How can managers mitigate impacts at the pulse peak?

Mitigating impacts at the peak depth of sediment accumulation, in the main body of the pulse, is best achieved by removing the sediment. This can be achieved by accelerating sediment transport to evacuate the pulse, or where downstream reaches are to be protected, by directly extracting sediment from the channel. Managers will face a balance between mitigating impacts and the potential for secondary consequences of a rapidly falling bed level, for example, tributary rejuvenation and bank instability. In some cases the size of the pulse will be too large for mitigation measures to affect the pulse, and managers might focus instead on building structures to simply protect assets while the peak of the pulse passes through. Managers can use an understanding of the pulse celerity when deciding the most appropriate intervention for such reaches. For example, a rapidly moving sediment pulse will only affect target reaches for a short time, while a slow-moving pulse will require longer term management.

This section has presented a decision framework to help managers align management goals with management actions and provided insights into how managers could sequence these interventions. Ultimately managers are likely to use a combination of the options presented here in different parts of the catchment, depending on the size of the sediment pulse, resources available, and the most urgent management goal.

10. Conclusions

This review has investigated, using case studies, the options available for managers to manage pulses of sediment that move as bed material in rivers. There are now abundant studies into the sources and dynamics of sediment pulses. There are also abundant studies into the problems caused by these pulses, particularly around flooding, avulsions, and environmental effects. The rise of stream restoration has provided another good reason to accelerate recovery of streams from sediment pulses. Placing stream restoration projects in a catchment-wide context, with the help of geomorphologists, can increase their probability of success as they are less likely to be undermined by processes such as the passage of a sediment pulse.

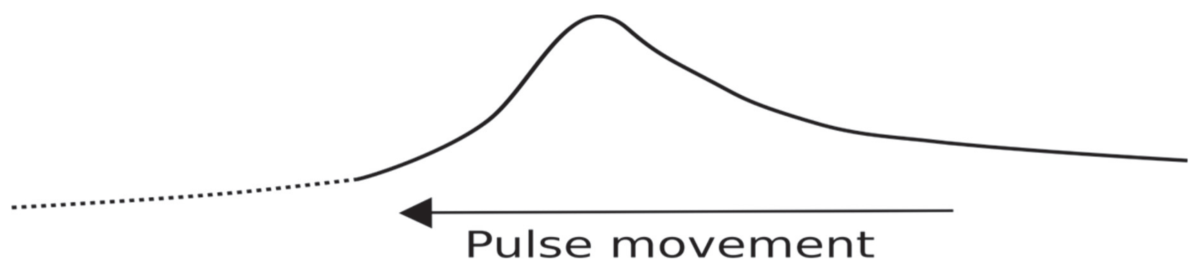
What this review has demonstrated, however, is lack of a correspondingly rich literature on what to do about sediment pulses. The many case studies, and the expanding theory of wave propagation (diffusion, translation, celerity) provide some basis for managers to decide the basic management question: should they do anything about a sediment pulse, and can they do anything about it? The case studies also demonstrate that managers should be aware that sediment pulses can cause secondary channel changes as they move downstream, including widening, avulsions, and tributary interactions.

If managers decide that something needs to be done about the sediment, they have four options: (1) reducing the sediment supply at source, (2) trapping sediment in the channel (3) accelerating sediment transport, and (4) directly extracting sediment. These techniques are not mutually exclusive and can be used in combination. The most common of these actions is undoubtedly to reduce the supply at source. This often happens naturally, and many types of human disturbance are characterised by a declining sediment supply (gully healing for example). While there are examples of catchment management, and mining regulation, that have succeeded in reducing sediment supply to streams, there are far fewer studies of the consequences of that reduction for sediment pulses. The better documented examples relate to generally high sediment loads from catchments (such as the Drôme River in France, or the loess plateau in the catchment of the Yellow River in China), rather than to sediment pulses directly.

The other three management actions for sediment pulses (trapping, accelerating and extracting sediment) appear to be either rarely

Table 3
Decision framework from table two applied to two case studies: management of a sediment pulse in the North Fork of the Toutle River, Washington, USA generated by the eruption of Mt. St Helens in 1980 (USACE, 1985, 2010a,b, 2014) and, management of a series of sediment pulses fed to the Glenelg River by its tributaries after land clearing accelerated catchment erosion (Erskine, 1994; Rutherfurd and Budahazy, 1996; Rutherfurd, 2001).

Schematic of the pulse



Pulse stage	Downstream of pulse - not yet affected	Pulse peak	Tail of pulse	Source area
North Fork of the Toutle River, Washington, USA				
Management goal	Protection	Mitigation	Remediation	Reduce further inputs
	● Maintain navigability of the Colwitz River Preventincreases in flood risk in the lower reaches of the North Fork of Toutle River and the Colwitz River	● Mitigate the increased flood risk for the 50,000 inhabitants of Longview, Kelso, Lexington and Castle Rock	● Not feasible due to the scale of the pulse and ongoing inputs from upstream	● Not feasible
Management actions	● Emergency dredging of the Colwitz River	● Increase levee heights to maintain flood protection standard ● Sediment trapped and stored behind a series of large sediment retention structures, capacity (dam height) increased as required	● Allow vegetation to re-establish and monitor post-eruption recovery processes	● None - not feasible due to size of source area, steep slopes and ongoing disturbance from storms and the potential for future eruptions
Glenelg River, Victoria, Australia				
Management goal	Protection	Mitigation	Remediation	Reduce further inputs
	● Protection of downstream reaches with high environmental value	● Re-instate habitat lost due to sedimentation ● Limit bank erosion	● Accelerate recovery of tributaries	
Management actions	● Extraction from the leading edge of the sediment pulse to protect downstream reaches	● Directly remove sediment from the deepest section of the pulse with commercial extraction in order to protect downstream assets ● Trap sediment using: fencing to exclude stock from the river, which allows vegetation to establish on sand bars and locks sand into storage; grade control structures to limit sediment movement ● Trap sediment in transit by reintroducing large wood removed in the 1960s ● Install bank protection structures to stop bank erosion	● Use fencing to exclude stock from the river and environmental flows to accelerate flshing of sediment downstream	● Reduce sediment supply from gullies by excluding stock, reducing sediment from erosion using re-vegetation and hard structures

implemented, or rarely described. The latter is probably the case. While the authors are aware of situations where sediment pulses have been managed, examples are difficult to find in the literature and we encourage practitioners to publishing their experiences. There is great potential for managing sediment by stabilising benches and bars with vegetation, which can also have the effect of confining flow and narrowing and deepening the active channel. Commercial extraction of sediment to accelerate recovery should also have great potential. If well managed, sale of the sediment could also fund the accelerated restoration of the channel. The literature also demonstrates that any action to control large sediment pulses will have secondary consequences that relate to tributary interactions, and to channel incision.

Finally, a framework that links management goals with management actions is presented. The framework can help managers identify the most appropriate management actions, and the sequencing of those actions through the catchment, based on their management goals.

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