

Local scale interventions accelerate recovery at the tail of a bedload pulse

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Key Points

- Reach scale interventions are used to improve the geomorphic condition of rivers degraded by pulses of bedload sediment (such as sand slugs)
- In Bryan Creek interventions are associated with profound changes in reach morphology, the transitions between different morphologies are abrupt, and coincide with the boundaries of interventions
- Where stock exclusion and bank re-vegetation has been implemented in sand bed reaches, emergent macrophytes (*Phragmites australis* and *Typha*) have colonised the bed and a sequence of deep pools have formed
- In reaches subject to in-stream extraction, or no treatment at all, spiny rush (*Juncus acutus*) has colonised the bed and an erosive, dissected morphology has emerged

Abstract

Sand slugs raise bed levels, destroy habitat and transform channel morphology. In rivers where sediment supply is declining, and the tail of the slug is migrating downstream, managers can undertake interventions to improve geomorphic condition. This research compares the effectiveness of several common, reach-scale (10^2 – 10^3 meters) interventions: fencing to exclude stock, fencing to exclude stock paired with in-stream extraction, and in-stream extraction alone, at improving the geomorphic condition of a river impacted by a sand slug. We expected a meandering low-flow channel, alternating bars, benches and shallow pools would emerge in upstream reaches first, and then steadily progress downstream. Instead we observed abrupt transitions between different morphologies, which coincided with the boundaries of interventions. In reaches where stock have been excluded and the banks re-vegetated (including reaches previously subject to in-stream extraction), emergent macrophytes have colonised the bed and the wide, flat, featureless channel has transformed to a remarkably well-defined sequence of pools. Where stock have not been excluded, beds of spiny rush have established and are dissected by a dense network of low-flow channels. While emergent macrophytes are associated with pool development, it is unclear whether vegetation drives pool development, or pool development provides the necessary conditions for in-stream vegetation to establish. These results suggest emergent macrophytes (also termed in-stream wetlands) could be leveraged to improve geomorphic condition and accelerate recovery in rivers affected by sand slugs.

Keywords

Sand Slug, Bedload Pulse, Recovery, Stock Exclusion, Extraction

Introduction

Bedload pulses are large, slow-moving accumulations of sediment that form when headwater streams deliver unusually large volumes of sediment to lowland rivers, overwhelming their transport capacity (Prosser et al. 2001; Wilkinson et al. 2006; Wohl 2015). These pulses of sediment (often termed sand slugs in Australia) are a common cause of stream degradation in south east Australia, where catchment clearing and conversion to

agriculture accelerated gully erosion and flushed vast quantities of sand into low-gradient streams. As the sediment migrated downstream it filled pools, smothered habitat and caused channels to widen (Abernethy et al. 2004; Davis & Finlayson 2000; Wayne D Erskine 1994; Wayne D. Erskine 1994). The result is a wide, flat channel that is constantly reworked, preventing vegetation growth or habitat development. These sterile bodies of sand provide little environmental, aesthetic or recreational value and limit channel capacity, which increases the magnitude and duration of flooding.

In many catchments historic interventions such as improved cropping practices to reduce runoff intensity, gully stabilization, and riparian planting have accelerated the natural decline of erosion rates, reducing the supply of sediment to lowland streams. Existing models of recovery suggest that channel adjustment will track the downstream movement of the tail of the sand slug, beginning upstream first and gradually moving downstream (Knighton, 1999; Madej, 2001; Sims and Rutherford, 2017; Wohl and Cenderelli, 2000). As adjustment proceeds, stable, alternating bars and benches form, a meandering low flow channel emerges and pools begin to scour (Fryirs & Brierley 2000; Hoyle et al. 2008; Wohl & Cenderelli 2000). In downstream reaches these improvements materialise slowly and managers use local scale interventions ($10^2 - 10^3$ meters in river length) to accelerate the process.

This study uses Bryan Creek, a valley-floor incised stream in western Victoria, Australia that is recovering from a sand slug, to assess the consequence and interaction of three local-scale interventions used to accelerate recovery. They are: fencing to exclude stock from the channel bed and banks, re-vegetation of the channel banks, and commercial sand extraction to starve downstream reaches of sediment. Bryan Creek is an excellent place to evaluate interventions because:

- Erosion control in headwater gullies has aided the natural decline in sediment delivery, and the tail of the sand slug is now migrating downstream, revealing a ~30 km stretch of river in a recovery phase.
- It has experienced a full range of management interventions; extraction, stock exclusion and revegetation, but in different, distinct locations. This pattern of interventions allows us to compare the effectiveness of different interventions, alone and in combination. Further, the resulting pattern of change is remarkably distinct between these reaches, isolating the effect of local interventions.
- A wealth of historical photography, channel surveys and records of management actions exists for the entire river, so interventions can be evaluated over management timeframes (~50 years).

Field Site

Bryan Creek is a tributary of the Wannon River in Western Victoria and has a catchment area of 560 km², most of which lies in the highly dissected Dundas Tablelands. This study focuses on the meandering portion in the floor of the valley, between the Douglas Bridge and Wannon River junction (Figure 1).

Like much of western Victoria (see Yazdanparast, 2016 for a summary) clearing in the early 19th century altered catchment hydrology and initiated widespread erosion in the Bryan Creek catchment (Erskine, 1994; Prosser et al., 2001; Rutherford and Budahazy, 1996). These alterations caused Bryan Creek, originally a chain of ponds, which are intermittently spaced pools separated by densely vegetated, anabranching channels, to first incise and then fill with sediment as a sand slug formed (Eyles 1977; Rutherford 2001). As the sand slug migrated downstream, aided by a 100-year ARI flood in 1946 (Flood Victoria, 2009), the channel widened and the bed transformed into a flat, featureless ribbon of sand with no vegetation on the bed or banks (Figure 3C and E). This pattern of incision generating a deep, wide clay-bed channel that then fills with sand prevents Bryan Creek from ever returning to a true chain of ponds configuration. The flat expanse of sand present in 1946 was the template for the subsequent interventions which are outlined below.

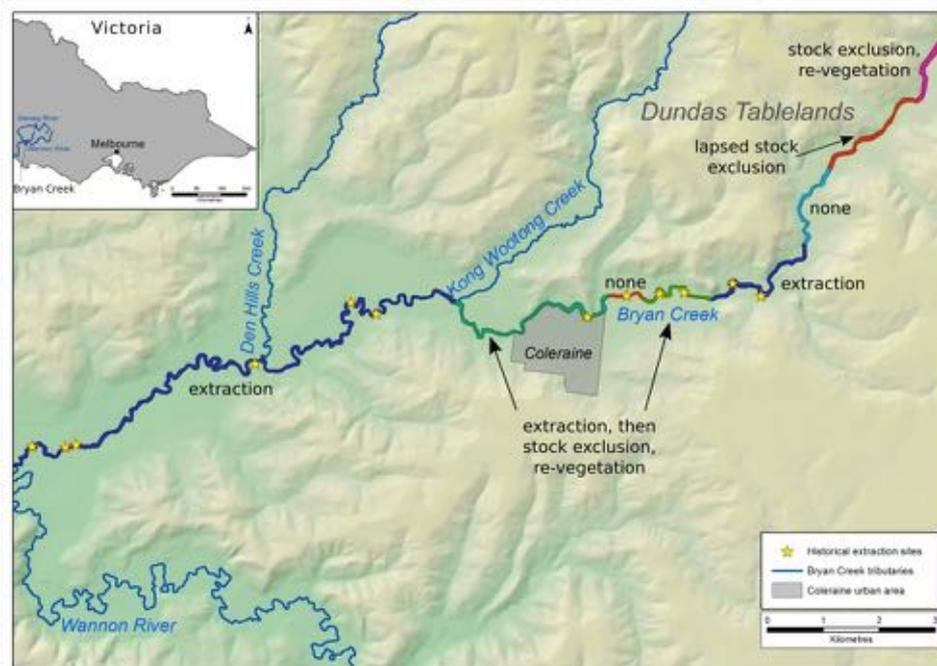


Figure 1: Bryan Creek, western Victoria.

Management Interventions

Each of the management interventions is superimposed on the channel adjustments already taking place along Bryan Creek, which is experiencing a declining sediment supply. As the tail of the slug moves downstream, upstream reaches will begin to recover first and stability will gradually decrease in a downstream direction. We expect that interventions will interact with each other and have the net effect of enhancing this pattern of recovery. We now outline the distribution of the different interventions.

Stock exclusion

Stock suppress vegetation growth by trampling seedlings and feeding on vegetation. Exclusion promotes in-channel sediment storage and channel contraction by allowing vegetation to grow and stabilise bars, benches and the banks (Erskine et al., 2009a; Gurnell, 2014; Gurnell et al., 2016; Sims and Rutherford, 2017). Stock have been excluded from the reach adjacent Coleraine township since at least 1950 (via residential land use), as well as six discrete reaches which had exclusion fencing erected in the late 1980s and early 1990s. Stock exclusion fencing was not maintained in two of these reaches.

Re-vegetation

Re-vegetation is often used to supplement stock exclusion and accelerate reach improvement by stabilising banks and shading the channel (Rutherford et al., 2000). In Bryan Creek re-vegetation was concentrated on the stream banks of reaches where stock was also excluded, and in several upstream reaches that have intermittent stock access.

In-stream extraction

Several studies have identified in-stream extraction as a tool to manage sand slugs, either as a means of starving downstream reaches of sand, or accelerating recovery once the peak of the slug had passed through (Rutherford 2001; Wilkinson et al. 2006; Sims & Rutherford 2017). As in most cases, extraction from Bryan

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Creek, which ceased in 1989, was driven by commercial, not management, imperatives (construction of the Portland aluminum smelter). Over 415,000 m³ of sand was extracted from several discrete, intermittently spaced sites in four different reaches, two of which had stock excluded and their banks re-vegetated when extraction ceased. The sheer volume of material extracted, the lack of additional inputs from tributaries, and the intervening recovery time make this an excellent site to assess whether the sediment deficit caused by extraction accelerates recovery at the tail of a sand slug.

Methods

The approach of this study was to compare the morphology of Bryan Creek pre- and post-intervention for each of the different intervention reaches. We did this both qualitatively, using historical photos, aerial photo and field inspections, and quantitatively, using cross sections surveys. We developed a simple morphological classification to describe the contemporary channel. The classification considers: the condition of the bed, condition of the banks, and the presence (or absence) of different types of vegetation. Comparing the mapped extent of each intervention with our classification allowed the strength (or weakness) of spatial association between intervention and morphology to be established. A strong spatial association between intervention and morphology provides some evidence that changes in morphology are the result of the local scale intervention.

We combined several thalweg surveys from 1984 to establish a pre-interventions baseline. To build a post-intervention profile we combined cross sections surveyed in 2007, LiDAR surveys flown in 2010 where bare sand was exposed, and where there was dense vegetation or standing water, we used an RTK GPS to survey cross sections in 2017. We then de-trended the longitudinal profiles and plotted pre- and post-intervention datasets together to identify any changes in relative bed elevation and structure.

Results

Morphological Boundaries

There is a profound association between the extent of an intervention and the morphology of the reach: rather than a gradual change from upstream to downstream, morphology changes abruptly at the boundaries of interventions (Figure 3A and B). Three distinct morphologies were identified in Bryan Creek:

1. Dissected: a network of low-flow channels cut through beds of Spiny Rush (*Juncus acutus*) and occasional clusters of emergent macrophytes (*Phragmites australis*), some bench development and pervasive erosional features such as bar cut-offs and near-vertical, exposed banks.
2. Sequence-of-pools: channels that alternate between dense stands of emergent macrophytes (*Phragmites australis*) and pools (~2-4 m deep), well-vegetated banks of mature red gums (*Eucalyptus camaldulensis*).
3. Gully: channels that alternates between dense stands of emergent macrophytes (*Phragmites australis*), long, shallow pools (~0.5 – 1 m deep) and wide, flat sections with exposed clay, sporadic in-channel vegetation and high, steep banks.

Stock Exclusion

The impact of stock exclusion in clay-bed reaches has been markedly different than in sand bed reaches. Clay bed reaches are further upstream and have developed a *Gully* morphology. These reaches have incised and contracted since 1947 (Figure 2).



Figure 2: The Douglas Bridge reach (most upstream) of Bryan Creek showing the (A) the original bed with wide, flat channel full of sand, (B) the same location showing the clay bed incising and, (C) aerial view of the same site, looking downstream, showing bank re-vegetation and gully morphology. Photo source: A- Coleraine Historical Society, B- Glenelg Hopkins Catchment Management Authority, C- Alex Sims.

In the sand bed reaches where stock have been excluded (further downstream) the featureless sheet of sand has made a remarkable transformation to a *sequence-of-pools* morphology. Pool development progressed the same way in all sand bed reaches, regardless of when exactly stock were excluded (late 1950s cf. late 1980s): a steady transition from a braided morphology to a well-defined, meandering low flow channel in an unvegetated sand bed (sometimes over several decades), emergent macrophytes (*Phragmites australis* and *Typha*) sporadically colonise the bed and pools start to develop and then, as vegetation spreads across the width of the channel, pool development accelerates and they stabilise (Figure 3C-F).



Figure 3: (A and B) Boundaries between different interventions where morphology abruptly changes from dissected to sequence-of-pools, (C) looking downstream into the reach adjacent Coleraine in 1944, (D) and in 2017, (E) looking downstream into the reach immediately below Coleraine in 1944 and (F) in an aerial view of the same reach in 2017. Source: C and E- Coleraine Historical Society, A, B, D, F- Alex Sims.

Re-vegetation

Bank re-vegetation accompanied stock exclusion, but trees were also planted in two reaches where fencing was either not maintained or never installed. The bed of these reaches was sand when seedlings were planted, but both are now a combination of clay and a thin, intermittent veneer of sand and fine gravel. We classify these reaches as having a *dissected* morphology (Figure 4). The banks in these reaches are near vertical, several metres high and do not shade the low flow-channels.



Figure 4: A 2017 aerial view, looking downstream into a reach that had its banks re-vegetated in 1989. Source: Alex Sims

In-stream Extraction

Reaches subjected to in-stream extraction have a *dissected* morphology and are indistinguishable from the reaches not treated by intervention of any kind. Despite having a similar morphology preintervention, the 12 km long extraction reach downstream of Coleraine has high banks and bank-attached benches, while the extraction reach upstream of Coleraine has no benches and low, steep banks (Figure 5). spiny rush (*Juncus acutus*) was absent from these reaches as recently as 1994 (Figure 5C) but is now pervasive.

Thalweg variability

Figure 6 illustrates the relative elevation of the thalweg, pre- (1984) and post- (2017) intervention. The most dramatic change in thalweg elevation coincides with the sequence of pools which have formed in the sand bed reaches subject to extraction then stock exclusion and re-vegetation. In these reaches pools have scoured the bed at the same time the 'riffles' separating them have aggraded. Upstream reaches with a clay bed morphology have incised (relative thalweg elevation has decreased) while the extraction reaches immediately below them have aggraded since 1984. The lower 12 km of the river, where in-stream extraction was widespread until 1991, exhibits both minor aggradation and incision since 1984, with the boundaries of these zones coinciding with road crossings that fix bed elevation. While changes in thalweg elevation have varied according to intervention, all reaches have a net loss of sediment since 1984.

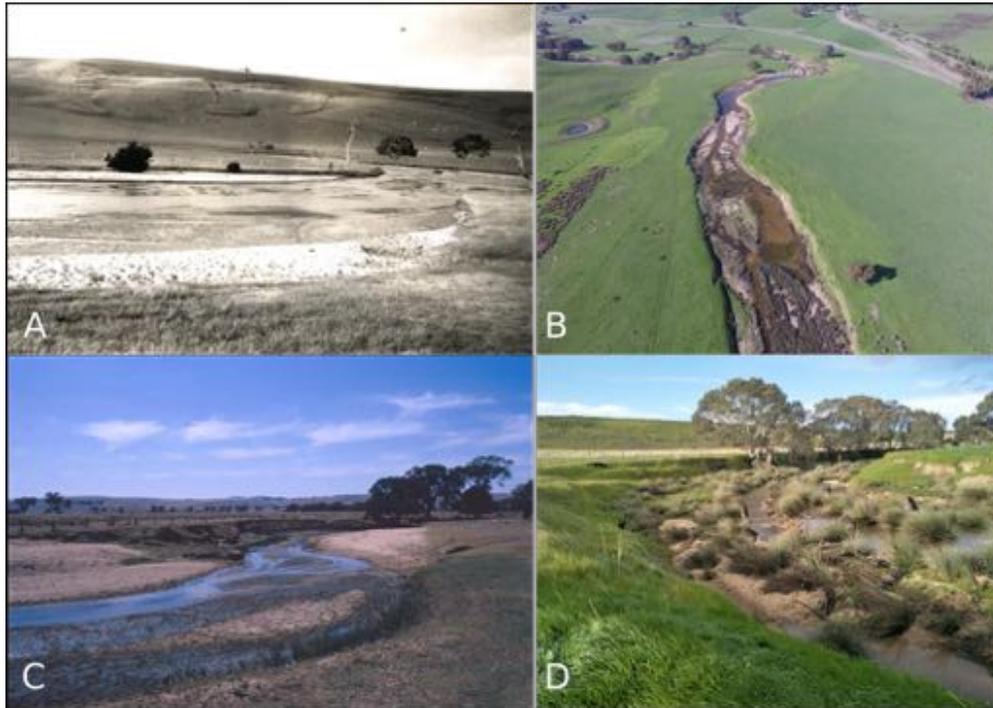


Figure 5: Reaches subject to in-stream extraction (A) immediately above Coleraine in 1946, (B) aerial view looking upstream into the same reach in 2017, (C) looking upstream in the downstream extraction reach in 1994, (D) looking downstream into the same reach in 2017 where a dissected morphology has emerged. Source: A- Coleraine Historical society, C- Ian Rutherford, B and D – Alex Sims.

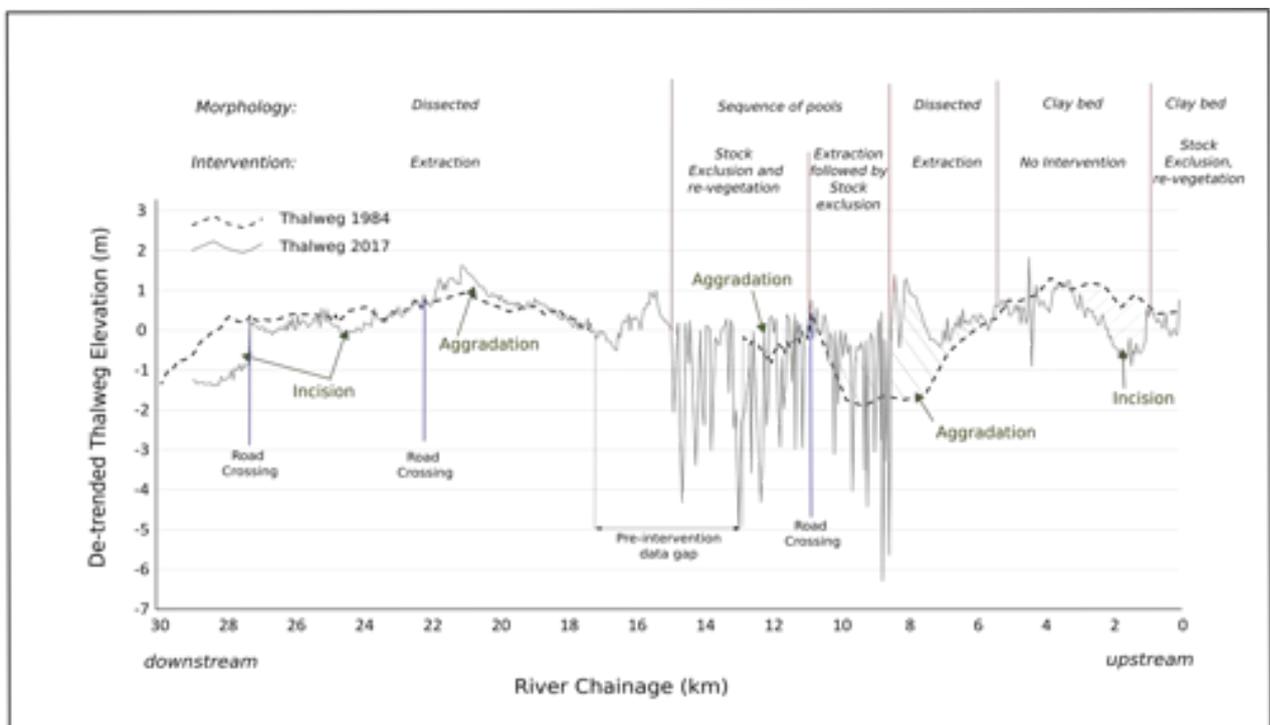


Figure 6: De-trended longitudinal profiles of the pre- and post-intervention thalweg of Bryan Creek, with intervention type and the 2017 morphology classification superimposed.

Discussion and Conclusions

This study examined how reach scale morphology changes when local scale interventions are superimposed on the tail of a sand slug. We expected interventions to accelerate the existing pattern of channel adjustment, and for improvements in geomorphic condition to track the gradual downstream movement of the sand slug, with upstream reaches being further along this recovery trajectory than those further downstream (Madej 2001; Bartley & Rutherford 2005). Instead, Bryan Creek alternates between three completely different morphologies: gully, dissected and sequence-of-pools. Morphology in Bryan Creek varies by substrate (clay vs. sand) and intervention type (in-stream extraction, re-vegetation and stock exclusion).

The most important finding of this study was that in reaches where stock have been excluded, emergent macrophytes have colonised the bed and a sequence of deep pools have formed. This morphology, and its sharp boundaries, stands in contrast to existing models of channel change at the tail of a sand slug. While there is an association between emergent macrophytes and deep pools, it is unclear whether the vegetation drives pool development or if pools develop independently, and in turn provide suitable conditions for in-stream vegetation. However, aggradation between pools suggests emergent macrophytes are trapping and storing sediment on the channel bed (Figure 6), a phenomenon observed in other streams affected by excess sediment (Zierholz et al. 2001; Erskine et al. 2012).

Clay bed reaches appear to be adjusting to the decline in sediment supply by resuming a trajectory of slow incision and gully development (Bartley & Rutherford 2005). Incision in these reaches is concentrated into a several narrow low-flow channels that appear to prevent pools from scouring. The morphological changes caused by intervention in clay bed reaches are overwhelmed by the catchment-scale changes driving gully development.

In sand bed reaches the major determinate of geomorphic condition is whether stock can access the stream bed. Where stock can access the bed, emergent macrophytes are suppressed and the salt-tolerant spiny rush dominates. A dissected morphology dominates extraction reaches, including the long reach downstream. Spiny rush act as erosion-resistant nodules that concentrate flow into narrow channels. At the same time the bed adjusts to the extraction-induced sediment deficit, leading to the dissected morphology (Figure 5B and C). It is unclear whether the beds of spiny rush lock sediment into storage by shielding underlying sand from erosion, or whether they simply divert flow and change the distribution of scour, leading to no net change in storage. The geomorphic condition of dissected reaches is not meaningfully better than the flat expanse of sand present pre-intervention. Starving downstream reaches of sediment does not, on its own, appear to accelerate improvements in geomorphic condition.

Conclusion

A sequence of deep pools has developed in sand bed reaches where stock have been excluded. These reaches show the greatest improvement in geomorphic condition compared to their pre-disturbance morphology. This suggests that in-stream vegetation, which is able to establish once stock are excluded, is a key driver of improved geomorphic condition, and possibly pool development, in streams impacted by sand slugs.

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