Sell the sand to save the river: how in-stream extraction accelerates recovery from a sand slug

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Key Points

- Hundreds of kilometres of streams across Australia have been degraded by excess sediment inputs. In-stream sediment extraction has the potential to accelerate the recovery of these degraded streams.
- Extraction from deep, long discrete extraction pits minimizes channel disturbance while maximizing sediment rapping within the pits.
- In-stream extraction accelerated the recovery of the reach, but only in sections where stock had also been excluded and vegetation had established on the streambed.
- In-stream extraction and stock exclusion can be used together in rivers impacted by sand slugs to accelerate recovery.

Abstract

Hundreds of kilometres of Victorian streams have been permanently altered by sediment pulses triggered by accelerated catchment erosion. Sediment inputs have since declined, and downstream reaches have entered a recovery phase. In-stream sediment extraction has the potential to accelerate the recovery of these degraded streams.

This study examines an 8 km reach of the Glenelg River which has previously been degraded by a sediment pulse and has been treated with managed in-stream sand extraction since 2010. Repeat cross-section surveys, extraction records and hydraulic and sediment transport modelling were used to build a decadal scale sediment budget for the reach. Channel morphology and the type and distribution of riparian and in-channel vegetation was also mapped.

In-stream extraction accelerated the recovery of the reach, but only in sections where stock had also been excluded. In reaches fenced to exclude stock, cross-section and thalweg variability was higher, in-stream vegetation more abundant and the diversity of habitat notably higher. The improvements in river condition were driven by the tendency of in-stream vegetation (Phragmites) to trap sediment and increase bed variability. In reaches with unfettered stock access, erosion lowered bed levels but did not generate a meaningful increase in channel complexity, the number and size of pools, or overall stream health.

The results of this study show that the sediment deficit caused by in-stream extraction, or other means of decreasing reach sediment supply, can accelerate the recovery of sand bed streams from a sediment pulse, but only when stock are also excluded from the channel.

Keywords

Sediment pulse, sand extraction, river recovery, in-stream vegetation, Glenelg River

Introduction

Extraction of sand and gravel from streambeds is usually driven by commercial imperatives: extracted material is sold as an input to cement production or as aggregate for roads (Torres *et al*., 2017). Most studies documenting the geomorphic impacts of in-stream of extraction have also focused on historic commercial over-extraction, usually in gravel bed rivers (Mathias Kondolf, 1994; Padmalal et al., 2008; Rinaldi et al., 2005). However, in-stream sand extraction has the potential to be used as a management tool: to remove contaminated sediment (Melbourne Water (2019), or accelerate the recovery of rivers impacted by a bedload pulse (Sims & Rutherfurd, 2017; Wilkinson et al., 2006).

The basic premise of using in-stream sand extraction to accelerate river recovery is that extraction decrease sediment supply to downstream reaches, so that sediment stored on the channel bed erodes, filled pools re-scour and channel recovery begins. We define recovery as an increase in channel complexity, the return of a well-defined low-flow channel, stable in-channel bedforms that support vegetation and an increase in in-stream habitat (pools and smaller scour holes).

Because the use of in-stream extraction to accelerate recovery is not well documented in the literature, the most appropriate extraction technique and the impact of extraction on downstream reaches is poorly understood. This research addresses this gap by documenting extraction technique and the type, magnitude and downstream extent of channel adjustment downstream of extraction pits excavated in the bed of the Glenelg River, Australia.

Study site

Catchment clearing in the mid to late 19th century triggered widespread erosion in gullies and tributaries feeding the Glenelg River. Increased erosion delivered large pulses of coarse sand to the Glenelg River and its tributaries. Sand slugs are now the major geomorphic control on in-stream habitat and recreational opportunities in the upper catchment. The migrating pulses bury large wood on the streambed, fill pools and smother habitat on the bed. In sections with deep but permeable sand deposits, low flows move downstream through the body of sand, rather than as surface flow, which disconnects the river during the dry summer months.

Catchment sediment supply has since declined, and many reaches of the Glenelg River are entering a recovery phase. Managers intervene to prevent (or at least slow) pulses entering the highly valued estuary reach, to protect remaining habitat pools form sand ingress, and to shape the morphology developing at the tail of the pulses, where sand deposits are being reworked.

This study concentrated on an 8 km long reach of the Glenelg River adjacent the township of Casterton (Figure 1). The study reach has been impacted by a sand slug and was subject to periodic commercial sand extraction between 1990 and 2010. The most recent phase (2010-2018) of managed in-stream extraction has been undertaken with the aims of protecting habitat pools in downstream reaches and accelerating river recovery. Sand extraction is undertaken by a private company (but regulated by the Glenelg Hopkins Catchment Management Authority) who fund extraction via sale of the sand.

Methods

Extraction records were used to quantify the total volume of sediment removed from the reach between 2010 and 2018. Interviews with extractors and a review of available repots were used to document the technique used to extract sand from the bed of the Glenelg River, and the impact repeated extraction had on the banks surrounding extraction sites.

Channel change immediately upstream of extraction pits, and in the reaches downstream of extraction pits, was quantified using repeat channel cross-sections surveyed in 2005 and again in 2018. A single variability metric was calculated for each cross-section (std deviation of cross-section depths) for both 2005 and 2018 and was used as a proxy for channel complexity. Field inspections aided by a small UAV were used to map in channel features (bars, benches and low-flow channels), the type and extent of in-stream vegetation and to aid the development of a simple morphological classification.

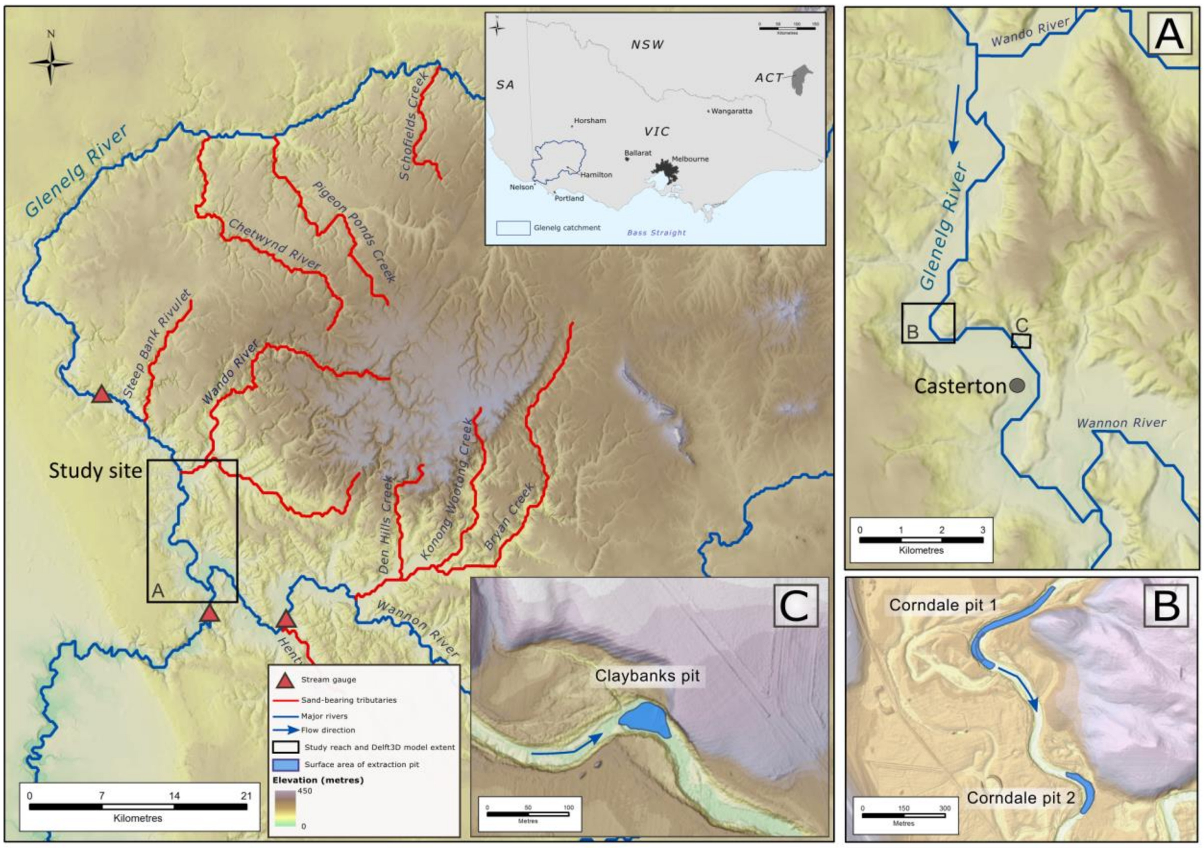

Figure 1. The study reach adjacent the township of Casterton, within the Glenelg River catchment, location of the three main extraction pits shown in blue. Sand-bearing tributaries that inject sediment into the Glenelg River are shown in red.

Results

Extraction technique

Historically a combination of bucket excavators, drag-line excavators and front-end loaders have been used to remove sand from the bed of the Glenelg River. The resulting extraction 'pits' varied in depth and width, and often disturbed large areas of the stream bed. Since the mid-2000s the Glenelg Hopkins Catchment Management Authority (GHCMA) has worked with extractors to minimise disturbance to the river bed and protect the channel banks from being undermined during extraction. These more 'environmentally sensitive' techniques are driven by a shift in how the GHCMA manage in stream extraction in the Glenelg River: from a passive role that focused on coordinating removal of a commercial resource, to the use of extraction as a management tool that is funded through the sale of extracted sand.

Overall, the extraction reports and interviews with extractors has led to four main findings:

1. The deep, discrete extraction pits excavated in the Glenelg River do not disturb the channel banks, they have been excavated in straight sections and at the toe of point bars. Not every pit at every extraction site is excavated each year.
2. Extraction pits are excavated in an upstream direction, as excavators 'back-out' of the channel. On meander bends, excavation starts from a temporary sand platform on the point bar and bed on the outside of the meander is removed first (Figure 2). The temporary platform is removed last, leaving a discrete pit. The extraction technique leaves a pit that resembles extraction pits modelled in flume studies.

3. When two pits are excavated at the same extraction site, both pits begin to re-fill at the same time (the upstream pit did not 'protect' the downstream pit from filling). Each pit fills at a different rate.
4. The rate pits re-fill depends on the magnitude and frequency of winter flows, which are stochastic. Pits completely re-fill during floods and sheets of sand are deposited on the streambed between pits.

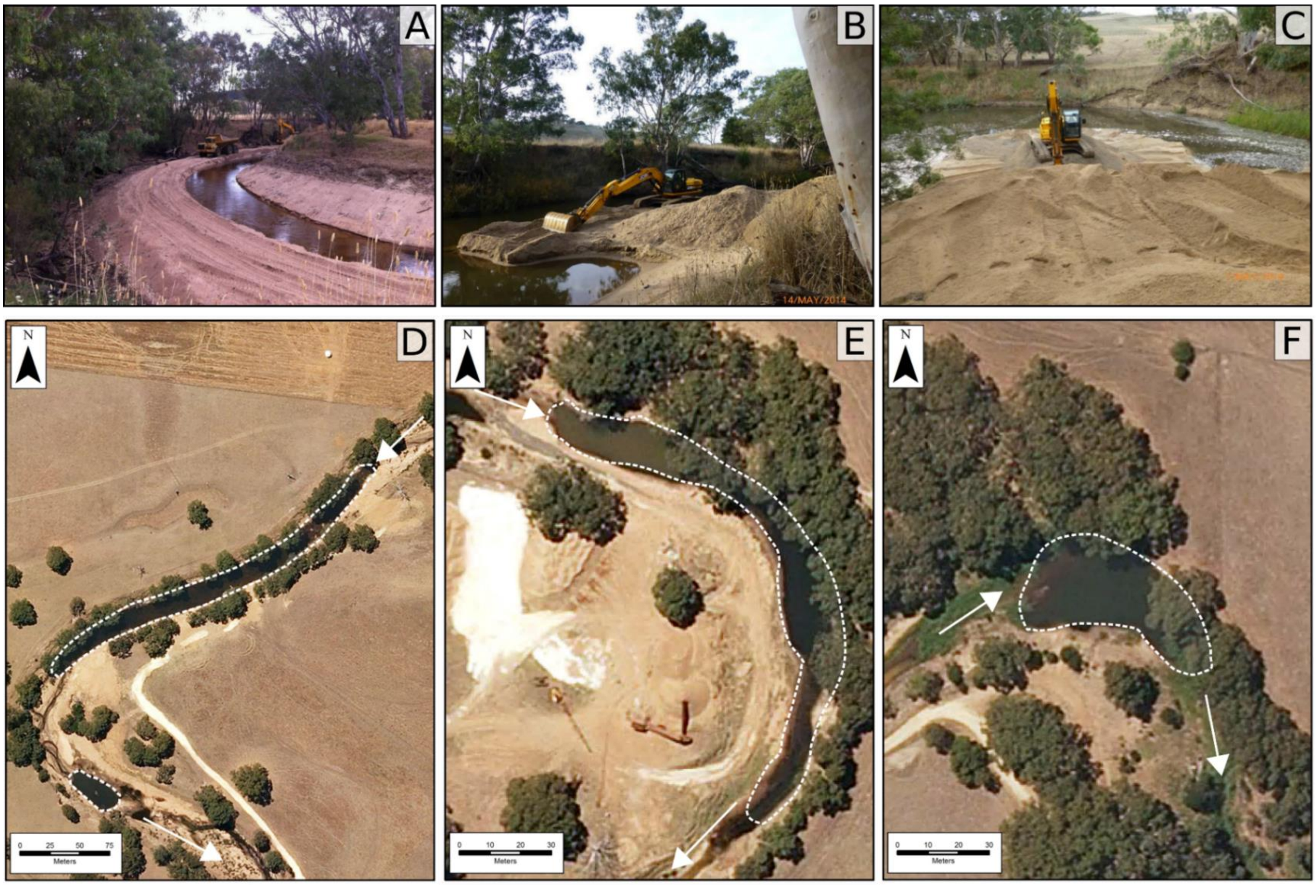

Figure 2. The extraction technique used in the Glenelg River (A) looking upstream at an extraction access ramp on the bend of the river, (B) an excavator in the final stages of 'backing-out' from an extraction pit in the bed of the river, (C) an excavator on the remainder of a platform during point bar removal on a sharp meander bend, (D) plan view of two pits immediately after excavation at the Corndale extraction site, (E and F) plan view of freshly excavated extraction pit at the toe of a point bar at the downstream end of the Corndale extraction site and the Claybanks extraction site, respectively. Photos A-C supplied by Vickery Bros, aerial photos D-F were captured in 2010, as part of the Victorian Index of Stream Condition program, white arrows show flow direction.

Chanel morphology

Overall, the study reach is comprised of two different morphologies which we term *upstream* morphology and *downstream* morphology. The *upstream* morphology is confined to the section of the reach upstream of the Claybanks extraction site. Stock can freely access the riverbed in this section (although this is somewhat restricted on meander bends with very steep banks). The *upstream* morphology contains three extraction pits. The *downstream* morphology is the remaining, downstream portion of the study reach and includes the Claybanks extraction pit (extracted twice over the study period). Stock cannot access the streambed in this reach, due to a combination of stock-exclusion fencing and residential land use adjacent to the river.

The *upstream* morphology is generally a flat, featureless sheet of sand that meanders through irregular, low-elevation benches on the channel margins (although at some cross-sections these benches are absent entirely) (Figure 3). The channel banks support sparse, discontinuous stands of mature vegetation (mainly *Eucalyptus camaldulensis* and *Eucalyptus globulus*), but few trees shade the low-flow channel (Figure 3A). Steep, eroding banks are common in straight sections and on the outside of meander bends. Bank erosion is most pronounced in a highly sinuous sub-reach that includes bank protection structures, some of which have collapsed (Figure 3C) and exposed clay on the channel bed. Abundant in-situ tree stumps are exposed in the bed (having been previously buried by sand, or sawn off in-situ during 'de-snagging' in the 1960s) (Figure 3A and B). The inner margins of some of the benches have been colonised by red gum seedlings (*Eucalyptus camaldulensis*) and small patches of spiny rush (*Juncus acutus*) have established on the benches. Some isolated stands of *Phragmites australis* have established in meander bends with high banks and limited stock access.

Figure 3. The morphology of the upstream part of the study reach showing (A) the low-flow channel immediately downstream of Corndale pit 2, looking upstream, erosion has exhumed abundant in stream wood that was previously buried, (B) the low-flow channel with remnant island in the channel, (C) bank protection structures on the outside of a meander bend (flow is from right to left), (D) the low-flow channel inset within benches, showing exposed tree stumps on the channel bed.

The *downstream* morphology is very different from the *upstream* morphology. A deep low flow channel cuts through benches and bars, most of which have been colonised with dense stands of *Phragmites australis*. The banks support mature vegetation (also a mixture of *Eucalyptus camaldulensis* and *Eucalyptus globulus*) that shade the low-flow channel (Figure 4). Several portions of the banks exhibit signs of erosion, especially on the outside of meander bends. Several small, *Phragmites*-covered islands occur within the active portion of the channel, and sand is accumulating at their downstream margin (Figure 5). There are deep pools on the outside of several meander bends (Figure 4B). Aerial imagery shows these pools were in place by 2010 and have not changed in size. Isolated scour holes have developed on the surface of several of the benches and bars, despite the cover of *Phragmites* (Figure 6).

Figure 4. The morphology of the lower section of the study reach, where stock have been excluded from the riverbed and *Phragmites* have colonised many surfaces, showing (A) *Phragmites*-lined benches on the channel margins, which support some mature vegetation near the base of the adjoining bank, and a deep low-flow channel, (B) bank erosion and collapse of vegetation (flow is from away from viewer), (C) a deep low-flow channel cutting through *Phragmites*-covered benches that have been partially eroded and, (D) The uneven colonisation of the channel margins by *Phragmites* which have established on the true left (left of the image) but not on the true right in this part of the channel. Here the low-flow channel is relatively shallow.

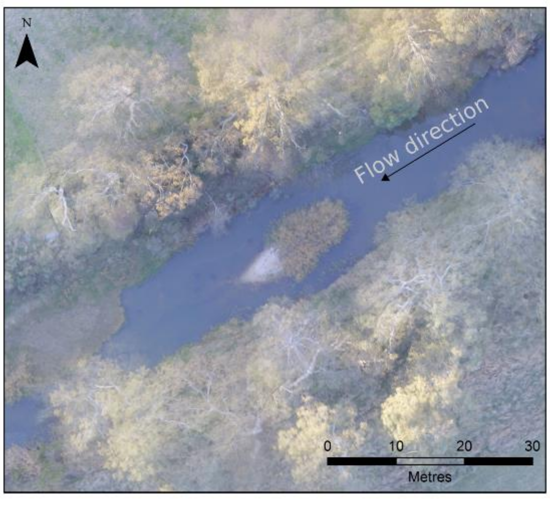

Figure 5. A mid-channel bar that has been colonised by *Phragmites*, with sand depositing in the lee of the bar.

In segments where bars and benches are subtle and have low relief (relative to the thalweg) *Phragmites* have spread across the entire feature. In sections where features have much greater relief, such as steep point bars or 'benches' that slope upwards towards the channel banks, *Phragmites* tend to be confined to the lower sections, where they line the margins of the low-flow channel. Higher-elevation sections of bars and benches are usually bare sand or are covered by short grasses (Figure 6A).

High-resolution aerial mapping using a UAV revealed that even when cross-section surveys documented bench aggradation, this pattern is longitudinally discontinuous. Several of the 'aggrading' benches also exhibit scour zones on their surface, whether they have been colonised by *Phragmites*. Bench scour occurs at the head and tail of bars, as elongated patches on the bench/bar surface (Figure 6) and as cut-off channels against the toe of adjoining banks (Figure 6C).

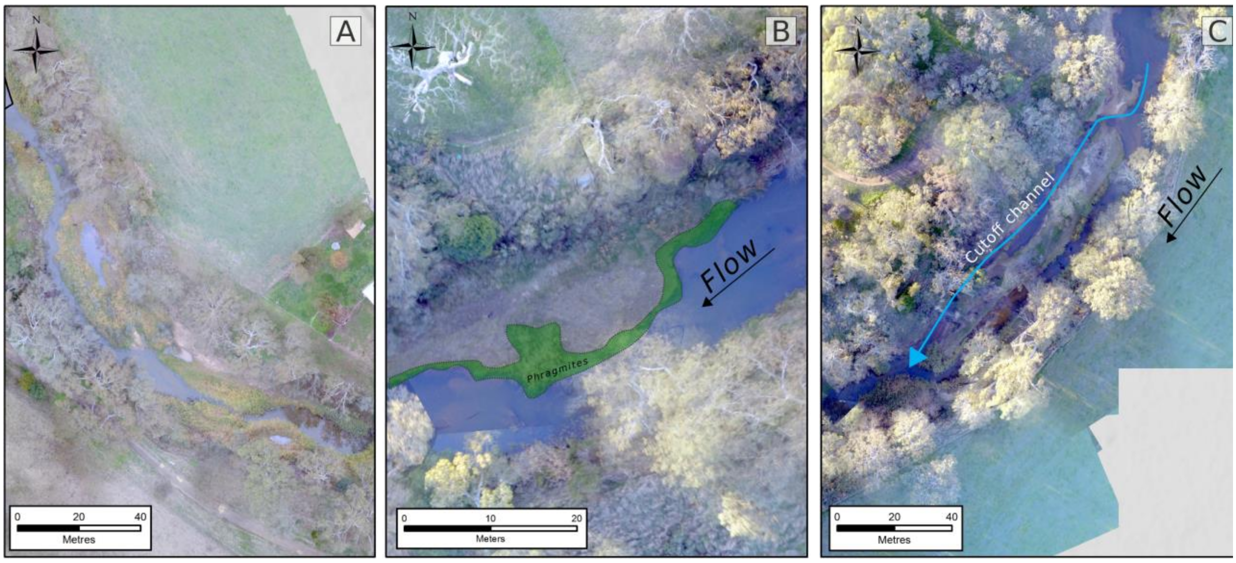

Figure 6. (A) benches and point bars covered in Phragmites with elongated scour holes forming, (B) *Phragmites* line the low-elevation margin of a feature, (C) a cut off channel dissecting a *Phragmites* covered bench in the downstream section of the study reach.

Changes in thalweg elevation

Between 2005 and 2018 thalweg elevation decreased (the bed eroded) at most cross sections (Figure 7). Thalweg elevation increased (the bed aggraded) at a small number (n= 5) of cross-sections, but these cross sections were an exception to the overall trend: increasing bed erosion with distance downstream.

The decrease in thalweg elevation was most pronounced in the downstream morphology. Interestingly, thalweg elevation changed very little in the un-vegetated stretch of river between the Corndale extraction pits and the Claybanks extraction pit (2.5-4 km downstream of Corndale pit 1).

Channel complexity

The two distinct channel morphologies described above gave rise to two different levels of channel complexity, which was quantified using the standard deviation of cross section elevations. In 2005 the upstream morphology was less complex than the downstream morphology (Figure 8). Channel complexity increased for almost every cross section between 2005 and 2018. As a result, the 2018 pattern of cross section variability follows the same trend as it did in 2005, but overall complexity was higher in both parts of the study reach (Figure 8).

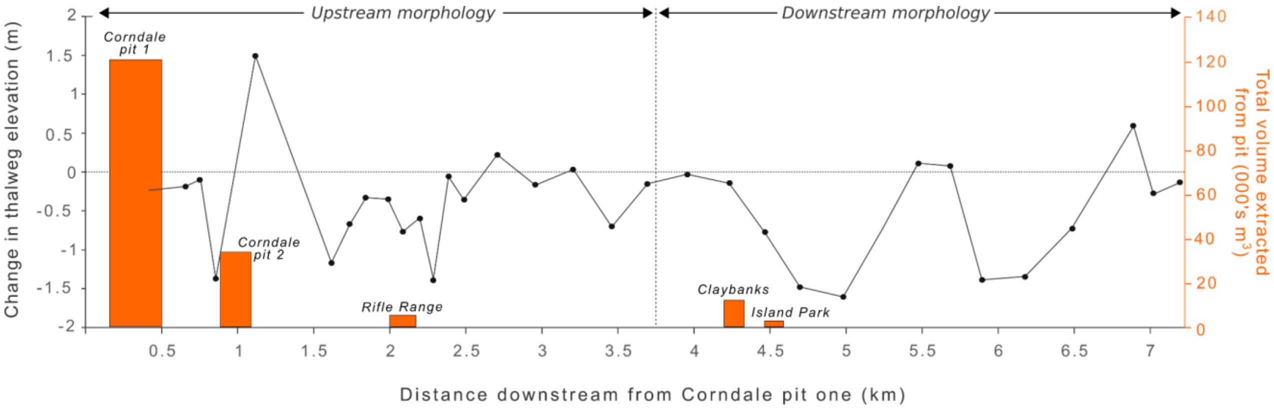

Figure 7. Longitudinal profile of change in thalweg elevation between 2005 and 2018. The height of orange bars denotes the total volume of sand extracted from each pit between 2005 and 2018 and the width of each bar denotes the length of streambed occupied by the pit, pits are labelled.

The average increase in the standard deviation of cross section elevations was 0.38 standard deviations in the upstream morphology but only 0.19 standard deviations in the downstream morphology. The exception to this pattern was a segment downstream from Corndale pit 2 (between 1 and 1.8 km downstream of pit 1), where complexity slightly decreased between 2005 and 2018.

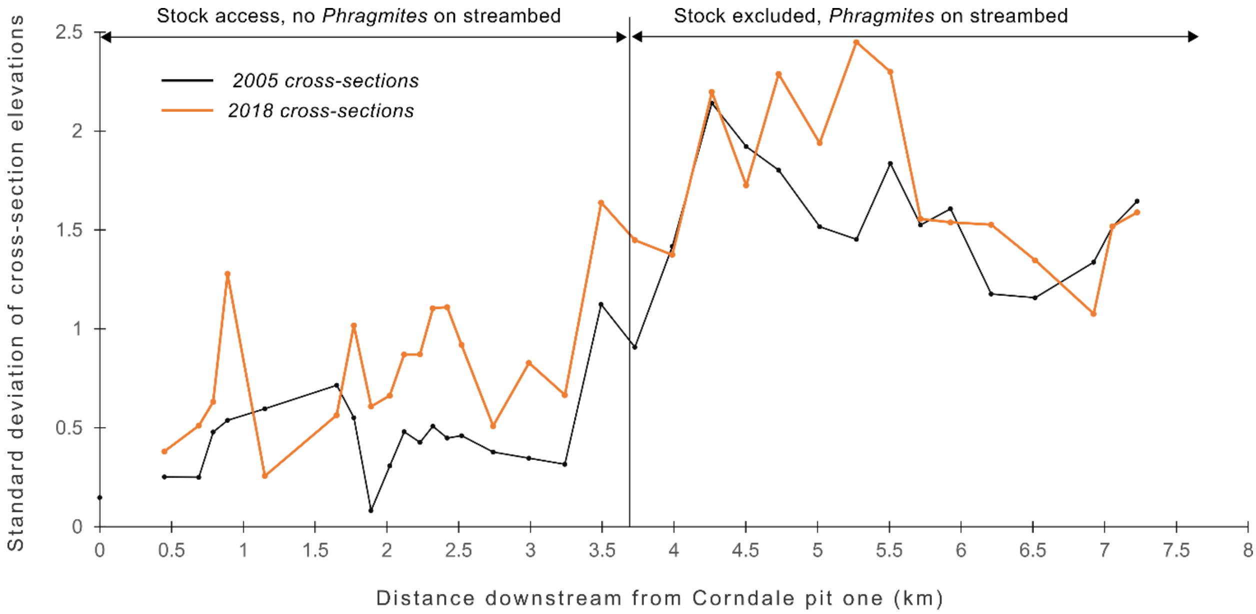

Figure 8. Standard deviation of cross-section elevations in 2005 (black) and in 2018 (orange) for the study reach. Stock have been excluded downstream of 3.7 km mark since at least 2000.

Discussion

Channel adjustments downstream of extraction pits are complex. Bed erosion is greatest in the most downstream part of the reach, rather than the sections of river immediately downstream of the extraction pits. The stark difference in morphology between the upstream and downstream sections of the reach is mirrored by a shift from lower channel complexity to higher channel complexity. We now consider the controls on channel adjustment downstream of extraction pits and the important role of in-stream vegetation in accelerating river recovery.

Controls on channel adjustment

The complicated series of changes in thalweg elevation and sediment storage are partially explained by the pre-existing shape of the channel (width, depth and slope), which determine the magnitude and distribution of bed shear stress and sediment transport. This variation in bed shear stress across the channel and along the reach determines where flow energy is concentrated and sets the overall boundary on the channel evolution. However, in sand-bed rivers such as the Glenelg River, in-stream vegetation plays a fundamental role in controlling how the channel responds to extraction. For example, studies of the downstream impact of extraction have shown that incision of the low-flow channel can promote vegetation growth on channel benches (Calle *et al*., 2017), which promotes sediment storage *or* lower water tables can inhibit vegetation growth on benches (Martin-Vide *et al*., 2010), which promotes erosion.

How in-stream vegetation impacts recovery

Many of the bars covered in *Phragmites* have been dissected by scour (i.e. *Phragmites* does not prevent *all* erosion), and several islands in the channel appear to have originally been connected to the adjacent benches. This scour, which occurs on the surface of bars and benches elevated several metres above the channel bed, necessarily occurred during larger, deeper flows. At the same time, sand appears to be accumulating in the lee of small *Phragmites*-covered islands in the channel bed. Assuming the *Phragmites* encroach onto these fresh deposits and stabilise them, sand may be transferred from eroding benches to accumulating islands. The fate of these *Phragmites* is either continued aggradation to form more elevated islands that can be colonised by other species (i.e. they proceed along the biogeomorphic succession path, Corenblit *et al.* (2007), partial degradation to become wetland features (Gurnell, 2014), or complete removal by erosion. At present, these features are moving towards the wetland phase and if extraction continues to starve sediment to the *downstream* morphology, they will be removed entirely.

The point here is that the presence of vegetation on the channel bed changes how the erosion caused by upstream extraction is expressed. When stands of *Phragmites* can colonise channel landforms and divert flow, scour becomes more concentrated, and bed relief increases. This explains why thalweg erosion was so pronounced in the *downstream* morphology, even though 87 % of the total volume of sand extracted was excavated from pits 5 km upstream. The lack of in-stream vegetation between the upstream pits (where most sand was removed) and the start of the *downstream* morphology also explains why thalweg scour was so much less in this segment: erosion was distributed across the entire width of the streambed. Some exposure of the more resistant clay bed may also have limited thalweg erosion in this middle segment of study reach.

Interventions to accelerate recovery

Stock can access most of the *upstream* morphology, where they suppress the growth of emergent macrophytes such as *Phragmites*. The absence of these suitably adapted species means sediment is not readily trapped, pioneer landforms (*sensu* Gurnell, 2014) such as bars and benches are not built and the scour caused by extraction is more widely distributed across the channel bed. As a result, a wider low-flow channel develops and cross-section are less complex than their vegetated counterparts. Despite the decrease in sediment supply caused by extraction the upstream morphology has made little improvement in overall condition. Conversely, the downstream reach, where stock have been excluded, has made substantial improvements in condition under a similar sediment deficit. The interaction of sediment starved water that drives erosion and localised portions of erosion resistance caused by *Phragmites* has generated a much more complex channel that is in better overall condition.

Conclusions

The combination of in-stream sand extraction and the growth of in-stream vegetation has accelerated the recovery of a reach impacted by a sand slug. This research has demonstrated that extraction alone is insufficient to accelerate river recovery and that stock exclusion, which allows in-stream vegetation to establish, should be paired with extraction to accelerate recovery. In-stream vegetation should also be effective at improving channel complexity in other reaches experiencing a sediment deficit.

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