The use of long-term monitoring data to inform the analysis of, and prognosis for, an incised stream system: The Cann River in Far East Gippsland, Victoria, Australia

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Key Points

- *The floodplain reach of the Cann River in Far East Gippsland has been subject to historic channel incision.*
- *A program of grade control and revegetation commenced following a major flood in 1998 to limit ongoing incision and initiate channel recovery.*
- *A long-term program of monitoring has been undertaken to assess the channel response to the interventions.*
- *The monitoring program has revealed bench formation and vegetation establishment. However, the monitoring program has also revealed net sediment export from the reach and associated ongoing channel incision.*
- *The monitoring program has also identified a potential decline in long term sediment supply to the floodplain reach.*
- *The authors hypothesise that ongoing incision in the subject reach is a function of the ongoing decline in sediment supply to the reach and that channel adjustments including channel incision will continue until sediment transport capacity within the reach matches sediment supply.*

Abstract

The floodplain reach of the Cann River, located in far East Gippsland, is a sand bed river that has been transformed by large-scale channel incision triggered by post European settlement floodplain clearing and removal of large wood from the channel. Following a large flood in 1998, a long-term program of management, aimed at limiting the scale and extent of channel incision was initiated by the East Gippsland Catchment Management Authority. The subsequent monitoring and evaluation program provides a rare opportunity to evaluate the effectiveness of this extensive program of grade control, implemented over a river length of tens of kilometres, and to guide future management.

We used Cann River monitoring data (repeat LiDAR, longitudinal bed profiles, aerial photo imagery and vegetation mapping) collected and analysed over the last 25 years to describe the response in the Cann River to both catchment processes and the management interventions. We use these insights to predict the ongoing response of the system in the absence of management intervention, and to explore implications for management.

The monitoring program revealed channel recovery within the subject reach of the Cann River including developing instream, bench and bank vegetation communities. However, the monitoring has also revealed persistent channel adjustments including an ongoing net loss of sediment from the reach, and a pattern of decline in the bed grade between structures. Bed sediment upstream of the intervention reach has coarsened, which we interpret to be due to a decrease in sediment supply, suggesting the potential for a renewed phase of channel incision within the floodplain reach.

Keywords

Incision, Recovery, Geomorphology

Introduction

Grade control programs, which typically consist of installing one or more structures along the bed of a channel, have seen widespread use in addressing incision in waterways in Australia and internationally. Effective grade control programs halt the incision cycle by decreasing channel grade over one or more lengths of channel, reducing stream power, promoting sediment deposition and vegetation establishment. Once fully established, vegetation provides the erosion resistance and roughness elements that aid channel 'stability' (in the sense that rates of bed level change are low or minimal) in the long term. In most cases, such grade control programs have been implemented in smaller waterways or gullies. Although grade control programs in these smaller waterways have been demonstrated to be effective at halting incision and aiding vegetation establishment, we are not aware of any studies that assess their effectiveness in larger waterway and over greater length of channel (10's of kilometres).

This paper addresses this gap by evaluating the effectiveness of a substantial grade control program implemented in the Cann River, a sand bed river transformed by large-scale channel incision following floodplain clearing and removal of large wood from the channel during European settlement. The monitoring data used in this study captures channel change that occurred between 2011 and 2023, after a second phase of grade control structures were installed and includes several flood events and the impacts of the 2019/20 black summer bushfires.

Study area and grade control works

The floodplain reach of the Cann River is a 20 km long (approx.) section of sand bed river, located adjacent the Cann River Township, East Gippsland (Figure 1). The floodplain reach is bound upstream by a bedrock gorge within Coopracambra National Park, and downstream by a bedrock gorge within Croajingalong National Park. Clearing of riparian and floodplain vegetation and removal of large wood from the Cann River caused the Cann River to pass several geomorphic thresholds, triggering a phase of incision. Incision transformed the Cann River from a meandering, fine grained, low energy and aggrading waterway (similar to the contemporary Thura River) into a significantly deeper, wider and steeper waterway. Channel change resulted in a 360% increase in depth, a 240% increase in channel slope, a 700% increase in channel capacity and in some sections, up to a 150-fold increase in the rate of lateral channel migration (Brooks *et al*., 2003).

Successive phases of intervention since the 1970s have used rock beaching, alignment training and a combination of timber and rock groynes to limit the rate of channel widening. A large flood in 1998 renewed incision and motivated substantial program of works by the East Gippsland Catchment Management Authority. Those works consisted of a grade control program that utilised two types of structure: rock chutes, which localise an oversteepened section and hydraulic jump over armoured sections of the bed, preventing incision, and intermediate structures; rows of piles that span the channel bed.

Grade control works were installed in two phases (See Figure 1 and Figure 2):

- four major grade control structures, nine intermediate structures and a vegetation establishment and management program were installed in the reach upstream of the Princess Highway Bridge in 1999. The primary grade control structures were based on an estimated long-term bed grade in the Cann River. The bed grade adopted for the design of the 1998 flood recovery program was 0.0013 m/m (refer figure 2) i.e. less than the observed 0.0015 to 0.0017m/m grade observed in the system.
- nine additional intermediate structures were installed in the reach downstream of the Princess Highway Bridge, accompanied by installation of large wood (logs) aimed at creating localised scour for habitat in 2010. The location and number of grade control structures was designed based on what was observed at the time as a developing bed grade of between 0.0012 and 0.0006m/m.

Each of the intermediate structures comprised 2 rows of piles across the river located approximately 10 metres apart. The section between the rows of piles and the bed immediately downstream of the structure were filled with loose rock.

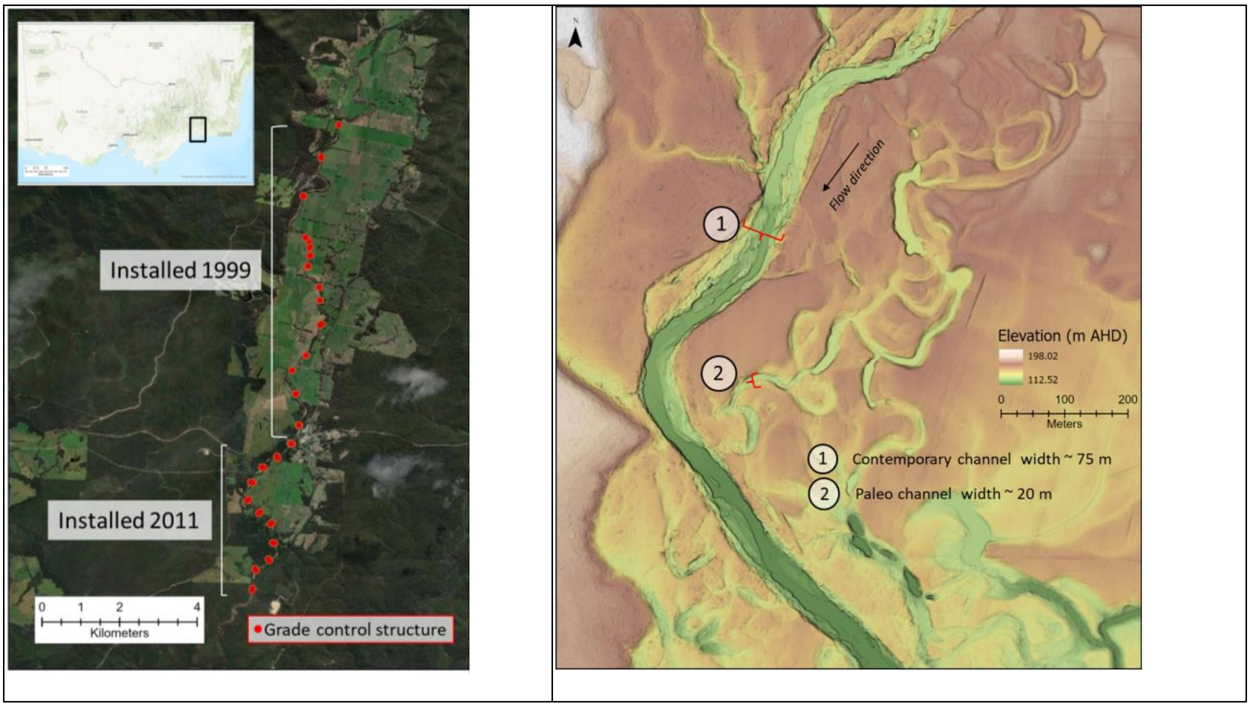

Figure 1.Cann River location, structures and channel width assessment

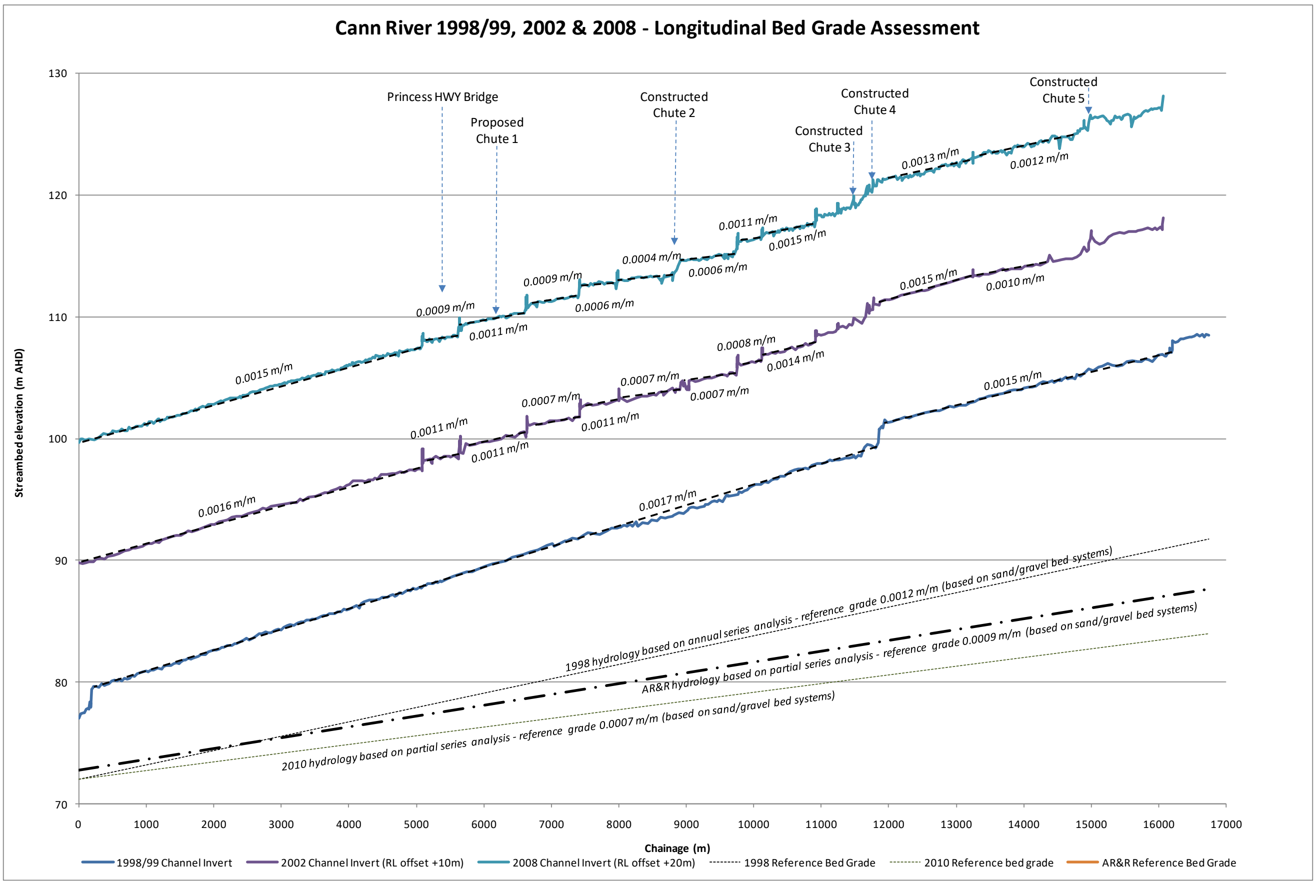

Figure 2 Cann River bed grades 1998 to 2008 and bed grade analysis: note elevation of 2002 and 2008 bed grades have been offset vertically by 10m and 20m respectively to aid visualisation.

The aim of the rock chutes, which are larger and more expensive to design and construct than the intermediate structures, is to locally fix grade and prevent incision. The aim of the intermediate structures

(Figure 3D) was to limit (but not halt) the rate of bed incision. Limiting the rate on incision allows for the grade of the channel bed to adjust while, in theory, promoting vegetation establishment in the backwater of the structures. Intermediate structures in the upstream reach are intended to compliment the rock chutes and prevent the toe of the chutes from being undermined (Figure 3C). The intermediate structure in the downstream reach were intended to limit the rate of incision that would be triggered by a reduction in sediment supply from the upstream reach (i.e. the downstream structures address the unintended consequences of halting incision in the upstream reach).

An assessment undertaken by the East Gippsland Catchment Management Authority in 2010 (S Phillipson pers. comm) found the floodplain reach of the Cann River to have unit stream power within and or close to the typical range, found by Hardie (2004) for stable alluvial sand bed stream systems (i.e. stream systems not subject to accelerated rates of channel change) subject to:

1. the presence of instream and riparian vegetation, and
2. the system being transport limited i.e. that there being an ongoing bed load sediment (sand) supply to the reach

However, it was noted that there were several cross sections that exceeded the range of unit stream power typical for such systems and that some ongoing channel adjustments could be expected.

Methods

This study used a variety of monitoring data to quantify the changes in longitudinal bed profile, sediment storage and the type and extent of vegetation between 2011 and 2023. The monitoring data used to construct this pattern of change include:

- Historical records of channel intervention and morphology from published literature and consultancy reports undertaken between 1997 and 2023.
- Repeat field observations and photos captured in 1998, 2010, 2011, and 2023.
- Repeat LiDAR surveys for captured in 2011 and 2023. Note that additional LiDAR surveys were also captured in 2018 but we have chosen to utilise the more recent (23023) surveys.
- High-resolution aerial imagery captured at the same time as the respective LiDAR surveys.

Historic photos were compiled so that the approximate channel dimensions, extent of vegetation and the calibre of bed sediment could be estimated at key locations (largely centred on instream structures). Photos of channel form, vegetation and bed sediment were captured for the entire reach upstream of the Princess Highway bridge in late 2023.

Longitudinal profiles of bed elevation were extracted from the 2011 and 2023 LiDAR-derived digital elevation models (DEM). Water levels at the time of each survey mean that bed elevation in some channel sections could not be captured. The 2011 LiDAR survey was conducted in the waning stages of the Millenium drought, when water levels were very low and much of the bed was exposed. Water levels at the time of the 2023 survey were similar to those during the site visits in late 2023, when water depth in much of the channel was observed to be in the order of 0.2 m. While not free of error, comparison of the 2011 and 2023 LiDAR derived elevation profiles does provide a good measure of change in bed elevation.

A DEM of difference was established by subtracting the 2023 DEM from the 2011 DEM using the freely available geomorphic change software of Bailey *et al.,* 2020. Areas where water obscured the channel bed in 2023 were excluded from the differencing calculation. Change in total sediment storage was calculated by first defining a total of 32 sub-reaches along the river and then summing the volumetric change in sediment storage within all 1m grid cells within each sub-reach. Error assessment and error propagation were not performed as relevant input variables were not available for the 2011 LiDAR survey. The boundaries of these reaches were defined by the location of rock chutes or intermediate structures. Given that the length of sub-reaches varied, we normalised the change in sediment storage between 2011 and 2023 by the total area of channel bed within each reach. Change in sediment storage are reported in units of m^3/m^2.

Results

The results of our analyses have been organised in order of increasing quantitative rigour below. We begin with describing the condition of rock chutes and intermediate structures and the pattern of sediment calibre from upstream to downstream, observed during site visits in 2023. We also integrate the results of repeat aerial imagery in this section to clarify how channel form has changed. We then present comparison of the 2011 and 2023 longitudinal bed profiles before describing how the net volume of sediment stored in the study reach changed between 2011 and 2023.

Field observations and repeat aerial imagery

Exposed bedrock and coarse gravel dominate the upper reaches of the study reach (Figure 3A), compared to a dominantly sand bed prior to 1998. Sediment calibre generally fines in a downstream direction and the bed is largely free of bedrock outcrops and is sand dominated from 3 kilometres upstream of Chute 5 onwards (Figure 3B). All rock chutes were intact (Figure 3C) and backwaters, approximately 1 m deep, were present immediately upstream. The condition of intermediate structures varied and the crest height of the structures, marked as the elevation of the rock boulders placed between the rows of piles, was up to 1 m below the top of the piles (Figure 3D).

Figure 3.Coarse gravels that dominate the upper section of the study reach (A), sandy sediment downstream of Chute 5 (B), looking upstream at a rock chute (C), the crest of an intermediate structure which has lowered by ~ 1m (D). All photos captured November 2023.

Aerial imagery captured in 2011 and 2023 confirms the loss of sand and decrease in bed level at each of the intermediate structures (Figure 4). Beds of *Phragmites* that had colonised sand deposited immediately upstream of the structures in 2010 were largely gone by 2023 but at some structures, *Phragmites* patches had been replaced by woody vegetation. Bed erosion was concentrated between existing terraces that were already in place by 2010, with only minor erosion at the toe of those terraces.

Figure 4. Changes in bed structure and vegetation at two intermediate structures. Aerial imagery captured in 2010 and 2023.

Longitudinal profile

Comparison of the 2011 and 2023 longitudinal profiles revealed a stark pattern of bed level lowering along the entire study reach (Figure 5, Figure 6). The crest elevation of all intermediate structures appears to have dropped, but incision was greatest immediately downstream of each intermediate structure, producing a step-like profile by 2023. The pattern of greater bed level lowering downstream of structures led to an overall decline in grade between all structures, but the total magnitude of incision was greatest in the reach downstream of the Princess Highway (Figure 6). While the crest of the rock chutes remains intact, the longitudinal bed profile (Figure 5) indicate that there has been some bed lowering at or immediately adjacent the crest. With the exception of chute 2, the 2011 and 2023 profiles at the crest of each chute overlap, suggesting that sediment (rather than rock) has been eroded from the bed immediately adjacent the crest. The reason for the slight mismatch in bed profile at chute 2 is unclear, and may be a result of uncertainty in the corresponding DEMS.

Change in sediment storage

The unit change in sediment storage in each sub-reach (where a sub-reach is the area between successive intermediate structures, or a 500 m length – whichever is less) revealed net sediment loss in all sub-reaches (Figure 7). The magnitude of that loss in sediment storage declined in a downstream direction so that upstream reaches had lost, on average, double the unit volume of sediment than downstream reaches between 2011 and 2023.

Scouring occurred along much of the channel bed throughout the study reach (as evident by the changes in longitudinal profile elevation), which, in some areas, led to deposition on some of the adjacent benches. Erosion was also focused on the outside of meander bends, while relatively minor levels of deposition occurred on the opposing point bars. Together, the changes in bed elevation and bank erosion resulted in the net export of approximately 547,000 m^3 of sediment from the study reach between 2011 and 2023.

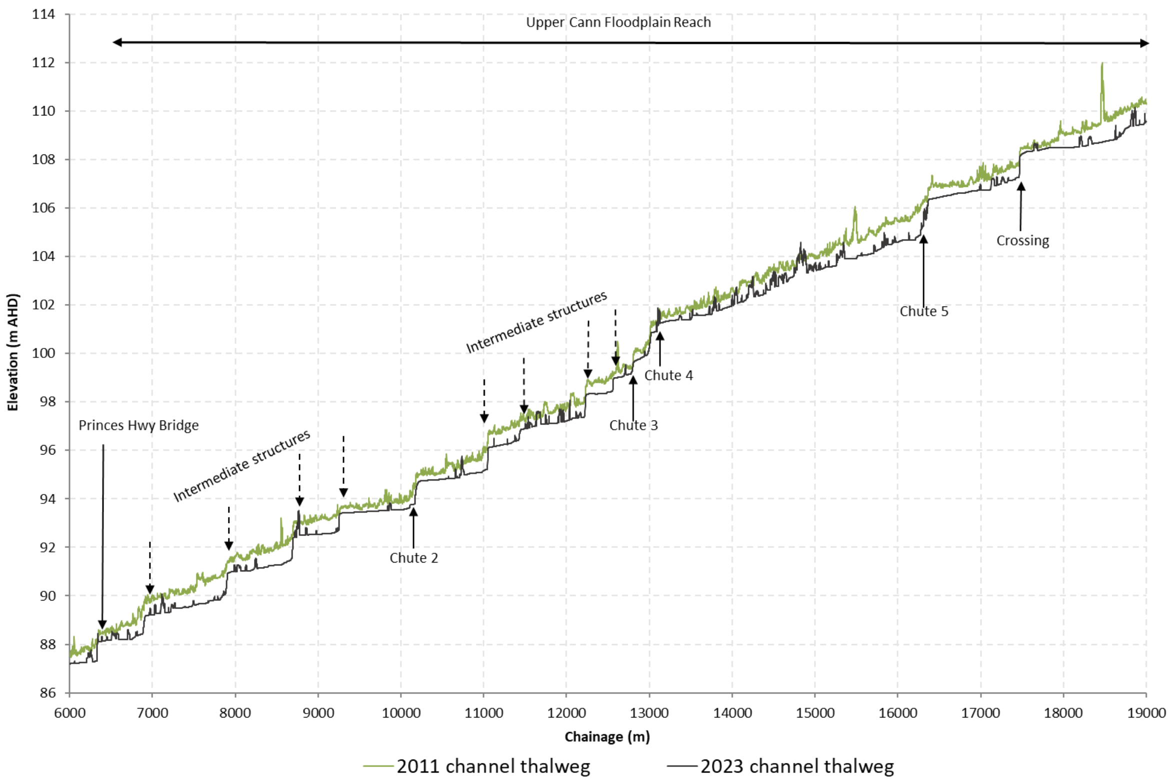

Figure 5. Longitudinal profiles extracted from DEMs surveyed in 2011 and 2023 for the reach upstream of the Princess Highway Bridge.

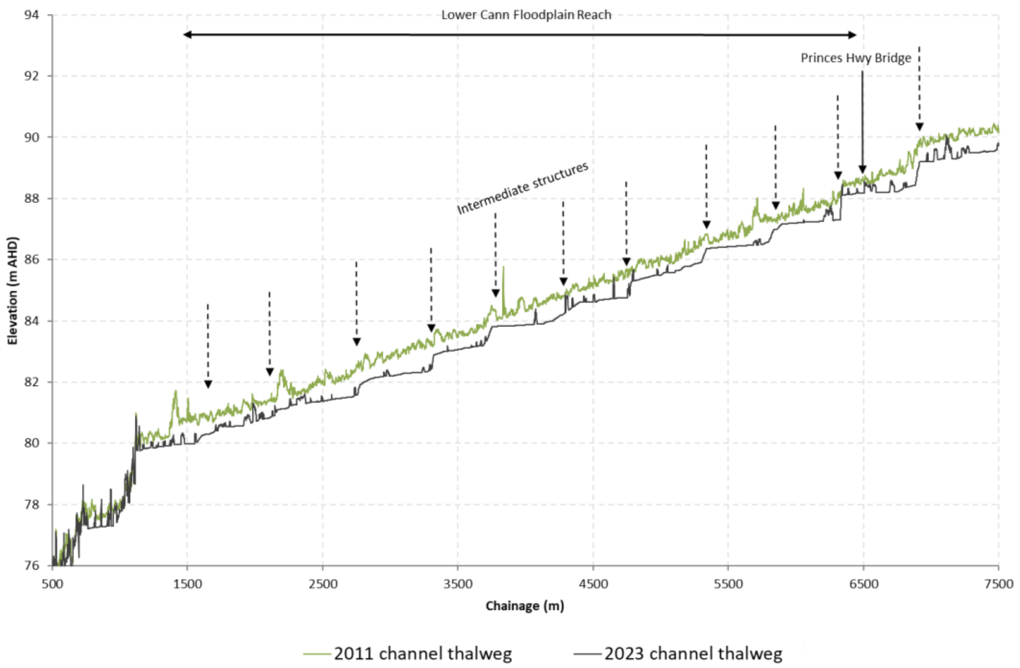

Figure 6. Longitudinal profiles extracted from DEMs surveyed in 2011 and 2023 for the reach downstream of the Princess Highway Bridge.

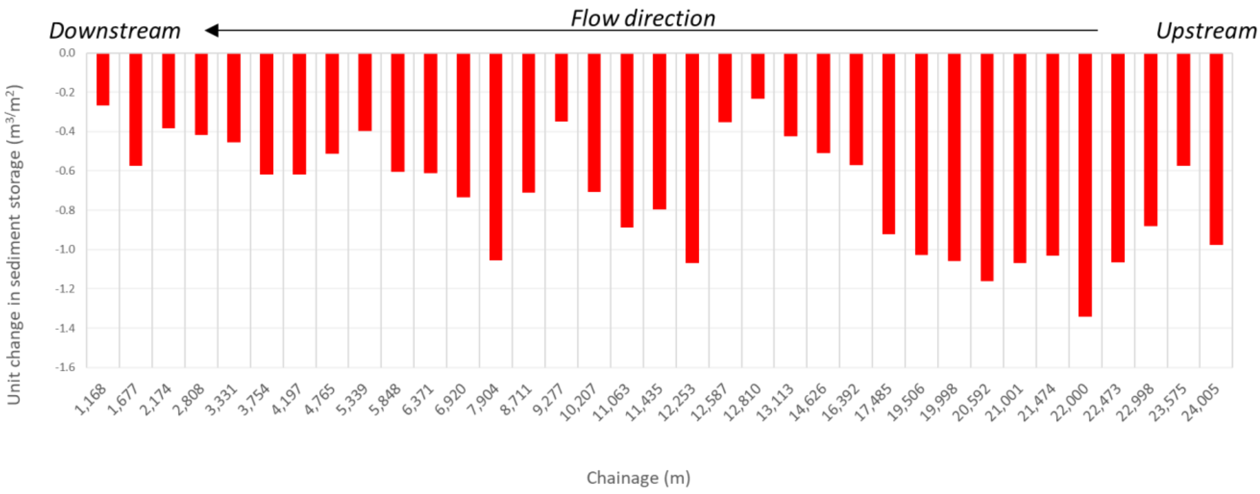

Figure 7. Unit change in sediment storage in each sub-reach of the Cann River between 2011 and 2023

Discussion

A simplistic conceptual model of channel change in the Cann River following European settlement was developed to aid communication of processes in the system. This model is based on our review of the literature and contemporary observations and is shown in Figure 8.

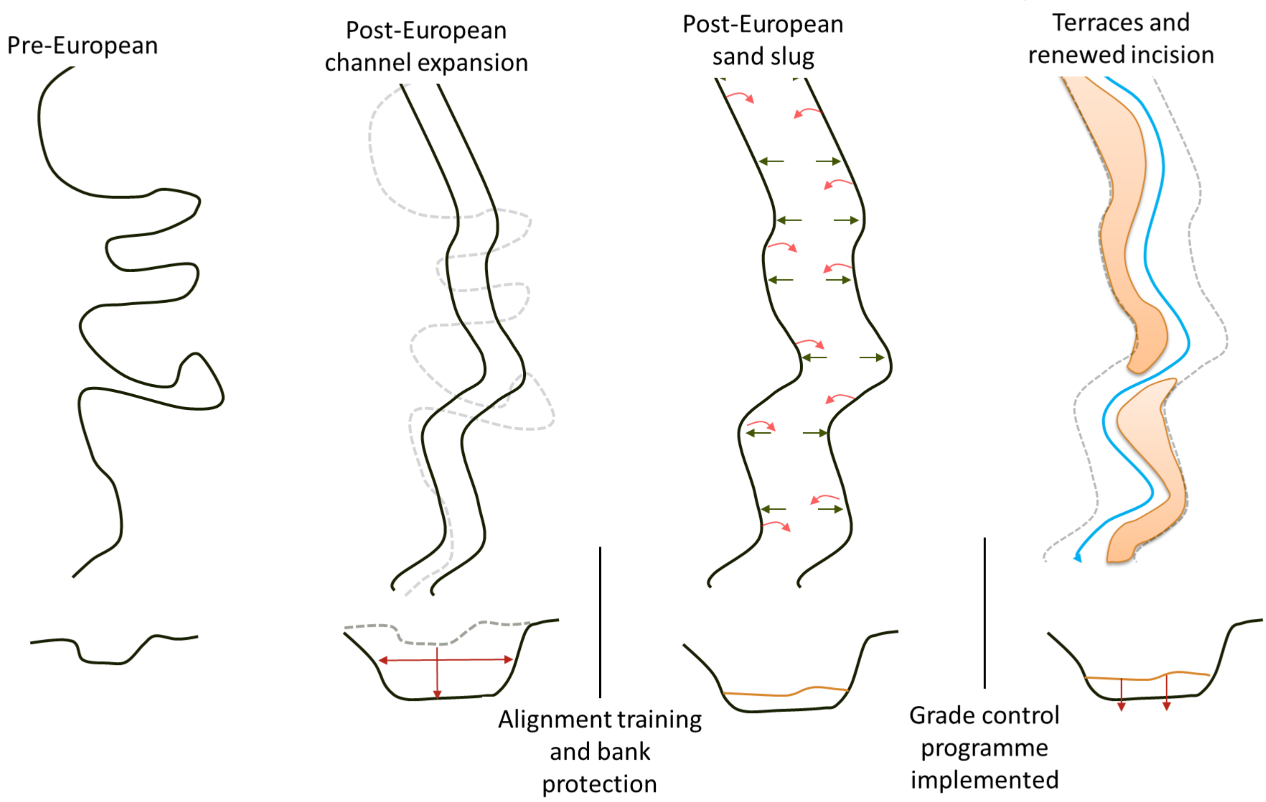

Figure 8 Conceptual model of post settlement Cann River channel change

Our working hypotheses on contemporary geomorphic processes within the reach are that:

1. The floodplain reach of the Cann River has been impacted by post European settlement including:

   a. Channel change in the form of channel incision, driven largely by clearing of vegetation and removal of instream timber/ wood from the floodplain reach.
   b. Incision triggered channel straightening as successive meanders were cut off, which caused channel grade to increase, accelerating the overall rate of incision.
   c. Elevated sediment supply derived from bank erosion, itself a by-product of incision.
2. The supply of bed load sediment (sand) to the floodplain reach of the Cann River is now declining. Evidence for this hypothesis is the observed coarsening of the bed of the Cann River since 1998 and the decline in the extent and rate of bank retreat in the reach (which was the primary driver of increased sand supply to the reach).
3. Despite the construction of grade control structures, and accompanying revegetation program, the sediment transport from the reach remains elevated over the bed load sediment supply. This means that the Cann River has been sediment starved. The evidence for this hypothesis is the ongoing net loss of bed load sediment from the reach.
4. The implication of an ongoing mismatch between sediment supply and transport capacity will be continuing downstream-progressing incision. The past incision has been documented using the repeat DEM analysis in this project.
5. Continued incision and associated channel adjustments can be expected in response to the ongoing mismatch between sediment supply to the reach and transport through and from the reach. These adjustments will be interrupted to some extent by the intermediate structures. However, through time and in the absence of further interventions there is potential for these structures to be lost and the larger and more significant grade control structures to be lost.
6. Loss of the grade control structures and the intermediate structures would initiate a renewed phase of accelerated channel change through the floodplain reach with impacts to upstream, downstream and adjoining ecological, cultural and economic values.

Overall, the grade control program in the Cann River appears to have limited the rate of channel incision since 1999. Like all rivers recovering from disturbance, the works in the Cann River were superimposed on an existing trajectory of channel adjustments. Given that the rock chutes and intermediate structures were installed in the bed *after* the bank erosion triggered by earlier incision had delivered large volumes of sand to the reach, the structures were inadvertently stabilising what now appears to a transient pulse of sand that is being flushed from the reach. Successful grade control programs can halt the incision cycle. In the Cann River that incision cycle appears to have been slowed significantly but not halted. While grade control has been effective in the sense that rates of channel change have been limited, we believe that the grade control program has been unable to completely pause incision because sediment supply to the reach exceeds that exported from the reach. More particularly:

- Stream power, and the overall sediment transport capacity of the reach remains high. Sand deposition and vegetation establishment observed circa 2010 was likely the result of a prolonged dry period where transport capacity was lower than wetter periods (such as that between 2010 and 2023).
- The reach is now sediment starved, and the corresponding stable grade at which incision will be halted is lower than the reference grades adopted during the design of the grade control program.

The Cann River example suggests that grade control programs can be used to effectively slow the rate of channel incision in larger rivers with high unit stream power for a period of several decades, but that if a mismatch between sediment supply and sediment transport capacity persists, the stable grade the channel will evolve towards may be much lower than those determined using typical reference grade approaches.

Conclusions

Post European settlement, floodplain clearing and removal of LWD and riparian vegetation triggered a phase of channel incision in the floodplain reach of the Cann River. The downstream-progressing incision caused substantial channel widening, which delivered large volumes of sand to the reach. Incision continued to remove the excess sand delivered to the reach from the bank erosion, causing a lowering of the bed.

Successive phases of interventions have been applied to the system with the aim of halting channel widening and more recently, since 1999, to halt the incision process. The incision control program was based on the establishment of structural works in the form of grade control structures and stabilising vegetation with the expectation of ongoing sediment (sand) supply to the reach.

The long-term data has revealed net sediment loss from the reach associated with an ongoing decline in bed grade and channel incision.

While vegetation has been established in the reach, this is limited to the benches and not to the active channel and bed. We have not observed any significant contraction in the channel bed between 2011 and 2023. Perhaps more importantly the monitoring has revealed a coarsening of the streambed upstream of the reach, suggesting a decline in bed load (sand) sediment supply to the reach. Ongoing incision and widening can be expected in the reach until the channel form adjusts and transport capacity of the reach matches sediment supply.

The monitoring program provides essential information on the ongoing processes in the Cann River aiding the development of a prognosis of the future. Further investigations are required to identify long-term bed load sediment supply to the reach. Any refinement of management interventions should be based on estimations of long term sediment yield and the sediment transport capacity of the subject reach.

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