Choking the River Murray: explaining the declining flow capacity through the Barmah-Millewa Forest

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Key Points

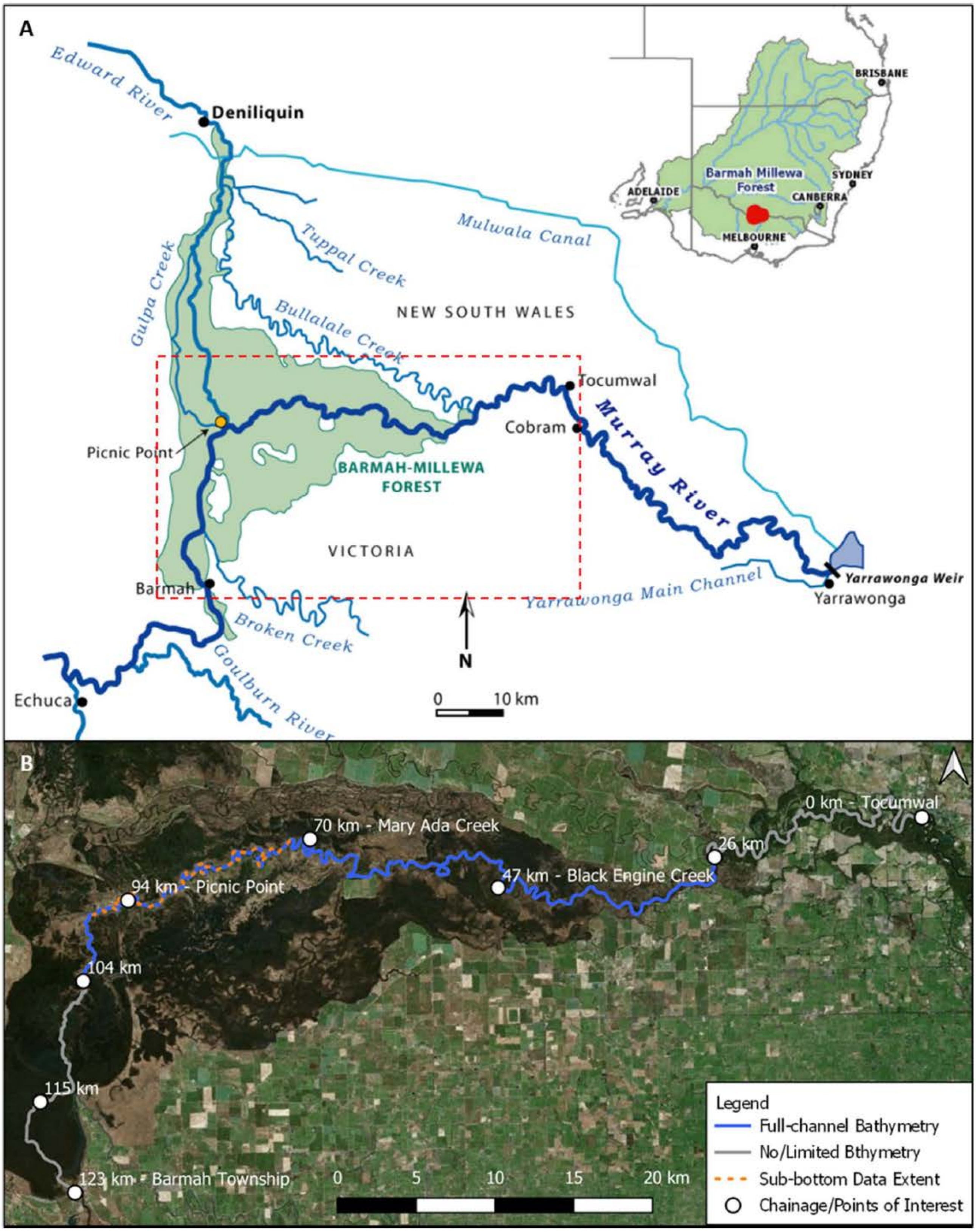
- The Barmah Choke is a narrow section of the River Murray's channel that restricts flow capacity from the upper to lower Murray River.
- The flow capacity of the Choke has declined nearly 20% since the 1980s, which imposes a constraint on regulated flows supplied down-valley.
- Whilst there could be multiple factors explaining the decline, the most likely is a sheet of coarse sand shallowing the river, much of which originated from historical gold mining.
- The sheet of sand is reducing depth diversity, filling pools up to 5m deep, and degraded the ecological and cultural values of the river.
- The whole length of the river through the Barmah Forest has shallowed over the last 30 years, aggrading by 1.9 m at the upstream end and 0.70 m in the most downstream section of the Choke (about 10% decrease in area).
- The total volume of sand stored between Yarrawonga and Barmah is over 20 million m^3, and the average total annual sand load transported into the 82km long Choke ranges between 130,000 m^3 in a normal flow year to 500,000 m^3 in a flood year (which translates into 2 – 9 cm of aggradation per year).
- Surprisingly, overall, flow regulation has *decreased* the rate of sand transport through the Choke
- Decreasing downstream flow capacity across the Barmah Fan is a natural characteristic of this type of distributive fluvial system but the sand sheet is accelerating the rate of decline.
- Without intervention, conveyance through the Choke will inevitably continue to decline until the river avulses into a new channel.

Keywords

River Murray, Choke, Flow Conveyance, sand-sheet, Barmah-Millewa Forest

Introduction

The River Murray provides water to Australia's largest irrigation systems. Water is released from a series of dams into the River Murray, mostly from the Hume Dam, and then distributed to irrigators and multiple other users. Water is distributed to irrigation systems from Lake Mulwala (above Yarrawonga Weir) (Figure 1), and the balance is passed through Yarrawonga Weir for delivery to western irrigation areas (such as Mildura and Renmark) and also to supply Adelaide. However, about 70 river km below Yarrawonga Weir the River Murray enters the Barmah-Millewa forest, which it flows through for 110 km (Figure 1a). The forest is a low gradient (0.0001 m/m), low-energy, triangular alluvial-fan (Figure 1b). Multiple distributary channels (also called effluent channels) leave the Murray through the forest, carrying water *away* from the main channel and across the floodplain. The result of these flow losses is that the size of the Murray's channel naturally declines downstream (width decreases from 150 m at Yarrawonga to just 40 m at the narrowest point below Picnic Point, Figure 1c). The narrowest section is known as the 'Choke' because it has limited capacity, which constrains the volume of water that can be delivered to the Lower Murray and to Adelaide. Attempts to transfer large volumes of water through this restricted section means that it is flowing at or near bankfull capacity for much of the summer, and most of the distributary offtakes are now blocked by regulator structures to limit flooding into the forest. In the past, bankfull flows (of around 10,000 Ml/d) used to occur 10% of the time in March occurred nearly 90% of the time (Chong and Ladson, 2003, but these flows have reduced in recent years.


A
Edward River
Deniliquin
Tuppal Creek
Mulwala Canal
Gulpa Creek
Bullatale Creek
NEW SOUTH WALES
Tocumwal
Cobram
Murray River
Picnic Point
BARMAH-MILLEWA FOREST
VICTORIA
Barmah
Yarrawonga Main Channel
Yarrawonga Weir
Yarrawonga
Broken Creek
Goulburn River
Echuca
N
0
10 km
BRISBANE
SYDNEY
ADELAIDE
Barmah Millewa Forest
CANBERRA
MELBOURNE
B
0 km - Tocumwal
26 km
70 km - Mary Ada Creek
47 km - Black Engine Creek
94 km - Picnic Point
104 km
115 km
123 km - Barmah Township
0
5
10
15
20 km
Legend
Full-channel Bathymetry
No/Limited Bthymetry
Sub-bottom Data Extent
Chainage/Points of Interest

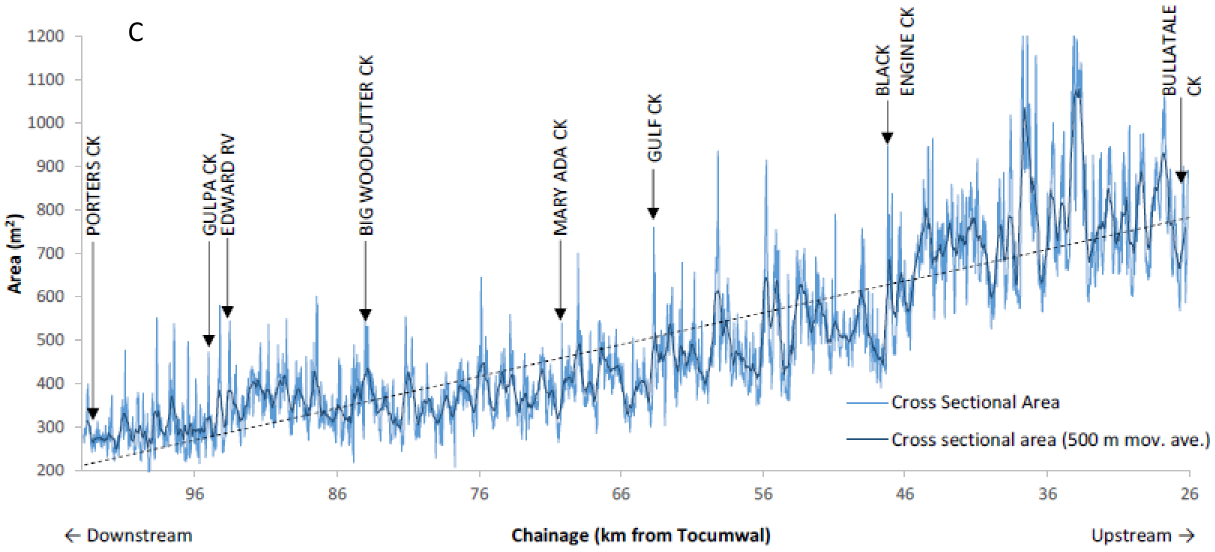


Figure 1. Map of the Murray-Darling Basin showing the location of the Barmah-Millewa forest (MDBA 2008). (B) Map of the Barmah Choke from Tocumwal to Barmah township, showing the coverage extent of key datasets, including the 2020 Sub-Bottom Profiler extent, and chainage distances used in this paper. (C) Downstream decreasing cross-sectional area through the Barmah-Millewa forest from Bullatale Ck to the 104 km point showing a remarkable 75% decrease in cross-sectional area.

The flow capacity of the Choke has been declining. Releases from Yarrawonga Weir must currently be kept below 9,200 ML/d to keep the water in the channel at Picnic Point (Figure 1b); this limiting volume has reduced by 18.6 %, from the 11,300 ML/d that could be kept in the channel in the early 1980s (this issue is covered in detail in MDBC, 2009; SKM, 2012; Water Technology, 2020a; Grove 2020). Small changes in flow capacity have a range of potential environmental, social, economic and financial impacts.

Many factors could contribute to decreasing conveyance. These processes have been reviewed by Water Technology (2020) and Grove (2020) who conclude that erosion and breaching of the natural levee by channel widening could be a factor. However, recent bathymetry commissioned by the MDBA (Acoustic Imaging 2020) shows spectacular sand waves migrating down the stream bed (Figure 2) and Grove (2020) concludes that aggradation of coarse sand in the bed is likely to be a major contributor to the decreasing conveyance through the Choke. In a separate report Grove (2021) concludes that the coarse sand is likely to have come from two main sources. The first is from a pulse of sand from historical gold mining that would have been moving down the river since the 1880s, and predates the Yarrawonga Weir. The second source is from erosion of the riverbanks, particularly below Yarrawonga Weir. The Murray channel between Yarrawonga Weir and Bullatale Creek has widened by an average of 30-40 m (47%) since 1876, whilst average widening in the Barmah Forest has been lower at 3-15 m or 9%.

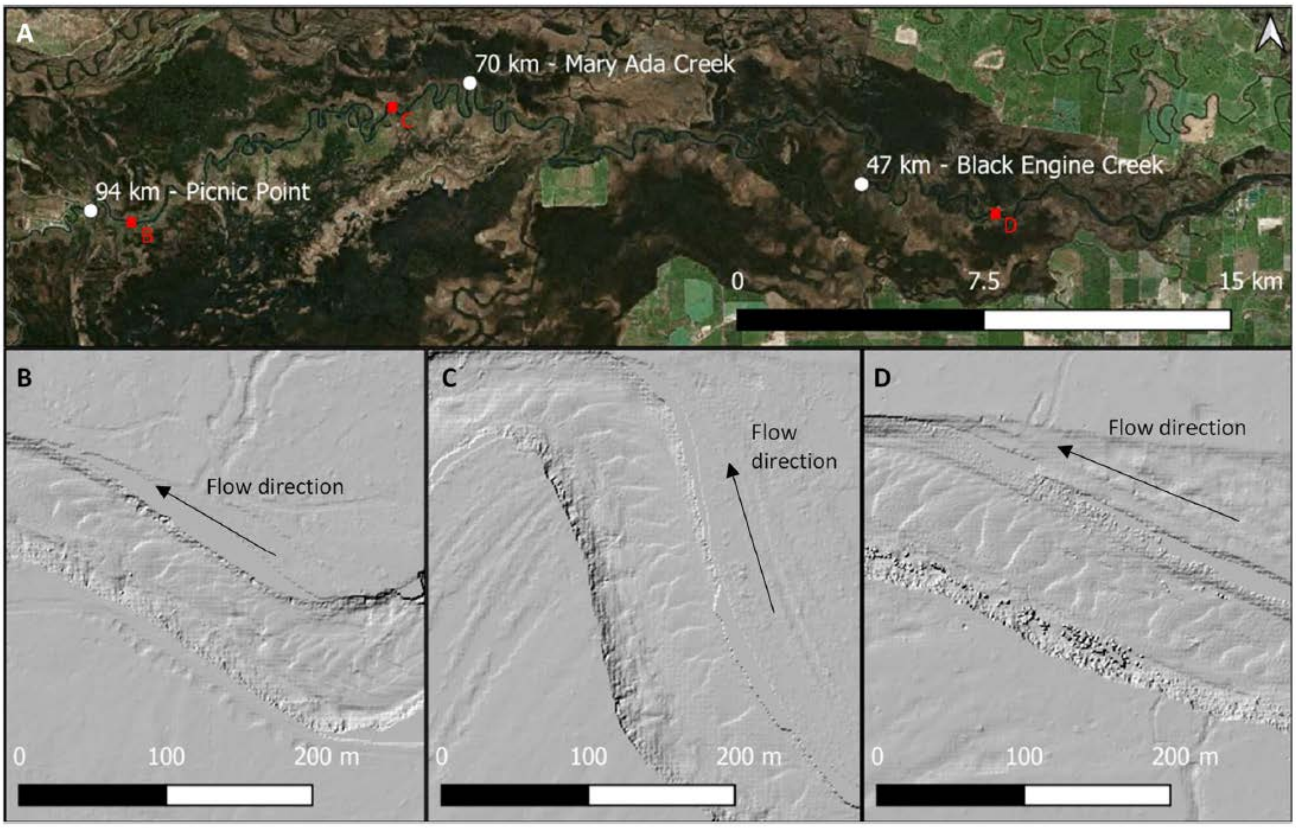


Figure 2: Sand dune bedforms in the Barmah Choke. (A) Map of the Choke upstream of Picnic Point, showing the location of panels (B-D) shaded relief maps of the channel bed showing dunes.

Responding to the discovery of this sand in the channel, the MDBA commissioned two studies: one on sources of sand (Grove, 2021), and another by Streamology on sand movement through the Barmah Forest (Figure 1) (Gower et.al. 2020). These two reports are the focus of this paper where we: (a) estimate the volume and spatial distribution of bed sediment currently stored in the Barmah Choke; (b) estimate the rate at which sediment moves down the River Murray and through the Barmah Choke (c) predict the consequences for the future capacity of the Barmah Choke. We will briefly describe our methods at the start of each section.

Volume and spatial distribution of sand

Elevation measurements were extracted from available bathymetric and lidar digital elevation models (DEMs) to determine channel dimension metrics for the Barmah Choke including bed elevation, bankfull width and bankfull depth. Average bed sediment thickness measurements were generated from sub-bottom profile data (Acoustic Imaging 2020).

Bed Forms

The depth of sand can be reconstructed from bathymetric surveys.

- The bed is dominated by highly regular *dune-like bedforms* with amplitudes ranging from 0.5 to 1 m, and with wavelengths of 20-40 m.
- Samples of bed material along the Choke show that these dunes are dominantly composed of *coarse sand* (200-2,000 µm), although there is 20% gravel in the most upstream sample, and 30% silt and clay in the most downstream sample.
- Mean *bedload layer thickness* is 1.17 m (S.D. 0.5 m) with a minimum of 0.3 m and a maximum of 4.9 m. Sand thickness increases slightly downstream from 1.12 to 1.22m.

- Importantly, the deepest sand occurs at *river bends* where former pools of the river are now filled with 3-5 m of sand. Sand depth is also high at anabranch offtakes.
- The average proportion of the channel cross section occupied by bedload 17 % (standard deviation 6 %), and this is slightly higher downstream where the cross-section area is smaller.
- The *total estimated volume* of sediment stored in-channel along the 24 km of the Barmah Choke covered by the data, is 2 million m^3 (an average of 120 m^3 of sand per metre of channel length), with slightly more volume stored in the wider channels upstream. Volume estimates from more recent bathymetry that extends up to Yarrawonga Weir suggests that there is more than 20 million m^3 of sand in the 190 river kilometres between Yarrawonga and Picnic Point.
- Grove (2021) investigated the source of the sand. He concluded that about 9% of the sand could have come from bank erosion below Yarrawonga between 1876 - 2015, about 6% could have come from erosion of sandy point bars below Yarrawonga between 1940 - 2017, and the remainder must have come from the catchment before the construction of Yarrawonga Weir was completed in 1939. Whilst much of the sand will be natural, he concludes that the likely source of most of the sand was from historical gold mining in the catchment, combined with post-European channel and gully erosion.

We interpret the sand in the Barmah Choke as being an anthropogenic pulse (or slug) moving by dune-migration. Historical descriptions of this reach of river describe a variable bed of clay and sand with pools up to five metres deep. This has been replaced by a fairly uniform sheet of sand. The sand slug peak has not moved downstream of Picnic Point yet because the bathymetry clearly shows that there were no large dunes there, and the bed still retains its complexity with scour pools, clay-ledges, and submerged wood clearly visible (Water Technology 2020a). Comparing an 1876 bed survey of this reach with a 1976 survey shows that most of the bed had already aggraded by nearly a metre by 1976.

Impact of the Sand Slug (or Sheet)

This investigation began with the measured reduction in flow conveyance in the Choke, but the sand-pulse will have other impacts on the River Murray that are still being explored. The typical impacts of such sand slugs are reviewed by Sims and Rutherfurd (2017). The most obvious physical effect is the reduced depth of pools. This would be likely to have an effect on fish and other biota in the river by altering habitat, smothering large-wood, and altering flow velocity distributions. By pushing more water into distributary/effluent channels the sand might accelerate the development of avulsive channels. As we discuss below, an avulsion of the river around the Choke is inevitable eventually. Another common effect of sand slugs is channel widening. The Murray right through this reach has widened substantially (Grove, 2020) but this could also be related to flow regulation. Overall, the sand-slug is further degrading a river that has already been degraded by many processes. It is also important to note the significance of this section of river, referred to as the 'Pama Narrows', to traditional owners the Yorta Yorta people (Weir, 2009).

The rate of sediment movement through the Choke

How fast is sand moving into the Choke? The instantaneous sediment transport rate (kg/s) was calculated at fifteen cross-sections (a well as up and downstream of key offtakes) using multiple sediment transport equations (Yang 1973; Ackers & White 1973; van Rijn 1984; Bagnold 1980; Myer-

Peter and Muller 1948). Input variables for the sediment transport equations were drawn from the MDBA's linked 1D–2D hydraulic model (MDBA/Water Technology, 2020). Transport rates were calculated for four steady-state flow scenarios, intended to cover a range of typical discharge conditions at the upstream boundary of the model (at Tocumwal): winter low flow (2,500 ML/d), regulated irrigation flow (10,000 ML/d), 20,000 ML/d and minor flood level (60,000 ML/d). Results from the equations were compared with a method that uses the celerity of migrating dunes as an independent check on transport rates. Pre and post-regulation transport rates were estimated by using 'Without Development' (i.e. natural) flow scenarios provided by the MDBA (Gower et al. 2020).

The model results were consistent between sediment transport models, and were very similar to the independent method using dune celerity. Figure 3 shows the averaged transport rates for all equations. Mean transport rates upstream (at the entrance to the Barmah-Millewa Forest) range from 12 kg/s (2,500 ML/d scenario) up to 124 kg/s (60,000 ML/d scenario) but all transport rates converge to between 3 and 8 kg/s at the most downstream point in the Choke. For regulated irrigation discharges (<10,000 Ml/d) the transport rates are constant downstream, whilst for larger discharges that connect with offtake channels, there are step change decreases in transport rates downstream. These step decreases correspond distributary channels (offtakes) like Gulf Creek, Mary Ada Creek and the Edward River (Figure 3) where flow is diverted from the main channel, decreasing transport capacity. Thus, sediment transport in the narrow downstream sections of the Barmah Choke are very consistent, irrespective of the size of flows or floods passing down the river. This is because so much flood water is lost to distributary channels and the floodplain. The key result here is that floods transport more sediment into the Choke than can be carried through the Choke, resulting in inevitable sand storage and declining channel capacity.

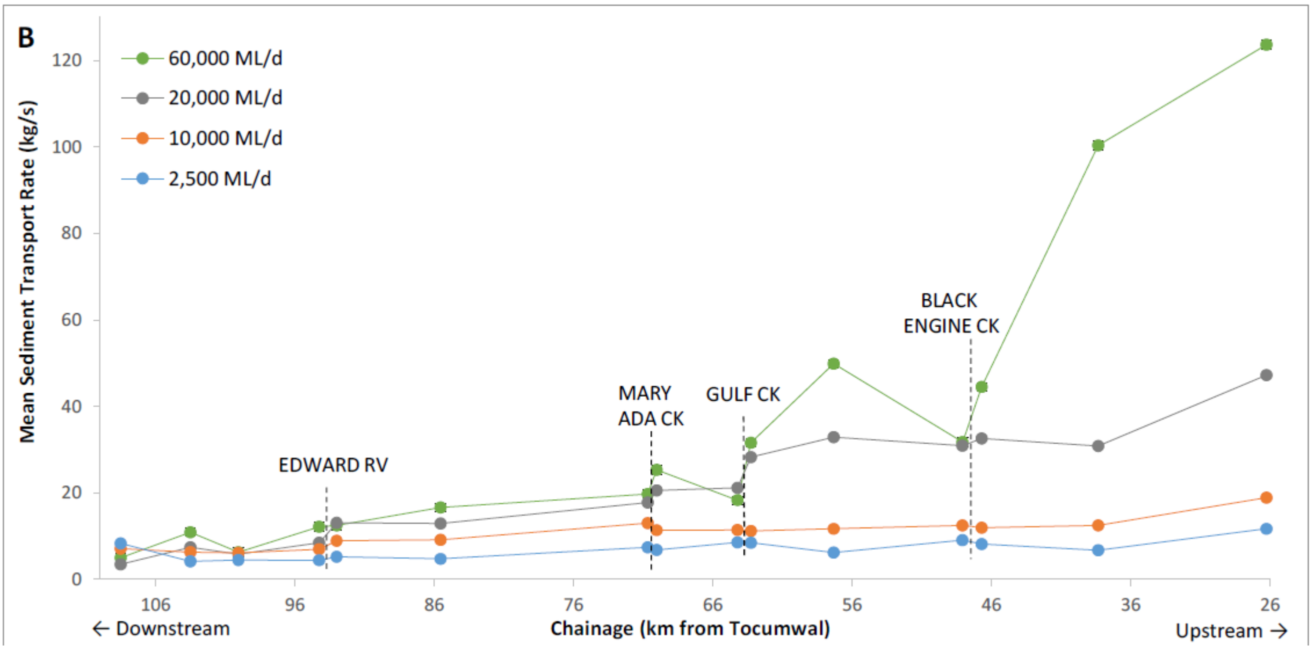


Figure 3: Sediment transport modelling results (mean of all transport equations) for all four discharge scenarios.

We expected to see more sand accumulation in the Choke than upstream but this is not the case. Sand is accumulating throughout the length of the channel below Tocumwal. In absolute terms there is more deposition in the wider upstream half of the forest than the narrower downstream reach.

During non-flood years estimated vertical aggradation can be as much as 5-6 cm/year in the widest upstream parts of the forest, compared to around 2 cm/year for the narrowest downstream sections (Figure 4b). After a large flood year aggradation rates may be substantially higher, at 9 cm/year upstream and 4.5 cm/year in the downstream Choke (Figure 4a). Thus, sediment transport modelling suggests bed aggradation over the last 30 years of around 70 cm for the most downstream section of the Choke, compared to 1.9 m at the upstream end (Table 1).

Table 1: Estimated total deposition volumes and aggradation amounts over 30 years (between 1991 and 2020) for five zones along the Barmah Choke (note Zone 1 begins 26 km below Tocumwal and Zone 5 ends near Barmah downstream), based on actual regulated discharge.

Zone 1 26-38 km	Zone 2 38-57 km	Zone 3 57-71 km	Zone 4 71-93 km	Zone 5 93-108 km
Deposition Volume (m^3)				
2,846,563	964,985	881,810	1,327,949	681,573
Aggradation (m)				
1.898	0.484	0.721	0.755	0.736

Effects of Flow Regulation on sediment transport

Our expectation was that the long-duration of regulated bankfull flows would dramatically increase sediment transport rates into, and through, the Choke. Surprisingly, this is the not the case. Large dams reduce the size of floods entering the Barmah Choke. Because floods transport most of the sand (Figure 3), this has the effect of reducing the total volume of sediment transported into the choke by up to 100,000 m^3 per year (about 20%), even though in isolation long-duration irrigation flows do increase sand transport *into and through* the Choke by about 10,000 m^3 per year. Thus, flow regulation means that of the 20% *less* sand that comes into the Choke (due to reduced flooding) there is still slightly more sand moving *through* the choke (due to long-duration bankfull irrigation flows).

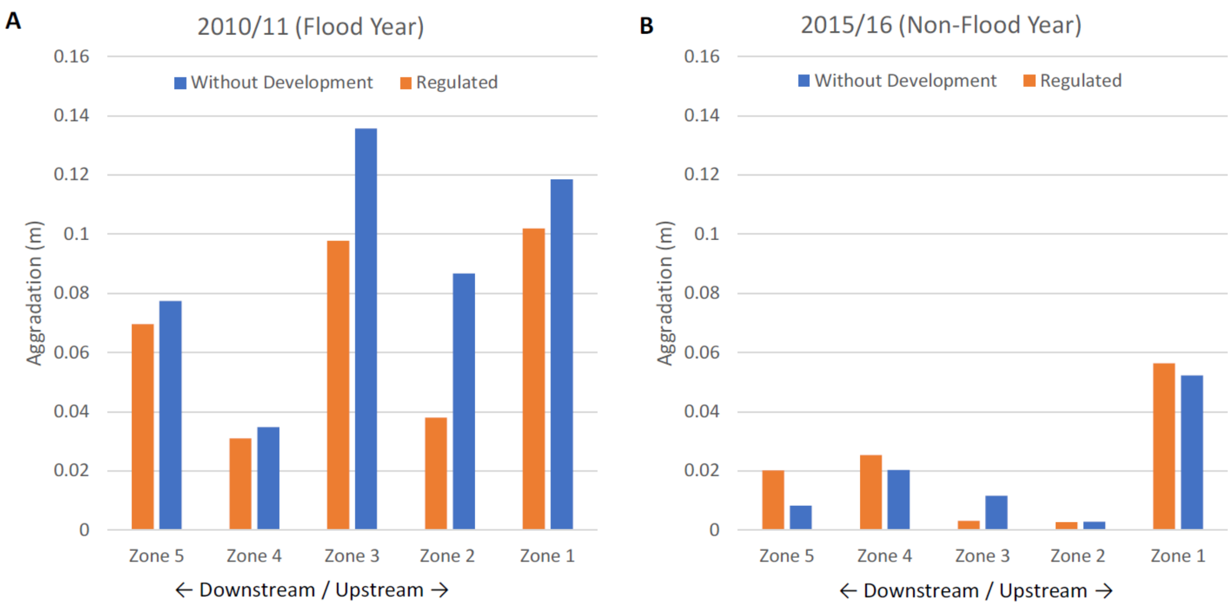


Figure 4: Estimated annual aggradation for five Barmah Choke zones for (A) the 2010/11 flood year, and (B) the 2015/16 non-flood year, based on actual regulated discharge (orange bars), and modelled

'without development' flows (blue bars).

The sand sheet has accelerated a natural filling process

What is the longer-term future for the sand moving down the River Murray through the Choke? This question must be answered in the context of the broader geomorphology of the Barmah-Millewa alluvial fan (i.e. the Barmah-Millewa Forest). Over the last decade there has been considerable research work on what are termed distributive fluvial systems (DFS) (Weissmann et.al., 2010). These systems are characterised by "*a radial network of channels and associated deposits dispersed below an apex where a river emerges from valley confinement and enters a sedimentary basin*" (Davidson et.al. 2013). Hartley et.al. (2010) has mapped over 400 DFS around the world. These DFS have also been referred to as megafans, and low-angle alluvial (or fluvial) fans in geomorphic and sedimentological literature, but they tend to have an apex-to-toe distance over 30 km. The Barmah Fan is a beautiful example of a DFS and is nearly 50 km in apex-to-toe distance. DFS are characterised by flow *distributaries* (often called offtakes or effluents along the Murray) as opposed to flow *tributaries*. Davidson et al. (2013) states that: "*downstream channel changes on DFS can include: a decrease in discharge, a decrease in bed material transport and calibre of sediment, a decrease in stream-power, an overall decrease in channel width, and an overall decrease in channel depth (but this is not as systematic as decrease in width)*" (p.83). This exactly the pattern of channel changes that we see in the Murray across the Barmah-Millewa DFS. Recognition that the Barmah Fan is a DFS is important because, in the past, we believed that the Choke, an Avulsive channel, would gradually increase in size as we see on other avulsive floodplains such as the Ovens River (Schumm et.al. 1996).

The critical decrease in sand transport downstream occurs because the Barmah-Millewa forest is a distributary system where flow is lost to multiple distributary offtake channels along its course. This decants flow while leaving the same amount of bed sediment in the channel with less energy available to transport it. This contrasts with the typical longitudinal trend where most streams increase in discharge and channel dimensions down-valley. The main channel in these distributary systems becomes less and less capable of transporting the sediment delivered to the fan, leading to eventual avulsion. The result is that the sediment that drove the avulsion will then be stored in the abandoned channel. The new avulsion channel will again progressively fill with sediment until it avulses. This is what is happening on the Barmah-Millewa DFS. The downstream decrease in transport capacity is an inevitable characteristic of this type of system. Because there appears to have been an increase in the volume of sand delivered to the fan due to anthropogenic erosion and mining, then that increase (sand-sheet) simply serves to accelerate the process of abandonment. In other words, there is little prospect of the sand-sheet in this section of the River Murray migrating downstream in this system and the conveyance problem resolving itself. Instead, the Choke will progressively fill with sand, forcing more water from the channel leading to an inevitable avulsion. We conclude that conveyance of water through the Barmah Choke will continue to decline, with up to a 25-35% reduction in channel capacity in the next 30years.

Further investigations of the sand sheet in the Choke could include: (1) field measurements of sand-transport rates (2) environmental and cultural impacts of the sand, and (3) options for solutions (e.g. water diversion or sand extraction) to address the declining flow capacity and bank instabilities and impacts on the surrounding country.

Conclusions

The Barmah Choke is a narrow section of the River Murray's channel through the Barmah-Millewa Forest that restricts flow, with implications that include reducing the volume of water that can be delivered through the River Murray system. Regulated flows through this 110 km long reach often flow at bankfull for several months of the year. The bankfull discharge capacity of the Choke has declined by approximately 20% over recent decades, constraining the ability for flow delivery downstream. Whilst there could be many factors explaining the decline, the most likely is a sheet of anthropogenic sand (>20 million m^3) shallowing the river that probably originates predominantly from post-European gold mining and gullying. Over the last 30 years, this sand-sheet has filled pools by over 5m, shallowing the bed by 1.9 m at the upstream end and 0.70 m in the most downstream section of the Choke over the last 30 years (up to 9cm per year). The sand-sheet has reduced channel cross-sectional area by about 18%. The sand-sheet has degraded (simplified) habitat in the river, and has probably contributed to increased bank erosion. Sand transport rates decline downstream as flow is lost from the main channel into distributary channels. Surprisingly, despite the frequent bankfull flow conditions through the Choke, regulation has decreased the overall rate of sand transport through the Choke because it has also reduced flood peaks. Thus, Europeans have increased the amount of sand entering this section of river, but reduced the rate at which it is transported. Decreasing downstream flow capacity across the Barmah Fan is a natural characteristic of this type of distributive fluvial system but the sand-sheet is accelerating the rate of decrease. Without intervention, conveyance through the Choke will inevitably continue to decline until the river avulses into a new channel.

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